Preliminary survey on CPS testing in various domains of the industry

Guillaume Nguyen[1,*], Xavier Devroey[1]

[1]NADI, University of Namur, rue de Bruxelles 51, Namur, 5000, Belgium

Abstract

Cyber-Physical Systems (CPSs) help solve real-world challenges by gathering data and reacting physically to it in real-time. Through advanced driving assistance systems (ADAS), medical devices, or uncrewed aerial vehicles for agricultural purposes, CPSs are already well-present across various application domains. However, the testing techniques and strategies are often specific to those domains due to the versatile deployments of those systems. Furthermore, the constituent elements of CPSs are similar, so testing techniques from a specific domain could be adapted to fit the requirements of another one. In this paper, we perform a preliminary survey to probe the testing tendencies across CPS application domains.

Keywords

Survey, CPS, Testing, Standards, Regulations

1. Introduction

Cyber-Physical Systems (CPS) are ubiquitous and help solve daily challenges in many industry domains. From medical devices to advanced driving assistance systems (ADAS), they facilitate and enable the smooth operation of previously human-carried tasks. Of course, they should not endanger the security and safety of human bystanders (users, operators, patients, etc.). Rajkumar et al. define CPS as

> "*... physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core.*" [1, p. 1]

Emphasizing applied CPS across different industries, we can see that the application domain is as wide as the number of human activities. Tekinerdogan et al. provide us with a general and complete feature model for CPS [2]. They also listed 10 application domains which seem relevant when looking at applications in the literature: **Health** where wireless medical devices presence is growing in hospital and operating rooms [3], **Smart Manufacturing** with smart factories through industry 4.0 which aim at increasing the efficiency of the product line either by reducing the costs or improving the flexibility of the resources by using interconnected devices, sensors and actuators [4], **Transportation** with advanced driver assistance systems (ADAS) alongside with other technologies aiming at self driving and connected cars [5], **Process Control** with the detection of chemical compounds in water for pollution detection and communication with waste-water plants [6], **Defence** with the upcoming of Lethal Autonomous Weapon Systems (LAWS) [7], **Building Automation** with connected devices to help monitoring and controlling a home and support the residents [8], **Robotic Services** in space exploration for example with the Ingenuity mars copter which had to adapt itself to the aerodynamics of Mars to perform the first successful flight there [9], **Critical Infrastructure** and the transitioning from classical grid management tools to smarter ones in order to improve the efficiency of a grid [10], **Emergency Response** by using CPS to increase the safety on construction sites [11], and **Other** for other types of CPSs.

Our research aims to find a test-oriented classification framework for CPS to perform efficient testing, considering the requirements and challenges of the various application domains. Indeed, as presented

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*Corresponding author.

guillaume.nguyen@unamur.be (G. Nguyen); xavier.devroey@unamur.be (X. Devroey)

0000-0002-9724-6634 (G. Nguyen); 0000-0002-0831-7606 (X. Devroey)

earlier, CPSs are classified mainly by application domain. However, the constituent elements for those systems are pretty similar (sensors, actuators, computing unit, etc.). Thus, the testing effort could be alleviated by consolidating the testing tools while keeping the domain-specific tests at later stages of the testing process. For this classification, we approached CPS from 3 central axes:

CPS Testing - How are CPS tested across industries?

CPS Engineering - How are CPS built across industries?

CPS Context - What are the non-functional requirements of CPS across industries?

2. Background

We understand that CPS are ubiquitous and benefit from a great versatility in their deployment. However, it seems to collide with other concepts from the industry, such as Embedded Systems, Internet of Things (IoT), real-time systems, or more generally operational technologies. Indeed, IoT is a "*concept used to define or reference systems that rely on autonomous communication of a group of physical objects*" [12]. We can see that IoT and CPS are related and should not be separated when defining and classifying CPSs. When bringing CPS and IoT together, Liu et al. suggest that CPS "*... deeply integrates the ability of computing, communication, and control based on information acquisition in IOT.*" [13, p. 28]. Lee and Seshia see CPS as an approach to embedded systems [14]. In their book, they define IoT as offering a means to interconnect sensors and actuators through networks to an interface inspired by the IT world, such as *Web Interfaces*. However, while IoT could fit the earlier definition of CPS, it is not suitable for time-critical real-world interactions. Indeed, *Real-Time Control* and *Safety-Critical Systems* require low-level logic and architectural designs. Lee and Seshia intend to give an introductory course on all the technical challenges of designing a CPS. In short, we could say that embedded systems are CPS components that use IoT to communicate.

The literature concerning testing and testing methods for CPS is quite complete. Indeed, Zhou et al. reviewed methods and test beds for testing CPS [15], they showed that CPS testing was a particularly rich field with many different and complementary techniques. Indeed, they list the following testing methods:

1. Model-Based testing (MBT), which is a formal method of checking the correctness of a model.
2. Search-Based testing uses meta-heuristics such as a genetic algorithm to generate test cases or test data automatically.
3. Online Monitoring, when complete formal verification is not possible, analyzing systems at runtime provides a formal technique that might leverage useful information.
4. Fault Injection testing, as producing failures artificially and consciously, speeds up the testing process.
5. Big Data Driven testing and prospects on using big data analysis by storing a large amount of data in CPSs.
6. Cloud Testing inspired by the advances of cloud computing and IoT.

They classify the testing methods into 4 objectives: **conformance testing**, **robustness testing**, **security testing**, and **fragility testing**. Of course, they also list the various contributions in terms of simulation-based testing, test-beds, and simulation-based test-beds for CPS by application domains, which have their own set of techniques and objectives.

3. Survey

The target population of the questionnaire was people working for Belgian or at least European companies in charge of governing whole or part of processes, including CPS design, development, test, and production, with a good knowledge of technical requirements, corporate internal processes, industry standards, and legal requirements. The initial sampling intention is to target as many actors across industries as possible and provide an industry-specific overview of the more general challenges faced when dealing with CPSs.

The 53-question questionnaire was built using a French online tool called ”Drag n Survey” that allows the user to drag fields onto a form and complete the questions. Due to license limitations, we could not use the automatic translation module, and we created three separate questionnaires in English, French, and Dutch.

The participants were solicited via a LinkedIn post, LinkedIn direct messages, contact lists from the Belgian CyberExcellence project, and contact lists from the computer science faculty of the University of Namur. We also participated in 4 industrial forums (2 local and 2 international) to interact with relevant companies directly.

Non-responses and dropouts were not monitored in real-time; however, as the level of knowledge required to answer the questions was relatively high, we assumed that participants might not have had sufficient knowledge to complete the questionnaire. As for missing data, we cleaned the data set of unusable responses.

We downloaded an Excel file with two sheets for all three questionnaires to analyze the responses. The ”Questions” sheet has all the consolidated responses to the questions, with the number of responses to a specific question, for each multiple choice. The ”Respondents” sheet or participants have all the individual responses to the questionnaire with IP addresses and time codes. A ”+” sign separates multiple choices.

The extraction process is the following:

1. Load the three files in RStudio.
2. Load the questions from the ”Respondents” sheet columns from the three questionnaires inside an R data frame.
3. In a new R data frame, load the information from the ”Questions” sheet and assign question ID based on the ”Respondents” data frame.
4. Extract and consolidate all the rows from the ”Respondents” sheet from all questionnaires.
5. Remove NA rows and participants who said they couldn’t answer the questionnaire from the final data frames.
6. Finally, identify dropouts and delete responses.

We had nine exploitable responses after soliciting respondents for 5 months and cleaning the data. It might be because it targeted C-level personnel with highly technical knowledge of the systems and corporate and regulatory expertise. They might not have the time to answer questions or be reluctant. However, we do not have enough information to elaborate more on that. On the other hand, 5 of those nine respondents agreed to be contacted for a case study, which is quite encouraging and will allow us to push the quality of our research further. We are well aware that this research constitutes preliminary research and should not be used to generalize the challenges regarding CPS across industries. However, it offers a nice probe for further study.

4. Results

In this section, we present the various results from our survey. The tables are gathered in Section A.

Out of the 9 respondents, we gathered responses from a telecom company marked as **Other**, a **Process Control**, a **Robotic Service**, three **Smart Manufacturing**, and three **Transportation** companies. We chose to present the following results by aggregating the data by domain of application. A description of the respondents is shown in Table 1. Even though we received 9 answers, we gathered a wide sample of industries and companies. All those companies used multiple devices at the same time, and sometimes more than 10,000 different devices. Only the robotic service and the telecom company didn’t use interactive devices, while we suspect our question was not understood correctly. Although we formulated it as such: “*How many OT devices does your company use? For example, a smoke detection* *system with a smoke sensor, an alarm centre, and a sound alarm is composed of 3 devices.*" and "*As previously mentioned, those devices often interact with each other. Is that the case in your company?*" Systems used within those companies usually comprise devices from different manufacturers with proportions varying from 10 to more than 90%. Most of them also use industrial computers. Concerning the management and the number of departments using CPSs, we had different responses and mostly no answers.

Table 1
Overview of CPSs, interactions, and management by industry

Question	Other	Process Control	Robotic Service	Smart Man--ufacturing	Transporta--tion
Number of devices	1,000–10,000	>10,000	1,000–10,000	100; >10,000	10; >10,000
Device interaction	No	Yes	No	Yes	Yes
Avg. devices interacting	NA	10–100; 100–500	NA	10–100; 100–500	1–10; 10–100
Number of systems	NA	>100	NA	< 10; >100	< 10; >100
Systems with devices from different manufacturers	NA	50–90%	NA	10; >90%	10–50%
Industrial computer used	NA	Yes	NA	Yes	Yes
Same department manages systems	NA	Yes	NA	depends	No
Number of departments	NA	NA	NA	1; >3; NA	>3

Results for testing CPSs In Table 2, we can see that most respondents carry out tests at various levels, including functional and non-functional tests. Yet for the **Other** company, they don't seem to perform any testing themselves. In Table 3, we can see that most of them carry out tests before integrating a new device into their systems. They also perform quality insurance tests. Concerning the testing time spent at various phases of a product development, *design*, *development*, *prototype* and *production* we can see in Table 4 that **Smart Manufacturing** and **Transportation** perform testing from very short period of time to very long period of time at each phase while the **Process Control** company did not perform tests in production when the **Robotic service** company only carried out tests in production. In Table 5, we can see that various non-functional tests are performed at different phases of the development process.

Results for engineering CPSs In Table 6, we see that the **Smart Manufacturing** and **Transportation** companies have code developed internally, by manufacturers, and by third parties, which is consistent with previous answers. Concerning the Other company, the results are intriguing; they didn't seem to perform tests while they developed the code internally. Overall, the responses seem to be quite varied. Concerning programming languages and communication protocols presented in Table 7 and Table 8, the results are coherent with the industry standards, while we were surprised to find high-level languages such as Python, Java, and C# in the programming languages of CPSs.

Results for context surrounding CPSs The context in which the various companies operate follows the previous observations. Indeed, when looking at Table 9, the smart manufacturing and transportation companies with risk analyses at the various phases of the product development process follow multiple regulations and standards. However, every company only ticked the few regulations and standards we suggested, showing a misunderstanding of the regulatory and standardization landscapes of their industry. Free answers showed they had no idea about those, or they were following the provided requirements lists received from headquarters (in the case of international companies). When looking at the approval process in Table 10, we can see that there are multiple steps and multiple hierarchical levels involved with sensibly more complex processes for Transportation companies. This is consistent with Table 11 showing a longer period of time required to introduce new devices or components within a system.

5. Conclusion

We presented results from 9 different companies grouped in 5 domains of industry. We encountered many difficulties in gathering information from multiple companies. We tried hard to interact directly with industrial actors during national and international forums, and we received enthusiastic responses from people met in person; however, we could never reach past the legal department of those companies. Furthermore, we never even reached a point where a non-disclosure agreement (NDA) was suggested.

Nevertheless, this survey offers interesting preliminary results showing the great variability in the companies using or developing CPSs. Interestingly, **Smart Manufacturing** and **Transportation** companies were particularly more tested, while we cannot reach conclusions with such a small dataset.

Concerning the future work, the *Context* surrounding the CPS development in the industry attracted our attention concerning the lack of understanding of the various regulations and standards applicable. This is similar to Zhou et al., who state that the CPS conformance (between a system and its specification) is not well exploited, probably due to the complexity of the various standards applicable to those systems [15]. Indeed, when looking at the regulatory landscape in the European Union, for example, multiple challenges arise [16]. Thus, we will investigate the CPS compliance verification capabilities in the industry. We will also contact the companies willing to perform a use case to continue gathering data on industrial CPSs.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] R. Rajkumar, I. Lee, L. Sha, J. Stankovic, Cyber-physical systems, in: Proceedings of the 47th Design Automation Conference, ACM, New York, NY, USA, 2010.

[2] B. Tekinerdogan, D. Blouin, H. Vangheluwe, M. Goulão, P. Carreira, V. Amaral, Multi-Paradigm Modelling approaches for cyber-Physical Systems, Academic Press, San Diego, CA, 2020.

[3] M. R. Mahfouz, G. To, M. J. Kuhn, Smart instruments: Wireless technology invades the operating room, in: 2012 IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems (BioWireleSS), IEEE, 2012.

[4] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, M. Hoffmann, Industry 4.0, Bus. Inf. Syst. Eng. 6 (2014) 239–242.

[5] F. Arena, G. Pau, A. Severino, An overview on the current status and future perspectives of smart cars, Infrastructures 5 (2020) 53.

[6] V. Garrido-Momparler, M. Peris, Smart sensors in environmental/water quality monitoring using IoT and cloud services, Tren. Environ. Anal. Chem. 35 (2022) e00173.

[7] P. Scharre, Army of none: Autonomous Weapons and the future of war, W. W. Norton & Company, 2019.

[8] D. Marikyan, S. Papagiannidis, E. Alamanos, A systematic review of the smart home literature: A user perspective, Technol. Forecast. Soc. Change 138 (2019) 139–154.

[9] T. Tzanetos, M. Aung, J. Balaram, H. F. Grip, J. T. Karras, T. K. Canham, G. Kubiak, J. Anderson, G. Merewether, M. Starch, M. Pauken, S. Cappucci, M. Chase, M. Golombek, O. Toupet, M. C. Smart, S. Dawson, E. B. Ramirez, J. Lam, R. Stern, N. Chahat, J. Ravich, R. Hogg, B. Pipenberg, M. Keennon, K. H. Williford, Ingenuity mars helicopter: From technology demonstration to extraterrestrial scout, in: 2022 IEEE Aerospace Conference (AERO), IEEE, 2022.
[10] X. Fang, S. Misra, G. Xue, D. Yang, Smart grid — the new and improved power grid: A survey, IEEE Commun. Surv. Tutor. 14 (2012) 944–980.
[11] W. Jiang, L. Ding, C. Zhou, Cyber physical system for safety management in smart construction site, Eng. Constr. Archit. Manage. 28 (2020) 788–808.
[12] J. P. Espada, R. R. Yager, B. Guo, Internet of things: Smart things network and communication, Journal of Network and Computer Applications 42 (2014) 118–119. URL: https://doi.org/10.1016/j.jnca.2014.03.003. doi:10.1016/j.jnca.2014.03.003.
[13] Y. Liu, Y. Peng, B. Wang, S. Yao, Z. Liu, Review on cyber-physical systems, IEEE/CAA J. Autom. Sin. 4 (2017) 27–40.
[14] E. A. Lee, S. A. Seshia, Introduction to embedded systems, The MIT Press, 2.2 ed., MIT Press, London, England, 2017.
[15] X. Zhou, X. Gou, T. Huang, S. Yang, Review on testing of cyber physical systems: Methods and testbeds, IEEE Access 6 (2018) 52179–52194. URL: http://dx.doi.org/10.1109/ACCESS.2018.2869834. doi:10.1109/access.2018.2869834.
[16] G. Nguyen, M. Knockaert, M. Lognoul, X. Devroey, Towards comprehensive legislative requirements for cyber physical systems testing in the european union, 2024. doi:10.48550/ARXIV.2412.04132.

A. Tables

Table 2
Testing levels and types by industry

Industry	Testing levels	Functional tests	Non-functional tests
Other	NA	NA	NA
Process Control	Unit tests + Integration tests + System tests	Yes	No
Robotic Service	Integration tests + System tests	Yes	Yes
Smart Manufacturing	Unit tests + Integration tests + System tests	Yes	Yes
Transportation	Unit tests + Integration tests + System tests (sometimes only System tests)	Yes	Yes

Table 3
Integration tests and quality assurance practices

Industry	Integration tests before introduction	Quality assurance / testing on devices
Other	Yes	No
Process Control	Yes	Yes
Robotic Service	No	Yes
Smart Manufacturing	Yes	Yes/No (depending on case)
Transportation	Yes/No (depending on case)	Yes

Table 4
Available testing time per development phase

Industry	Design phase	Development phase	Prototyping phase	In production
Other	NA	NA	NA	NA
Process Control	1 week to 1 month	1 day to 1 week	1 week to 1 month	NA
Robotic Service	NA	NA	NA	Less than 1 hour
Smart Manufacturing	1 day to 1 year (depending on case)	1 day to 1 year (depending on case)	1 day to 1 year (depending on case)	1 day to 1 year (depending on case)
Transportation	1 day to 1 year (depending on case)	1 month to 1 year (depending on case)	1 month to 1 year (depending on case)	Less than 1 hour to 1 year (depending on case)

Table 5
Non-functional tests by industry

Industry	Non-functional tests performed	When performed
Other	NA	NA
Process Control	NA	NA
Robotic Service	System documentation compliance with actual behavior	Production
Smart Manufacturing	Load testing, Data security	Design + Development + Prototyping + Production
Transportation	Data security, System documentation compliance, Load testing	Prototyping + Production

Table 6
Summary of code development by industry

Industry	Internally	By manufacturers	By third parties
Other	X		
Process Control	X		X
Robotic Service		X	
Smart Manufacturing	X	X	X
Transportation	X	X	X

Table 7
Programming languages by industry

Industry	Programming languages used
Other	–
Process Control	ST, Ladder, FBD, C++, Python, Java, Javascript, C#
Robotic Service	–
Smart Manufacturing	C, Python, Java, Javascript, PowerShell/Script
Transportation	C, C++, Python, C#, ADA

Table 8
Communication protocols by industry

Industry	Communication protocols used
Other	–
Process Control	Modbus TCP, CAN, USB, Ethernet, MQTT, OPC UA, IP
Robotic Service	Ethernet, 4G/5G, Don't know
Smart Manufacturing	Modbus TCP, UART/USART, USB, Ethernet, MQTT, OPC UA, OPC DA, LoRA, 4G/5G, IP, Modbus Serial (disappearing)
Transportation	CAN, USB, Ethernet, MQTT, OPC UA, LoRA, 4G/5G, IP, MVB, CIP

Table 9
Risk analysis, regulations, and standards by industry

Industry	When do you perform a risk analysis?	Regulations / directives (laws)	Standards followed
Other	NA	NA	NA
Process Control	Design + Development	GDPR (EU 2016/679); NIS2 (EU 2022/2555); Regulation (EU) 2019/2144 (Automated driving system)	ISA/IEC 62443 (cybersecurity); ISO 27002 (information security management)
Robotic Service	Prototyping	NA	NA
Smart Manufacturing	Design + Development + Prototyping + Production	GDPR (EU 2016/679); NIS2 (EU 2022/2555)	ISA/IEC 62443; ISO 27002; Summary by HQ
Transportation	Development + Production; Prototyping + Production	NIS2 (EU 2022/2555); GDPR (EU 2016/679) + NIS2 (EU 2022/2555); IATF (PFMEA required)	ISA/IEC 62443; Internal; IATF

Table 10
Approval process: steps and people involved

Industry	Steps (approx.)	People (hierarchical levels)
Other	1	>3
Process Control	NA	NA
Robotic Service	2	2
Smart Manufacturing	1–3	2 to >3
Transportation	3–5	3 to >3

Table 11
Average time to introduce a new device or component

Industry	Average duration
Other	1 month to 1 year
Process Control	1 week to 1 month
Robotic Service	1 week to 1 month
Smart Manufacturing	1 day to 1 year (depending on case)
Transportation	1 week to >1 year (depending on case)