Unifying Control and Verification of Cyber-Physical Systems (UnCoVerCPS)

WP6 Dissemination and Exploitation

D6.6 – Final Report on Dissemination and Exploitation

WP6	**D6.6 – Final Report on Dissemination and Exploitation**
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Short Description	This document is the final report on dissemination and exploitation of the Horizon 2020 project UnCoVerCPS (grant agreement number 643921). It covers the dissemination and exploitation strategy and activities during the 48 months of the project (January 2015 — December 2018).
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Date of acceptance	

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Contents

1 Introduction

This document is the final report on dissemination and exploitation of the Horizon 2020 project UnCoVerCPS (grant agreement number 643921). It covers the dissemination and exploitation strategy and activities during the whole 48 months of the project (January 2015 - December 2018), including the conclusion of the project.

Dissemination mainly aims at publishing and spreading the scientific and technical achievements of the project to demonstrate the value of the project and to stimulate future research. Dissemination is achieved by means of publications in journals and presentations at conferences, via workshops, lectures, seminars, etc. Target audiences of dissemination activities include academia, industry, government bodies and the general public. Key dissemination platforms for UnCoVerCPS have been the Cyber–Physical Systems Week (CPSWeek) conferences in 2015 (Seattle, WA), 2016 (Vienna), 2017 (Pittsburgh, PA), and 2018 (Oxford, UK). Numerous members of the consortium attended the conferences and presented papers. Goran Frehse was co-organizer of the 20th ACM Int. Conf. Hybrid Systems: Computation and Control (HSCC), the leading conference on foundations of cyber-physical systems. Matthias Althoff and Goran Frehse organized workshops on Applied Verification for Continuous and Hybrid Systems (ARCH'15, ARCH'16, ARCH'17, ARCH'18). The workshops included the presentations of tools, including tool evaluations, industrial experience reports, and proposals for new, industrially relevant benchmark problems. The proceedings of the 2015, 2016, 2017 and 2018 workshops have been published and are available at http://easychair.org/publications/volume/ARCH15, http://easychair.org/publications/volume/ARCH16, http://easychair.org/publications/ volume/ARCH17, and http://easychair.org/publications/ volume/ARCH18, respectively.

An important aspect of the dissemination activities in UnCoVerCPS is around open source software tools. Software tools for system synthesis and verification developed within the UnCoVerCPS project are made available under open source licenses so that third parties can apply these tools to their particular problems and/or contribute to further developments of the tools and methods. Key tools in UnCoVerCPS are SCADE Suite, commercially available from Esterel, CORA, developed at TUM, and SpaceEX from UJF. As part of the UnCoverCPS project, new versions of these tools have been released in 2015, 2016 and 2018.

Exploitation includes all measures for creating commercial value from the project results such as to strengthen competitiveness and create and secure jobs in the domain of cyber–physical systems in Europe. Based on the horizontal UnCoVerCPS approach, some of the industrial partners in the UnCoVerCPS consortium (Bosch, GE, R.U. Robots) mainly pursue an exploitation route around the application of project results and tools to vertical applications

in their respective industries (automotive, avionics, smart grids, human–robot interaction in food assembly), with the aim to enable more cost–and time–efficient design, development, and verification of safety–critical cyber–physical systems. In all four industries, different regulatory and legislative regimes are applicable with regards to systems safety. UnCoVerCPS also aims at addressing and/or influencing these regulatory regimes and ensuring that systems developed with the UnCoVerCPS approach will ultimately be certifiable in the respective industries.

2 Dissemination and Exploitation Management

Dissemination and exploitation activities in UnCoVerCPS are bundled in work package WP6, led by Politecnico di Milano. The UnCoVerCPS consortium strongly believes that dissemination and exploitation is the joint responsibility of all consortium members. Hence, the tasks and responsibilities have been widely distributed in such a way that most of the partners have a relevant responsibility for at least one task, deliverable, or milestone related to dissemination and exploitation. Obviously, multiple project partners contribute to each task, deliverable and milestone.

The responsibilities of the project partners are detailed in the table below.

Responsibility	**Description**	**Owner**	**Month**	**Status**
Task 6.1	Project website setup and maintenance	TU Munich	Continuous	
Task 6.2	Data and knowledge management	Tecnalia	Continuous	
Task 6.3	Workshop and summer schools	Politecnico di Milano	Continuous	
Task 6.4	Educational activities	TU Munich	Continuous	
Task 6.5	Exploitation	RU Robots	Continuous	
Deliverable 6.1	Website setup	TU Munich	3	Completed
Deliverable 6.2	First version of data management plan	TU Munich	6	Completed
Milestone 31	First version of internal exploitation plan	RU Robots	6	Completed
Deliverable 6.3	First dissemination and exploitation report	GE	12	Completed
Milestone 32	Presentation of results at a European event	GE	24	Completed[1]
Deliverable 6.4	Second dissemination and exploitation report	GE	30	Completed
Deliverable 6.5	Final version of data management plan	TU Munich	48	
Deliverable 6.6	Final dissemination and exploitation report	TECNALIA	48	Ready for submisssion

[1] Computing and CPS, June 2016, Brussels

3 Dissemination Report

3.1 Dissemination Plan

The objectives of the UnCoVerCPS dissemination activities are:

- to reach out to a large set of target groups via a broad spectrum of dissemination channels;
- to become an integral and visible part of the international cyber–physical systems research community;
- to provide academic services such as organizing workshops and special sessions at conferences; to implement structures that allow open-access to scientific results, software tools, and benchmarking examples.

A summary of the dissemination activities influenced or driven by UnCoVerCPS and their number are listed in the table below. More details can be found in the respective sections.

Activity	Number	References
Workshops	more than 25	Section 3.4
Conference papers	123	Section 3.5
Journal articles	26	Section 3.6
Teaching activities	more than 30	Section 3.7.1
PhD theses supervised	8	Section 3.7.2
Master theses supervised	26	Section 3.7.3
Bachelor theses supervised	7	Section 3.7.4

3.2 Project Website

The central platform of the UnCoVerCPS dissemination activities is the project website available at http://cps-vo.org/group/UnCoVerCPS. It contains up–to–date information on the consortium members, publications, events, etc. as well as a platform for internal information and document sharing among the consortium members. Figure 1 below shows a screenshot of the homepage of the website. The website has continuously been updated throughout the lifetime of the project and will stay online for several years after the project completion.

3.3 Project Flyer

The UnCoVerCPS project has published a flyer as a double–sided A4 sheet with key program facts (Figure 2 below). The flyer can be downloaded via the project website (Dissemination).

Figure 1: Screenshot of the homepage of the UnCoVerCPS website.

MISSION STATEMENT

UnCoVerCPS provides methods for a faster and more efficient development process of safety- or operation-critical cyber-physical systems in (partially) unknown environments.

Cyber-physical systems are very hard to control and verify because of the mix of discrete dynamics (originating from computing elements) and continuous dynamics (originating from physical elements).

We present completely new methods for de-verticalisation of the development processes by a generic and holistic approach towards reliable cyber-physical systems development with formal guarantees.

In order to guarantee that specifications are met in unknown environments and in unanticipated situations, we synthesise and verify controllers on-the-fly during system execution. This requires to unify control and verification approaches, which were previously considered separately by developers. For instance, each action of an automated car (e.g. lane change) is verified before execution, guaranteeing safety of the passengers.

We will develop completely new methods, which are integrated in tools for modelling, control design, verification, and code generation that will leverage the development towards reliable and at the same time open cyber-physical systems. Our approach leverages future certification needs of open and critical cyber-physical systems.

CONSORTIUM

Technische Universität München (TUM) - *Coordinator*
Germany

Université Joseph Fourier Grenoble 1 (UJF)
France

Universität Kassel (UKS)
Germany

Politecnico di Milano (PoliMi)
Italy

GE Global Research Europe
Germany

Robert Bosch GmbH
Germany

Esterel Technologies
France

Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Germany

Tecnalia
Spain

R.U.Robots Limited
United Kingdom

UnCoVer CPS

Unifying Control and Verification of Cyber-Physical Systems
UnCoVerCPS

More information about the project is available online.
Please visit **http://cps-vo.org/group/UnCoVerCPS**

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HORIZON 2020

OBJECTIVES

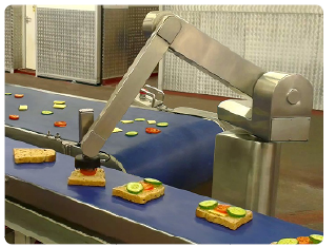
- Novel on-the-fly control and verification concepts.
- Ground-breaking methods for unifying control and verification to quickly react to changing environments.
- Seamless integration of modelling and conformance testing.
- A unique tool chain that makes it possible to integrate modelling, control design, formal verification, and automatic code generation.
- Prototypical realisations of the novel methods in automated vehicles and human-robot collaborative manufacturing.
- Analysis of the benefits of formal methods on wind turbines and smart grids case studies.
- A new development process that reduces development time and costs for critical cyber-physical systems to strengthen European companies which design or produce cyber-physical systems.

 Version 1.5

DEMONSTRATORS


Automated Vehicles


Wind Turbines


Human-Robot Collaboration


Smart Grids

A total of 1,250 of high–quality printouts of the flyer have been produced and are being distributed by all of the consortium partners on conferences, workshops, etc. The flyer contains information on the technical mission of the project, the partners, the use cases and contact information. Its main goal is to raise interest in and awareness of the project, and direct interested parties to the project website for more details. Additionally, a new flyer was printed for UnCoVerCPS workshop organized by Politecnico di Milano, June 2018 (Figure 3).

3.4 Workshops

Results and current developments within UnCoVerCPS project have been presented to the CPS research community by the following workshops and sessions.

3.4.1 Workshop and conference organization

CPSWeek (Cyber–Physical Systems Week) is the leading annual international conference for cyber–physical systems, under technical sponsorship of IEEE, ACM (Association for Computing Machinery) and others. Under one umbrella, it brings together multiple conference, workshops and tutorials on different aspects of cyber–physical systems research, including embedded systems, hybrid systems, real–time systems, and sensor networks.

Matthias Althoff (TUM) and Goran Frehse (UJF) organized workshops on Applied Verification for Continuous and Hybrid Systems ("ARCH") as part of CPSWeek 2015, 2016, 2017 and 2018 (http://cps-vo.org/group/ARCH).

- The 5$^{\text{th}}$ International Workshop on Applied Verification of Continuous and Hybrid Systems **ARCH'18**. The workshop took place in Oxford, UK, on July 13$^{\text{th}}$, 2018 as part of the IFAC Conference on Analysis and Design of Hybrid Systems (ADHS). The fifth edition had a record number of participants and nine accepted papers.

  The ARCH workshop also hosted the friendly competition **ARCH-COMP**. The competition showcases which methods are particularly suitable to which types of problems. As a side effect, it aims at establishing a consensus for comparing different software implementations in the context of verification, as such comparisons are routinely demanded by reviewers of scientific publicatio

  All participating tools were represented in the competition jury, headed by the organizers. The submitted results were approved by the jury and verified by an independent repeatability evaluation lead by Taylor T. Johnson. To establish further trustworthiness of the results, the code with which the results have been obtained is publicly available.

UnCoVerCPS Workshop

June 6, 2018
Aula Rogers, Politecnico di Milano

Program

- 8:30 – 09:00 Registration of the participants
- 9.00 – 09:15 Opening
  Matthias Althoff, TUM
- 9:15 – 10:00 Automated driving and conformance testing
  Daniel Hess, DLR
  Alexander Rausch, Bosch
- 10:00 – 10:15 Coffee break
- 10:15 – 11:00 Distributed model predictive control of smart grids
  Carlo Sandroni, RSE
  Olaf Stursberg, Kassel University
- 11:00 – 11:45 Human-robot interaction and on-line verification
  Geoff Pegman, R U Robots Limited
  Matthias Althoff, TUM
- 11:45 – 12:30 Tools integration
  Goran Frehse, Université Grenoble Alpes
  Xavier Fornari, Ansys
- 12:30 – 13:30 Lunch break
- 13:30 – 15:00 Panel session
  Invited speakers from Politecnico di Milano, ABB, Bosch, and Leonardo S.p.A.
  Moderator: Maria Prandini, Politecnico di Milano
- 15:00 – 15:10 Concluding remarks
  Matthias Althoff, TUM

Registration

The event is free, but registration is required at the website:
https://www.uncover-cps.deib.polimi.it

Registration closes May 31, 2018

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Sponsored by

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Project website: https://cps-vo.org/group/UnCoVerCPS

POLITECNICO MILANO 1863

DIPARTIMENTO DI ELETTRONICA INFORMAZIONE E BIOINGEGNERIA

UnCoVerCPS - Unifying Control and Verification of Cyber-Physical Systems

Figure 3: UnCoVerCPS Workshop flyer.

Overall, 24 tools have participated. The competition was divided into the following categories:

1. Hybrid Systems with Piecewise Constant Dynamics (lead: Goran Frehse)
2. Continuous and Hybrid Systems with Linear Continuous Dynamics (lead: Matthias Althoff)
3. Continuous Systems with Nonlinear Dynamics (lead: Xin Chen)
4. Bounded Model Checking of Hybrid Systems with Piecewise Constant Dynamics (lead: Lei Bu)
5. Falsification (lead: Georgios Fainekos)
6. Stochastic Models (lead: Alessandro Abate)
7. Hybrid Programs (lead: Stefan Mitsch)

The 2018 prize for the most promising result was sponsored by Bosch and went to the tool JuliaReach (Marcelo Forets and Christian Schilling).

- The **ARCH'17** workshop took place in Pittsburgh, PA, on April 17, 2017, co–located with CPSWeek 2017. During the workshop, results from a friendly competition on verification of continuous and hybrid systems in different categories, and applied to different benchmark problems, were presented.

- The **ARCH'16** workshop took place as part of CPSWeek 2016 in Vienna, Austria, from April 11-14, 2016. Eight benchmark contributions and six tool contributions were presented, including three contributions from the UnCoVerCPS project. Moreover in 2016, Bosch sponsored the best tool award which went to Stanley Bak, Sergiy Bogomolov and Christian Shilling for their tool "Hypy", a phython library for high–level hybrid systems analysis which is capable of running several hybrid systems analysis tools, such as SpaceEx, Flow, dReach, and HyCreate, parsing their output, and modifying the models based on the output.

- The **ARCH'15** workshop took place as part of CPSWeek 2015 in Seattle, WA, from April 13–16, 2015. A total of 15 contributions were presented on benchmarks, tools, and experience reports. Many consortium members attended CPS week and this particular workshop. Bosch sponsored the best tool result award at ARCH. The awarded contribution by Chuchu Fan, Parasara Sridhar Duggirala, Sayan Mitra, and Mahesh Viswanathan presented significant "Progress on Powertrain Verification Challenge with C2E2".

As part of CPSWeek, Maria Prandini was co-program chair of the 21st ACM International Conference on Hybrid Systems: Computation and Control **HSCC 2018** (https://www.hscc2018.deib.polimi.it/), Porto, April 11-13, 2018. HSCC is a leading conference on hybrid systems theory.

Maria Prandini also organized the joint ICCPS-HSCC panel session "What are the challenges posed to CPS theory by modern applications?", during the **CPS week 2018**, Porto, Portugal, 12th April 2018.

Maria Prandini organized the **UnCoVerCPS Workshop** at Politecnico di Milano on June 6th, 2018 to present the results achieved within the project (https://www.uncover-cps.deib.polimi.it/). Most of the UnCoVerCPS participants contributed with a presentation. A panel session was also organized. In particular, Daniel Heß and Alexander Rausch gave a talk on "Automated Driving and Conformance Testing".

Maria Prandini co-organized a workshop on "Computation-aware Algorithmic Design for Cyber-Physical Systems" as part of the 57th IEEE Conference on Decision and Control **CDC'18** in Miami Beach, FL, on December 16th, 2018 (https://cdc2018.ieeecss.org/workshops.php).

Maria Prandini and Axel Busboom organized a workshop on "Verification and Control of Cyber–physical Systems: Theory and Application" as part of the 55th IEEE Conference on Decision and Control **CDC'16** in Las Vegas, NV, from December 12–14, 2016 (http://cdc2016.ieeecss.org/workshops.php#w06). CDC is a premier scientific and engineering conference dedicated to the advancement of the theory and practice of systems and control. The workshop comprised eight presentations from high–profile speakers from industry and academia. It started with application–driven presentations from several domains (road freight transport, intelligent robots, autonomous systems, automated vehicles) and went on to talks on verification, testing, safe control design and supervisory control.

The following presentations were given by PI's from the UnCoVerCPS consortium:

- Matthias Althoff reported on "Self–verification of automated vehicles"
- Olaf Stursberg spoke about "Controller synthesis for probabilistic cyber–physical systems using reachable set computation."

- Maria Prandini discussed on "Advances in control, game theory, and identification for stochastic systems."

Maria Prandini co-organized with Kostas Margellos a workshop on "Distributed and Stochastic Optimization and Applications" at the European Control Conference, that took place in Aalborg, Denmark from June 29 to July 1, 2016 (https://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=7792520). The European Control Conference **ECC'16** aims to bring together academic and industrial professionals in the field of systems and control, and to promote scientific cooperation and exchanges within the European Union and between Europe and other parts of the World. The workshop provided a concise, yet complete, exposition to the topic of distributed and stochastic optimization. A diverse group of internationally recognized researchers, affiliated with outstanding institutions in Europe and in the United States, were brought together to expose the workshop attendees to cutting edge research on the field as well as to present new vistas on the field. Olaf Stursberg from Universität Kassel delivered a presentation on "Model predictive control for jump Markov linear systems."

Finally, RUR, as future activity to UnCoVerCPS, is helping to organise an upcoming workshop at the European Robotics Forum in Bucharest (**ERF '19)** on provable safety for robots.

3.4.2 Workshop and conference talks

Next, the following talks have been delivered, by most recent dates:

- In November 2018, Daniel Heß gave a talk on "Negotiation of Cooperative Lane Change Maneuvers via Vehicle-To-Vehicle Communication", SuB1T6 Workshop / Industry Panel on Cooperative and Automated Driving, Nov 4^{th} 2018, IEEE **ITSC 2018**.

- In September 2018, Daniel Heß gave a talk on Online Absicherung kooperativer Autonomer Fahrzeuge", **DLR-Symposium 2018** "Testen – Automatisiertes und Vernetztes Fahren", Sept. 4^{th} 2018, DLR Braunschweig.

- In September 2018, Maria Prandini gave a plenary talk entitled "Reachability in Cyber-Physical Systems", at the 12^{th} International Conference on Reachability Problems (**RP'18**), Marseille, France, 24-26 September 2018.

- In April 2018, Goran Frehse was tool chair of the 24^{th} International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS), held

April 14-20, 2018, in Thessaloniki, Greece. TACAS is a leading conference on embedded systems and is part of ESWeek.

- In May 2017, Maria Prandini gave a seminar on "Randomized methods for decision making in presence of uncertainty" at TUM on May 20th, 2016 and Oxford University on September 7th 2016.

- In April 2017, Goran Frehse was co-chair of the 20th ACM International Conference on Hybrid Systems: Computation and Control **HSCC 2017** (http://hscc2017.ece.illinois.edu/), April 18-20, 2017, Pittsburgh, PA, USA. HSCC is a leading conference on hybrid systems theory and is part of CPSWeek.

- In January 2017, Matthias Althoff gave a talk on "The UnCoVerCPS Approach Towards Certifiable Human-Robot Co-Existence" in Smart Cyber-Physical Systems Concertation Event, Brussels, Belgium, Jan. 31st 2017.

- In December 2016, Matthias Althoff gave a talk on "Self-Verification of Automated Vehicles" at the Workshop Verification and Control of Cyber-physical Systems: Theory and Applications, Las Vegas, USA, Dec. 11th 2016.

- In October 2016, Matthias Althoff gave a talk on "Safe Human-Robot Co-Existence through Online Verification" at the Workshop *PUMA* graduate school, St.Martin, Austria, Oct. 12th 2016.

- In October 2016, Maria Prandini gave a plenary talk on "A big-data approach to decision making under uncertainty" at the 2016 International Conference on Control, Automation, and Systems (**ICCAS 2016**).

- In September 2016, Matthias Althoff gave a talk on "Online Verification of Cyber-Physical Systems" at the International Symposium on Networked Cyber-Physical Systems, Garching, Germany, Sept. 19th 2016.

- In September 2016, Maria Prandini gave a seminar on "Distributed optimization over networks and its application to multi-building energy management" at TUM on May 2nd 2017.

- In May 2016, Matthias Althoff gave a talk on "Safe Human-Robot Co-Existence through Online Verification" at the GlobalTech Alliance Robotic Workshop, Munich, Germany, May 22nd 2016.

- In July 2015, Matthias Althoff presented a podium discussion on the International Scientific Conference on Mobility and Transport (**mobil.TUM 2015**) in Munich, Germany, from June 30 – July 1, 2015. The title of the podium was "Cyber physical transport systems - ITS on the move towards the Internet–of–Things".

- In July 2015, Matthias Althoff gave two presentations at the **BMW workshop 2015** "We live innovations – dialogue Munich" which was held in Munich, Germany, from July 13–15, 2015:

  - Provably correct collision avoidance systems
  - Formalisation of traffic rules for defending against liability claims in automated driving

3.4.3 Industry events

SafeTRANS Industrial Day

SafeTRANS ("Safety in Transportation Systems") is a German competence cluster combining research and development expertise in complex embedded systems in transportation systems. It drives research in human centred design, in system and software development methods for embedded systems, as well as in safety analysis – for avionics and rail – and its integration in certification processes.

- At the 23$^{\text{rd}}$ **SafeTRANS Industrial Day 2017** Workshop, Daniel Heß gave a talk on "Online-Verification of Cooperative Systems", Nov. 16$^{\text{th}}$ 2017, Hella Berlin.

- Several consortium members attended the **SafeTRANS Industrial Day 2015** in Renningen, Germany, on May 20$^{\text{th}}$ 2015. The topic of the workshop was "Modelling of Context and Environment for Verification and Testing of Highly Autonomous Systems".

ARTEMIS

ARTEMIS is a European industry association in embedded and cyber–physical systems. The over 180 members include industry, SME's, universities and research institutes. ARTEMIS is responsible for the Strategic Research Agenda (SRA) on embedded and cyber–physical systems

- Matthias Althoff gave a presentation on "Unifying Control and Verification of Cyber-Physical Systems" at the ARTEMIS Spring Event, Vienna, Austria, April 14$^{\text{th}}$ 2016

- Several consortium members attended the **ARTEMIS Co–Summit 2015** in Berlin, Germany, on March 11–12, 2015 (https://artemis-ia.eu/co-summit-2015/index.html) and represented the UnCoVerCPS project with an exhibition booth.

- Matthias Althoff gave a presentation at the **ARTEMIS Technology Conference 2015** in Turin, Italy, on October 6–7, 2015 (https://artemis-ia.eu/calendar/402-artemis%20technology%20conference%202015.html), on "Provably Safe Maneuvers of Automated Vehicle".

Assises de LÉmbarquee 2016

Goran Frehse participated in a podium discussion at the French "**Assises de l'Embarquée 2016**", a major industrial forum on embedded systems, on Nov. 29th 2016 (the event is reported at http://www.assisesdelembarque.fr/assises-de-lembarque-2016). The title of the discussion was "Simulating Cyber-Physical Systems: Which gains for the Industry?"

TÜV Süd GmbH Industry Talk

Matthias Althoff presented "Self-Certification of Cyber-Physical Systems", Garching, Germany, March 31st 2016.

Robert Bosch GmbH Industry Talk

Matthias Althoff presented "Safe Human-Robot Co-Existence through Online Verification", Renningen, Germany, March 14th 2016.

3.4.4 Invited sessions

Next, the following invited sessions have been presented, by most recent dates:

- In December 2018, Maria Prandini presented "Multi-agent Distributed Optimization over Networks", IEEE Conference on Decision and Control (CDC 2018), Miami Beach, USA.

- In September 2018, Maria Prandini presented "A set-based approach to model checking of nonlinear systems", during the 20th Symposium on Symbolic and Numerical Algorithms for Scientific Computation (**SYNASC 2018**), Timisoara, Romania.

- In September 2018, Maria Prandini presented "Distributed optimization over networks: some recent results and an outlook", Vistas in Control, ETH Zurich, Switzerland.

- In September 2018, Matthias Althoff presented "Safe Human-Robot Co-Existence through Online Verification", Forum on Specification & Design Languages, Munich, Germany.
- In June 2018, Matthias Althoff presented "Guaranteeing Safety of Robotic Systems using Formal Methods", Robocluster Automatica, Munich, Germany.
- In May 2018, Matthias Althoff presented "Composable Benchmarks for Safe Motion Planning on Roads", Seminar series of the Field Robotics Center, Carnegie Mellon University.
- In May 2018, Matthias Althoff presented "Formal Methods for Online Verification of Motion Planning", Industry talk, Argo, Pittsburgh, USA.
- In May 2018, Maria Prandini presented "A set-based approach to robust control and verification of piecewise affine systems subject to safety specifications", MORE on Automotive: Cyber-Physical-Systems (Control, Robustness, Security), Modena, Italy.
- In January 2018, Matthias Althoff presented "Formal Methods for Online Verification of Motion Planning", Industry talk, Ford, Dearborn, USA.
- In December 2017, Maria Prandini presented "Multi-agent Games and Optimization over Networks", "Advances in stochastic systems, estimation and control - Part I" and "Advances in stochastic systems, estimation and control - Part II" in IEEE Conference on Decision and Control (CDC 2017), Melbourne, Australia.
- In October 2017, Matthias Althoff presented "Online Verification of Autonomous Vehicles", Industry talk, BMW, Garching, Germany.
- In August 2017, Matthias Althoff presented "Ensuring Safety of Autonomous Vehicles by Set-Based Techniques", International Summer School on Cooperative Interacting Automobiles, Schwäbisch Gmünd, Germany.
- In July 2017, Jens Oehlerking gave an invited presentation on "Hybrid systems verification at Bosch" at the Verification Mentoring Workshop at the 29th Conference on Computer Aided Verification (**CAV 2017**), Heidelberg, Germany.
- In July 2017, Maria Prandini presented "Multi-agent and networked systems" at the **IFAC 2017** World Congress, Toulouse, France.

- In April 2017, Jens Oehlerking presented "Experiences in Testing and Verification" at the 2nd Workshop on Monitoring and Testing of Cyber-Physical Systems **(MT-CPS 2017**), Pittsburgh, PA, USA.

- In April 2017, Matthias Althoff presented "Ensuring Safe Human-Robot Co-Existence by Reachability Analysis", Seminar series of the Field Robotics Center, Carnegie Mellon University, USA.

- In January 2017, Maria Prandini presented "Distributed optimization over networks: application to multi-building energy" at the workshop Optimization techniques for hybrid dynamical systems: from theory to applications (**OptHySYS 2017**) organized in Trento.

- In December 2016, Maria Prandini presented "Advances in control, game theory, and identification for stochastic systems" at the 55th IEEE Conference on Decision and Control (**CDC 2016**), Las Vegas, USA.

- In October 2016, Bastian Schürmann gave an invited talk on "Formale Reglersynthese mittels konvexer Kombinationen" at the Regelungstechnisches Kolloquium in Boppard, Germany on February 18, 2016. He was invited to present this talk again at the Dresden Colloquia on Automation Technology of the Fraunhofer Institute for Transportation and Infrastructure Systems (IVI) and the Technical University of Dresden, Germany.

- In July 2016, Maria Prandini presented "Coordination and communication issues in energy networks" and "Challenges for optimization and control in power systems and networks" at the American Control Conference (**ACC 2016**), Boston, USA.

- In July 2016, Bastian Schürmann presented "Convex Interpolation Control with Formal Guarantees for Disturbed and Constrained Nonlinear Systems" as part of the seminar series of the Field Robotics Center at Carnegie Mellon University, Pittsburgh, USA.

- In May 2016, Olaf Stursberg gave an invited talk on 'Robust stabilization of power grids with larger shares of renewable energy" at the **3rd JST-NSF-DFG-RCN 2016** workshop "Distributed energy management systems: frontiers of multimodal energy systems" which was held in Heidelberg, Germany.

- In December 2015, Maria Prandini presented "New developments in stochastic systems, control and their applications" at the 54th IEEE Conference on Decision and Control (**CDC 2015**), Osaka, Japan.

- In October 2015, Matthias Althoff presented invited sessions on workshops at the IEEE/RSJ International Conference on Intelligent Robots and Systems (**IROS 2015**) which was held in Hamburg, Germany, from September 28 to October 2, 2015:
  - "Determining the nonexistence of evasive trajectories for collision avoidance systems," part of the 7^{th} Workshop on Planning, Perception and Navigation for Intelligent Vehicles.
  - "Safety Control of Robots," part of the workshop Robotic Co–workers: Methods, Challenges and Industrial Test Cases.

- In October 2015, Jens Oehlerking presented "Specification models, testing and verification in industrial practice" at the final colloquium of the transregional research collaborative **AVACS 2015**, Oldenburg, Germany.

- In September 2015, Olaf Stursberg gave an invited talk entitled "On optimization–based control of switched uncertain systems" at the **MOBOCON Symposium 2015** Optimization and Control of Uncertain Systems in Dortmund, Germany.

3.5 Conference Papers

Many conference papers have already been published in the context of the UnCoVerCPS project. Pivotal conferences for the consortium were CPSWeek 2015, 2016, 2017 and 2018 where the UnCoVerCPS consortium also organized dedicated workshops. The accepted papers published by UnCoVerCPS are listed in Appendix A.

3.6 Journal Articles

The accepted journal articles published by UnCoVerCPS are listed in Appendix B.

3.7 Teaching Activities

This chapter collects UnCoVerCPS teaching activities in the context of the project, organised by courses, PhD, Master and Bachelor theses.

3.7.1 Tutorial, PhD courses and summer schools

Consortium members have created new teaching material and taught related courses listed below:

Tutorials

- Matthias Althoff: "Vorlesung Cyber-Physical Systems (2015 - now)"
- Joshué Manuel Pérez Rastelli: Lectures on "Standards for Automobiles," François Rabelai University (Tours, France. 2015 - now)
- Joshué Manuel Pérez Rastelli: Lectures on "Digital enfironment and road — ITS applications," François Rabelai University (Tours, France. 2015-now)
- Maria Prandini co-organized with Sergio Grammatico, Kostas Margellos, and Giuseppe Notarstefano a tutorial on "Cooperative and noncooperative decision making in multi-agent systems: An operator theoretic perspective" as part of the IFAC 2017 World Congress in Toulouse, France, July 9–14, 2017 (https://www.ifac2017.org/workshops-and-tutorials). Motivated by applications in energy and transportation networks, this tutorial presents a mathematical framework to analyse and design distributed decision making in multi-agent systems seeking convergence to cooperative or noncooperative equilibria.
- Goran Frehse: Mini-course on "Verification of Hybrid Systems," Politecnico di Milano, February 22–23, 2017.
- Olaf Stursberg: Course on "Hybrid and Networked Control Systems," University of Kassel, winter semester 2016/2017.
- Olaf Stursberg: Course on "Adaptive and Predictive Control," University of Kassel, winter semesters 2015/2016 and 2016/2017.
- Matthias Althoff: "TUM Winter School: How to Guarantee Safety of Cyber-Physical Systems?", Garching, Germany, Feb. 6^{th} 2017
- Matthias Althoff: "Seminar Cyber-Physical Systems" (WS 2016/17)
- Goran Frehse: DigiCosme Spring School, organized by ENSTA, Paris, France, May 12, 2016 (https://www.ensta-paristech.fr/fr/actualites/retour-sur-la-spring-school-digicosme-2016)
- Olaf Stursberg: Course on "Hybrid Control Systems," University of Kassel, winter semester 2015/2016.
- Matthias Althoff: Improvements made to regular TUM lecture on Cyber–Physical Systems (http://www6.in.tum.de/Main/TeachingSS2015CyberPhysicalSystems).

- Matthias Althoff: Seminar Cyber–Physical Systems, 17 participants (http://www6.in.tum.de/Main/TeachingWs2015SeminarCyberPhysicalSystems).
- Jens Oehlerking: Guest Lecture at TUM, "Specification models for cyber–physical systems in industrial practice," Garching, Germany, July 14$^{\text{th}}$ 2015.

PhD courses

- In October 2018, Maria Prandini (organizer and one of the lecturers) of PhD Course on Cooperative and Noncooperative Optimization and Control, Politecnico di Milano, October 2-5, 2018.
- In February 2017, Maria Prandini (organizer and lecturer), Olaf Stursberg (lecturer), Goran Frehse (lecturer): PhD course on hybrid systems at Politecnico di Milano, February 20–24, 2017 (http://home.deib.polimi.it/prandini/Hybrid_Systems_2017.html).
- In October 2015, Maria Prandini: PhD course on hybrid systems at Lund University, October 5–8, 2015 (http://www.control.lth.se/Education/DoctorateProgram/hybrid-systems.html).
- In June 2015, Maria Prandini: PhD course on hybrid systems at Politecnico di Milano, June 15–19, 2015 (http://home.deib.polimi.it/prandini/hybrid-systems.htm).
- One Ph.D. student at Bosch, Hendrik Röhm, is supervised by Matthias Althoff from TUM on topics related to UnCoVerCPS.
- GE Global Research has supervised two student interns as part of the UnCoVerCPS project:
  - Dipankar Maity, Ph.D. student at University of Maryland,
  - Matei Catalin Moldoveanu, MEng student at University of Sheffield.
- Bosch also supervised one student intern as part of the project.

Summer school

- SIDRA summer Ph.D. School on Optimization Methods for Decision Making over Networks, Bertinoro, Italy, July 12-14, 2018
- Olaf Stursberg: Course on "Discrete Event Systems and Control Theory," University of Kassel, summer semesters 2015, 2016, 2017.

- Olaf Stursberg: Course on "Optimal Control," University of Kassel, summer semesters 2016, 2017.
- Matthias Althoff: "Seminar Cyber-Physical Systems (WS 2016/17, SS 2017)"
- Matthias Althoff: "Proseminar Bahnplanung für autonome Fahrzeuge (SS 2017)"
- Matthias Althoff: "Master-Praktikum/Lab Course Safe Human-Robot Co-Existence (SS 2017)"
- Bastian Schürmann and Matthias Althoff: Practical course "Path Planning and Tracking Control for Autonomous Driving" (SS 2016)
- Goran Frehse: AVACS Summer School, Oldenburg, Germany, September 30-–October 2, 2015 (http://www.avacs.org/autumn2015/).
- Goran Frehse: SyDe Summer School on Modelling and Verification of Cyber–Physical Systems, Bremen, Germany, September 9–11, 2015 (http://www.informatik.uni-bremen.de/syde/index.php?summerschool-21).
- Maria Prandini (lecturer): Mini–Symposium on "Stochastic Control: Computational Approaches to Large–Scale Problems," in SIAM Conference on Control and its Applications, Paris, July 8–10, 2015.
- Maria Prandini (co–organizer and lecturer): Mini–Symposium on "Stochastic Systems and Applications," in SIAM Conference on Control and its Applications, Paris, July 8–10, 2015.
- Goran Frehse: French Summer School MACS, organized by GT MOSAR and SDH, Bourge, France, June 16–17, 2015 (http://jdjnmacs2015.sciencesconf.org/resource/page/id/3).
- Matthias Althoff: TUM Summer Seminar on Cyber–Physical Systems, June 8th 2015 (http://www6.in.tum.de/Main/TeachingSs2015SeminarCyberPhysicalSystems).

3.7.2 PhD Theses

Some **PhD theses** related to UnCoVerCPS topics have been supervised in the context of the project:

1. A. Falsone: "Distributed decision making with application to energy systems". Ph.D. in Information Technology - Area: Systems and Control. Politecnico di Milano, 2017. The thesis was awarded the Dimitris N. Chorafas prize, 2018

2. Nikolaos Kekatos: “Formal Verification of Cyber-Physical Systems in the Industrial Model-Based Design Process”. Université Grenoble Alpes, 2018.

3. Damian Kontny: “Control of systems with time–varying constraints by using homotopy methods”. Universität Kassel, 2015-2017.

4. Zonglin Liu: “Controlling distributed systems with uncertain interaction”. Universität Kassel, 2015-2017.

5. R. Vignali: “Automatic verification and input design for dynamical systems: an optimization-based approach to the detection of non-influential inputs”. PhD in Information Technology - Area: Systems and Control. Politecnico di Milano, 2016.

6. G. Manganini: “Optimal control of large scale stochastic hybrid systems with a finite control space”. PhD in Information Technology - Area: Systems and Control. Politecnico di Milano, 2016.

7. L. Deori: “A Model Predictive Control approach based on randomized methods to aircraft motion control”. PhD in Information Technology - Area: Systems and Control. Politecnico di Milano, 2016.

8. Leonhard Asselborn: “Probabilistic control of stochastic hybrid systems based on reachability analysis”. Universität Kassel, 2015-2016.

3.7.3 Master Theses

Several **Master’s theses** have been supervised in the context of the UnCoVerCPS project to date:

1. Jannik Huber: “Fast Model Predictive Control of Robot Interacting with Humans”, University of Kassel, 2018.

2. Yannick Masanz: “Real-Time Model Predictive Control of Robot Manipulators Interacting with Humans”, University of Kassel, 2018

3. Anna-Katrin Kopetzski: “Reinforcement Learning with Safety Guarantees”, Technische Universität München, 2018

4. Deepthi Gopalakrishna: “Using Game Engines for Verification and Testing”, Université Grenoble Alpes, 2018

5. Florian Grötzner: “Automated Construction of Maneuver Automata for Autonomous Vehicles with Formal Guarantees”, Technische Universität München, 2017.

6. Niklas Kochdumper: “Improvements and Extensions for the Convex Interpolation Control Algorithm”, Technische Universität München, 2017.

7. Moritz Klischat: “Formal Set-Based Control as a Safety Net for Unverified Controllers”, Technische Universität München, 2017.

8. Gerardo Lopez Alonso: “Set-Based Optimal Control with Formal Guarantees for Robotic Manipulators”, Technische Universität München, 2017.

9. Sudishna Sthapit: “A Client-Software Architecture for Interactive Modeling of Cyber-Physical Systems”, Univ. Grenoble Alpes, 2017

10. M. Kaiser: “Untersuchung zur Online Abgesicherten Fahrer-Fahrzeug Interaktion in Kollisionsvermeidungs-Szenarien”, Sept. 5th 2017, Technische Universität Braunschweig.

11. Riccardo Desimini: “Robust constrained control of piecewise affine systems based on reach sets computation”, Politecnico di Milano, 2017

12. Pouria Tajvar: “Verification of nonlinear systems through hybridization and invariant set computation”, Politecnico di Milano, 2017

13. Paolo Verbari: “Multi-RRT*: A sample-based algorithm for multi-agent planning”, Politecnico di Milano, 2017

14. Mohammad K. Daaboul: “Cooperative control of quadcopters considering obstacles and coupling”. Control and System Theory, Universität Kassel, 2017.

15. Fabio Belluschi: “Energy management of a multi-building system via distributed optimization”. Automation and Control Engineering, Politecnico di Milano, 2016.

16. Vedad Causevic: “Optimal energy management in a multi-building set-up via distributed stochastic optimization”. Automation and Control Engineering, Politecnico di Milano, 2016.

17. Cigdem Yazili: “Cost optimization for vehicle-to-grid application”. Automation and Control Engineering, Politecnico di Milano, 2016.

18. Stefano Mutti: “A novel distributed approach to power control in wireless cellular networks”. Automation and Control Engineering, Politecnico di Milano, 2016.

19. Zhou Huang: “Modelling of driving situations and verification of collision freedom for an automated vehicle model”, Bosch/Karlsruhe Institute for Technology (KIT), 2016.

20. Petio Dimitrov: “Distributed allocation of a shared energy storage system”. Automation and Control Engineering, Politecnico di Milano, 2015.

21. Caterina Brocchini: “A chance–constrained approach to the quantized control of a heat ventilation and air conditioning system with prioritized constraints”, Politecnico di Milano, 2015.

22. Wuqiang Sun: “Algorithms for the identification of the parameters of nonlinear vehicle–dynamic models”, DLR, 2015.

23. Joao de Campos Salvado: “Contingency planning for automated vehicles in urban traffic”, DLR, 2015. [Task 5.3]

24. Friderike Meier: “Adaptive control of linear systems with time–varying constraints”. Control and System Theory, Universität Kassel, 2015.

25. Maximilian Müller: “Cooperation of autonomous cars by auction–based control”. Control and System Theory, Universität Kassel, 2015.

26. Zonglin Liu: “Optimization of multi–agent Markov decision processes using game theory”. Control and System Theory, Universität Kassel, 2015.

3.7.4 Bachelor Theses

Several **Bachelor’s theses** have been supervised by members of the consortium:

1. Simon Schmitz: “Derivative-free optimisation of a set-based controller for autonomous vehicles”, TUM 2017

2. Cedric Stark: “Validation of a Conservative Low-Order Human Model using a High-Order Biomechanical Model”, TUM 2017

3. Lukas Markolf: “Efficient Graph Search in Optimal Control of Discrete-Time Switched Linear System”, University of Kassel, 2017.

4. Jannik Hahn: “Design of LPV–controllers for wind turbines contributing to grid stabilization”. Control and System Theory, Universität Kassel, 2016.

5. Ute Schiehlen: “Formally correct vehicle prediction on road networks”. Robotics and Embedded Systems, TUM, 2015.

6. Natalie Reppekus: "Representation of reachable sets in human–robot interaction with a view to online safety control". Robotics and Embedded Systems, TUM, 2015.

7. Hannes Rewald: "Auction–based mechanisms for intelligent control of autonomous cars". Control and System Theory, Universität Kassel, 2015.

3.8 Liaisons with Other EU Projects

UnCoVerCPS was represented in several collaboration and liaison events, in particular:

- the collaboration workshop "Advanced Computing and Cyber–Physical Systems 2017," jointly organized by DG CONNECT and HiPEAC, which took place in Brussels on June 14$^{\text{th}}$ 2016,

- the Digital Innovation Forum (DIF), organized by ARTEMIS–IA and ITEA, which took place in Amsterdam on May 10–11, 2017.

Consortium members have formed an informal liaison with **INTO-CPS**, a Horizon 2020 project (grant agreement number 644047) working on an integrated tool chain for model–based design of cyber–physical systems. Both projects are obviously highly synergistic, as UnCoVerCPS requires as a prerequisite the ability to do model-based design of its systems, all the way from requirements to hardware and software implementations. On the other hand, UnCoVerCPS provides the tools and methods for controller synthesis and verification which, in return, will be required by INTO-CPS, in particular in the case of stochastic and/or hybrid systems.

UnCoVerCPS has also established an informal liaison with **Smart-E**, a Marie Curie ITN under FP7 (http://smart-e-mariecurie.eu/). Smart-E works on training for early-stage researchers and experienced researchers in the area of advanced robotics to ensure a sustainable manufacturing sector in Europe. The consortium involves a team of experts in a broad range of areas, including embodied intelligence, soft robotics, compliant robotics, smart materials, safety and human–machine interaction, autonomous systems, dexterous end effectors and statistics. TUM and R.U. Robots are members in Smart-E and will help ensure that UnCoVerCPS results will be applied in Smart-E for certified human–robot interaction. Smart-E researchers, on the other hand, will provide a modular robot for experiments within UnCoVerCPS for testing of on–the–fly control design and verification.

A third liaison has been established with the FP7 Support Action for Vehicle and Road Automation, **VRA**. VRA shares interests with UnCoVerCPS in the application area of vehicle automation and allows participants to share expertise and cooperate at a European

and international level. It aims at maintaining an active European network of experts and stakeholders in the area of vehicle and road automation, contributing to EU-US-JPN international collaboration, identifying deployment needs for the different domains in vehicle and road automation, and at promoting European research through an innovative set of dissemination tools. UnCoVerCPS is represented in VRA and the associated discussion group iMobility Forum (iMF) via DLR. This enables to directly contribute with ideas and results developed in UnCoVerCPS, such as online verification for automated driving, amoung the discussion groups. An official affiliation of DLR with the VRA network is finalized.

DLR has further participated in the standardisation meeting within the EU FP7 call 10 on June 30, 2015, which was dedicated to vehicle–to–vehicle (V2V) standardisation. Results of these discussions, as well as other projects such as AutoNet2030 and iGame, are considered with the UnCoVerCPS Task 5.3 (Automated Driving). The standardisation meeting also included standards for the use cases and testing methodologies which are relevant to UnCoVerCPS Task 6.5 (Exploitation). In addition, DLR has presented the UnCoVerCPS project at the iMF Automation Working Group (AWG) meeting on July 1, 2015 at ERTICO Brussels and contributed ideas of UnCoVerCPS to an iMF AWG white paper.

Since three project partners are also in the EU project **interACT** (https://www.interact-roadautomation.eu/), there is a natural liaison, but not an official one. In parallel, and on a national level, during 2018 partner Bosch had with **Pegasus** project an exchange on safety argumentation for the HAD (Highly Automated Driving) use case, on basis of the UnCoVerCPS method.

3.9 Liaisons with Industry Organizations and Competence Clusters

ARTEMIS–IA is a non–profit association for the area of embedded and cyber–physical systems in Europe. It represents its members — industry, SME's, universities and research institutes — in the ECSEL Joint Undertaking. ARTEMIS–IA continuously promotes the research and innovation interests of its members to the European Commission and the public authorities of the participating states. It continues the work of the European Technology Platform ARTEMIS and is therefore responsible for the ARTEMIS Strategic Research Agenda (SRA) on Embedded and Cyber–Physical Systems which reflects the research and innovation needs in industry. The association aims at a coordinated, pan-European strategy. GE Global Research and Bosch are members.

Further, Bosch is a long–term member of Safetrans (see Section 3.4.3).

Tecnalia is an active member of several European Automotive platforms, such as the

European Green Vehicles Association (www.egvi.eu, EGVIA), where a specific "Automated Driving Roadmap" was launched in the frame of the European Road Transport Research Advisory Council (www.ertrac.org, ERTRAC) in July 2015, and it is being deployed.

3.10 International Academic Exchange Activities

The UnCoVerCPS project has also contributed to the attraction of several professors in cyber-physical systems for international exchange stays: Prof. Anca Muscholl from the Laboratoire Bordelais de Recherche en Informatique at Université Bordeaux received a three–year Hans Fischer Senior Fellowship from TUM. Prof. Marco Caccamo from the Department of Computer Science at University of Illinois at Urbana–Champaign received a three–month stipend at TUM as a TÜV Süd Foundation Visiting Professor.

An international collaboration was also initiated between TUM and the Robotics Institute at Carnegie Mellon University (CMU). As part of this collaboration, a TUM student, Robert Lösch, will write his Master thesis in collaboration with John M. Dolan, Principal System Scientist at CMU. In addition, Master student Mirko Gschwindt spent a six-month research stay with Sebastian Scherer (Senior System scientist).

TUM has hosted the August-Wilhelm Scheer Visiting Professor Peng Zhang, from University of Connecticut, Electrical and Computer Engineering, USA from August to November 2018.

4 Exploitation Report

4.1 Exploitation Plan

UnCoVerCPS will enable faster time-to-market in the design of controls for safety-critical cyber–physical systems, and hence yield a significant competitive advantage over traditional approaches consisting of manual control algorithm design and verification by means of time–intensive and error–prone manual testing. As part of the project, four use cases are studied in detail (wind turbine controls, automated vehicles, smart grids, and human–robot collaboration); however, it should be obvious that the technology has a much wider range of potential applications in automotive, manufacturing, aerospace, construction, energy and many other industries. Figure 4 below shows the anticipated timeline for bringing the innovations developed in UnCoVerCPS to market. It visualizes both the four vertical applications as well as the horizontal research on methodologies and application–agnostic tool chain development.

The exploitation path of the industrial partners will either be geared towards one or

more of the specific use cases (GE, Bosch, RUR) or on the development of world–class tools (Esterel). The academic partners pursue an open source strategy for academic exploitation and dissemination by means of granting open access to all tools developed under the UnCoVerCPS umbrella.

4.2 Bosch Exploitation Plans and Activities

Bosch Mobility Solutions *Bosch Mobility Solutions* is the largest Bosch Group business sector. In 2014, its sales came to €33.3bn, or 68% of total group sales. This makes the Bosch Group one of the leading automotive suppliers. The Mobility Solutions business sector combines the group's expertise in three mobility domains – automation, electrification, and connectivity – and offers its customers integrated mobility solutions. Its main areas of activity are injection technology and powertrain peripherals for internal combustion engines, diverse solutions for powertrain electrification, vehicle safety systems, driver–assistance and automated functions, technology for user–friendly infotainment as well as vehicle–to–vehicle and vehicle–to–infrastructure communication, repair–shop concepts, and technology and services for the automotive aftermarket. Bosch is synonymous with important automotive innovations, such as electronic engine management, the ESP anti–skid system, and common–rail diesel technology.

Robert Bosch GmbH targets to leverage the UnCoverCPS tool chain to efficiently develop new technologies and services (i) with decreased development costs and (ii) with shorter development times to bring products and services faster to the market. Bosch's main interest for exploitation is the UnCoVerCPS tool chain for efficiently developing new and safe technologies and services.

Bosch Mobility Solutions has a total revenue for embedded control units of approximately €6bn; this translates to sales of about 150 million embedded control units per year. The development cost for these embedded control units can be estimated to about €1bn. We estimate that leveraging the UnCoVerCPS tool chain, we can save two development iterations for a software function; this corresponds to at least 30% of development cost. Assuming 5% of software functions are safety–critical and amenable to the UnCoVerCPS toolchain, we can save at least €15m.

The application domain of interest for Bosch is automated driving and in particular the aspect of verified safety of vehicle dynamics. Hence, we focus on the results from the application of the UnCoVerCPS toolchain to the automated driving use case in task 5.3. To this end, we discuss with the mobility business unit applications of UnCoVerCPS to internal pre–development projects in the context of automated driving. In the following, we discuss how

such an internal pre–development project may progress along the activities in UnCoVerCPS.

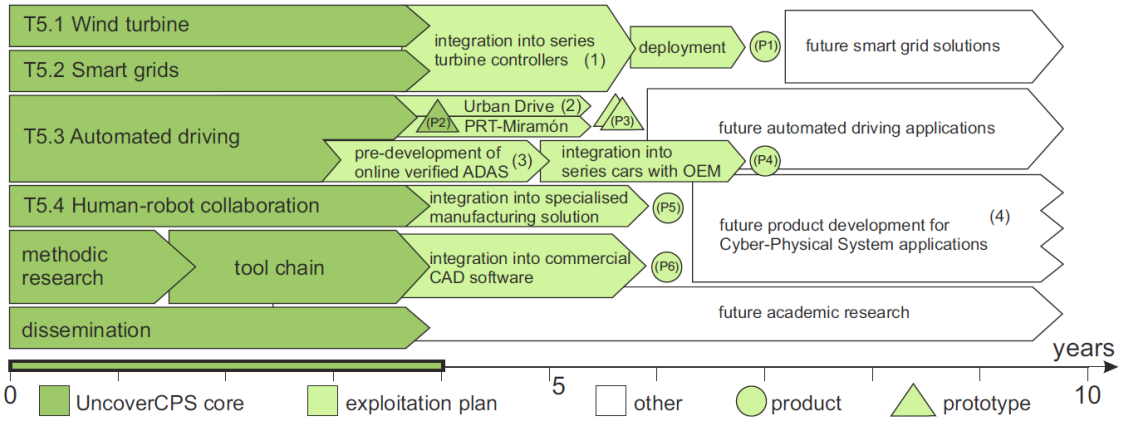

Figure 4: UnCoVerCPS exploitation timeline.

The pre–development phase in Figure 4 (3) for an advanced driver assistance systems (ADAS) with safety guarantees will begin in parallel to our project. Assuming successful technology transfer from academic to industry partners, a pre–development phase of two to four years can be expected. Product and series development in cooperation with an original equipment manufacturer (OEM) will integrate the functions into a real vehicle, taking approximately another two years. The optimal outcome is to bring an advanced driver assistance system to the market as shown in Figure 4 (P4), which has greater flexibility and is better able to adapt to varying traffic situations due to on–the–fly verification.

In order to bring UnCoVerCPS methods to fruition within Bosch, contacts to the relevant players in the field of highly automated driving have been established. This includes the business unit *Chassis Systems and Control*, which is responsible for the automated driving use case and acts as a contact to the relevant OEMs. In addition, a contact to the regulatory organization TÜV Süd has been established, with the goal of a letter or certification of the UnCoVerCPS approach by an additional external body. Feedback by TÜV Süd has been very positive so far, and there has been a strong interest in the UnCoVerCPS methods. Talks with TÜV Süd are ongoing at this point in time, both parties agreed to establish contact again at the beginning of next year. The online reachability computation concept, as developed on the UnCoVerCPS automated driving use case, is currently one of the techniques that is used in a research project providing methods and tools for the generation of test cases for the planning component of Bosch automated driving software on highways. Essentially, reachable set computations of traffic participants are used to provide a specification against which to test the system.

Robotics at Bosch Since its foundation in 2013 as a subsidiary of the Robert Bosch GmbH, the *Robert Bosch Start-up GmbH* has acted as an incubator for start-ups within the Bosch group. Among the startups that have been established is *Zenoway*, which is active in the field intralogistic robotics. In the business sector *Bosch Industrial Technology*, the business unit *Drive and Control Technology*, in cooperation with the *Bosch Engineering GmbH*, is also working on intralogistics solutions. The products of these two units within the Bosch group are mobile robots which need to interact safely with humans in their environment.

In the field of mobile robots, safe interaction between robots and humans is paramount and regulated by norms such as ISO 13482, ISO 13855, or European Machinery Directive 2006/42/EC . In this field, online reachability analysis is a promising approach to arrive at human behavior predictions that are less conservative than the state of the art, enabling less conservative motion planning that is still safe.

Through the course of UnCoVerCPS, we established connections to robotics researchers within Bosch, who act as contact persons to these start-ups, working, among other topics, on norm-compliant safety verification of mobile robots. In cooperation with Prof. Althoff, we conducted a study applying UnCoVerCPS online verification methods to a mobile robot prototype with promising results. In particular, we conducted conformance testing on pedestrian models and used reachability analysis for online prediction of pedestrian behavior. The results showed that the robot can maneuver in large groups of people significantly more efficiently than state-of-the-art approaches.

Furthermore, we expanded on our original work on conformance monitors from deliverable D1.3 into the tool setup of the mobile robot prototype. Here, we implemented and evaluated online trace conformance and reachset conformance monitors within our existing setup with the goal to distinguish between different classes of pedestrians. Since our conformance monitors are based on physical models of pedestrians, the online monitors can serve as a means allow to validate the classification stemming from perception algorithms during system operation. This work will be continued on more complex models after the conclusion of UnCoVerCPS with the goal of including UnCoVerCPS methods in mobile robots of the Bosch group as well as within our automotive businesses.

4.3 GE Exploitation Plans and Activities

General Electric (GE) is a widely diversified industrial conglomerate with eight globally operating industrial businesses: Power, Renewable Energy, Oil & Gas, Aviation, Healthcare, Transportation, Energy Connections and Lighting. In all these businesses, cyber–physical

systems are playing an ever–increasing role, either as systems or components that GE markets, or as tools that GE or its customers use in manufacturing, operations, and maintenance of complex systems.

GE has coined the terms “Industrial Internet” and “Brilliant Machines” to describe its conviction that the combination of embedded intelligent controls, advanced sensing and cloud connectivity will be a disruptive trend across many industries that unlocks huge opportunities to increase efficiency, safety, performance, and reduce operational cost. The expectation is that industrial assets as diverse as aircraft, distributed energy systems, locomotives, or intelligent, interactive lighting systems will have increasing capabilities to:

1. Observe, i.e. sense and process sensor data into information;
2. Orient, i.e. put the observed information into context;
3. Decide, based on the information and context;
4. Act, i.e. close the control loop.

At the same time, many of the industrial assets that GE makes, maintains or operates, are highly safety–critical in nature. This is obviously true for avionics such as flight management systems or FADEC's[2] controlling jet engines, but it also holds for locomotives, wind turbines, medical imaging systems, power plants or subsea oil production systems where a failure or an incorrect decision of the control system could cause severe damage to property, the environment or even human life. In most industries GE operates in, regulatory and certification requirements are in place to ensure the appropriate level of safety.

In areas such as embedded software for avionics, the cost of validation and verification already accounts for 40-50% of overall software engineering cost. This number increases further as the system complexity and autonomy advance. GE has put substantial effort into developing integrated tool chains for the validation and verification of complex embedded software systems all the way along the V–model, i.e. from high–level requirements engineering all the way to overall system validation. These tool chains, however, are only applicable to pure software systems which can be modelled as discrete systems. They cannot be readily transferred to systems where the embedded controller interacts with a physical system whose dynamics and disturbances are continuous or hybrid in nature.

Due to restructuring efforts, GE Global Research Europe in Garching terminated end 2017. Hence, UnCoVerCPS partner GE left the consortium on December 31, 2017. The following chapter goes through the former proposed exploitation plan in deliverable D6.4.

[2]Full Authority Digital Engine Control

4.3.1 Wind Turbine Conformance Testing

The original intent was to apply techniques for unified controller design and verification to wind turbine rotor controls. The UnCoVerCPS team has been in regular communication with GE Renewable Energy in Salzbergen, Germany, and kept the business updated about progress in the project. Based on this, the potential applicability of UnCoVerCPS tools to this application seems to be rather far out in the future.

However, the business is highly interested in adopting methods for reachset conformance testing that some partners in the UnCoVerCPS consortium (Bosch, TUM) have developed. GE Renewable Energy uses high–fidelity aero–elastic and structural dynamics modelling tools such as FAST, Flex5, ADAMS, BLADED in its structural and aerodynamic design, controller design as well as system certification. The expectation is that the fidelity of such tools is high enough so that if they comply with the IEC 61400 series of standards with sufficient safety margins, they will also be safe in reality. Among many other safety measures, simulations of design load cases specified in IEC 61400-1 are run against the simulation tools in SIL[3] or HIL[4] types of tests. These include normal turbine operation, including start–up and shut–down, normal power production, but also dynamic wind events, extreme wind conditions, failure cases, such as control failures or yaw errors. For each of these events, compliance of the turbine design with resulting fatigue load and ultimate load limits is verified. There is, however, a remaining uncertainty with regards to the fidelity of the models under all conditions, in other words, an uncertainty whether it is correct to assume that a turbine design that is safe is the simulated environment is also safe in the real world. This remaining uncertainty needs to be mitigated by appropriate safety margins in the turbine design.

The conformance testing work done in UnCoVerCPS is geared towards guaranteeing transference of safety properties between a model and the actual system, and towards establishing best practices for selection of test cases for conformance testing. These techniques could be used by GE Renewable Energy to establish conformance between a real wind turbine and the respective modelling tools, to reduce the number of tests that need to be run on the real turbine, and to reduce any excessive safety margins in the turbine design.

Likewise, the work can be applied to establish conformance between the above mentioned high fidelity simulation environments, and simplified, reduced–order models that are used, for example, for designing model–based control algorithms.

Work on conformance testing applied to wind turbine models in collaboration with Bosch

[3] Software–in–the–loop

[4] Hardware–in–the–loop

and TUM has been completed.

4.3.2 PV Plant Prediction and Optimization

As one of the outcomes of the first UnCoVerCPS review, a collaboration between GE and Politecnico di Milano (PoliMi) was initiated, regarding work that PoliMi had done on the smart grid use case. In this use case, a hybrid, distributed energy system is considered which comprises several modalities of power generation and energy storage and is characterized by stochastic uncertainty, e.g. with regards to renewable generation and to loads.

As part of UnCoVerCPS, this work by PoliMi which had originally been verified against simulation models, was ported to and verified on a smart grid test rig on the GE Global Research premises in Munich, Germany. To this end, a researcher from PoliMi spent several months at GE Global Research. The test rig comprises a rooftop photovoltaic (PV) installation, battery storage, a grid interface, and programmable three–phase load simulators. The objective of the prediction and control algorithms developed by PoliMi – adapted to this particular test rig – is to optimize overall cost of operations, taking into account time–varying energy prices, physical constraints such as battery storage properties, as well as stochastic properties of PV generation and energy demand.

This work is highly relevant for GE Energy Connections, in particular with regards to the ability to improve forecasting and provide better dispatchability of utility–scale photovoltaic plants.

4.3.3 Unmanned Aerial Vehicles

GE's interest in Unmanned Aerial Vehicles (UAV's) is twofold:

- For GE Aviation System, a leading provider of navigation and guidance systems for commercial aircraft, the rapidly growing market of unmanned aviation is an obvious adjacency to their current business.
- For many of GE's industrial businesses which sell large and complex industrial assets and services around these assets, UAV's offer enormous potential to optimize and automate inspection and repair tasks, especially tasks which would be risky or dangerous to perform manually.

Navigation and Guidance systems are today verified by first establishing conformance between the real system and a high–fidelity model by means of extensive flight test, similar to the conformance testing for wind turbines described above. Then, a huge number of verification runs are performed against this high–fidelity model, e.g. in SIL or HIL tests.

There is enormous potential in automated synthesis and verification of such algorithms, either in an off–line fashion, or on–the–fly, for example in collision avoidance scenarios. There are regular communications with the interested GE businesses, in particular with GE Aviation Systems with whom there is UnCoVerCPS review at least once per month and who also internally co–fund the project. GE also adopted results and tools from other project partners working on the automated driving use case (Bosch, Tecnalia, TUM, UJF) to a number of scenarios relevant to these businesses. The challenges are very similar to the automated driving use case, including collision avoidance scenarios with or without vehicle–to–vehicle or vehicle–to–infrastructure communication, with the obvious difference of the third dimension and very different kinematic and dynamic vehicle models.

4.4 R.U. Robots Exploitation Plans and Activities

R.U. Robots Limited (RUR) develops specialised solutions for human–robot collaborative manufacturing and plans to integrate on–the–fly verification methods developed in UnCoVerCPS into food assembly robots collaborating with human workers. The food industry is Europe's largest manufacturing sector. 99.1% of the food industry is made up of SME's that generally have an extremely poor take up of automation. Food assembly, in particular, is very much a labour intensive task partly due to the uncertain nature of the products being handled, but mainly due to the requirements for ultra-flexibility — in certain cases with entire product changes every 15 minutes. One aspect of ultra–flexibility that arises is the need to mix people and robots on a single line (robots cannot do all tasks cost effectively) and then the need for operatives to work in close proximity to robots. Current guidelines for safety of robots at work prevents uncaged robots, except in special circumstances. RUR intend to first implement the UnCoVerCPS approach on their GRAIL robot, which supports ultra-flexibility and requires no operator IT skills.

The UnCoVerCPS approach and toolset promises to provide a way to address this issue of safety under close, collaborative working between robots and people. In order to address the exploitation potential of these results, RUR has been undertaking five distinct actions throughout the project, namely:

- Tracking and discussing standards and legislative issues.
- An implementation–options study regarding the incorporation of the UnCoverCPS results in product options.
- A market study of the potential exploitation routes.

- Promotion of the UnCoVerCPS tool to the wider robotics community.
- Development of an exploitation plan.

This section provides an update on these actions.

Tracking and discussing standards and legislative issues

As previously reported, there is a current draft ISO standard which specifically addresses collaborative working between humans and robots. RUR has been tracking the developments of this standard. However, as the standard is primarily centred on the potential impact forces that may arise when humans and robots make contact, it is not particularly relevant to UnCoVerCPS which, at its core, is about ensuring that no contact can arise between humans and robots. Rather, in implementing the UnCoVerCPS approach, RUR would have to rely largely on existing safety standards relating to the safety of programmable electronic systems in order to show that the mitigations associated with the approach were commensurate with the potential risks of the system failure. Note that while the approach may be mathematically provable in principle, there will always be risks associated with the software and hardware systems within which the safety system is implemented. This in turn relates to the integrity of the hardware and software systems themselves and, in particular, means that any software directly related to the safety function would need to be developed to Safety Integrity Level (SIL) 2, which has implications for, particularly, further development costs. To further validate that this was the correct approach RUR maintained contact with the UK Health and Safety Laboratory, which looks at future requirements for legislation.

An implementation–options study regarding the incorporation of the UnCoverCPS results in product options

A series of implementation options studies were a major part of the work carried out in respect to exploitation options for RUR. These studies covered:

- The types and nature of sensors that could be used within the safety systems.
- The robot hardware options.

The review of sensors addressed one of the shortcomings of the implemented system within the UnCoverCPS project, that of the use of "simplistic" sensing involving only a light curtain to detect human-robot proximity. While this does potentially provide a workable, safe system at a relatively low cost, it does so at the expense of assembly throughput, i.e. in

order to guarantee safety, a series of worst case assumptions have to be made which results in over-cautious behaviour by the robot. The review revealed a number of alternative sensors which could provide high integrity safety while also provide continuous, or near continuous tracking of the human movements. However, these came with the penalty of either high cost, or impracticable implementation, or both. However, one alternative that emerged from this review was the idea of using a non-safety sensor to help improve the efficiency of assembly throughput by predicting human behaviour prior to any interaction with the light-curtain so that the robot could be at the most advantageous position to cope with such an incursion. This approach was implemented on the UnCoVerCPS human-robot test bed and is dealt with more fully in D5.3.

The other major assessment that has been undertaken relates to the robot hardware on which the UnCoVerCPS approach could be implemented for exploitation. RUR have looked at two ways of implementing their assembly robot system. The first is by utilising the prototype GRAIL robot developed by RUR in conjunction with other organisations. The second is to implement the GRAIL software on a standard industrial manipulator. The latter option confers the advantage of high reliability hardware and more immediate consumer acceptance, but requires either close cooperation with an industrial robot manufacturer or the reverse engineering of the low-level control system in order to implement the full functionality of the GRAIL system. At the start of the project it was assumed, somewhat naively, that the UnCoVerCPS safety system could be implemented as a "wrapper" around the existing control system. As such the adoption of the UnCoVerCPS approach would have been neutral as to which hardware option to adopt. However, as the project development continued, it became clear that such a clear separation could not be achieved and that an analysis had to be carried out regarding those parts of the control system that would need to be developed to SIL 2. When this is mapped onto the existing control system it becomes apparent that significant parts of both the trajectory planning system and the low level controllers would have to be SIL 2 compliant for a claim of guaranteed safety to be made. While this is achievable using the GRAIL hardware system, which is totally under the control of RUR, achieving the same on a third-party robot would be extremely difficult. This has effectively ruled out the implementation of the UnCoVerCPS approach on a third-party robot as an exploitation route in the immediate future.

A market study of the potential exploitation routes

Although food assembly is the primary target for RUR's GRAIL robot, an evaluation of other assembly task markets has been carried out. However, it is clear that none have the same imperatives, nor the potential volumes of the food industry. It was therefore decided to carry out a more detailed analysis of the UK food-assembly market.

The current UK food and drink market is worth approximately £76bn in terms of turnover with a gross added value of over £20bn per annum. The industry employees approximately 400,000 people, or about 15% of the UK manufacturing workforce (Europe as a whole employs around 4.57 million people). Over 98% of the industry consists of Small and Medium sized Enterprises (SMEs) who collectively account for just under half of the total food output.

The primary targets for the GRAIL robot are the SME companies. There are a number of reasons for this. First it is in the smaller companies where there is most likely to be a lack of IT skills, which is one of the key characteristics targeted by the GRAIL system. Second, SMEs are more likely to want to undertake an incremental approach to automation, which is again where GRAIL wins out over more standard industrial robotic systems. Conversely large companies are more likely to automate a full line and link such automation in with other manufacturing resource planning systems, which is an area where industrial robots have comparative strength over GRAIL. Third is that many SME food manufacturers suffer from a chronic lack of space in their factories. GRAIL's small footprint and the potential for not needing to cage the manipulator again have distinct advantages that may not be so apparent in a large food manufacturer.

However, having said that large manufacturers may prefer a more standard industrial robot solution, there are cases even in these larger firms where the GRAIL will be a cost-effective solution, particularly for automating smaller or (automation-wise) isolated tasks.

The level of robot automation in the food industry is very low. In general, there are inroads being made but these are generally in the back-end packaging, boxing and palletising applications or at the front end with bulk material handling. There is relatively little penetration into the food assembly tasks that are the core target for the GRAIL robot and where it has happened it is generally by the larger firms looking for a more flexible alternative to hard automation.

The route to market for food automation is through system integrators and line builders of which there are many hundreds of mainly small companies. Generally, these organisations in the UK have little experience of robotics, although this is changing. While the ease of set up of the GRAIL robot is a benefit for these organisations, the lack of knowledge about robotic

requirements and the provision of service is going to be a challenge that is going to require gradual roll-out through a limited number of trained system integrators in the first instance.

The UK food industry (as in many other countries) is well known for high staff turnover. Anecdotally, figures ranging from 10% to 40% per annum are quoted. This makes staff recruitment both a difficult and costly exercise, with many areas of the food industry relying on transitory migrant workers to fill vacancies and which is becoming more problematical. Even at 10% this amounts to 40,000 vacancies needing to be filled every year by the food industry.

Many food assembly line workers are at or near minimum wage. This makes the direct annual cost to their employer just over €20,000 without considering other direct costs such as training and hygiene provision.

The results of a PESTLE (**P**olitical **E**conomic **S**ociological **T**echnological **L**egal **E**nvironmental) analysis, which showed a favourable outlook for the GRAIL robot, can be summarised as:

Political: The food industry is an important industry and there are signs that there is growing political support for increasing technology investment in the industry. The food industry is a major customer for UK agriculture which has a strong political lobby. The UK food industry takes nearly 80% of UK agriculture output and is an important element in ensuring the UK can maintain secure food production.

Economic: The food industry is the largest UK manufacturing sector, both in terms of turnover and employment. The food industry is characterised as being a non-cyclical sector and has fared better than most other sectors in the recent economic downturn. However, while product volumes have been maintained, there has been a switch by consumers away from the mid-priced which has reduced margins, particularly in SMEs. This in turn increases the requirement for higher productivity in these firms for them to remain competitive.

Sociological: Although the food industry is a major employer in the UK, the rate of churn is high. Also, the skill level for many food assembly tasks is low. A significant proportion of the labour force is made up of transitory migrant labour which is becoming more difficult to access. Therefore, although the GRAIL robot essentially replaces employees, the effect is not significant in the medium term at a national level. At a local firm level, it overcomes an employment problem at an individual firm level and, by making firms more competitive, increases employment options.

Technological: The level of IT skills in the food industry, particularly SMEs, is low. This is a competitive advantage for the GRAIL robot as the skill requirements for operation and re-tasking are low to negligible. However, the level of R&D investment by the food

industry is very low (approximately 0.26% of turnover, according to FoodDrink Europe: FoodDrinkEurope_Data_and_Trends_2018_FINAL.pdf) with most of what is spent going into food and food preparation science. Therefore, it is unrealistic to expect the food industry to further invest in the development of an automation product, meaning that the development must be undertaken independently and presented to the industry as a fully developed product.

With regard to competitor technologies, there are trends in manufacturing to address the general needs of SME manufacturers through cheaper, more flexible and easier to use robots. However, to date, all the efforts in the USA and Europe are focussing on making the programming of robots easier rather than eliminating the programming and concentrating on the task. There are also robots being developed specifically to meet food industry needs. However, it is clear that while these robots address the hygiene needs they fail to address the other needs of the UK food SMEs addressed by the GRAIL robot.

Legal: The main factors in the legal realm relevant to the GRAIL robot are traceability and safety. The GRAIL robot concept can clearly embed traceability support, but in the current version demonstrated in the trials, this is not supported. Such support needs to be built in. On the safety side, the ability to operate without fences greatly extends the sales potential of the GRAIL robot. This is the area where the addition of the UnCoVerCPS approach greatly enhances the offering.

Environmental: The GRAIL robot does not have any specific factors which address environmental issues in a significant manner. It is lighter than conventional industrial robots and is therefore more energy efficient, but this is not a significant issue in the purchase decision. The required hygiene issues are well addressed by the GRAIL robot.

Promotion of the UnCoVerCPS tool to the wider robotics community

An important part of the exploitation work is the adoption of the UnCoverCPS approach by potential end users and other robot suppliers. To this end RUR have proposed a workshop at the next European Robotics Forum (the largest gathering of robotics researchers and engineers in Europe). This forum will be held in Bucharest in March 2019, as already mentioned on section 3.4.1 of this document.

Exploitation Plan

RUR has, largely with its own funds, developed a confidential exploitation plan for the GRAIL robot incorporating the UnCoVerCPS approach. A summary of this plan is, however, presented here. The main elements of this plan are:

- The value proposition.
- The routes to market.
- Development costs and return on investment.
- Potential sources of funding.

The value proposition: The GRAIL robot will initially be sold to SME food manufacturers whose main tasks revolve around food assembly, mainly ready meals, sandwich and pizza making and associated tasks. The aim is not to replace whole lines of people but to provide individual workstations as islands of automation that can work alongside existing line workers. In this way the automation can be provided incrementally. It is also not intended that the initial offerings should provide a solution for all the food assembly tasks, but actually to tackle only the most basic (and from an automation point of view the easiest) tasks. While initially this may be counterintuitive, it is exactly these tasks that are the most boring for existing operatives to undertake and therefore where mistakes often occur. Moving people off these boring tasks will also not present too many problem within the factories. With an anticipated end customer price of around €30,000, the payback time on replacing a single employee is about 18 months, without considering hiring and training costs for the employees. With the current system already displaying performance levels at least equivalent of a single employee, this is well achievable. However, much more attractive is where the factory is working 2 or more shifts where the payback comes down to well under a year and the resistance to investment reduces drastically. The other barrier to investment is the fact that many small food companies operate without long-term (or any) contracts and therefore they need flexibility in their workforce to move on to new products. However, with the re-tasking ability of the GRAIL robot this resistance can also be overcome.

Therefore, initial customers targeted will be those that undertake food assembly and working more than one shift. While other areas such as packing will be considered, these will not be the focus of the initial targeting. The value proposition will therefore be a four strand one of:

- Greater consistency, reliability and hygiene.
- Reduction in employment turnover concerns.
- A payback of under a year (with 2 shifts working).
- Guaranteed safety provided by the UnCoVerCPS approach.

Traceability and on-line quality assurance may be other additional value propositions that can be built into the final product offering.

The routes to market: The two options for long-term routes to market are either direct from the manufacturer or through a network of system integrators. The first option is a poor one for SMEs in the food industry as they will generally need support in installation and initial set-up that could be difficult to provide from an organisation that is primarily a manufacturer. The alternative route of providing the product through a system integrator network is more robust although they would need initial training and incentivisation to adopt the GRAIL robot. They would also need to be encouraged to feedback customer comments as on-going product development will benefit greatly from such feedback.

However, in the shorter term it is intended to explore a lead customer approach to getting the system installed and integrated into existing food factories. A lead customer has been identified, who is a major manufacturer and supplier of sandwiches to UK supermarkets and this company will be incentivised to work closely with RUR in fine tuning the market offering by offering them an initial 2 years exclusivity deal.

Development costs and return on investment: There is considerable further development to be undertaken to achieve a robust and marketable product, complete with all approvals. The current estimate is that it will take between £4m and £4.5m and 24-30 months to undertake the development, both of the control system incorporating the UnCoverCPS approach (developed to SIL 2 standards where appropriate) and a robust electromechanical system. The estimated build cost for the final system manufactured in batches of 50+ is of the order €15,500 for a single robot workstation including cameras and feeder conveyors. With an ex-factory mark up of 45% this becomes a selling price to the system integrators of €22,500. Allowing a further mark-up of 20% to the system integrators produces a customer price of €27,000 to which would need to be added the installation, calibration and initial tasking costs. However, given the ease of use characteristics of the system, this should be less than a few thousand pounds providing a final price to the customer of between €30,000 and €33,000. The system integrators would benefit from additional work associated with the provision of additional equipment such as conveyors and end of line equipment, i.e. much the same as they already provide but with the added unique selling point of the GRAIL robot. On this basis, a conservative estimate would see an achievable market being in the region of 1.5% of the annual employee churn rate within 4 years. Taking the low-end estimate of churn rate gives a target of 600 manipulators per annum within 4 years. However, assuming that sales start to level off after year 4, and assuming an overhead level for the manufacturing business of 20%, this scenario only provides a payback on investment after 4 to 5 years. It does, however, provide healthy profits thereafter

and the options for further growth are significant. By the sixth year after starting sales the internal rate of return of the €4m development investment is 10% and it climbs significantly thereafter.

Sources of finance: Funding of the required €4m - €4.5m of product development costs is not within the financial capabilities of RUR. Although there are several schemes to support the late stages of development they nearly all require a significant proportion of the funding to be put up by the organisation undertaking the development. This in turn means that some additional finance is required, either from an end customer, loan funding or equity funding. As already mentioned, the target end customers are SMEs and they are in no better position to fund a 30 month development with upwards of £3m. Even larger food companies (such as the potential lead customer mentioned above) would not be in a position to fund development but, rather, would look to purchase complete end product. Large loan funding for smaller SMEs is non-existent in the current climate. Equity funding is potentially available but the relatively long-term nature of the return is not attractive to the fund managers (see further details below).

Potential sources of late stage development funding include:

- Innovate UK: Innovate UK offer a variety of funding schemes to support SMEs undertake R&D projects. However, in terms of late stage support the most relevant is the innovation loans programme, but this offers a maximum of £1m (aprox. €1.1m).

- EC SME instrument (part of the Horizon 2020 programme): This offers a structured programme of grants and loans (€50k grant at 100% funding, followed by up to €2.5m grant at 70% funding followed business acceleration services and facilitated access to capital). This is a rolling programme with regular assessment and reviews. However, at the time of writing, the current status of the UK Brexit negotiations makes this an uncertain funding route.

- Horizon Europe funding: Under the proposals for Horizon Europe support for near market activities by SMEs will continue to be supported. Therefore, a development project could be envisaged which would help RUR perform further risk reduction and reduce the capital outlay for final product development. However, as with the previous option, the current uncertain status of the UK within Europe makes this a difficult option when operating from a UK base.

- Private equity finance: Although the GRAIL project is at the right stage to benefit from equity finance, this community has generally got used to the relatively quick returns

and incremental funding of web-based products and services. Compared to these, all hardware-based projects require relatively large up-front funding and offer relatively long periods before the investment is paid back. For the GRAIL robot this is some 5-6 years. Nevertheless, the rate of return on the GRAIL robot can still be attractive achieving up to 10% over 6 years and over 13% over 7 years. However, so far it has not been possible to attract the interest of equity investors.

4.5 Esterel Exploitation Plans and Activities

Esterel Technologies, as a subsidiary of ANSYS, Inc, is in charge of the development of the virtual system paradigm with the goal to aggregate multi-physics simulation and embedded software controllers. Our solutions can be applied to various domains such as Aerospace & Defence (A&D), Automotive, Railway Transportation, Industry and Energy. System complexity is increasing, in particular in the cyber–physical systems class. This is particularly true in Automotive with Advanced Driver Assistance Systems (ADAS), but also in A&D systems requiring a high safety level and for which on–line failure prediction is key. Esterel Technologies expects to get a better understanding of the needs of real application cases from the UnCoVerCPS project. Leveraging these applications and the cooperation with research partners, the SCADE and Simplorer toolsets will be improved.

The automotive use case offers two opportunities. The first one is related to the development of the controller in charge of the trajectory selection. The second one, although not directly related to cyber–physical systems, is vehicle–to–vehicle communication, which could be also a good example of the use of SCADE tools for protocols. In that context, a trajectory tracking controller and a first communication controller have been implemented in SCADE by DLR and Tecnalia. This is the first automotive demonstrator for the UnCoVerCPS toolchain. This work has been presented at the ASWC[5] 2016 [3].

The Scade language has been extended with hybrid constructs allowing for a complete mix of discrete and continuous parts. This work is a continuation of research work leading to the implementation into an industrial prototype [2] adapted to the automotive demonstrator for the UnCoVerCPS toolchain. This work has been presented at the ASWC[6] 2016 [3]. The continuous part is integrated in the textual form of the Scade language and a dedicated library allows for its use within the graphical environment. The addition of the hybrid support within Scade also permits to import a FMU[7] in both model-exchange or co-simulation flavours. This

[5] Ansys Automotive Simulation World Congress

[6] Ansys Automotive Simulation World Congress

[7] Functional Mock-Up Unit, see `https://www.fmi-standard.or`

integration extends the simulation capability as a complex physical model can be imported to provide an environment for the software controller.

Interoperability between SCADE and SpaceEx has been realised. An analysis of the semantics of the languages supported by the two tools has been performed. Based on this analysis and considering UnCoVerCPS automotive case as an example, the flow using the two tools has been derived.

As of today, SCADE Hybrid that has been industrialized in the context of the UnCoVerCPS is now part of the ANSYS' *Twin Builder* tool. The Twin Builder tool is used to build a digital twin of a system. The obtained digital twins are used for predictive maintenance or "debugging" . SCADE Hybrid is used as the internal synchronizer of the various components of the digital twin. This technology is deployed in two co-operations with PTC Thinkwork and SAP Predictive Engineering Insights.

4.6 DLR Exploitation Plans and Activities

DLR plans to incorporate results and methods from UnCoVerCPS into ongoing research projects and future demonstrations such as Urban Drive, which strives to realise fully automated passenger vehicles in urban areas by 2020. By reducing the risk of technical failure, safety verification is a key enabler for automated driving. DLR will integrate on–the–fly verification techniques developed in UnCoVerCPS into its Urban Drive roadmap. We have started this process by replacing the trajectory tracking controller of the automated vehicle by a controller developed in SCADE Suite. We will derive correctness properties for this controller using the CORA toolbox. A combinatorial search algorithm for contingency manoeuvre planning has been developed which makes use of on–the–fly verification principles and builds on the correctness properties derived for the underlying SCADE Suite trajectory tracking controller. In addition to safeguarding the automated vehicle operation in UnCoVerCPS and future projects, the newly-developed control systems serve as demonstrators for the UnCoVerCPS paradigms. The developed control systems also demostrated the improved development process, and serve as an example for the UnCoVerCPS toolchain.

4.7 Tecnalia Exploitation Plans and Activities

In the framework of the UnCoVerCPS project, Tecnalia will use the project results for further private and collaborative research activities. The most valuable result for Tecnalia is the autonomous vehicle demonstrator, which will be able to perform safe collaborative manoeuvres demonstrated at the end of UnCoVerCPS project.

In November 2015 a new instruction 15/V–113 was launched by the Spanish DGT (Dirección General de Tráfico), directly related to the Ministry of Internal Affairs of Spain. The denomination of this new instruction is "Authorization trials or research studies with automated vehicles driving on roads open to general traffic". It gives an oportunity to accelerate the real implementation of Automated Driving. New business opportunities for Tecnalia are framed in research project activities such as the following ones:

- New private contracts for implementing UnCoVerCPS project results into different urban vehicle types developed by Spanish industrial companies, spin-offs and SME's, such as MASER, LARRAIOZ, MONDRAGON AUTOMOCION and others.
- AIRPORTS "Airport Improvement Research on Processes & Operations of Runway, TMA & Surface". Spanish Collaborative project where the vehicle demonstrator will be further developed for airport areas.

Tecnalia will test its development activities thanks to the use of the resulting autonomous vehicle of UnCoVerCPS into new collaborative projects in the frame of the ERTRAC "Automated Driving Roadmap", in running and future projects such as the following ones:

- IOSENSE "Flexible FE/BE Sensor Pilot Line for the Internet of Everything": ECSEL Innovation Project; project started at the end of 2015.
- MOB-ON-PARKS "Mobility Plans Based on Integrated Staff Management for Technology Parks": European proposal in the frame of LIFE Program 2014–2020 for environment and climate action.

OEM's and Tier1's from the automotive sector specially focused on road automation can have access to UnCoVerCPS results (i.e. paper, wrokshops, etc.).

4.8 Open Source Software Releases

Two of the central tools which are developed and improved within UnCoVerCPS are SpaceEx (http://spaceex.imag.fr) and CORA (http://www6.in.tum.de/Main/SoftwareCORA). New versions of these tools have been released from 2015 and to 2018.

SpaceEx and CORA apply different technologies to perform reachability analysis; reachability and safety verification is particularly challenging for continuous and hybrid systems due to the complexity of representing and computing with continuous sets of states.

The development of SpaceEx was spawned by recent progress in finding efficient data structures and algorithms for reachability computation. Reachset approximations are efficiently computed for continuous linear dynamics with hundreds of variables. Its wrapping–free

algorithm is particularly efficient when zonotopes or support functions are used as set representations. The underlying model in SpaceEx is a composition of hybrid automata, including extensions such as hierarchy and templates. The tool allows the development of heterogeneous analysis methods, such as using different set representations in different parts of the state space, or at different levels of refinement, or when combining symbolic computation with simulation. The SpaceEx analysis tool is available as a virtual machine server that can be run locally in a protected environment with a web–based frontend. It is also available as a command line tool for experienced users. In addition, there is a Java–based model editor for the creation and modification of SpaceEx model files. All three components are released under the GPLv3 license. SpaceEx is made available by Verimag, which is a research institution affiliated with the University Joseph Fourier in Grenoble. Multiple updates of the SpaceEx components have been released throughout the duration of UnCoVerCPS.

The Continuous Reachability Analyser (CORA) is a collection of MATLAB classes for the formal verification of cyber–physical systems using reachability analysis. CORA can be applied to nonlinear differential equations and even to nonlinear differential–algebraic equations. This is particularly important for industrial applications, a vast majority of which involve nonlinear systems. CORA is designed in such a way that representations can be exchanged without the need to modify the code for reachability analysis. Since the toolbox is based on MATLAB, its installation and use are platform independent.

The CORA update released in 2016 includes the following new features:

- CORA no longer requires the MATLAB toolbox INTLAB for interval arithmetic. Instead it contains an own implementation of interval arithmetic, making CORA independent of the commercial INTLAB tool.

- Unit tests have been added to ensure that functionality is maintained after major software changes. The unit tests can also be used as guiding examples to set up own verification problems.

- It is no longer required to implement all systems as hybrid automata in order to the method *reach* for computing the reachable set. The method is now also applicable to purely continuous systems.

- Auxiliary files, such as the Lagrange remainder, now contain the name of the model and are no longer overwritten when changing the investigated model.

- To shorten to the code without compromising functionality, we have integrated the class *intervalhull* into the new class *interval*, and the classes *vehicleSys* and *vehicleSys_td* into

the existing class *nonlinearSys*.

- Faster plotting of reachable sets thanks to a new routine from Daniel Heß at DLR.
- The 2015 version only contained a single example (bouncing ball). The new version contains at least one example for each implemented category of dynamic systems.
- Many unused or prototypical files have been removed, and the code has been decluttered for various functions.

The 2018 release of CORA includes the subsequent list of improvements:

- **Reading SpaceEx format**: it is possible to read SpaceEx models, which have become the quasi-standard for formal verification tools of hybrid systems. This also has the advantage to use the SpaceEx model editor for modelling hybrid systems.
- **Parallel hybrid automata**: It is infeasible to model larger hybrid systems using a single hybrid automaton. It is now possible to specify parallel hybrid automata so that it is no longer required to model a system by a single hybrid automaton. For analysis purposes, the dynamics of parallel hybrid automata on-the-fly have been assembled.
- **New zonotope reduction methods**: New methods for the order reduction of zonotopes are now available in CORA.
- **Lazy symbolic computations**: CORA performs symbolic computations for nonlinear systems, e.g., to linearize them for various linearization points. These computations used to be performed for each reachability analysis. Now these time-consuming computations are only performed if the model files are changed or options concerning the symbolic computations are modified.
- **Taylor models**: In current new version, there is a class to compute with Taylor models.
- **Affine arithmetic**: As a by-product of the Taylor model implementation, it has also been implemented an affine arithmetic when the number of noise terms does not exceed the system dimension.
- **Constrained zonotope**: This new set representation from Scott et al. is as general as polytopes, but makes it possible to use lazy computations.
- **Discrete time models**: It is now possible to compute reachable sets of discrete time models. A class for linear discrete time models has not been implemented, since this is too trivial.

- **More compact implementation**: the class linVarSys has been integrated into the class linParamSys. Also, all symbolic computations have been unified, which are now inherited from all other classes for continuous dynamics.

- **Miscellaneous**: There are many other interesting improvements: Better organization of models (now under /models), directly changing parameters for nonlinear systems during reachability analysis, better controlling simplifications of symbolic expressions, more unit tests, vector and matrix norms for vector and matrix sets, extending linear systems to affine systems, etc.

UnCoVerCPS also aims at the integration of CORA and SpaceEx which is an ongoing effort. A student at TUM, Evgeny Agamirzov, has worked on porting MATLAB based CORA algorithms to C++ such as to enable integration into SpaceEx. In 2016, we have finished transferring the zonetope toolbox from CORA to SpaceEx. As a result, computation times in SpaceEx could be substantially reduced. The results of this are documented in [1].

4.9 IP Strategy

The protection of intellectual property has not been a central element for the UnCoVerCPS project to date; the focus has instead been on an open–source approach. This is due to the fact that the industrial partners will typically benefit from applying the developed tools and methods to faster design and verification of cyber–physical systems. This will give them a competitive advantage.

5 Summary and Outlook

This report has described the dissemination and exploitation activities of UnCoVerCPS for the period of January 2015 to December 2018. Core elements of dissemination throughout the whole project duration have been:

- numerous conference and journal publications;

- workshops organized by the UnCoVerCPS project, in particular the ARCH Workshops as part of Cyber–Physical Systems Week, the workshop "Verification and Control of CPS: Theory and Applications" as part of CDC 2016, as well as the UnCoVerCPS workshop 2018 organised by PoLiMi in Milano;

- open source software releases, in particular CORA and SpaceEx;

- participation in collaboration and liaison events, e.g. “Advanced Computing and CPS 2016”, “Digital Innovation Forum” in 2017;
- the UnCoVerCPS web site and flyers;
- teaching activities.

The ARCH workshops have not only raised awareness of UnCoVerCPS in the relevant scientific and industrial communities, but also provided the consortium with valuable input in the form of industrially-relevant benchmark problems that the UnCoVerCPS toolchain will be evaluated against. In particular, in ARCH'17 and ARCH'18 a competition took place, where tools were evaluated against benchmark problems, and compared to each other.

Besides significant improvements and open–source releases of CORA and SpaceEx, TUM and UJF have commenced a joint activity towards integration of both tools. To this end, CORA 2018 new version algorithms have been ported to C++ for integration into SpaceEx.

Commercial exploitation activities are ongoing, both horizontally with regards to tools (Esterel, TUM, UJF, Universität Kassel) and vertically with regards to a wide range of safety–critical CPS applications (Bosch, R.U. Robots, Politecnico di Milano, DLR, Tecnalia). Commercial exploitation is expected to gain more momentum, going forward, and will also take into consideration regulatory and legislative aspects from the individual application domains.

Appendix A: Conference papers published in the context of UnCoVerCPS

References

[1] *2018 Annual American Control Conference, ACC 2018, Milwaukee, WI, USA, June 27-29, 2018*. IEEE, 2018. ISBN: 978-1-5386-5428-6. URL: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=8410068.

[2] *56th IEEE Annual Conference on Decision and Control, CDC 2017, Melbourne, Australia, December 12-15, 2017*. IEEE, 2017. ISBN: 978-1-5090-2873-3. URL: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=8253407.

[3] M. Althoff. “An Introduction to CORA 2015”. In: *Proc. of the Workshop on Applied Verification for Continuous and Hybrid Systems*. 2015.

[4] M. Althoff and G. Frehse, eds. *ARCH16. Proceedings of 3rd International Workshop on Applied Verification of Continuous and Hybrid Systems*. Vol. 43. EPiC Series in Computing. EasyChair, 2017.

[5] M. Althoff and G. Frehse. "Combining Zonotopes and Support Functions for Efficient Reachability Analysis of Linear Systems". In: *Proc. of the 55th IEEE Conference on Decision and Control*. 2016.

[6] M. Althoff and G. Frehse, eds. *Post-Proceedings of the 1st and 2nd International Workshop on Applied Verification of Continuous and Hybrid Systems*. Vol. 34. EPiC Series in Computing. EasyChair, 2015.

[7] M. Althoff and D. Grebenyuk. "Implementation of Interval Arithmetic in CORA 2016". In: *Proc. of the 3rd International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2016.

[8] M. Althoff, D. Grebenyuk, and N. Kochdumper. "Implementation of Taylor Models in CORA 2018". In: *Proc. of the 5th International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2018, pp. 145–173.

[9] M. Althoff et al. "ARCH-COMP17 Category Report: Continuous and Hybrid Systems with Linear Continuous Dynamics". In: *Proc. of the 4th International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2017, pp. 143–159.

[10] M. Althoff et al. "ARCH-COMP18 Category Report: Continuous and Hybrid Systems with Linear Continuous Dynamics". In: *Proc. of the 5th International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2018, pp. 23–52.

[11] Matthias Althoff et al. "ARCH-COMP18 Category Report: Continuous and Hybrid Systems with Linear Continuous Dynamics". In: *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems*. Ed. by Goran Frehse. Vol. 54. EPiC Series in Computing. EasyChair, 2018, pp. 23–52. DOI: 10.29007/73mb. URL: https://easychair.org/publications/paper/4cGr.

[12] L. Asselborn and O. Stursberg. "Control of discrete-time piecewise affine probabilistic systems using reachability analysis". In: *2016 IEEE Conference on Computer Aided Control System Design (CACSD)*. Sept. 2016, pp. 661–666. DOI: 10.1109/CACSD.2016.7602542.

[13] Leonhard Asselborn and Olaf Stursberg. "Probabilistic control of switched linear systems with chance constraints". In: *Control Conference (ECC), 2016 European*. IEEE. 2016, pp. 2041–2047.

[14] L. Bascetta, I. Mendizabal Arrieta, and M. Prandini. "Flat-RRT*: A sampling-based optimal trajectory planner for differentially flat vehicles with constrained dynamics". In: *20th World Congress of the International Federation of Automatic Control (IFAC 2017), Toulouse, France*. July 2017.

[15] D. Beckert, A. Pereira, and M. Althoff. "Online Verification of Multiple Safety Criteria for a Robot Trajectory". In: *Proc. of the 56th IEEE Conference on Decision and Control*. 2017.

[16] A. Belloni, L. Piroddi, and M. Prandini. "A stochastic optimal control solution to the energy management of a microgrid with storage and renewables". In: *2016 American Control Conference (ACC)*. July 2016, pp. 2340–2345. DOI: 10.1109/ACC.2016.7525267.

[17] S. Bogomolov et al. "Counterexample-guided refinement of template polyhedra". In: *23rd Int. Conf. on Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*. LNCS. Springer, 2017.

[18] Sergiy Bogomolov et al. "Reach Set Approximation through Decomposition with Low-dimensional Sets and High-dimensional Matrices". In: *Proceedings of the 21st International Conference on Hybrid Systems: Computation and Control (part of CPS Week), HSCC 2018, Porto, Portugal, April 11-13, 2018*. ACM, 2018, pp. 41–50. DOI: 10.1145/3178126.3178128. URL: https://doi.org/10.1145/3178126.3178128.

[19] Sergiy Bogomolov et al. "Reach set approximation through decomposition with low-dimensional sets and high-dimensional matrices". In: *Proceedings of the 21st International Conference on Hybrid Systems: Computation and Control (part of CPS Week)*. ACM. 2018, pp. 41–50.

[20] Timothy Bourke et al. "A Synchronous-based Code Generator For Explicit Hybrid Systems Languages". In: *International Conference on Compiler Construction (CC)*. LNCS. London, UK, Apr. 2015. URL: cc15.pdf.

[21] C. Brocchini et al. "A chance-constrained approach to the quantized control of a heat ventilation and air conditioning system with prioritized constraints". In: *Proceedings of the 22nd International Symposium on Mathematical Theory of Networks and Systems (MTNS 2016), Minneapolis, Minnesota, USA*. July 2016, pp. 137–144.

[22] Axel Busboom, Simone Schuler, and Alexander Walsch. "formalSpec – Semi-Automatic Formalization of System Requirements for Formal Verification". In: *ARCH16. 3rd International Workshop on Applied Verification for Continuous and Hybrid Systems*. Ed.

by Goran Frehse and Matthias Althoff. Vol. 43. EPiC Series in Computing. EasyChair, 2017, pp. 106–114.

[23] Davide Calzolari, Bastian Schurmann, and Matthias Althoff. "Comparison of Trajectory Tracking Controllers for Autonomous Vehicles". In: *Proc. of the 20th IEEE International Conference on Intelligent Transportation Systems*. 2017, pp. 1675–1682.

[24] A. Casalino, P. Rocco, and M. Prandini. "Hybrid control of manipulators in human-robot coexistence scenarios". In: *American Control Conference (ACC)*. June 2018, pp. 1172–1177. DOI: 10.23919/ACC.2018.8431763.

[25] V. Causevic et al. "Energy management in a multi-building set-up via distributed stochastic optimization". In: *American Control Conference (ACC)*. June 2018, pp. 5387–5392. DOI: 10.23919/ACC.2018.8431043.

[26] X. Chen, M. Althoff, and F. Immler. "ARCH-COMP17 Category Report: Continuous Systems with Nonlinear Dynamics". In: *Proc. of the 4th International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2017, pp. 160–169.

[27] Hana Chockler and Georg Weissenbacher, eds. *Computer Aided Verification - 30th International Conference, CAV 2018, Held as Part of the Federated Logic Conference, FloC 2018, Oxford, UK, July 14-17, 2018, Proceedings, Part I*. Vol. 10981. Lecture Notes in Computer Science. Springer, 2018. ISBN: 978-3-319-96144-6. DOI: 10.1007/978-3-319-96145-3. URL: https://doi.org/10.1007/978-3-319-96145-3.

[28] L. Deori, S. Garatti, and M. Prandini. "A stochastic strategy integrating wind compensation for trajectory tracking in aircraft motion control". In: *55th IEEE Conference on Decision and Control (CDC)*. Dec. 2016, pp. 256–261. DOI: 10.1109/CDC.2016.7798279.

[29] L. Deori, S. Garatti, and M. Prandini. "Stochastic control with input and state constraints: A relaxation technique to ensure feasibility". In: *54th IEEE Conference on Decision and Control (CDC)*. Dec. 2015, pp. 3786–3791. DOI: 10.1109/CDC.2015.7402807.

[30] L. Deori, K. Margellos, and M. Prandini. "On decentralized convex optimization in a multi-agent setting with separable constraints and its application to optimal charging of electric vehicles". In: *55th IEEE Conference on Decision and Control (CDC)*. Dec. 2016, pp. 6044–6049. DOI: 10.1109/CDC.2016.7799197.

[31] Luca Deori, Simone Garatti, and Maria Prandini. "A model predictive control approach to aircraft motion control." In: *American Control Conference, Chicago, USA*. July 2015.

[32] Luca Deori, Kostas Margellos, and Maria Prandini. "On the connection between Nash equilibria and social optima in electric vehicle charging control games". In: *20th World Congress of the International Federation of Automatic Control (IFAC 2017), Toulouse, France*. July 2017.

[33] P. Dimitrov, L. Piroddi, and M. Prandini. "Distributed allocation of a shared energy storage system in a microgrid". In: *2016 American Control Conference (ACC)*. July 2016, pp. 3551–3556. DOI: 10.1109/ACC.2016.7525464.

[34] A. Falsone et al. "Distributed constrained convex optimization and consensus via dual decomposition and proximal minimization". In: *55th IEEE Conference on Decision and Control (CDC)*. Dec. 2016, pp. 1889–1894. DOI: 10.1109/CDC.2016.7798540.

[35] A. Falsone et al. "Linear programs for resource sharing among heterogeneous agents: The effect of random agent arrivals". In: *IEEE 56th Annual Conference on Decision and Control (CDC)*. Dec. 2017, pp. 3853–3858. DOI: 10.1109/CDC.2017.8264226.

[36] A. Falsone et al. "Optimally shaping the stationary distribution of a constrained discrete time stochastic linear system via disturbance compensation". In: *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*. Dec. 2017, pp. 629–634. DOI: 10.1109/CDC.2017.8263731.

[37] Alessandro Falsone and Maria Prandini. "An iterative scheme for the approximate linear programming solution to the optimal control of a Markov Decision Process". In: *2015 European Control Conference (ECC 2015), Linz, Austria*. July 2015, pp. 1200–1205. DOI: http://doi.org/10.1109/ECC.2015.7330703.

[38] Goran Frehse. "Computing Maximizer Trajectories of Affine Dynamics for Reachability". In: *IEEE Conf. Decision and Control (CDC)*. IEEE Press, 2015.

[39] Goran Frehse. "Reachability of Hybrid Systems in Space-Time". In: *Int. Conf. on Embedded Software (EMSOFT'15)*. ACM, 2015.

[40] Goran Frehse, Mirco Giacobbe, and Thomas A Henzinger. "Space-Time Interpolants". In: *International Conference on Computer Aided Verification*. Springer. 2018, pp. 468–486.

[41] Goran Frehse, Mirco Giacobbe, and Thomas A. Henzinger. "Space-Time Interpolants". In: *Computer Aided Verification - 30th International Conference, CAV 2018, Held as Part of the Federated Logic Conference, FloC 2018, Oxford, UK, July 14-17, 2018, Proceedings, Part I*. Ed. by Hana Chockler and Georg Weissenbacher. Vol. 10981. Lecture Notes in Computer Science. Springer, 2018, pp. 468–486. ISBN: 978-3-319-96144-6. DOI:

10.1007/978-3-319-96145-3_25. URL: https://doi.org/10.1007/978-3-319-96145-3%5C_25.

[42] Goran Frehse et al. "A Toolchain for Verifying Safety Properties of Hybrid Automata via Pattern Templates". In: *2018 Annual American Control Conference, ACC 2018, Milwaukee, WI, USA, June 27-29, 2018*. IEEE, 2018, pp. 2384–2391. ISBN: 978-1-5386-5428-6. DOI: 10.23919/ACC.2018.8431324. URL: https://doi.org/10.23919/ACC.2018.8431324.

[43] Goran Frehse et al. "A Toolchain for Verifying Safety Properties of Hybrid Automata via Pattern Templates". In: *2018 Annual American Control Conference, ACC 2018, Milwaukee, WI, USA, June 27-29, 2018*. 2018, pp. 2384–2391. DOI: 10.23919/ACC.2018.8431324. URL: https://doi.org/10.23919/ACC.2018.8431324.

[44] Goran Frehse et al. "ARCH-COMP18 Category Report: Hybrid Systems with Piecewise Constant Dynamics". In: *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems*. Ed. by Goran Frehse. Vol. 54. EPiC Series in Computing. EasyChair, 2018, pp. 1–13. DOI: 10.29007/p11g. URL: https://easychair.org/publications/paper/bXtM.

[45] Goran Frehse et al., eds. *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems, ARCH@ADHS 2018, Oxford, UK, July 13, 2018*. Vol. 54. EPiC Series in Computing. EasyChair, 2018. URL: http://www.easychair.org/publications/volume/ARCH18.

[46] Goran Frehse et al. "Eliminating spurious transitions in reachability with support functions". In: *Proceedings of the 18th International Conference on Hybrid Systems: Computation and Control, HSCC'15, Seattle, WA, USA, April 14-16, 2015*. ACM, 2015, pp. 149–158.

[47] A. Giusti and M. Althoff. "Ultimate Robust Performance Control of Rigid Robot Manipulators Using Interval Arithmetic". In: *Proc. of the American Control Conference*. 2016, pp. 2995–3001.

[48] F. Gruber and M. Althoff. "Anytime Safety Verification of Autonomous Vehicles". In: *Proc. of the 21st IEEE International Conference on Intelligent Transportation Systems*. 2018.

[49] A. El-Guindy et al. "Formal LPV Control for Transient Stability of Power Systems". In: *Proc. of the IEEE PES General Meeting*. accepted. 2017.

[50] Daniel Heß, Christian Löper, and Tobias Hesse. "Safe Cooperation of Automated Vehicles". In: *Automatisiertes & Vernetztes Fahren*. ITS automotive nord e.V. 2017.

[51] Daniel Heß et al. "Contributions of the EU projects UnCoVerCPS and Enable-S3 to Highly Automated Driving in Conflict Situations". In: *Automatisiertes & Vernetztes Fahren*. ITS automotive nord e.V. 2019.

[52] Daniel Heß et al. "Fast Maneuver Planning for Cooperative Automated Vehicles". In: *IEEE Intelligent Transportation Systems Conference ITSC*. 2018.

[53] Christian Hillmann and Olaf Stursberg. "Decentralized control of distributed discrete event systems with linear dependency structure". In: *Automation Science and Engineering (CASE), 2015 IEEE International Conference on*. IEEE. 2015, pp. 551–557.

[54] F. Hisch, A. Giusti, and M. Althoff. "Robust Control of Continuum Robots using Interval Arithmetic". In: *Proc. of the 20th World Congress of the International Federation of Automatic Control*. accepted. 2017.

[55] F. Immler et al. "ARCH-COMP18 Category Report: Continuous and Hybrid Systems with Nonlinear Dynamics". In: *Proc. of the 5th International Workshop on Applied Verification for Continuous and Hybrid Systems*. 2018, pp. 53–70.

[56] Fabian Immler et al. "ARCH-COMP18 Category Report: Continuous and Hybrid Systems with Nonlinear Dynamics". In: *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems*. Ed. by Goran Frehse. Vol. 54. EPiC Series in Computing. EasyChair, 2018, pp. 53–70. DOI: 10.29007/mskf. URL: https://easychair.org/publications/paper/gjfh.

[57] D. Ioli, A. Falsone, and M. Prandini. "An iterative scheme to hierarchically structured optimal energy management of a microgrid". In: *54th IEEE Conference on Decision and Control (CDC)*. Dec. 2015, pp. 5227–5232. DOI: 10.1109/CDC.2015.7403037.

[58] D. Ioli, A. Falsone, and M. Prandini. "Energy management of a building cooling system with thermal storage: a randomized solution with feedforward disturbance compensation". In: *2016 American Control Conference (ACC)*. July 2016, pp. 2346–2351. DOI: 10.1109/ACC.2016.7525268.

[59] D. Ioli et al. "A compositional framework for energy management of a smart grid: A scalable stochastic hybrid model for cooling of a district network". In: *12th IEEE International Conference on Control and Automation (ICCA)*. June 2016, pp. 389–394.

[60] Daniele Ioli, Alessandro Falsone, and Maria Prandini. "Optimal energy management of a building cooling system with thermal storage: a convex formulation". In: *9th IFAC Symposium on Advanced Control of Chemical Processes (ADCHEM 2015), Whistler, British Columbia, Canada*. Vol. 48. 8. June 2015, pp. 1150–1155. DOI: http://doi.org/10.1016/j.ifacol.2015.09.123.

[61] Daniele Ioli et al. "A smart-grid energy management problem for data-driven design with probabilistic reachability guarantees". In: *Workshop on Applied Verification for Continuous and Hybrid Systems (ARCH 2017)*. 2017.

[62] Daniele Ioli et al. "A two-layer decentralized approach to the optimal energy management of a building district with a shared thermal storage". In: *20th World Congress of the International Federation of Automatic Control (IFAC 2017), Toulouse, France*. July 2017.

[63] Xavier Fornari Javier Sanchez-Cubillo Daniel Heß. *Unifying Control and Verification for Autonomous Driving Development*. Automotive Simulation World Congress 2016. 2016.

[64] G. Juez Uriagereka et al. "Fault Injection method for Safety and Controllability Evaluation of Automated Driving". In: *IEEE Intelligent Vehicles Symposium, Redondo Beach, California*. 11-14 June 2017.

[65] Nikolaos Kekatos, Marcelo Forets, and Goran Frehse. "Constructing verification models of nonlinear Simulink systems via syntactic hybridization". In: *56th IEEE Annual Conference on Decision and Control, CDC 2017, Melbourne, Australia, December 12-15, 2017*. IEEE, 2017, pp. 1788–1795. ISBN: 978-1-5090-2873-3. DOI: 10.1109/CDC.2017.8263907. URL: https://doi.org/10.1109/CDC.2017.8263907.

[66] Nikolaos Kekatos, Daniel He{\ss}, and Goran Frehse. "Lane change maneuver for autonomous vehicles (Benchmark Proposal)". In: *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems*. Ed. by Goran Frehse. Vol. 54. EPiC Series in Computing. EasyChair, 2018, pp. 229–241. DOI: 10.29007/5hxt. URL: https://easychair.org/publications/paper/Hx1f.

[67] Nikolaos Kekatos, Daniel Heß, and Goran Frehse. "Lane change maneuver for autonomous vehicles (Benchmark Proposal)". In: *ARCH18. 5th International Workshop on Applied Verification of Continuous and Hybrid Systems, ARCH@ADHS 2018, Oxford, UK, July 13, 2018*. Ed. by Goran Frehse et al. Vol. 54. EPiC Series in Computing.

EasyChair, 2018, pp. 229–241. URL: http://www.easychair.org/publications/paper/Hx1f.

[68] D. Kontny and O. Stursberg. "Fast control using homotopy properties for obstacle-avoidance of systems with input constraints". In: *2016 IEEE Conference on Computer Aided Control System Design (CACSD)*. Sept. 2016, pp. 654–660. DOI: 10.1109/CACSD.2016.7602541.

[69] D. Kontny and O. Stursberg. "Fast optimizing control for non-convex state constraints using homotopy properties". In: *2016 IEEE 55th Conference on Decision and Control (CDC)*. Dec. 2016, pp. 4894–4900. DOI: 10.1109/CDC.2016.7799017.

[70] Damian Kontny and Olaf Stursberg. "Online Adaption of Motion Paths to Time-Varying Constraints using Homotopies". In: *IFAC World Congress, Toulouse*. IEEE (accepted). 2017.

[71] Anna-Kathrin Kopetzki, Bastian Schurmann, and Matthias Althoff. "Methods for Order Reduction of Zonotopes". In: *Proc. of the 56th IEEE Conference on Decision and Control*. 2017, pp. 5626–5633.

[72] R. Lattarulo, M. Marcano, and J. Perez. "Overtaking maneuver for automated driving using virtual enviroments". In: *Lecture Notes in Computer Science (Spinger)* (2017).

[73] R. Lattarulo and J. Perez. "Study of the Lane Change Maneuver: Automated Driving use Case". In: *16th International Conference on Computer Aided Systems Theory (EuroCAST)*. 2017.

[74] R. Lattarulo, J. Perez, and M. Dendaluce. "A complete modular framework for developing and testing automated driving controllers". In: *20th World Congress The International Federation of Automatic Control*. 9-14 July 2017.

[75] Ray Lattarulo, Daniel Heß, and Joshue Pérez. "A Linear Model Predictive Planning Approach for Overtaking Manoeuvres Under Possible Collision Circumstances". In: *IEEE Intelligent Vehicles Symposium IV*. 2018.

[76] Ray Lattarulo et al. "A Speed Planner Approach Based On Bézier Curves Using Vehicle Dynamic Constrains and Passengers Comfort". In: *IEEE International Symposium on Circuits and Systems (ISCAS)*. 2018.

[77] Ray Lattarulo et al. "Towards conformant models of automated electric vehicles". In: *IEEE International Conference on Vehicular Electronics and Safety ICVES*. 2018.

[78] S. B. Liu et al. "Provably Safe Motion of Mobile Robots in Human Environments". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2017.

[79] Stefan B. Liu et al. "Motion Verification for Robots in Human Environments based on Kinematic Pedestrian Models". In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2017)*. 2017.

[80] Z Liu and O Stursberg. "Optimizing online control of constrained systems with switched dynamics". In: *Decision and Control, 2018. Proceedings of the 57th IEEE Conference on*. IEEE(accepted). 2018.

[81] Z Liu and O Stursberg. "Optimizing online ontrol of constrained systems with switched dynamics". In: *European Control Conference. ECC 2018. Proceedings of the IEEE Conference on*. IEEE. 2018, pp. 788–794.

[82] G. Manganini, A. Falsone, and M. Prandini. "A majority voting classifier with probabilistic guarantees". In: *IEEE Conference on Control Applications (CCA)*. Sept. 2015, pp. 1084–1089. DOI: 10.1109/CCA.2015.7320757.

[83] G. Manganini, L. Piroddi, and M. Prandini. "A classification-based approach to the optimal control of affine switched systems". In: *54th IEEE Conference on Decision and Control (CDC)*. Dec. 2015, pp. 2963–2968. DOI: 10.1109/CDC.2015.7402667.

[84] G. Manganini et al. "A data-based approach to power capacity optimization". In: *IEEE 56th Annual Conference on Decision and Control (CDC)*. Dec. 2017, pp. 1663–1668. DOI: 10.1109/CDC.2017.8263889.

[85] K. Margellos et al. "Proximal minimization based distributed convex optimization". In: *2016 American Control Conference (ACC)*. July 2016, pp. 2466–2471. DOI: 10.1109/ACC.2016.7525287.

[86] Kostas Margellos et al. "Constrained optimal control of stochastic switched affine systems using randomization". In: *2016 European Control Conference (ECC 2016), Aalborg, Denmark*. June 2016, pp. 2559–2554. DOI: http://doi.org/10.1109/ECC.2016.7810675.

[87] Stefano Minopoli and Goran Frehse. "From Simulation Models to Hybrid Automata Using Urgency and Relaxation". In: *Proceedings of the 19th International Conference on Hybrid Systems: Computation and Control, HSCC 2016, Vienna, Austria, April 12-14, 2016*. 2016, pp. 287–296.

[88] Stefano Minopoli and Goran Frehse. "Running SpaceEx on the ARCH14 Benchmarks". In: *1st and 2nd International Workshop on Applied veRification for Continuous and Hybrid Systems, ARCH@CPSWeek 2014, Berlin, Germany, April 14, 2014 / ARCH@CPSWeek 2015, Seattle, WA, USA, April 13, 2015*. Vol. 34. EPiC Series in Computing. EasyChair, 2015, pp. 196–206.

[89] Stefano Minopoli and Goran Frehse. "SL2SX Translator: From Simulink to SpaceEx Models (tool paper)". In: *Proceedings of the 19th International Conference on Hybrid Systems: Computation and Control, HSCC 2016, Vienna, Austria, April 12-14, 2016*. 2016, pp. 93–98.

[90] S. Mutti et al. "A proximal minimization based distributed approach to power control in wireless networks: Performance and comparative analysis". In: *IEEE 56th Annual Conference on Decision and Control (CDC)*. Dec. 2017, pp. 3513–3518. DOI: 10.1109/CDC.2017.8264174.

[91] Luca Parolini, Simone Schuler, and Adolfo Anta. "Benchmark problem: an air brake model for trains". In: *Proc. of the Workshop on Applied Verification for Continuous and Hybrid Systems (ARCH)*. 2015.

[92] A. Pereira and M. Althoff. *A Cartesian-space method for calculating human reachable occupancy*. Tech. rep. TUM-I1759. Technical University of Munich, 2017.

[93] A. Pereira and M. Althoff. "Calculating Human Reachable Occupancy for Guaranteed Collision-Free Planning". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2017.

[94] A. Pereira and M. Althoff. "Overapproximative Arm Occupancy Prediction for Human-Robot Interaction Built from Archetypal Movements". In: *International Conference on Robotics and Automation*. 2016, pp. 1394–1401.

[95] Aaron Pereira and Matthias Althoff. "Online Formal Verification of Robot Trajectories for Guaranteed Safety of Humans". In: *ICRA-PlanRob-2017*. 2017.

[96] *Proceedings of the 21st International Conference on Hybrid Systems: Computation and Control (part of CPS Week), HSCC 2018, Porto, Portugal, April 11-13, 2018*. ACM, 2018. DOI: 10.1145/3178126. URL: https://doi.org/10.1145/3178126.

[97] M. Ragaglia, M. Prandini, and L. Bascetta. "Poli-RRT*: optimal RRT-based planning for constrained and feedback linearisable vehicle dynamics". In: *2015 European Control Conference (ECC 2015), Linz, Austria*. July 2015.

[98] Albert Rizaldi et al. “A Formally Verified Motion Planner for Autonomous Vehicles”. In: *Proc. of the International Symposium on Automated Technology for Verification and Analysis*. 2018, pp. 75–90.

[99] Albert Rizaldi et al. “Formalising Traffic Rules for Autonomous Vehicles Involving Multiple Lanes in Isabelle/HOL”. In: *Proc. of the 13th International Conference on integrated Formal Methods*. 2017.

[100] H. Roehm et al. “Industrial Examples of Formal Specifications for Test Case Generation”. In: *Proc. of the Workshop on Applied Verification for Continuous and Hybrid Systems*. 2015.

[101] H. Roehm et al. “Reachset Conformance Testing of Hybrid Automata”. In: *Proc. of Hybrid Systems: Computation and Control*. 2016, pp. 277–286.

[102] H. Roehm et al. “STL Model Checking of Continuous and Hybrid Systems”. In: *Proc. of the 14th International Symposium on Automated Technology for Verification and Analysis*. 2016, pp. 412–427.

[103] Hendrik Roehm et al. “Reachset Conformance Testing of Hybrid Automata”. In: *Proceedings of the 19th International Conference on Hybrid Systems: Computation and Control, HSCC 2016, Vienna, Austria, April 12-14, 2016*. Ed. by Alessandro Abate and Georgios E. Fainekos. ACM, 2016, pp. 277–286. DOI: 10.1145/2883817.2883828.

[104] Hendrik Roehm et al. “STL Model Checking of Continuous and Hybrid Systems”. In: *Automated Technology for Verification and Analysis - 14th International Symposium, ATVA 2016, Chiba, Japan, October 17-20, 2016, Proceedings*. Ed. by Cyrille Artho, Axel Legay, and Doron Peled. Vol. 9938. Lecture Notes in Computer Science. 2016, pp. 412–427. DOI: 10.1007/978-3-319-46520-3_26.

[105] Joao Salvado, Luis Custodio, and Daniel Heß. “Contingency Planning for Automated Vehicles”. In: *International Conference on Intelligent Robots and Systems*. 2016. DOI: 10.1109/IROS.2016.7759442.

[106] Javier Sanchez-Cubillo, Daniel Hess, and Xavier Fornari. “Unifying Control and Verification for Autonomous Driving Development”. In: *ASWC 2016*. 2016.

[107] Javier Sanchez-Cubillo and Jesus Marcos Olaya. “Technology Transfer Process for Autonomous Mobility as Cyberphysical Systems. The H2020 UnCoVerCPS project”. In: *Proc. of the 13th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2015*. ESA/ESTEC, Noordwijk, the Netherlands, Nov. 2015.

[108] Simone Schuler, Fabiano Daher Adegas, and Adolfo Anta. "Hybrid Modelling of a Wind Turbine (Benchmark Proposal)". In: *Proc. of the Workshop on Applied Verification for Continuous and Hybrid Systems (ARCH)*. 2016.

[109] Bastian Schurmann and Matthias Althoff. "Reachset Model Predictive Control of Disturbed Nonlinear Systems". In: *Proc. of the 57th Conference on Decision and Control*. 2018.

[110] Bastian Schürmann and Matthias Althoff. "Convex Interpolation Control with Formal Guarantees for Disturbed and Constrained Nonlinear Systems". In: *Proc. Hybrid Systems: Computation and Control*. 2017, pp. 121–130.

[111] Bastian Schürmann and Matthias Althoff. "Guaranteeing Constraints of Disturbed Nonlinear Systems Using Set-Based Optimal Control in Generator Space". In: *Proc. of the 20th IFAC World Congress*. 2017, pp. 12020–12027.

[112] Bastian Schürmann and Matthias Althoff. "Optimal Control of Sets of Solutions to Formally Guarantee Constraints of Disturbed Linear Systems". In: *Proc. of the American Control Conference*. 2017, pp. 2522–2529.

[113] Bastian Schürmann, Ahmed El-Guindy, and Matthias Althoff. "Closed-Form Expressions of Convex Combinations". In: *Proc. of the American Control Conference*. 2016, pp. 2795–2801.

[114] Bastian Schürmann et al. "Ensuring Drivability of Planned Motions Using Formal Methods". In: *Proc. of the Intelligent Transportation Systems Conference*. 2017, pp. 1661–1668.

[115] Cedric Stark, Aaron Pereira, and Matthias Althoff. "Reachset Conformance Testing of Human Arms with a Biomechanical Model". In: *Proc. of the IEEE International Conference on Robotic Computing*. 2018, pp. 209–216.

[116] F. Terraneo, A. Leva, and M. Prandini. "Poster: A switched control scheme to handle quantisation in the design of high-precision computing system components". In: *ICCPS '15: ACM/IEEE 6th International Conference on Cyber-Physical Systems (CPS Week 2015), Seattle, USA*. Apr. 2015.

[117] F. Terraneo et al. "FLOPSYNC-QACS: Quantization-Aware Clock Synchronization for Wireless Sensor Networks". In: *4th IEEE International Workshop on Real-Time Computing and Distributed systems in Emerging Applications (REACTION 2016)*. 2016.

[118] R. Vignali and M. Prandini. "A method for detecting relevant inputs while satisfying a reachability specification for piecewise affine systems". In: *2016 IEEE Conference on Control Applications (CCA)*. Sept. 2016, pp. 538–543. DOI: 10.1109/CCA.2016.7587885.

[119] R. Vignali and M. Prandini. "Model reduction of discrete time hybrid systems: A structural approach based on observability." In: *2nd International Workshop on Symbolic and Numerical Methods for Reachability Analysis (SNR'16), satellite event of CPS Week 2016, Vienna, Austria*. Apr. 2016.

[120] Riccardo Vignali, Daniele Ioli, and Maria Prandini. "A data-driven approach to stochastic constrained control of piecewise affine systems". In: *American Control Conference (ACC)*. 2018, pp. 1424–1429. DOI: 10.23919/ACC.2018.8430792.

[121] Michael Wagner et al. "Interval-Arithmetic-Based Trajectory Scaling and Collision Detection for Robots with Uncertain Dynamics". In: *Proc. of IEEE International Conference on Robotic Computing*. 2018.

[122] Y. Yang et al. "A Multi-Criteria Decision-Making Scheme for Multi-Aircraft Conflict Resolution". In: *20th World Congress of the International Federation of Automatic Control (IFAC 2017), Toulouse, France*. July 2017.

[123] M. J. A. Zeestraten et al. "Online Motion Synthesis with Minimal Intervention Control and Formal Safety Guarantees". In: *Proc. of IEEE International Conference on Systems, Man, and Cybernetics*. 2016, pp. 2116–2121.

Appendix B: Journal papers published in the context of UnCoVerCPS

References

[1] F. Bianchi et al. "A randomised approach for NARX model identification based on a multivariate Bernoulli distribution". In: *International Journal of Systems Science* 48.6 (2017), pp. 1203–1216. DOI: 10.1080/00207721.2016.1244309.

[2] L. Deori, S. Garatti, and M. Prandini. "4-D Flight Trajectory Tracking: A Receding Horizon Approach Integrating Feedback Linearization and Scenario Optimization". In: *IEEE Transactions on Control Systems Technology* (2018). Early access version available online, pp. 1–16. ISSN: 1063-6536. DOI: 10.1109/TCST.2018.2810201.

[3] L. Deori, K. Margellos, and M. Prandini. "Regularized Jacobi Iteration for Decentralized Convex Quadratic Optimization with Separable Constraints". In: *IEEE Transactions on Control Systems Technlogy* (2018). Early access version available online. ISSN: 1063-6536. DOI: 10.1109/TCST.2018.2827990.

[4] Luca Deori, Simone Garatti, and Maria Prandini. "Trading performance for state constraint feasibility in stochastic constrained control: A randomized approach". In: *Journal of the Franklin Institute* 354.1 (2017), pp. 501–529. ISSN: 0016-0032. DOI: http://dx.doi.org/10.1016/j.jfranklin.2016.10.019. URL: http://www.sciencedirect.com/science/article/pii/S0016003216303799.

[5] Luca Deori, Kostas Margellos, and Maria Prandini. "Price of anarchy in electric vehicle charging control games: When Nash equilibria achieve social welfare". In: *Automatica* vol. 96 (Oct. 2018), pp. 150–158.

[6] A. Falsone, K. Margellos, and M. Prandini. "A Distributed Iterative Algorithm for Multi-Agent MILPs: Finite-Time Feasibility and Performance Characterization". In: *IEEE Control Systems Letters* vol. 2.no. 4 (Oct. 2018), pp. 563–568. ISSN: 2475-1456. DOI: 10.1109/LCSYS.2018.2844353.

[7] A. Falsone, L. Piroddi, and M. Prandini. "A randomized algorithm for nonlinear model structure selection". In: *Automatica* 60 (Oct. 2015), pp. 227–238. DOI: http://doi.org/10.1016/j.automatica.2015.07.023.

[8] A. Falsone et al. "Finite-Time Distributed Averaging Over Gossip-Constrained Ring Networks". In: *IEEE Transactions on Control of Network Systems* vol. 5.no. 3 (sept. 2018), pp. 879–887. ISSN: 2325-5870. DOI: 10.1109/TCNS.2017.2653418.

[9] Alessandro Falsone and Maria Prandini. "A randomized approach to probabilistic footprint estimation of a space debris uncontrolled reentry". In: *IEEE Transactions on Intelligent Transportation Systems* vol. 18.no. 10 (2017), pp. 2657–2666. ISSN: 1524-9050. DOI: 10.1109/TITS.2017.2654511.

[10] Alessandro Falsone et al. "Dual decomposition for multi-agent distributed optimization with coupling constraints". In: *Automatica* vol. 84 (Oct. 2017), pp. 149–158.

[11] Daniele Ioli et al. "A compositional modeling framework for the optimal energy management of a district network". In: *Journal of Process Control* (2017). ISSN: 0959-1524. DOI: https://doi.org/10.1016/j.jprocont.2017.10.005.

[12] Zonglin Liu and Olaf Stursberg. "Optimierungsbasierte Regelung und Steuerung Hybrid-Dynamischer Systeme". In: *Automatisierungstechnik* 66 (2018), pp. 928–938.

[13] G. Manganini et al. "Policy Search for the Optimal Control of Markov Decision Processes: A Novel Particle-Based Iterative Scheme". In: *IEEE Transactions on Cybernetics* 46.11 (Nov. 2016). Published on line on October 26, 2015., pp. 2643–2655. ISSN: 2168-2267. DOI: 10.1109/TCYB.2015.2483780.

[14] Kostas Margellos et al. "Distributed Constrained Optimization and Consensus in Uncertain Networks via Proximal Minimization". In: *IEEE Transactions on Automatic Control* vol. 63.no. 5 (5 May 2018), pp. 1372–1387. DOI: 10.1109/TAC.2017.2747505.

[15] A. V. Papadopoulos et al. "Switched Control for Quantized Feedback Systems: Invariance and Limit Cycle Analysis". In: *IEEE Transactions on Automatic Control* vol. 63.no. 11 (Nov. 2018), pp. 3775–3786. ISSN: 0018-9286. DOI: 10.1109/TAC.2018.2797246.

[16] Alessandro Vittorio Papadopoulos and Maria Prandini. "Model Reduction of Switched Affine Systems". In: *Automatica* 70 (Aug. 2016), pp. 57–65. ISSN: 0005-1098. DOI: 10.1016/j.automatica.2016.03.019.

[17] Hendrik Roehm et al. "Model Conformance for Cyber-Physical Systems: A Survey". In: *ACM Transactions on Cyber-Physical Systems* (2019), accepted for publication.

[18] Konstantin Schaab and Olaf Stursberg. "Decentralized robust control of power grids using LPV-models of DAE-systems". In: *IFAC-PapersOnLine* 48.26 (2015), pp. 218–223.

[19] Konstantin Schaab and Olaf Stursberg. "Robust Decentralized LPV Control for Transient Stability of Power Systems". In: *IFAC-PapersOnLine* 48.30 (2015), pp. 566–571.

[20] Konstantin Schaab et al. "Robust control for voltage and transient stability of power grids relying on wind power". In: *Control Engineering Practice* 60 (2017), pp. 7–17. ISSN: 0967-0661. DOI: http://dx.doi.org/10.1016/j.conengprac.2016.12.003.

[21] Olaf Stursberg and Christian Hillmann. "Decentralized Optimal Control of Distributed Interdependent Automata With Priority Structure". In: *IEEE Transactions on Automation Science and Engineering* 14(2) (2017), pp. 785–796.

[22] Federico Terraneo et al. "FLOPSYNC-QACS: Quantization-aware Clock Synchronization for Wireless Sensor Networks". In: *SIGBED Rev.* 14.4 (Jan. 2018), pp. 33–38. ISSN: 1551-3688. DOI: 10.1145/3177803.3177809. URL: http://doi.acm.org/10.1145/3177803.3177809.

[23] Federico Terraneo et al. “FLOPSYNC-QACS: Quantization-aware clock synchronization for wireless sensor networks”. In: *Journal of Systems Architecture - Embedded Systems Design* 80 (2017), pp. 77–84. DOI: 10.1016/j.sysarc.2017.09.006. URL: https://doi.org/10.1016/j.sysarc.2017.09.006.

[24] R. Vignali and M. Prandini. “Minimum Resource Commitment for Reachability Specifications in a Discrete Time Linear Setting”. In: *IEEE Transactions on Automatic Control* (2016). Published on line on September 5, 2016. ISSN: 0018-9286. DOI: 10.1109/TAC.2016.2606082.

[25] R.M. Vignali et al. “Energy Management of a Building Cooling System With Thermal Storage: An Approximate Dynamic Programming Solution”. In: *IEEE Transactions on Automation Science and Engineering* (2016). To appear. Available online at http://ieeexplore.ieee.org/document/7814233/. ISSN: 1545-5955. DOI: 10.1109/TASE.2016.2635109.

[26] Y. Yang et al. “Multi-aircraft Conflict Detection and Resolution Based on Probabilistic Reach Sets”. In: *IEEE Transactions on Control Systems Technology* 25.1 (Jan. 2017). Published on line on April 1, 2016, pp. 309–316. ISSN: 1063-6536. DOI: 10.1109/TCST.2016.2542046.