Cyber Physical Social Systems: Towards Deeply Integrated Hybridized Systems

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***Abstract*—Research on Cyber Physical Systems (CPS) has led to quite a number of astonishing technical solutions that are becoming standard in many application domains affecting our everyday life. The technical innovations range from control theory concepts to real-time wireless communication to networked control. Some of the most challenging applications include cooperative autonomous driving and industry automation. Despite all these great findings, our research community frequently lost track on the impact of individual human beings that are an integral part of the systems – both as a user as well as a source of disruption. We thus need a paradigm shift from classical CPS to Cyber Physical Social Systems (CPSS). Studying the impact of CPS on humans and vice versa, hybridization, i.e., machines and human users covering parts of the system function in deep interaction, is required as a novel core concept. This is also a basis for final public acceptance as a key to success of new technologies. We investigate these ideas based on the application domain of cooperative autonomous driving and identify core research challenges of such hybridized CPSS.**

***Index Terms*—Cyber Physical Systems (CPS), Cyber Physical Social Systems (CPSS), Cooperative Automated Driving**

I. Introduction

Cyber Physical Systems (CPS) [1], [2] have been an active research topic for more than a decade. In this scope, lots of interesting application domains have been explored ranging from industry automation to e-health to home automation and to (semi-)automated driving. Even though the technology matured in general, there are still many aspects unsolved and considered fundamental research questions. We are looking at CPS from a networking perspective. Prime applications here can be found in the automotive [3] and the industry automation [4] domains. When considering the core research questions, most challenges can be reduced to distributed control systems and highly delay sensitive applications.

Most recent research on networking focused on the development of even faster networking technologies by increasing data rates to the extreme. This holds particularly for wireless technologies both in the cellular world with current developments in the scope of 5G [5] as well as for short range communications using the IEEE 802.11ac wireless LAN standard [6]. A novel trend is to strengthen the focus on communication delay and reliability. Modern communication technologies and current leading edge research therefore focus on ultra low latencies. In the wired networking domain, particularly in the field of industry automation, this is Time-Sensitive Networking (TSN) [4], which is an offspring of the former audio video broadcasting activities [7]. In the wireless domain, the Tactile Internet initiative has been initiated [8], [9] to add low-latencies to 5G networks with a strong focus on both automotive and industry automation applications.

One major component of the systems, however, has often been ignored or only partially considered: the actual user. There are, however, significant impacts of the human user being part of the CPS. A novel research domain incorporating human interactions has been termed Cyber Physical Social Systems (CPSS) [10]. In this scope, thus, new research activities have been started, for example, on work 4.0 to complement industry 4.0 solutions. In the automotive domain, we see the emergence of Advanced Driver Assistance Systems (ADAS) and even fully automated driving. Again, little focus on what the impact of user interactions, interventions, or more generally public acceptance will be.

In this paper, we focus on what we call *hybridization* of CPSS, thus, the deep interaction of human actions and partially automated technical systems. The change from classical CPS to next generation CPSS will have a strong impact on research activities in the technical domains. Using the automotive application domain as an example, we discuss the impact of human decision making, its interaction within hard real-time systems, and finally the need to also consider soft factors to support public acceptance.

The rest of this paper is structured as follows. In Section II, we introduce the changing worlds considering a typical CPSS system with an inherent hybridized nature of participating systems: semi-automated driving in platoons on a freeway. We continue with a retrospective view on the impact of human decision making when optimizing large scale technical systems in Section III, again sticking with an automotive scenario, namely an traffic information system. In Section IV, we study the requirements on reaction times in hard real-time systems using cooperative driving in a platoon as an example. In a last step, we briefly outline the different perception of decisions made by humans and machines when it comes to, possibly fatal, system failures in Section V.

II. From CPS to CPSS: Use Case Platooning

CPS are considered one of the most challenging engineering challenges in our research community. A prime example in the automotive domain is platooning, i.e., the fully automated driving of multiple cars with minimized gaps in between the

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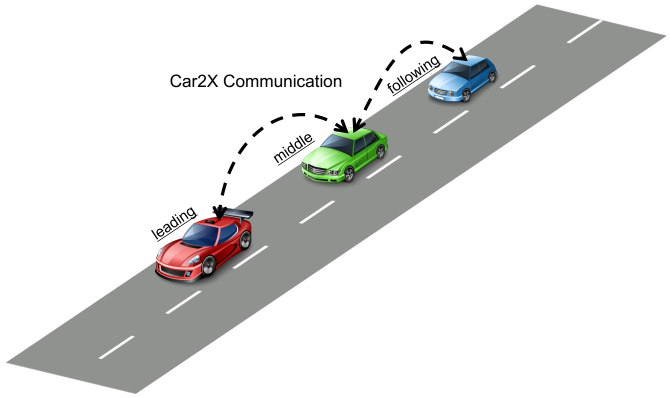
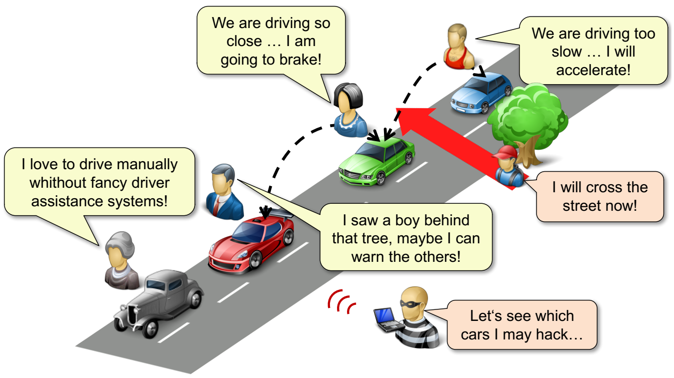


(a) Platooning as a CPS: Cars control their speed and acceleration to build a stable platoon using vehicular networking



(b) Platooning as a CPSS: Human users may influence the system based on desires, capabilities, and even malicious intentions

Figure 1. Transition from CPS to CPSS using the automotive platooning application as an example.

subsequent cars [11]. The control of platoons is considered to be realized by means of a Cooperative Adaptive Cruise Control (CACC) (cf. Figure 1a). From a commercial point of view, the optimized flow of road traffic on freeways (thus, also optimizing the use of the available road capacity) as well as the reduced fuel consumption of both lightweight vehicles and trucks are extremely attractive [12], [13]. Looking from an environmental perspective, the reduced gas consumption comes of course with a decrease in emissions. From the driver's perspective, improved safety might be the key argument for platooning. Vehicular networking (also called Car2X, car to car communication) helps coordinating the cars in the platoon [3], primarily based on broadcast communication [14]. Quite sophisticated protocol designs for solving the distributed control problem have been investigated in this scope [15], [16]. We will get to the specific real-time requirements in Section IV.

When transitioning the CPS into a CPSS, all possible human interactions with the CPS need to be considered [10]. Let us stick with the platooning example. Figure 1b shows selected interactions with the originally completely technical system. Besides of quite natural problems of transitioning from the current road usage to a fully automated one, most prominently the question how to deal with legacy systems, quite a number of social questions are coming up. Considering that the human user needs to be put first, also to increase public acceptance (cf. Section V), the (technical) system must be able to deal with these interactions – hopefully with little impact on efficiency and safety. Overall, we can classify the interactions into the following four groups:

- Legacy systems – Users that do not want or can participate in the (semi-)automated CPS.
- Contributors – Users positively interacting with the CPS, thus, becoming an integral part of the hybridized CPSS; contributors can also
- Disruptors – Users that are either disrupt the system function from within (e.g., by (unknowingly) misbehaving) or from the outside (e.g., as part of the dynamic environment).
- Attackers – Users that maliciously try disrupting or even crashing the system.

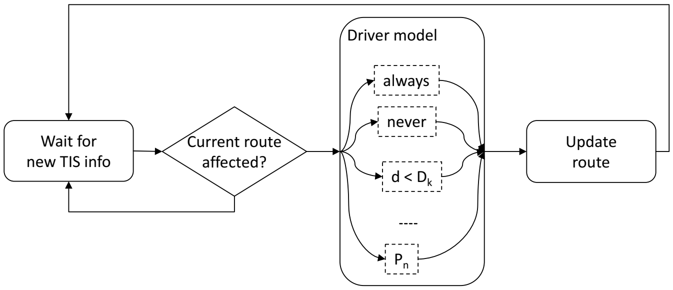
Contributors even help improving the overall system efficiency, whereas disruptors need to be guided to turn (in the best case) into contributors as well. Inactivation is probably the best way to help here (e.g., using gamification or even economical measures). The only class that the system needs to actively secure its parts from are attackers.

III. Technical Optimizations to Guide Human Drivers

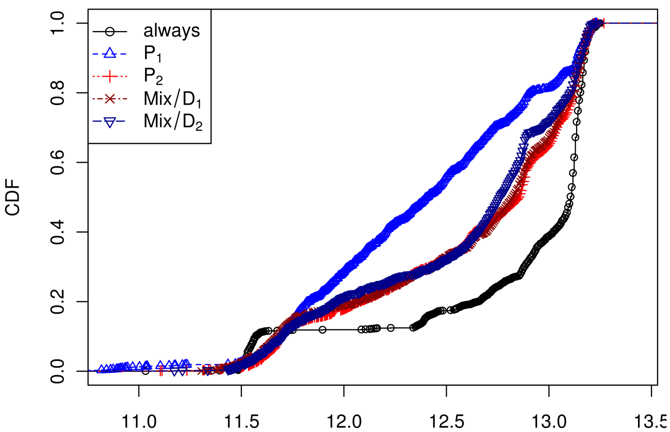
Our research community has experience and many insights on the optimizations of technical systems, even at large scale. However, the technical factors taken into consideration are often not sufficient to globally optimize the system. In fact, a major component is missing in many technical papers: The interaction of the system with the human user.

Some years back, we investigated this issue in the scope of Traffic Information Systems (TIS). In this application domain, optimization was typically based on optimizing the route cars take based on information received about (micro) congestions in the road network. This way, cars can travel faster with a reduced carbon footprint to their destinations. One key assumption, however, has been that drivers act as instructed by the TIS – which does not hold in reality. Instead, every human driver will act according to her experience, abilities, and current mood. This has already been considered in very early studies [17], [18]. In a study on human factors, for example Dingus et al. provided guidelines for advanced traveler information systems [18]. Human drivers tend to resist diverting from their present route to avoid congestions, i.e., they prefer following traditionally used routes. Based on cluster analysis techniques, four commuter subgroups have been identified with respect to their willingness to respond to the delivery of real-time traffic information.

Using this classifications of driver behavior available in the literature, we investigated the impact of human driver behavior on the quality of the TIS as a whole [19]. The core concept is depicted in Figure 2. Whenever the car received updated TIS data, first, a human driver behavior model is checked that is based on empirical psychological studies. As a



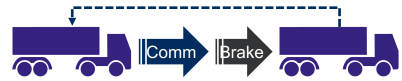
(a) Modeling human driver behavior



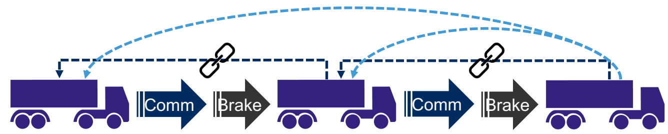
(b) Average driving speed when following the TIS advise always, with a certain probability, or accoring to a specific driver behavior profile

Figure 2. The impact of driver behavior in a Traffic Information System [19]

(a) Radar based ACC: minimum headway time 1 s, i.e., 28 m at 100 km/h



(b) Simple CACC (radar plus IV): minimum headway time 0.6 s, i.e., 16 m at 100 km/h



(c) Cooperative CACC (multiple IVC links): minimum headway time 0.2 s, i.e., 5 m at 100 km/h

(d) Manual driving (mainly depending on perception and response times): minimum headway time 2 s, i.e., 50 m at 100 km/h

Figure 3. Automated car following approaches

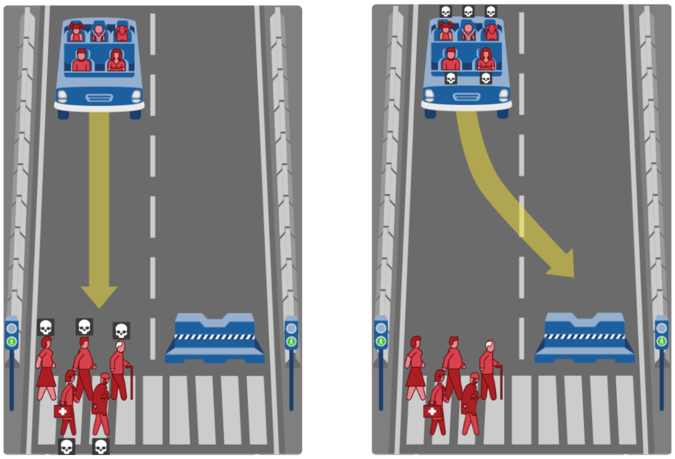
reference, classes ‘always’ and ‘never’ refer to perfect technical optimization or no optimization at all. In the results reported in [19], we found that on average rather simple probabilistic models can be used to asymptotically represent the same overall performance. However, on the microscopic scale, very precise empirical models are needed.

IV. Hard Real-Time Control and Human Reaction Times

Besides the demands for certain behaviors, also the final capabilities of human users need to be taken into consideration. We focus again on an automotive application scenario, getting back to platooning, i.e., cooperative Cooperative Adaptive Cruise Control (CACC). As already mentioned, there are many good reasons for making platooning a reality raging from efficient use of road network capacity to reduction of greenhouse gases to relieving the driver from its task of steering the car [11], [13]. This is particularly of interest for the logistic business but also for private rides.

The technical concept of cooperative CACC are depicted in Figure 3. The core basis is Adaptive Cruise Control (ACC), which is becoming a standard feature in all new cars these days. ACC uses radar (sometimes also lidar or camera-based techniques) to measure the distance to the car in front. This measurement takes time as multiple consecutive measurements are needed to derive speed and acceleration of the car in front from the simple distance measurements. In addition to the time for measurements, the non-negligible time between actuator initiation and actual breaking must be considered. This leads to a so-called headway time of about 1 s, which translates to a minimum distance of 28 m at 100 km/h (cf. Figure 3a). When also using Inter-Vehicle Communication (IVC), simple CACC helps reducing the headway time and thus minimum gap to about 0.6 s and 16 m, respectively (cf. Figure 3b). Using rather sophisticated communication protocol solutions, this distance can be reduced to less than 5 m for cooperative CACC solutions. Currently available IVC standards based on IEEE 802.11p have been studied in detail for platooning, e.g., in [15]. Considering the inherent control theory of such networked control applications, even guarantees can be made for large scale application of platooning [16]. Going beyond, complementary communication technologies help further stabilizing communications, thus, improving the safety requirements. A recent example is the use of Visible Light Communication (VLC) in combination with radio frequencies [20].

One of the core requirements is to coordinate among the cars about maneuvers in real-time with communication deadlines below 100 ms. Comparing that with manual driving, perception and reaction times of the human drivers need to be considered. As indicated in Figure 3d, these times sum up well above the time limits for automated distance management. In fact, the headway time increases to 2 s resulting to a minimum distance of 50 m at 100 km/h. Thus, human intervention while being in an automated platoon lead to unsafe situations and with high probability to crashes. In order to still focus on the human user’s demands, mechanisms can be integrated that first increase the safety gap before handing over control to the human driver.



(a) Continue driving will kill several pedestrians

(b) Maneuver to save pedestraians will kill driver and his family

Figure 4. MIT's moral machine: What would your decision be?[1]

V. Public Acceptance and Computerized Decision Making

The last issue to be discussed is public acceptance of modern CPSS solutions, where humans and machines get into deep interaction when becoming hybridized systems. In general, public acceptance cannot be taken for granted even if optimizing certain features and capabilities well beyond human abilities. The keyword here is technological impact assessment [21], [22]. For every new technology, it is important not only to ask if human safety is increased or if we can perform actions in a more efficient way. One of the key challenges here is to understand economical, psychological, and social demands.

Falling back to the automotive use case again, let us focus on ADAS systems and the road to fully automated driving. Human drivers are used to a certain approach to cars and driving. Changes in these behavioral concepts are very slow and often require generations to become accepted. We have seen this for many safety features that saved thousands or even millions of lives after becoming a mandatory standard. Examples include the safety belt, the airbag, and the EPS. More recently, many additional ADAS systems have been proposed and eventually deployed on modern cars.

The final challenge is now on fully automated driving. In many empirical studies (e.g., [23]), the question of public acceptance of automated driving has been investigated. The outcome is that a substantial group of people simply rejects the idea due to their (wrong) belief that they are able to handle problems better. This wrong self-assessment is based on the well-known Dunning-Kruger effect [24], which refers to the cognitive bias, wherein persons of low ability suffer from illusory superiority when they mistakenly assess their cognitive ability as greater than it is.

Ignoring such cognitive bias, another challenge is morality, for which our human kind has rather different definitions or thresholds when it comes to machine based decision making. Such a machine morality has been discussed in depth over the years [25]. In fact, it has a rather long tradition, think of Asimov's laws of robotics [26] that inspired engineers since [27]. The latest developments can be seen in the MIT moral machine [28], [29], which helps answering questions such as if a car will run into an accident, shall it aim killing pedestrians or the driver, if these are the final two options. An example is shown in Figure 4.[1] No generally accepted answer exists so far and we, as a society, will have to work on defining rules and conditions to constrain machine decision making processes.

VI. Conclusions

In this paper, we discussed the trend towards Cyber Physical Social Systems (CPSS). We are supported already in many parts of our life by technical assistance systems. This becomes particular interesting in the context of Cyber Physical Systems (CPS), where the capabilities of human parts help performing actions that computerized versions are not yet able to do. At the same time, these assistance systems extend the human abilities well beyond of his normal ones. We are thus talking about deeply integrated hybridized systems. Using automotive use cases, we discussed the shift from CPS to CPSS as well as limitations and general constraints such as public acceptance that influence this hybridization process.

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