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INtegrated TOol chain for model-based design of CPSs

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This public document presents the status of the four industrial partners' case studies at the end of the project. An overview of the different case studies is given, with an evaluation of their complementarity and the advantages of using the INTO-CPS tools and methods for the case studies. The Key Performance Indicators that relate to the case studies are discussed, followed by an introduction of each case study in more detail.

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1 Introduction

At this point of the INTO-CPS project, we can claim that the work between use case and tools providers has been mutually beneficial.

As benefits for the case studies we can testify to several points:

Modelling guidelines and examples from tool providers, like the public use cases, are a help for learning new methods or modelling patterns. These guidelines also greatly help planners evaluating tools and technology when defining processes.

We were offered much closer support than most commercial tools. At the price of an early development stage (at least in the beginning), we could benefit from fast corrections, and propose special requests.

Complex experiments set up for advanced tool chain features, like Design Space Exploration or Test Automation, that we were not aware of or that we couldn't have achieve alone, became accessible in the course of the INTO-CPS project.

The tool chain itself, by its extensive use of automation, drastically reduced the risk of bugs during tool or model configuration.

Thanks to the openness of the FMI standard, using INTO-CPS as a main tool chain in an industrial project allows the use of third party tools or legacy models.

Finally, the time to market reduction objective of the INTO-CPS project is of course the main benefit for the use-case providers. In some cases, model prototypes that were tested in simulation, instead of hardware, have saved months of development.

As benefits for the tool providers, we helped them by giving continuous feedback, bug report and improvement suggestions. This is particularly true for emerging features where the feedback in the literacy is almost nonexistent. Our use of the tools, different for each of the case studies has pushed the tools in different directions, while our specific needs such as compatibility with external tools, improved the possibilities of the tools.

Finally, parts of the case studies have been transformed into domain-specific use-cases, freely available as showcases for the tools or examples in research papers.

This deliverable is structured as follows: Section 1.1 discusses the complementarity of the case studies, with respect to the used technologies and methods. This part also contains a discussion of the advantages (see Section 1.1.1) of using

INTO-CPS, both from a common perspective, as well as from individual perspectives of each case study. This section ends with recommendations for future work (see Section 1.2), and a discussion of the Key Performance Indicators (KPI) (see Section 1.3) that relate to the case studies. In the following Section 2, the four individual case studies are introduced. More details on the case studies can be found in the confidential documents D1.3b [OLA+17], D1.3c [FVHGB17], D1.3d [CAB+17] and D1.3e [KM17].

1.1 Complementarity of the Industrial Case Studies

Table 1 summaries the different aspects and concepts of CPS and the related major industrial needs covered by the case studies of INTO-CPS. We see that all aspects appear in one or more case studies.

Table 1: Complementarities of the industrial case studies at Y3

Application area	Railways	Agriculture	Buildings	Automotive
Lead partner	CLE	AI	UTRC	TWT
SysML modelling	Yes	Yes	Yes	Yes
DE modelling	Yes	Yes	Yes	Yes
CT modelling	Yes	Yes	Yes	Yes
Test automation	No	No	Yes	No
Model checking	Yes	No	No	No
MIL simulation	Yes	Yes	Yes	Yes
SIL simulation	Yes	Yes	Yes	Yes
HiL simulation	Yes	Yes	Yes	Yes
DSE	Yes	Yes	Yes	Yes
Traceability	Yes	No	Yes	No
Code generation	Yes	No	Yes	No

1.1.1 Common advantages of using INTO-CPS

The industrial partners benefited from the INTO-CPS technologies in different ways, as expected due to their different domains. Nonetheless, certain aspects of the tool chain were of benefit to all industrial partners. We thus argue that these are the most broadly applicable benefits of INTO-CPS and the ones that can most successfully be transferred to other domains.

The use of SysML modelling with the INTO-CPS profile was valuable as a way to provide a common documentation of the system structure (particularly valuable for larger teams). It also enhanced communication within each case study project and across the disciplines and tools of the project. The connection with the simulation tools and the COE via the export of Model Description and Co-Simulation Configuration adds even more value to the SysML model.

The DSE component was valuable as a way to sweep parameters and automate co-simulations. This led to faster prototyping (and lessened the need for physical prototypes) and a better understanding of the complex interactions between the system parameters. The DSE component was well integrated into the tool-chain through a user friendly interface and its capability to reuse existing parts of the tools and models (through respectively the INTO-CPS application and FMUs).

The 3D visualization component was valuable for all industrial partners. As commercial entities, the 3D visualization has great value as a marketing and sales tool. It also greatly enhances the user experience when analyzing the models. These benefits are in addition to engineering benefits which can be gained for certain case studies, where the visual aspects of the problem are of interest and can be studied using the 3D visualization. This is not the case for all CPS problems, but any CPS company can benefit from the 3D capabilities for marketing purposes, which are of high importance to any business.

More generally, one of the greater benefits of the INTO-CPS tool chain was the ability to reuse models, including existing legacy models for new purposes. The broad tool compatibility (including tools outside the tool chain, this attesting its openness) increased the reuse even more. The tool chain is also fully compliant with the FMI standard which increases the value of models developed with INTO-CPS tools, as they can be reused further in the future. Finally, the baseline tools of INTO-CPS were all made compatible and tested with industry-grade and open source tools through the FMI standard, thus opening new possibilities for the tools and their users.

1.1.2 Case-studies specific advantages of using INTO-CPS

Railways The railways domain has high standards of certification and well-established processes and tool; thus, changes and innovation always receive a lukewarm welcome. Adding more simulation is initially an overhead since it is not useful for the certification but there is a need for formal verification and testing and simplifying those aspects are an added value. Formal modelling and verification are known and used in the railways domain, ClearSy uses models for safety demonstration and automatically generated software in some specific projects. INTO-CPS brought to ClearSy knowledge about generating systematic tests that directly benefit to the industrial projects. Tests used to be written manually and results collected in long textual documents that demonstrated the conformity of the systems to its specifications; but more and more, because of upstream model verification and testing, tests on the final products have become a formality, still required by the process but rarely raising defaults. From this time forward and thanks to INTO-CPS, we will be able to simplify testing and document generation while still producing exhaustive coverage, and invest the saved manpower in upstream tasks. Physical simulations are more of a novelty for the railways domain. It starts to be considered in control systems and in the long run, physical modelling is expected to enable development of more complex systems, such as autonomous trains. With the knowledge collected during the INTO-CPS process, ClearSy is ready to face this challenge and is currently a proactive force in proposing cyber-physical systems at national and international levels.

Buildings UTRC already has strong experience in model-based design which is used to design and develop multiple commercial products at United Technologies. Modelling and simulation is heavily used to evaluate performance and robustness of the system with regards to requirements. Aspects such as simulation speed, and model fidelity are of high importance. Going beyond model-based design and single model simulation, co-simulation enables the analysis of physical interactions of systems that were previously uncaptured, due to the different domains at which the physics were modeled. Multi-physics analysis enables early analysis and detection of issues that were only uncovered at the physical prototyping stage, thus saving time and money. The 3D visualization feature is particularly appealing for UTRC, for engaging with non-technical stakeholders and demonstrating results to our business units. In addition, certain business units operate in domains where the visual aspect of the 3D co-simulation can bring genuine insights. Other capabilities of the INTO-CPS tool chain such as test automation and verification are not particularly in demand for HVAC systems, but are highly valuable to UTRC for aerospace applications.

Agriculture INTO-CPS has been the entry-point to multi-modelling, Co-simulation of CPS, and FMI at AI. In the development of technology for the agricultural industry the reduction of time to market, numbers of prototypes, and hours of field test is of great interest. It is found that by introducing simulations, assessment of a wide span of possible designs can be done rapidly in a virtual setting rather than spending hours in the field testing different system configurations. Simulation-based engineering allows for developing subsystems of a product before, or in parallel with, manufacturing of prototypes, which is of high value. Modern agricultural machinery consists of several interacting systems. As a consequence, every design comes with a number of variables that are significant for the system performance. It is found that Co-simulation can support the assessment and decision making in such complex systems. The 3D visualization features have been highly beneficial to AI. The 3D visualization features are well suited to the agricultural domain, in our case to illustrate conceptual designs of the robotic platform. The visualization of a product in an early stage of development has been applied thoroughly at AI in the research and development, as well as in describing features and functionalities to internal and external stakeholders.

Automotive The partner developing the automotive case study (TWT), has a broad experience in multi-modelling, Co-simulation and usage of FMI. In its daily business, CT simulations are often used for modelling of vehicle physics. In contrast, DE modelling (e.g. with VDM) is rarely used, and HiL simulation is also only done in rare cases. As the customers work in different tools and environments, model re-use and compatibility of tools is very important in this context. The access to data from online resources (via web services, such as the road or weather data), and its processing, is becoming more and more relevant. Due to the market position as an engineering service provider with varying customers, flexibility and modularity in design of its models, and re-usability in different technical settings (e.g. modelling tools, operating systems etc), are important characteristics. Flexibility and openness in design of the tool-chain, by using standards such as FMI (which originated from the automotive domain, and is becoming more and more of an industry standard) are the aspects of INTO-CPS which are particularly relevant to the automotive case study, in addition to the general features outlined above.

1.2 Common recommendations for future work

The industrial partners all see great benefits in the integration of tools and co-simulation technology provided by INTO-CPS. In the future, we recommend that this field continues to be developed through new research. Topics which should be addressed include: 1) enhanced traceability, including the ability to *navigate* in time to enable comparison and co-simulation of models and projects at different points in their lifetimes, more queries, the inclusion of more diverse information and reporting and lengthier industrial evaluations; 2) hierarchical co-simulations including different time resolutions, exploitation of specialized solvers and massive scalability; 3) combination of co-simulation and modelling with data analytic techniques.

1.3 Key Performance Indicators

There are three Key Performance Indicators that are related to WP1

KPI-A, utility assessment We can affirm that this indicator has been reached, all case studies in Y3 are developed following the methods and tools from INTO-CPS: development of Sys-ML models, CT and DE models of the different components, generation of FMUs from Overture, OpenModelica or 20-sim, execution of co-simulation with the COE, usage of DSE tools, test automation and model checking, as well as traceability.

KPI-B, Reduction of development time for CPS This indicator is evaluated indirectly and has to be detailed for each case study.

For ClearSy we can cite the early evaluation of the safety properties of the system that saved a lot of time: several propositions of distribution have been created and tested for safety properties as models, this phase could append before the choice of the hardware and the development of drivers or communication layers (middleware). This saved the time and money of developing several module prototypes. In the second phase, when the prototype has been tested, no reason came for questioning the choice of the distribution and requiring a second iteration. Automatic code generation of the prototype also saved a lot of time for two reasons. First the manual development of the code from the specification would have require roughly fifteen days whereas generating code from the formal model was almost instantaneous. Second, the code for the middleware alone costed around five days. The time for the development of the model itself is shared with the system specification phase.

For the agriculture case study, AI was able to work in parallel in the development of the SiL (tablet interface), which gave AI the opportunity to present results even before constructing a physical prototype, which would not have been possible without INTO-CPS. Being able to simulate the CPS has made it possible to rapidly develop, assess and deploy new features to the industrial applications.

As pointed out above, the INTO-CPS technologies are beneficial in the context of the automotive case study. The benefits comprise features such as model reusability and the openness of the tool-chain. While the development effort is hard to measure, in particular when the technological basis (i.e. the tools) are constantly evolving, TWT is confident that the INTO-CPS tools have the potential to decrease development time of a given system that is comparable to the automotive case study, on the order of 30 %.

For the HVAC case study, UTRC had a greater focus on developing knowledge about the FMI and co-simulation technologies to transition to other United Technologies business units and to build capability to solve new challenging problems. In this regard, INTO-CPS has already provided results in terms of enabling us to solve new problems such as multi-physics analysis which can lead to significant reduction of development times for our business units due to avoidance of certain physical prototypes as mentioned above.

In summary, we can claim that the overall reduction of CPS development time is on the order of 30 %.

KPI-C, Tool chain platform TRL This indicator can already be set above TRL 5, according to the definition of Horizon2020 ("TRL 5: technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)"). The tools have been validated in an industrially relevant setting, they allow to build operational prototypes, with directly exploitable simulation and testing results. The integration of the different tools together is complete.

2 Overview of Case Study Deliverables

In this section we present overview of all case studies. Further details of each case study can be found in the corresponding confidential deliverable.

2.1 Railway case study

2.1.1 Abstract of the Confidential Document D1.3b [OLA+17]

The confidential railway case study report presents the confidential version of the ClearSy Railway case study. During Year 3, the Railways Case Study reached a mature state. From industrial grade specification documents to models, simulations and a running prototype, we provided several aspects of the creation of a complex system. Beside this productivity oriented development, we took some time to dig into more academic research, by creating different versions of the models, able to demonstrate and evaluate the diverse aspects of the INTO-CPS tool chain. We can cite for this last year missions on traceability, testing and design space exploration, formal modelling, 3D simulation, code generation and hardware in the loop (HIL) Simulation.

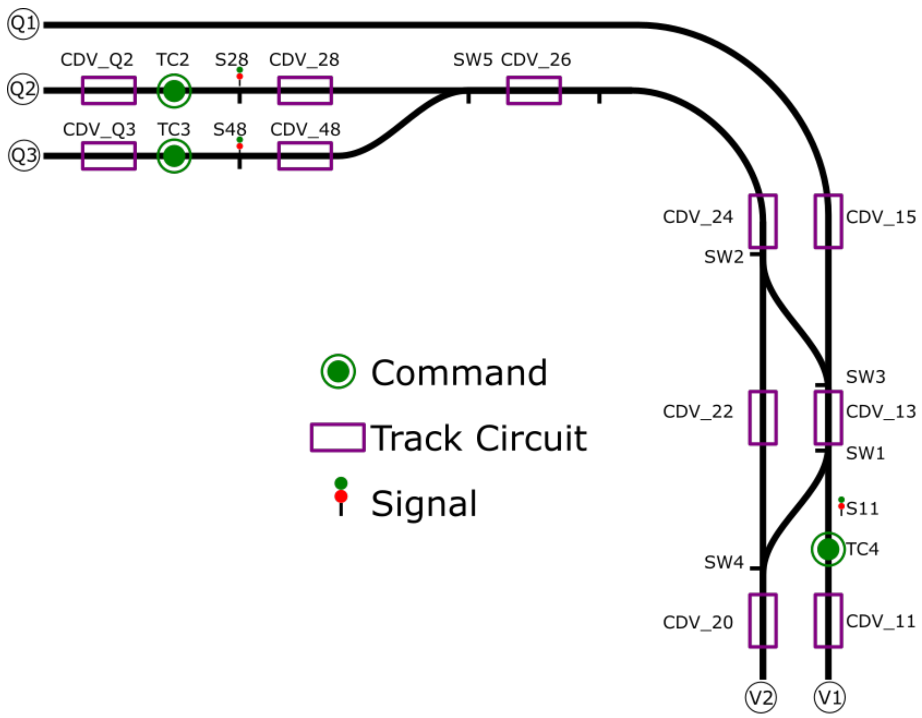

Figure 1: Partial scheme plan of a train line as seen from the sky, including track circuits, switches and traffic lights.

2.1.2 Description

In railway signalling, an interlocking is an arrangement of signal apparatus that prevents conflicting movements of trains through an arrangement of tracks, junctions and crossings. Usually, interlocking is in charge of a complete railways or tram line, computing the status of actuators (switches and signals) based on signalling safety rules that are encoded as "binary equations" as shown in Figure 2, usually managing $\sim 180,000$ equations that have to be recalculated several times per second. These equations compute the commands to be issued to track-side devices: they encode the safety behaviour that enable trains to move from one position to another through routes that are allocated and then released.

Currently, there are attempts to find the right trade-off between efficiency of an interlocking system (availability of routes, trains' delays and cost of interlocking system) and safety (collision avoidance, derailment prevention, availability and efficiency of emergency system).

In our case study, we consider an Interlocking system that controls a part of a tramway line, including two platforms and a bidirectionnal track (between SW5 and SW2). It involves eleven track circuits; sensors that detect the absence of a train on a railway track; three commands that can accept several positions and are activated by the train; five mechanical switches that allow changing direction (those switches have to be set accordingly to the route chosen) and three light signals, red when the train is not allowed on the track and green when it can pass. The interlocking system also makes use of five mechanical safety relays that externalize the state of a route and allow redundancy between software logic and electronic circuits.

2.1.3 Interlocking challenges

A centralised interlocking system is able to deal with a complete line, such that all decisions are made globally. However, the distance between devices distributed along the tracks and the interlocking system may lead to significant delays in updating the status of the devices. Moreover, this architecture, well dimensioned for metro lines, is often overkill for simpler infrastructures like tramway lines. So there is room for an alternate solution: a distributed interlocking system. A line is then divided into overlapping interlocked zones, each zone being controlled by an interlocking. Such interlockings would be smaller as fewer local devices have to be taken into account, and a local decision could be taken in a shorter amount of time resulting in potentially quicker train transfers. However, overlapping zones have to be carefully designed (a train cannot appear by magic in a zone without prior notice) and some variable states have to be exchanged between interlocking systems as the Boolean equations have to be distributed accordingly over the smaller interlocking systems.

This distribution implies several engineering problems. An “optimal distribution” i.e. the decomposition of the line into overlapping areas such as to minimise delays, availability, and costs, requires a smart exploration of the design space (decomposition is directly linked with railways signalling rules). It also implies that one has to define what information has to be exchanged between interlocking computers, and how many equations have to run on any of them (20,000 equations maximum, for example).

2.1.4 Accurate train movement simulations and challenges

In order to have a realistic model of train traffic that enables us toexplore safety concerns, the train movements along the track map have to be simulated in a realistic way. The finer the movement is simulated, the more one can ensure an effi-

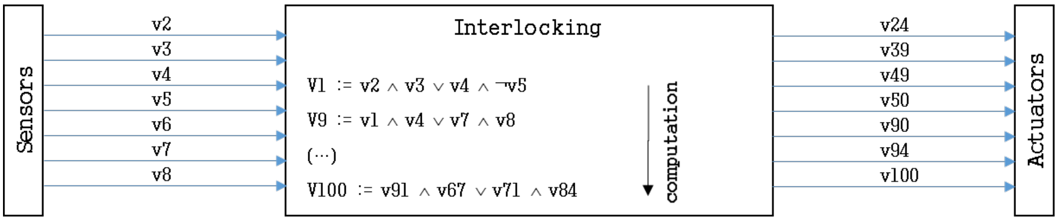

Figure 2: Boolean equations that lead the signalling system.

cient but safe interlocking system. Usually, a train receives/considers a Movement Authority Limit (MAL): a stop point that the train must never overshoot. Such a MAL is updated in real-time by interlocking mechanisms and communication facilities. For an automated train, Automatic Train Operation (ATO) computes the best movement for reaching and stopping at the MAL. In parallel, an Automatic Train Protection (ATP) guards against a failure of the "normal" service mode (e.g. service brakes failure, ATO software/sensor loss of train position). ATP checks that even in the worst case scenario, the MAL will never be overshot. Exploring the behaviour of a "manual mode" train (with possible roll-back movement) and ensuring a safe automatic protection is far from being clarified in the Railway community. Even ClearSy - which has used the ProB animator for years (a high level discrete modelling language, similar to VDM-RT) for railway use cases animations - cannot achieve, in a discrete way, a smart handling of continuous movement, of the maximal assessments of physical parameters or of the continuous time problems such as differential equations, Zeno paradox or controlling precision results.

Cosimulating in real-time an efficient interlocking system with train movement would enable to enhance train performance with respect to delay or availability whilst keeping it safe. In order to get a higher level of confidence about the safety of the case study, the co-simulation conducted must be accompanied with other techniques developed for the INTO-CPS tool chain such as the model checking feature.

2.1.5 Design of a Distributed Interlocking

Figure 1 on Page 14 shows the existing system which is based on central interlocking principles where all decision are made globally. This requires a powerful PLC (Programmable Logic Controller) for the many equations and kilometres of wires to connect individually each sensors and actuators to the PLC. The alternative approach based around a *distributed interlocking system* might help to reduce the global length of the connections and therefor the cost and the risk of failure. Figure 3 shows a possible division into five zones (highlighted in blue), namely ZQ2, ZQ3, ZP, ZV1 and ZV2, where each zone is ruled by an interlocking module on its own. Such modules would require less computational power than a global interlocking as fewer local devices have to be accounted and local decisions, that only involve local device could be taken faster and would result in potentially faster train transfers. However, the distribution has to be carefully designed so that each module can ensure the required local safety properties, and communications have to be introduced so that the global safety properties of the initial Interlocking System can be preserved. As a matter of fact, 9 mechanical relays are now required for the distributed version since most routes are distributed over several modules and all of them need to protect the different routes with different relays.

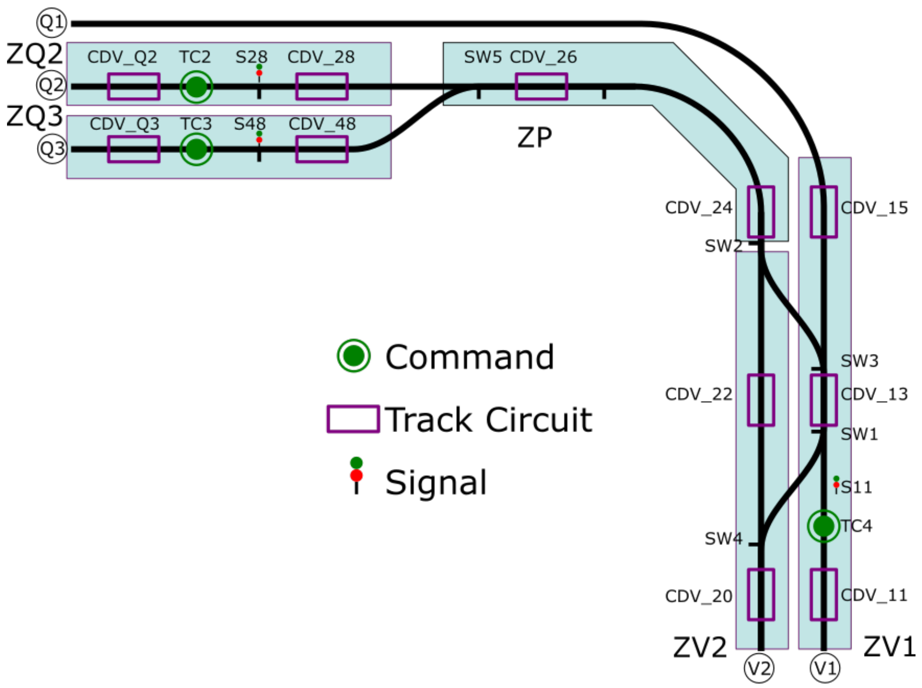

Figure 3: Distribution of the Interlocking system over the trackmap

2.2 Agriculture case study

2.2.1 Abstract of the Confidential Document D1.3c [FVHGB17]

The agriculture case study deliverable presents the results related to the agricultural domain of INTO-CPS. During year three, a substantial subset of the tool chain has been applied in the case study. The focus of the case study in year three is the continued development of the agricultural field robot, Robotti using the INTO-CPS technology. Models of the machine dynamics and controllers have been developed using the baseline tools and Co-simulated using the COE. The DSE feature is applied in the development and assessment of the steering controller which is crucial to the performance of the robot. The agricultural case study has been extended with an additional industrial application in year three, namely the AI-Mower. The dynamics of the mower is modelled and co-simulated to assess and optimize a new approach for steering the mower. Additionally, the 3D FMU feature has been applied to visualize the machine based on the models of the kinematics and dynamics. The details on the mower are kept confidential contrary to the Robotti project which is public.

2.2.2 The Robotti Case Study

The Robotti case study encompasses the development of a robotic platform designed for field operations in the agriculture industry. Robotti has been developed in Agro Intelligence since the company launch in 2015. Three versions of the robotic platform exist. Figure 4 illustrates the development of the robotic platform. The first generation Robotti, Figure 4a, is an electrically driven robot with tracks. This design was initially developed by Kongskilde Industries. The second generation Robotti, shown in Figure 4b, is likewise electrically driven, but with an updated mechanical setup. This version is differential steered with two driving wheels and two freely rotating caster-wheels.

(a)

(b)

(c)

Figure 4: (a) First generation Robotti. (b) Second generation Robotti. (c) Third generation Robotti with a seeder mounted.

During 2017, the design of the second version has been updated. The first Robotti has been sold to the Norwegian Institute of Bioeconomy Research (NIBIO). The updated version of Robotti is shown in D1.3c [FVHGB17].

Through the third year of INTO-CPS, the activities related to Robotti have been focused towards DSE-based optimization of the steering controller which is crucial to the performance of the machine. Several scenarios of different steering controller configurations are simulated using the COE and the DSE feature is applied to estimate the optimal controller configuration of the Robotti. The influence of the controller parameters are shown in Figure 5 where the six simulated trajectories are shown corresponding to six combinations of two controller parameters. The dashed line represents the desired route and the blue line represents the simulated trajectory of the Robot. Furthermore we have included the tablet-based

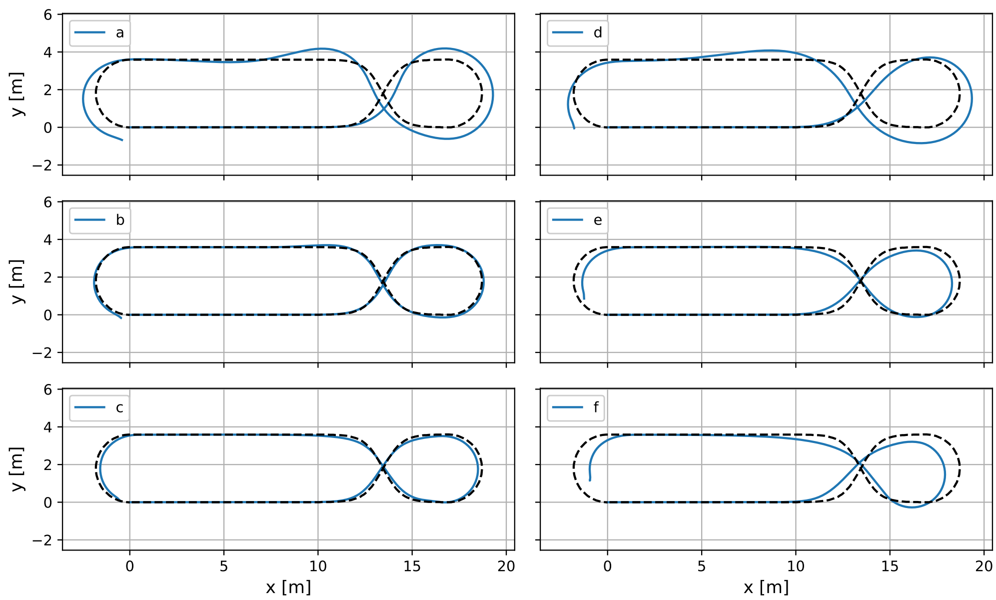

Figure 5: Simulated trajectories of the six controller configurations (a,b,...,f)

steering interface for manual navigation of a simulated Robotti in a virtual environment.

2.3 Building case study

2.3.1 Abstract of the Confidential Document D1.3d [CAB+17]

The building case study report presents the third year version of the UTRC industrial case study in the building domain. It outlines the case study, associated technical work and rationale behind it. For the third year, the focus of the work was to increase the complexity of the case study models to further test the capability of the INTO-CPS technology, and to experiment with various INTO-CPS tool chain features as they became available. In this document, we first describe the case study and objectives. From there, we present the models that are part of the case study: including the architecture in SysML, the supervisor model in VDM-RT (restructured from the Year 2 model) and the newly introduced Simulink Fan Coil Unit controller model. All models come together in a co-simulations executed on the INTO-CPS Platform to evaluate controller performance and robustness across a variety of scenarios. On top of these co-simulations, we explore tool chain features such as Design Space Exploration . We also report lessons learned and assess the INTO-CPS technology according to industrial needs. Finally, we present an overall assessment of the INTO-CPS technology benefits and its impact.

2.3.2 Description

The building case study focuses on modelling and analysis of energy and comfort for Heating, Ventilation and Air Conditioning (HVAC) systems that control the temperature of connected areas inside a building premises as shown in fig. 6.

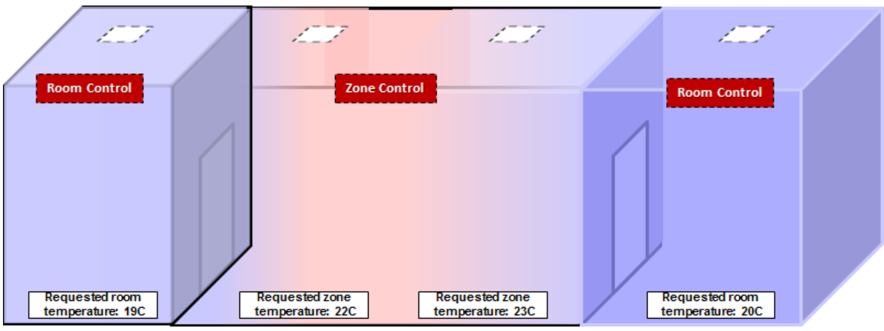

Figure 6: Rooms and Zone level schematic for the building case study

The case study models various concepts shown in fig. 7 such as: a) Fan Coil Unit (FCU) and control; b) Supervision and fault detection of FCUs; c) Communication between master-slave FCUs; d) Communication between FCUs and supervisor; e) Air Handling Unit (AHU) and control; f) Chiller load and control; g) Physical rooms and air flow; h) Water and air pipe connections.

Models for the year 3 case study have been both newly-developed and evolved from year 2 models, based on commercial HVAC products and control requirements.

The functionality of the HVAC is to regulate operation of various devices to ensure user comfort. User inputs are taken into account from room and zone thermostats

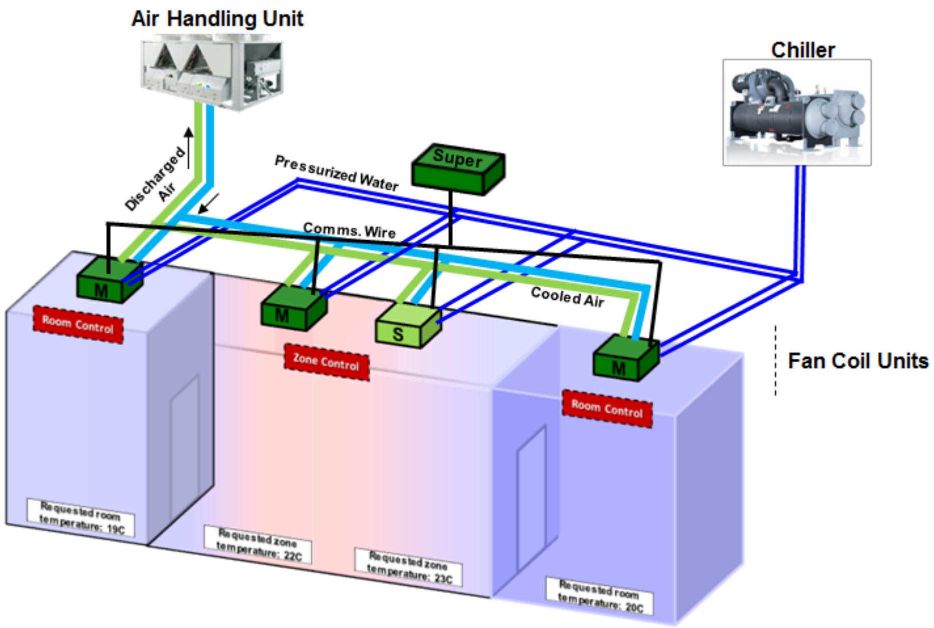

Figure 7: Detailed schematic of building case study

and are compared with current Room Air Temperature (RAT) sensed by the FCUs, triggering certain action on the FCUs to reach the desired temperature by a) regulating the air flow using its fan, b) regulating the water pipe valves to control the cooled water into the coil, c) synchronizing with the supervisor to coordinate with the rest of the FCUs. Fresh air is provided to the FCUs by the AHU and cooled by the Chiller.

The main objective for the Y3 case study is to respect high level requirements that span from temperature control of rooms and zone, energy consumption and safe operation of all of the devices that are involved in the HVAC system. One of the main reasons why the aforementioned feature remains a challenge is the product line engineering approach currently followed by the building automation industry. In the current work-flow, different types of engineers contribute to the creation of the same device and therefore affect the system design. Verification of the generated models or code is enabled in stages of the product life-cycle that leave the system open to delays due to late error discovery. To this end, INTO-CPS and co-simulation solutions will not only bridge the identified gap between engineers but also enable verification of the output models early in the design phase, thus rapidly increasing the product development time while respecting system requirements.

2.3.3 Cyber-Physical Aspects

The building case study is a Cyber-Physical System (CPS) composed, on the modelling side, by:

Cyber Part The cyber part of the building case study includes components such as the FCU controllers that will be embedded in the hardware devices, and the communication interfaces in order to handle communications between the FCUs and the supervisor. Communication modules will also coexist within the same FCU hardware device and will handle distributed communications exchanged between the FCUs and the supervisor. The aforementioned elements will be targeted for code generation in order to proceed with Software-in-the-Loop and Hardware-in-the-Loop simulations for the case study. Finally the communication medium used in the case study is also based on protocol message exchange between the supervisor and the FCU controllers (e.g. through UART).

Physical Part The physical part of the building case study includes components that will be co-modelled with the cyber part in the multi-models evaluated in the INTO-CPS platform. These components include the thermal modelling of the physical rooms and zones in order to study thermal effects in the areas including wall insulation parameters and air-mass heat capacity. Air pipes connections and air flow exchanged between the AHU and the FCUs is also continuously described by air mass flow inside the pipes used in the building. Water flow, circulating in the pipes, through the Heat Pump Unit (HPU)/Chiller, FCUs, and AHU, is also governed by Continuous Time (CT) equations describing fluid dynamics.

Bridging between the cyber and physical models is performed through the control model, where a control strategy is developed to regulate HVAC equipment according to the indoor temperature response, the user selected settings and the current operation of the devices. The control model optimizes the building performance through maximizing user comfort. For example, maintaining the comfort characteristics (e.g. indoor temperature) in a standardized comfort band.

2.4 Automotive case study

2.4.1 Abstract of the Confidential Document D1.3e [KM17]

The automotive case study report presents the status of the TWT automotive case study at the end of Year 3. After the case study models were ported to an FMU compliant Co-simulation in Year 2, the focus of the development during the third year was the implementation of the Hardware-in-the-Loop (HiL) scenario and the driving simulator scenario. For the HiL scenario, a model that was first developed in 20-sim, was then deployed to a Raspberry Pi using 20-sim4C, and coupled to the rest of the Co-simulation. This demonstrates the suitability of the INTO-CPS tool-chain for model-based design of CPS, since this model was first described in SysML, then developed in 20-sim, and finally deployed on hardware. In the driving simulator scenario, the main focus of the development was coupling of the TWT software "Tronis" to the Co-Simulation (which was mainly developed in Years 1 and 2). This included mainly the development of a FMI interface for Tronis, so that it can be initially used to visualize the vehicle position on a 3D environment. Secondly, a tool to generate such a 3D environment from map data (which is also used for the range prediction) was developed, allowing the use for generic routes. Furthermore, a "nested" Co-Simulation was developed, so that a simulation run can be re-started with new initial conditions from within another Co-Simulation. This is relevant for cases where deviations from the prediction are discovered, so that a new route prediction needs to be triggered. In addition, the INTO-CPS tools and methods were tested and evaluated, such as Design Space Exploration.

The general goal of the automotive case study is to provide a realistic range prediction for electric vehicles. This is done by simulating the dynamics of the vehicle, using a route and weather conditions for this route as an input. This was mainly developed in Years 1 and 2. In Year 3, the case study was extended in several directions. The models were further improved, regarding flexibility and performance. Furthermore, the original case study was extended, so that it can be used in a scenario where the result from the range prediction can be used for feedback. Here, this is shown by adapting the gas pedal curve, to influence the behavior of the real system. Furthermore, a 3D environment was coupled to the Co-Simulation for the range prediction, so that it can be used in a driving simulator set-up. The different scenarios take advantage of the modularity of the models and re-use some main components, such as the longitudinal dynamics. The scenarios and the constituent models are described in the remainder of this section.

2.4.2 Scenarios

In the final year of INTO-CPS, the automotive case study was divided into several scenarios, with increasing complexity. The single models are described in more detail below. As an overview, the three scenarios are shown in the following table 2 with the models that they use.

	Pure Co-Simulation	Hardware-in-the-Loop	Driving Simulator
Long. Dynamics	x	x	x
Weather	x	x	x
Route planning	x	x	x
Alarm controller		x	x
Gas pedal controller	x	x	x
Route prediction		x	x
Raspberry Pi		x	
Tronis FMI adapter			x

Table 2: Different scenarios of the automotive case study

Pure Co-simulation The "pure" Co-Simulation scenario is largely the same as in previous years. Its SysML connections diagram is shown below in Figure 8. This scenario is largely identical with the "offline" scenario described in Deliverable D1.2e [KB16]. Therefore, simulation results are not repeated here.

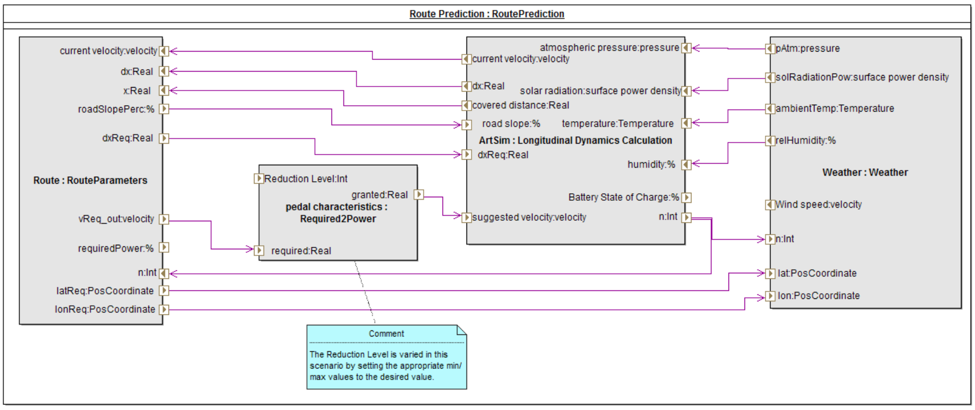

Figure 8: SysML Connections Diagram for the "pure Co-Simulation" scenario.

The Route module creates the coordinates for the route, and passes them to the weather module, which generates the weather data for this route. The vehicle dynamics are calculated by the longitudinal dynamics. Here, the gas pedal curve is not dynamically adapted.

Hardware in the Loop For the Hardware-in-the-Loop scenario, the gas pedal curve is adapted according to the predicted remaining range. A alarm controller is introduced, to monitor the system. Its SysML connections diagram is shown below in Figure 9. This scenario can be compared to the "online" scenario in

Deliverable D1.2e [KB16]. Here, deviations from the predicted route and scenario are monitored. In addition, one part of the system, the gas pedal controller, was first developed as a model (in 20-sim), and later transferred to hardware (a RaspberryPi 3) and connected to the Co-Simulation by using 20-sim4C.

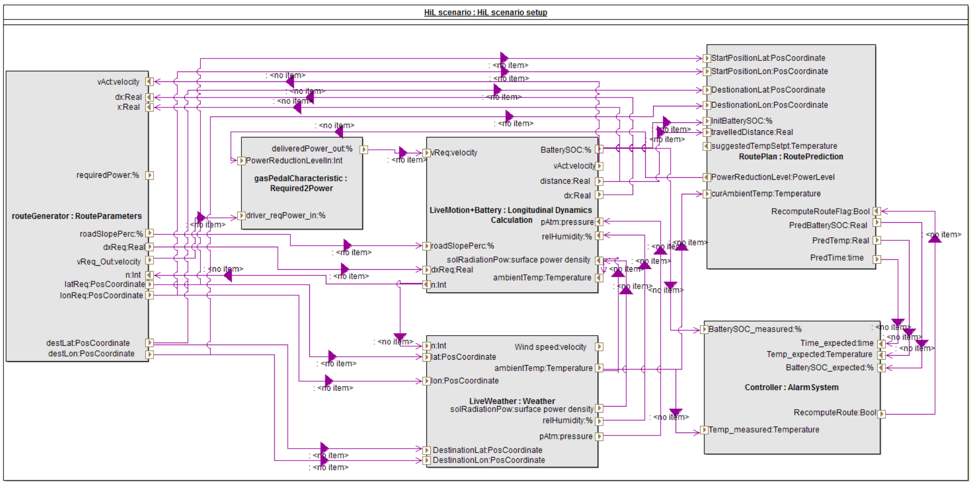

Figure 9: SysML Connections Diagram for the “HiL Co-Simulation” scenario.

The step from the pure Co-Simulation scenario to the Hardware-in-the-Loop scenario is schematically shown in Figure 10. Here, the model for the gas pedal adaptation was first modeled in 20-sim and evaluated in a Co-Simulation. Then, the model was transferred to a Raspberry Pi, which is running a real-time operating system (Xenomai Linux, see `https://xenomai.org/`). The model for the gas-pedal adaptation is running on the hardware, and receiving its inputs from 20-sim4C, which in turn communicates with the COE. This is described in Section 4 of Deliverable 4.3b [PBL+17].

This scenario therefore demonstrates how the INTO-CPS tool-chain can be used to develop embedded systems (here, for the adaptation of the gas-pedal curve) in multiple steps, with very little effort to change the tools, models or methods.

Driving simulator In the driving simulator scenario, the Co-Simulation is coupled with the TWT product “Tronis”. Tronis is a framework for testing of advanced driver assistance systems (for use in highly automated or autonomous driving), that is currently under development at TWT [1]. It is based on the Unreal 3D

[1] see `https://www.twt-gmbh.de/en/products/simulation-process/tronisr.html`

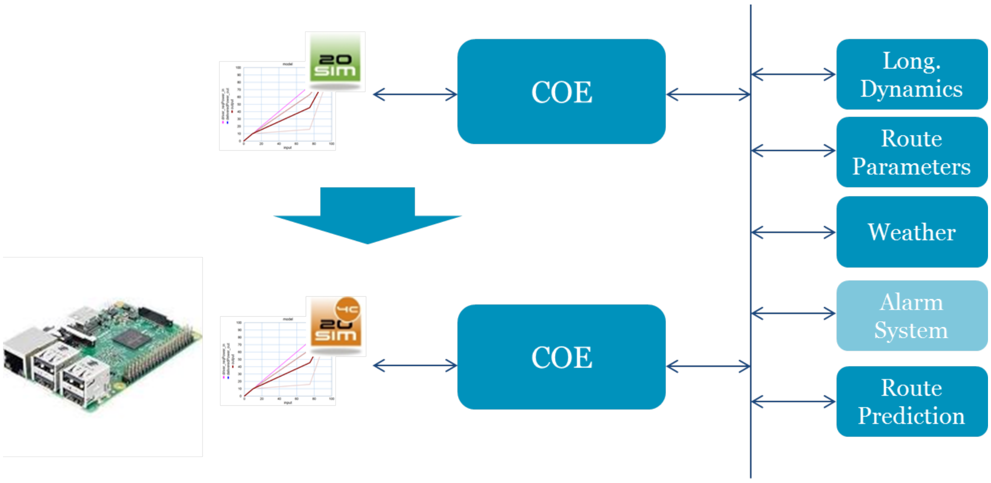

Figure 10: Schematic description of the transition from a pure Model-in-the-Loop scenario to the Hardware-in-the-Loop scenario.

graphics engine, and allows generation of realistic scenarios to test systems such as radar or lidar sensors for automotive applications.

Figure 11: Screenshot of the TRONIS environment.

Due to the powerful 3D engine, with access to highly-detailed 3D objects, it is possible to test different types of sensors or controller that are relevant for autonomous driving. In combination with simulation environments, such as the INTO-CPS tool chain, it shall then be possible to combine models of sensors or controllers (as FMUs), vehicle physics, driving scenarios, other calculations and the 3D environment. This is relevant since autonomous driving can be seen as an important class of Cyber-Physical Systems, that bring together all aspects of CPS; autonomous vehicles need to be highly connected (to the multitude of sensors within them, to other vehicles and to a backend), interact with the physical world by sensing it or influencing it, and contain complex logic. To establish such connection between the INTO-CPS tool chain and Tronis, two inital steps are taken.

In a first step, an FMI interface for Tronis was created, to use it as a 3D visualisation of the vehicle's path. Here, Tronis is only used to display the vehicle position, according to the output from the Route Planning module (see next section).

As a second step, a human driver should control the vehicles motion in the simulation, which is then taken as input for the simulation. With this setup it is planned to study ways to display and enforce suggestions from the route planning system.

References

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