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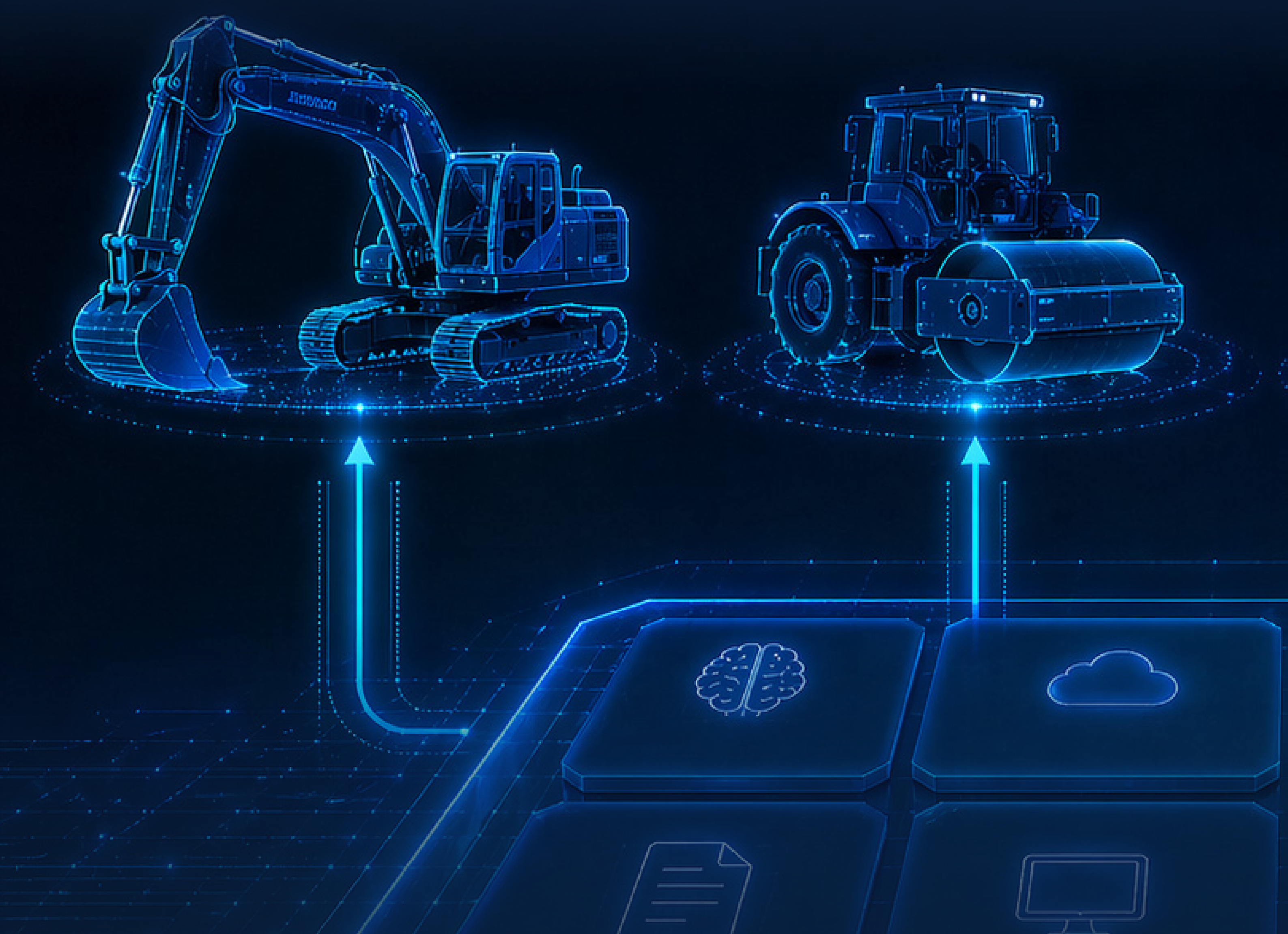

ARTIFICIAL INTELLIGENCE

Use in Software-defined Construction Machines

Managing Complexity in Software-defined Construction Machinery

The shift toward software-defined construction is fundamentally changing the industry. Artificial intelligence is exerting a growing influence on the functionality of modern machines. At the same time, increasing complexity of the systems is presenting manufacturers with new challenges. With its Software Factory, ITK Engineering is introducing an engineering system that automates repetitive and error-prone tasks involved in manual integration and validation, thereby also meeting safety requirements.

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The construction industry is currently undergoing a paradigm shift from inflexible hardware to smart, software-defined machines. Functions, performance, and even entire business models are increasingly stemming from software updates rather than new components. Something that the automotive industry is already modelling in the form of the Software-defined Vehicle (SDV) is now also changing construction sites, including business models and development processes.

This transformation is being driven by the principle of Software-defined Everything (SDX). SDX describes the separation between hardware and software, which lends flexibility to the management and administration of industrial systems. When applied to the construction industry, this gives rise to the concept of Software-defined Construction (SDC): Construction machines are no longer defined by inflexible hardware, but rather by smart software, **FIGURE 1**.

CHALLENGE OF ARTIFICIAL INTELLIGENCE

In the traditional, hardware-driven model, every new function required additional hardware components. This led to long innovation cycles, substantial costs, and product values that were set at the time of sale, **FIGURE 2**.

In the software-driven model, continuous software updates turn hardware into a flexible platform. This transformation is inevitable, since traditional, manual development processes are no longer able to keep up with the accelerating pace of software releases, the pressure to innovate, and long product life cycles. Driven by shortages of qualified personnel and new business models such as the post-purchase activation of additional features (functions-on-demand), the SDV serves as a role model.

Software-defined construction machines can be used in a way that is flexible and software-driven. The use of Artificial Intelligence (AI) plays a crucial role. In construction machines, AI can for example be used for environment recognition and process evaluation. But the continuous development and rapid provision of new functions requires a fundamentally different approach to software development.

SOFTWARE FACTORY AS DEVELOPMENT SYSTEM

The Software Factory addresses these challenges as an industrialized development system that applies the principles of streamlined production – that is standardization, automation, and error avoidance by design, – to software development, **FIGURE 3**. Besides, it is key for delivering algorithms securely via Over-the-Air (OTA) updates for the purposes of SDC. Its overarching goal is to drastically reduce lead times, reduce manual workloads, and ensure quality to a significant degree. Rather than a conventional Taylorist factory, the Software Factory is essentially a state-of-the-art workshop that provides experts with smart tools. It automates repetitive, manual integration and validation tasks, which are prone to error. This allows engineers to focus on creative design, complex problem-solving and innovation instead of handling those repetitive tasks.

This automation is achieved using a common DevOps platform with Continuous Integration/Continuous Development (CI/CD) pipelines and an integrated test infrastructure. The platform brings together all critical systems, from version control to the test environment, and in so doing lays the foundation for the integrated flow of data and end-to-end automation. In an SDX world, software is continuously undergoing development in order to iteratively provide new functions and improvements. Via its pipelines, the Software Factory provides the necessary connections in order to deliver new features and fixes in small, frequent, automated steps throughout the entire product life cycle.

AI AGENTS IN THE DEVELOPMENT PROCESS

One of these connections takes the form of AI-assisted engineering, in which AI agents support the entire development process. Examples include a failure triage agent to categorize build errors, a code review agent to identify patent violations and safety vulnerabilities, and a requirement consistency agent to check new requirements for ambiguity before the code is generated. This automation is implemented by means of integration, for example via a so-called Model Context Protocol (MCP). MCP is an open standard that enables standardized interaction with external data and systems (servers) for AI applications (host). This means that the AI can not only provide answers, but also independently access data and perform actions in other programs, **FIGURE 4**.

This approach can be supported by the so-called Documentation-as-Code (Doc-as-Code), which means that documentation is seamlessly integrated into the CI/CD workflows and the automated “assembly line” is extended to

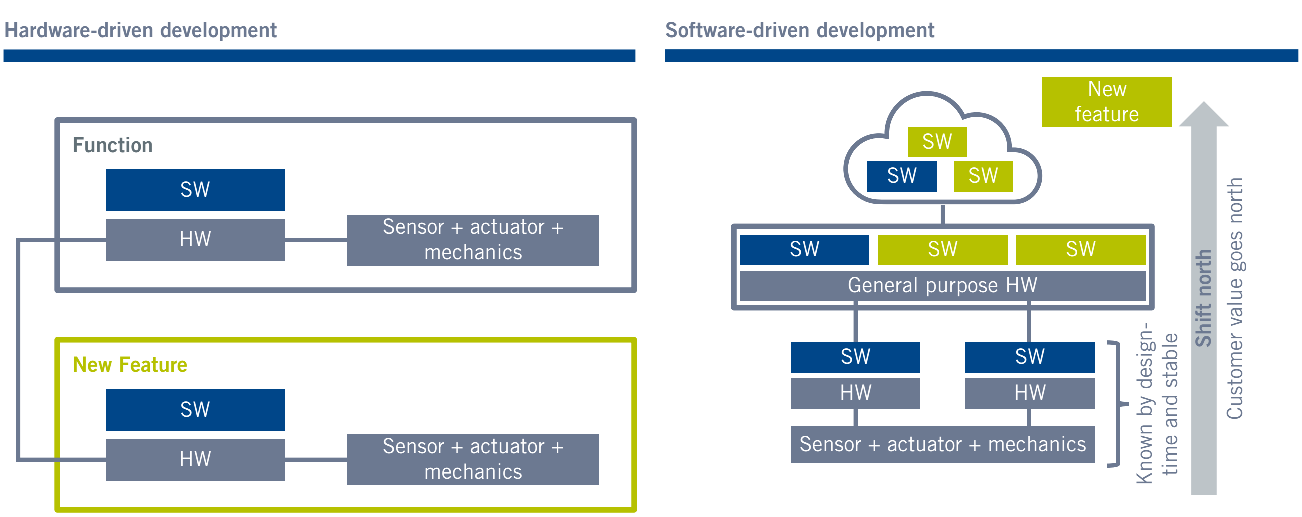

FIGURE 1 Difference between Hardware(HW)-driven (left) and Software(SW)-driven development (right) (© ITK Engineering GmbH)

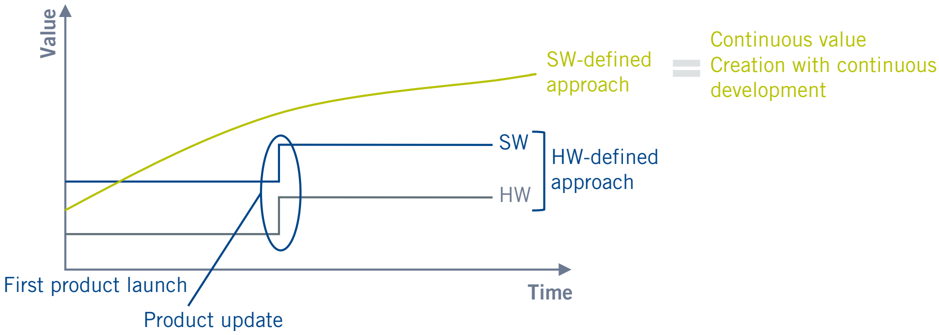

FIGURE 2 Software-defined X: from static products to continuous value creation (© ITK Engineering GmbH)

the start of the development life cycle. This enables the automated review of requirements and architectures along the lines of a so-called shift-left strategy at the start of product life cycle, ensuring that specifications have the same degree of precision as the code. The Software Factory offers the system-overarching context for this and the automation capabilities that AI requires to boost productivity, creativity and quality, from the requirements and code to test cases, as a smart co-pilot.

AI IN SAFETY-CRITICAL APPLICATIONS

Particularly when it comes to AI applications for machines that will be used in safety-critical functions in the future, the traceability of AI decisions is essential. The Software Factory integrates development processes closely with the real world of the machines and their Operational Design Domain (ODD). **FIGURE 3** shows the links to the real world in top right. The ODD defines the specific conditions under which a system is to operate safely, and is of crucial importance for AI systems on account of their data-driven nature. The Software Factory facilitates the continuous monitoring of the ODD during the machines' operation (open context). This allows deviations such as data or concept drift to be identified at an early stage and fed back directly into the development process.

This integration is crucial because the Machinery Directive applies to traditional machines and requires manufacturers to comply with safety standards, ideally based on harmonized standards such as ISO 13849. But there is currently no harmonized standard for safety-critical AI applications that describes a clear methodology. Although documents such as ISO/PAS 8800 and ISO/IEC TS 22440 are considered guidelines and future standards for the use of AI in safety-critical applications, they are still not standards in the conventional sense. This gap represents a legal risk for manufacturers.

This is where the Software Factory comes in, in order to provide assistance with this challenge in the field of SDC. As an industrialized development system, it applies principles such as standardization and automation to the field of software development in order to meet the strict requirements of these future standards. The concept of prevention-by-design is also taken into account, with risks being avoided or reduced as early as the design phase.

The combination of future standards with SDC is crucial in order to close the gap regarding AI in safety-critical applications. An ongoing AI safety life cycle with permanent monitoring (continuous assurance) in a so-called open world context is essential in this regard, since the environment and therefore the ODD are dynamic, which can lead

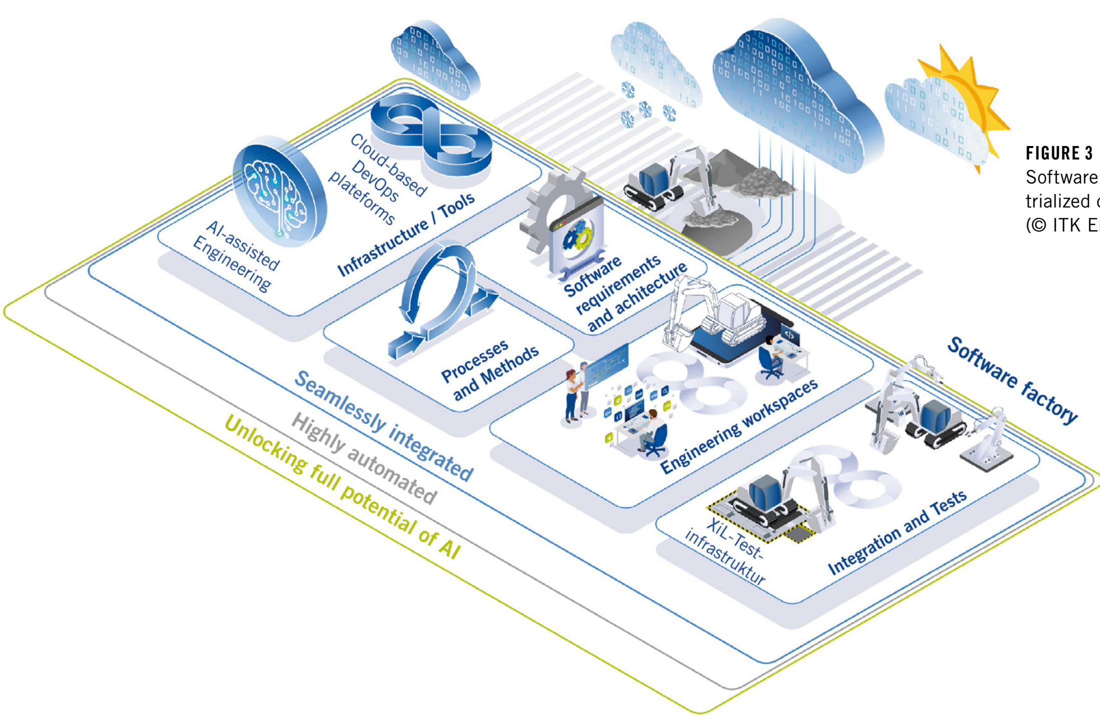

FIGURE 3 Key elements of the Software Factory as an industrialized development system (© ITK Engineering GmbH)

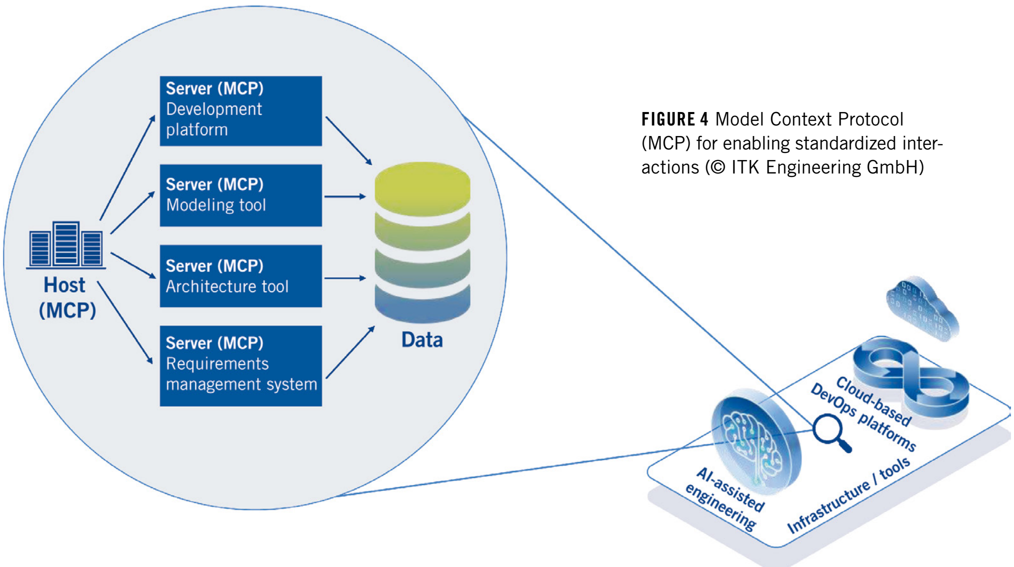

FIGURE 4 Model Context Protocol (MCP) for enabling standardized interactions (© ITK Engineering GmbH)

to a change in the functional correctness or performance of the AI application. The validity of the safety argument can be verified on an ongoing basis by means of iterative safety analyses and continuous assurance. This is essential for these kinds of AI systems since they operate in an open world context whose characteristics can change over time, and their behavior is determined to a significant extent by dynamic training data. If the validity of the safety argument is called into question, adjustments to the AI system, changes to the requirements, or measures at a higher system level are required in order to restore safety.

With its CI/CD workflows and XiL test infrastructure, the SDC approach is designed to facilitate this by ensuring continuous testing and validation. This supports continuous monitoring during operation, in order to identify safety-related incidents at an early stage and make adjustments. An AI fault analysis systematically identifies potential AI errors such as vague specifications, insufficient data coverage, and data and concept drift, and evaluates their criticality. This is used as a basis for developing AI fault mitigation measures intended to avoid errors or manage their impact on operation.

The data quality and life cycle also play a key role for the development of AI in safety-critical applications, because the behavior of AI models depends to a significant degree on their training data. With the SDC concept, the DevOps platform guarantees a central data base that is essential for the end-to-end flow of data. AI-assisted engineering and automated workflows also help ensure data quality, classification, and verifiability throughout the entire life cycle.

Finally, comprehensive test requirements must be developed, including statistical performance evaluations, IDD tests, and robustness tests. The XiL test infrastructure and its focus on comprehensive virtualization make it possible to reposition tests in line with the shift-left strategy, and thus make them scalable. This is crucial in order to meet the extensive test requirements for AI-supported functions in SDC construction machines.

CONCLUSION AND OUTLOOK

Machines are increasingly evolving into flexible, software-driven systems in which new functions are provided by means of software updates on general-purpose hardware or in the cloud, and interact bidirectionally with the environment. The Software Factory can play a central role here as an industrialized development system. It is fundamentally transforming the development of software for SDC through standardization, automation and prevention-by-design. Ongoing life cycle management, continuous assurance, AI-based error analysis and scalable test methods make it possible to manage safety, data and quality requirements throughout the entire development process.

AI-assisted engineering and the seamless integration of tools and workflows give rise to a full-system context in which AI acts as an intelligent co-pilot. But the progress of technology alone is not sufficient. Just as crucial is a cultural transformation to agile, cross-team working methods and shared responsibility. But architecture, organization, and Software Factory need to evolve together. Standardization lays the foundation for automation, integration multiplies its impact, and the reduction of throughput times becomes a key success metric. At the same time, the factory shall support the human – not replace them. When technological innovation and cultural transformation work together, the full potential software-defined construction can be reached.

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