Report from Dagstuhl Seminar 19222

Control of Networked Cyber-Physical Systems

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 19222 "Control of Networked Cyber-Physical Systems". Such systems typically operate under very tight timing constraints and at the same time witness an ever-increasing complexity in both size and the amount of information needed to main controllability. Yet, the development of control systems and of communication/computation infrastructures has traditionally been decoupled, so that valuable insights from the respective other domain could not be used towards the joint goal of keeping cyber-physical systems (CPS) controllable. In order to overcome this "black box" thinking, the seminar brought together researchers from the key communities involved in the development of CPS. In a series of impulse talks and plenary discussions, the seminar reviewed the current start-of-the-art in CPS research and identified promising research directions that may benefit from closer cooperation between the communication and control communities.

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1 Executive Summary

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Motivation and Purpose of the Seminar

Manufacturing cells and factories, transportation systems and various other parts of critical infrastructure such as energy grids have traditionally been controlled via self-contained, centralized systems continuously monitored and reconfigured by humans. The ever-growing

complexity and integration of these Cyber-Physical Systems (CPS) into reconfigurable value chains ("Industrie 4.0"), autonomous cars and other services with high reliability requirements necessitates a radical change in the control strategy: Classic controllers will not be able to handle the massive amounts of data generated by these emerging systems, not only because of restrictions with regard to computational power and complexities that might bar human interventions in the processes, but also due to missing or inadequate methods for the control and the interconnection of the devices comprising such systems. Whilst CPS have moderate bandwidth/throughput requirements, often in the range of a few bytes per control or sensor message, they require high delivery success rates and predictable latency bounds for these messages and the computations performed on the data, often in the order of a few milliseconds. Stable controllers can only be developed if a predictable behavior of the communication and computation infrastructure may be assumed. Otherwise, the systems may not reach the desired states or even become unstable, up to the point where they may cause physical injuries or the loss of human life. Hence, a paradigm shift towards real-time oriented communication and computation in CPSs is necessary.

Such a shift can, however, only be achieved by overcoming the traditionally loose coupling in the design of system components in networks. Currently, both the communication systems community and the control systems community consider the components of the respective other field as a "black box" and abstract from the variations. Valuable insights that the other domain might provide towards the joint goal of keeping a CPS controllable may hence not be available. Although solutions have already been developed that bring communication and control closer together for specific use-cases, the abstraction problem has not been approached from a general, overarching perspective.

The purpose of this seminar was hence to bring together experts working in the key communities relevant for the science of CPSs and Cyber-Physical Networking (CPN) to get a clearer and more detailed picture of the most important issues of the control and networking aspects that CPSs/CPNs bear and to identify the mutual relations and influences of the associated fields, in order to overcome the so-far strict abstractions and boundaries that exist, and to sketch a roadmap for further research in the field. The driving question was how it is possible to derive generalizable co-design methods and metrics that support the development of universal networked CPSs/CPNs.

Prior Dagstuhl Seminars have already addressed CPS aspects such as synthesis (Seminar 17201) and verification methods (Seminar 14122), robustness (Seminar 16362), as well as software engineering for control (Seminar 14382), yet none of these have focused on the interaction, interdependencies and the co-design of communication and control.

Participants and Structure

The seminar brought together a total of 30 participants from various fields within the communication and control domains, ranging from promising young scientists to leading authorities within their respective fields, but also including practitioners from industry with a strong research background, as well as representatives from funding organizations.

The first day of the seminar was dedicated to an in-depth introductory session. Besides as short personal introduction with background and current research interests, **each participant was asked to prepare a personal statement answering the following questions:**

- What are the most important problems to solve in the realm of CPS/CPN?
- What are the main scientific challenges and which fields can contribute to them?
- What have we achieved so far, and what are the pitfalls of past and current research?

Each personal statement was followed by a discussion round on the presented individual statements. The statements and discussions proved highly fruitful, as they allowed the organizers and the participants to gain an understanding of the current state and future challenges in the Control of Networked CPS from the different disciplinary perspectives.

Most often, opinions revolved around the need to understand more about the implications of the dynamic behavior of both the controlled systems themselves and of the communication networks. Research so far seems to have primarily focused on the "steady state", as participant termed it. The uncertainties introduced by controlled systems and (especially wireless) networks in coexistence with other systems, however, seem to call for various improvements in CPS/CPN design. Yet, as other participants expressed it, besides having fostered a better understanding of the basics of the respective other fields in recent years by programs such as DFG's Priority Programme 1914 *Cyber-Physical Networking*, "little" has been achieved be community so far, with a major pitfall being "lopsided" methods which are often attributed to "sticking to domain-specific models". Opening these models to incorporate knowledge from other domains, therefore, seems to be a major challenge for the upcoming time.

A further major topic discussed was the need for more realistic and relevant problem settings in the research efforts, since, as one participant put it, "real problems are more complex than a single inverted pendulum". Hence, to avoid "esoteric" research and thus "ending up as an academic field with zero practical impact", CPS/CPN is in the need of "prov[ing] that what we develop is useful/needed" within the upcoming years. This does not mean that basic research has or needs to be concluded in any way. Yet, further opinions voiced more than once regarded energy efficiency and usable abstraction/decomposition methods (which may at times even sacrifice optimality for applicability and efficiency) as interesting research challenges for the upcoming years, which shows that the community has already begun tackling more practical issues recently. A variety of additional comments showed that few, if any, of the issues of CPS/CPN can be considered as solved by today.

Plenary Discussion: Properties of Cyber-Physical Networks

The unexpected intensity of the discussions following the respective personal introductions revealed the extreme variety of opinions on the nature of CPS/CPN and the major challenges in this interdisciplinary field. To facilitate a common understanding, the personal introductions were thus followed by a plenary discussion on which properties define CPS/CPN and make them interesting for scientific study.

It was agreed that – besides the eponymous intertwining of control, networking and the physically tangible world – CPS/CPN are dominated by *uncertainties* of both the systems and their operational environments, *dynamics* of configuration and load, (usually) *limitations* e.g., with respect to the capacity of the network, computation power and energy, a *control objective* that is sought to achieve through the network (if it is not serving pure monitoring purposes), as well as the associated relative administrative and technical *autonomy* of CPN compared to their traditional counterparts. Regarding typical metrics of timing and scale, it was further agreed that **traditional complexity metrics do not apply to CPN**. There often exist intricate and counterintuitive relationships between timing constraints of control and the network, leading to situations in which certain upper- and lower(!)-bounded delays may even be beneficial for the simplification and stabilization of control. Hence, defining the time-criticality of a system is scenario-dependent. Likewise, scaling effects may lead to situations in which too many local observations may prove counterproductive to controllability so that, depending on the scenario at hand, issues arise regarding the "right" amount of

information sharing between local and global players in distributed decision-making processes. As such, **conceiving widely-applicable categories for the complexity of CPS/CPN was identified as an open problem**.

Impulse Talks & Plenary Discussions

For the remaining one and a half days of the seminar, the participants were asked to propose impulse talks on topics related to their respective areas of control of CPS/CPN research. Each talk served as the basis for a subsequent plenary discussion aimed at identifying worthwhile research directions for the community. **Out of a total of 18 proposed impulse talks, six talks were selected by the organizers.** In the following, we present the major insights from the talks and the discussions.

- The development of next-generation wireless communication technologies such as 5G and the increased efficiency of small-scale mobile devices in general, have fueled the interconnection of ever more devices into large-scale CPS. However, as the number of devices generating data and potentially taking action increase, so do the burdens on controllers and the network. In his talk, Carlos Canudas-de-Wit showed first results pointing at the fact that both state estimation and control may provide sufficient results even when only considering a well-chosen aggregating subset of a system's sensing and actuating nodes, as long as the distribution of these nodes follows a specific structure, which can, however, be found for many real-world scenarios. Together with another technique based on partial differential equations, the results of his work showed that when combining both control- and information-/network theoretic models, as well as upcoming techniques such as in-network computation that may provide the necessary aggregation infrastructure, even systems of immense complexity can be controlled without overloading controllers and networks.
- Another challenge of CPS arises when safety guarantees need to be fulfilled, especially when a failure to meet these guarantees can lead to injury or endangerment of human life. Adam Molin presented an industry perspective on the validation and verification of (increasingly) autonomous vehicles, a field in which scenario-based testing approaches represent the state-of-the-art. While the determinism of systems without humans in the loop may aid in the construction of such scenarios, only probabilistic guarantees can be given when humans are involved in the operation of a system. This fact reflects not just on automotives but on multiple other scenarios discussed in the seminar and highlights the importance of joint analysis methods for the control and the communication components of such systems.
- In her talk on 5G Service Automation, Chrysa Papagianni expressed the view that upcoming mobile networks will witness a shift from open-loop to hierarchical closed-loop control as customers shift towards a pay-per-use scheme for the offered services. Whether the control problems (e.g., regarding network slicing) can be considered to exhibit sub-minute or even real-time requirements (as witnessed in most other systems discussed in the seminar) is still an open question. Yet, considering the anticipated, wide-spread application scenarios of 5G also in the area of CPS/CPN, the seminar identified the issue of base station multi-tenancy as an area for future research within the context of CPN.
- A cornerstone for the successful operation of CPS/CPN are easily-calculable metrics to assess the operational status, as well as to guide the generation, transmission and evaluation of signals within the systems. Vahid Mamduhi in his talk showed that simple age-of-information (AoI) – a common metric applied both by the control and the

communications communities in theoretical and practical scenarios – bases on assumptions that can hardly be met by the systems. As a consequence, AoI needs to be augmented by notions of state, timing constraints of the system, and the objective of the control function (all related to a single piece of information) to really provide benefits. Such metrics are arguably hard to conceive for the general case, yet the talk inspired discussions among the participants regarding sensible metrics with broader applicability.

- From a more communication-oriented perspective, James Gross presented his group's efforts towards determining latency bounds in wireless CPS/CPN. Both a queuing-theoretic and a model checking-based approach (the latter concerning a practical implementation of an ultra-reliable low latency protocol) yielded qualitative results that seem promising. Yet, the practical applicability of such approaches is currently hampered by assumptions regarding distortion that may not hold in practice. In the subsequent discussion, topics included *(a)* the question whether making the network completely deterministic (or the ability to make determinism assumptions) is actually needed and achievable, and how possible compromises may look like, *(b)* to which degree techniques such as software-defined networking, in-network processing, time slicing and standards such as 5G can contribute towards such goals, and *(c)* which interfaces, abstractions and design patterns should exist that allow specifying and proving certain guarantees in CPN, especially regarding the interplay of control algorithms and networks.
- The complexity and variety of communication protocols within automation is addressed by the recent Time-Sensitive Networking (TSN) efforts of the IEEE, which seek to offer a vendor-neutral Ethernet-based solution catering both legacy and future real-time applications, including control. Eventually, the automation pyramid will be transformed into an automation pillar at which TSN serves as the (sole) connectivity provider for control loops which will span the whole automation network from virtualized (/centralized) controllers and the field level. In his talk, Tobias Heer provided an overview of the changes that TSN brings with regard to medium access methods to enable real-time capabilities in Ethernet. While TSN brings significant improvements to wired settings, the subsequent discussion round revolved around the difficulties in achieving this in wireless scenarios. Besides the apparent issues of jamming and/or other attack vectors in wireless control systems, the possibility of trading reliability against capacity and the resulting implications on control algorithms was identified as a research issue.

Conclusion

Throughout the presentations and especially the discussions both during the plenary sessions as well as during off-hour activities, the seminar successfully brought together researchers from control and communication from both academia and industry, and undoubtedly fostered a deeper understanding of the intricate interplay of the disciplines in the research area of CPS/CPN. A variety of open problems and promising research areas were identified, with some in dire need of increased cooperation between the involved fields. This underlines the need in CPS/CPN research for formats valuing open and honest discussions, and both the organizers and the participants hope to be able to continue these discussions in the following years through additional summits and – once the insights gained in this first edition have shown visible impact on the scientific community – possibly another Dagstuhl Seminar. As a concrete follow-up, the organizers and participant James Gross are planning to conduct a seminar in Stockholm/Sweden in 2020 on this diverse research area.

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3 Overview of Talks

3.1 Scales Paradigms in Large-scale networks: micro-control / macro-output

Carlos Canudas-de-Wit (GIPSA Lab – Grenoble, FR)

Joint work of ERC Scale-FreeBAck group
Main reference see several publications at http://scale-freeback.eu/publications/conference-journal/
URL http://scale-freeback.eu

In this talk we presents some results from the ERC Scale-FreeBAck (This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement N° 694209)).

The talk deals with the problems of controlling aggregates of large-scale complex systems with a few inputs (micro-control). Aggregates here are "aggregated" variables functions of the systems state-space variables such as mean values (macro-outputs). Examples of such a class of systems are traffic networks, Brain neural networks, heating systems, among others. The basic idea is to devise a "virtual" aggregated model of the original large-scale system using the scale-free (SF) metric, which indicate that the degree distributions of the associated graph follows an exponential decaying law. Then, we discuss different partitioning algorithms leading to aggregated graphs with the SF desired distribution but also with the suited control/observation properties. In the talk, I also present the mathematical properties necessary for the average observability.

In the second part of the talk, I present a different alternative for cutting system complexity, which consist in representing a large traffic network as a continuum. That is, to approximate a large-scale dynamic graph (where each node represent a variable), by a Partial Differential equation. The objective of this second approach is to use the PDE model for designing boundary estimators and control.

3.2 The future of automation networks in the IIoT; The impact of Time Sensitive Networks

Tobias Heer (Hochschule Albstadt-Sigmaringen, DE)

TSN is a technology that will enable real-time scheduling in standard industrial ethernets. This will facilitate the transformation of industrial network architectures from the classical automation pyramid towards the new paradigm: the automation pillar.

3.3 Modeling of Uncertainty vs. Reality: A Dilemma?

James Gross (KTH Royal Institute of Technology – Stockholm, SE)

This talk discusses modeling and interfacing issues in networked CPS from the perspective of the network, and more importantly, from the perspective of wireless systems. Wireless systems are fundamentally subject to random variations. In theory, models exist of these variations which allow a great deal of reasoning with respect to information-theoretic, communication-theoretic or queuing-theoretic perspectives. In the first part of the talk we explore recent contributions of our group with respect to queuing-theoretic aspects. For networked CPS this is interesting, as it allows a reasoning about the likelihood of a wireless system to exceed predetermined latency thresholds, so called delay violation probabilities, which have practical applications with respect to safety layers. However, the achieved results are theoretic in nature, and allow at best qualitative insights into design trade-offs of future systems. From a different perspective, we discuss other efforts of the research group to capture the delay violation probability of an implemented system by probablistic model checking. This effort is more practical in nature, and at least with respect to ex-post analysis, it possible to bound the error behavior of an implemented wireless system, if the channel parameterization is chose correctly.

3.4 Age-of-Information in net-CPS

Mohammad Hossein Mamduhi (KTH Royal Institute of Technology – Stockholm, SE)

In this talk we discuss the advantages and disadvantages of using age-of-information (AoI) metric in networked control systems. AoI has emerged as a concept that models delay from the receiving end point of view and has shown to be beneficial in communication society. Whether AoI can be employed when quality of control is of utmost interest is still not fully understood. Therefore, we try to summarize the results of some of our early works that quantify the quality of control when AoI is used as a metric for delay and show that age, in its original formulation, is not all that matters in networked systems. Comparing the efficiency of using AoI with the other conventional approaches such as vale-of-information (VoI) clearly shows that AoI is under-performant in many cases. We discuss that age can be used in other formats than its original linear formulation to capture more of the requirements of the networked control systems, e.g. nonlinear age functions or state-dependent age functions.

3.5 A Safety Perspective for Future Mobility

Adam Molin (Denso Automotive – Eching, DE)

Complexity of automotive systems is steadily growing witnessed through the increasing level of autonomy, increased amount of real-time data, and increasing number of interconnections. In order to tame the complexity of such networked CPS and to be able to provide safety guarantees under the vast degree of uncertainties, current systems engineering practices need to be reconsidered. This talk displays recent activities within the automotive domain towards this endeavor. Herein, scenario-based verification and validation (V&V) plays a focal point, in which coverage metrics need to be defined within the operational design domain. In accordance with the safety of the intended functionality, the V&V methods shall aim at minimizing the set of unknown critical instances related to the tested automated driving function. Finally, new opportunities and new V&V challenges emerging from connected mobility are outlined in form of infrastructure-supported decision making and the ability of data collection and update mechanisms.

References

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3.6 5G Service Automation

Chrysa Papagianni (Nokia Bell Labs – Antwerp, BE)

5G systems are set out to address the business contexts of 2020 and beyond, by enabling new network and service capabilities, opening up innovation opportunities for vertical markets. Communication service providers should be able to provide tailor-cut solutions to service requests from the verticals over the same network infrastructure. Network slicing provides a solution for realizing 5G's vision of supporting the highly diversified network needs of emerging applications involving Cyber-Physical Systems (e.g., smart manufacturing, smart grids and railway cyber physical systems). However, to support the multiplicity and demands of emerging networking applications, we need to fully automate network slice management and orchestration. Automation should be enabled throughout all phases of the network slice lifecycle through optimized closed-loop control at different levels and time-scales. In this talk, we discuss the envisioned 5G service automation architecture. We focus on the developing challenges related to network slice management and orchestration and data plane programmability. These research topics are investigated in the context of the forthcoming 5G trials, planned in the framework of the 5G Public Private Partnership co-led by the European Commission and European ICT industry.

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