Towards realizing the information backbone of robotized construction – Computational methods and cyber-physical architectures for collaborative robotic fleets

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Abstract
Recent developments related to Industry 4.0, Internet of Things (IoT) and new robot architectures have revolutionized industrial manufacturing and have led to a large degree of automation in various industry branches. Also in building construction, robotic systems have significantly progressed in recent years. However, so far, the automation achieved in construction by robotic systems mostly remains on the level of isolated, highly specialized processes. Hence, a paradigm shift towards realizing a comprehensive system-of-systems approach is required that facilitates fleets of autonomous and semi-autonomous robotic systems to collaboratively work on site in a well-coordinated manner aside with and observable by humans. To achieve reliable robotized construction, adequate and precise information about the buildings under construction, the construction methods and processes, the position, action and interaction of robots as well as the status of the site must be available in a coherent digital representation. We denote this representation as "information backbone" of the cyber-physical system. Currently, fundamental concepts for an information backbone of robotized construction are missing and urgently require intense research. The paper thus provides a roadmap for developing fundamental computational concepts and cyber-physical architectures required for planning, deploying, and controlling robotized construction.

Keywords: Cyber-physical system, Robotic construction, Industry 4.0, Information backbone

1 Introduction
Recent developments related to Industry 4.0, Internet of Things (IoT) and new robot architectures have revolutionized industrial manufacturing and have led to a large degree of automation in various industry branches. Also in building construction, robotic systems have significantly progressed in recent years. However, so far, the automation in construction achieved by robotic systems mostly remains on the level of isolated, highly specialized processes. Hence, a paradigm shift towards realizing a comprehensive system-of-systems approach is required that facilitates fleets of autonomous and semi-autonomous robotic systems to collaboratively work on site in a well-coordinated manner aside with and observable by humans. To achieve reliable robotized construction,

adequate and precise information about the buildings under construction, the construction methods and processes, the position, action and interaction of robots as well as the status of the site as a whole must be available in a coherent digital representation, referred to as "information backbone". Currently, fundamental concepts for an information backbone of robotized construction are still missing and urgently require intense research.

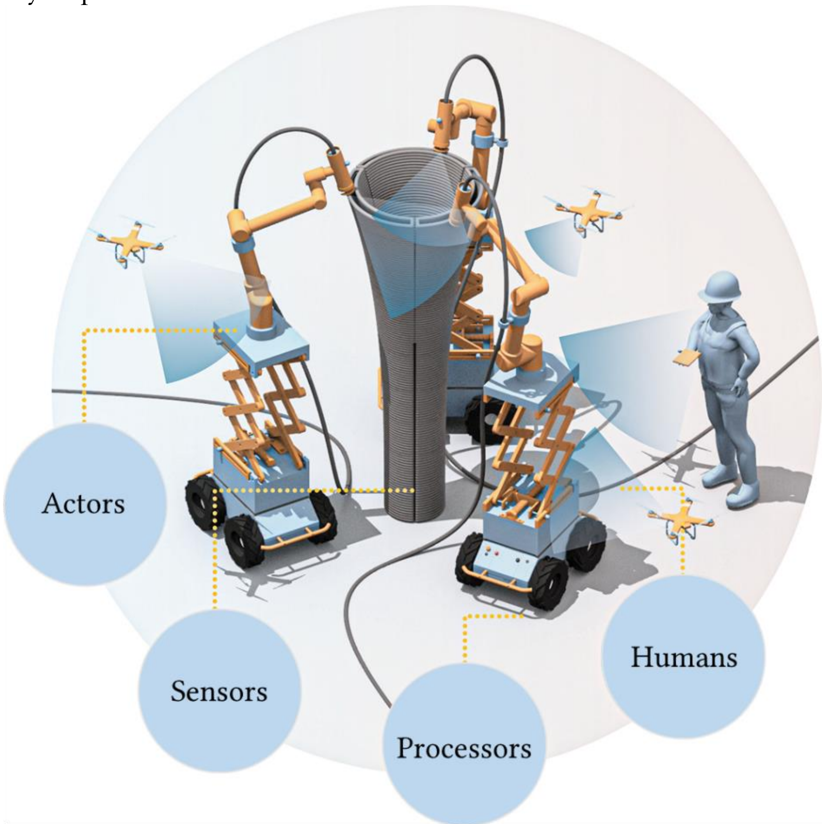

Figure 1: Illustration of the robotized construction site its main components that must be considered when conceiving the information backbone

The use of robots in the pre-fabrication industry has traditionally been associated with off-site assembly lines, in which constant conditions and fixed installations have determined the role of robots in the production process (Bock 1999). However, recent developments indicate the rise of robots beyond structured factory conditions in semi-structured or even unstructured environments, such as construction sites (Buchli et al. 2018; Melenbrink, Werfel, and Menges 2020). Robots and automated machinery stand to fundamentally change the way the construction industry operates. By leveraging the complementary skills of both humans and robots, human-robot collaborative processes have the potential to significantly increase the productivity in the construction sector. While there are clearly similarities with manufacturing industries, as addressed in the context of "Industry 4.0", particularly in the context of robotic prefabrication, where one-of-a-kind production and flexible production lines are part of the core features, the building construction domain is different from assembly of consumer products and manufacturing in four distinct areas:

- <u>One-of-a-kind production</u>: While in the manufacturing industry, products are typically produced in large series, a building is usually constructed once, considering individual boundary conditions (site, function, layout, etc.). Accordingly, high flexibility is required for adopting robot-assisted approaches both in prefabrication and on construction sites.
- <u>Production location</u>: While major emphasis in automation in construction has been put on prefabrication processes, even if large parts of the building components are pre-fabricated off-site, a significant part of the assembly and finishing work will continue to be carried out on-site. This becomes apparent when the logistics are considered, which allow only elements of a limited size to be moved on roads using standard or heavy-weight trucks.
- <u>Dynamic production environment</u>: In the construction industry, as opposed to the manufacturing industry, the position of a "product", i.e. a building, at construction sites is

fixed and usually large-scale. While in traditional manufacturing the product is positioned and moved along robot workspaces, robots at building sites need to move along the product to coordinate their tasks. Thus, challenges for developing robotic approaches are caused by the fundamental role of status and position of potentially interacting robots.

- Less well-defined, changing, and harsh outside environments: Construction sites are less well-defined environments than manufacturing plants, entailing challenges with respect to sensing, state recognition, and protection of complex robot devices.

Tremendous advances in autonomous systems, sensor networks, software engineering, artificial intelligence, the revolution in machine learning techniques, and mechatronics, fueled the progress of production technologies in the broader area of industrial production in recent years. However, while in other industry sectors, the concepts of Industry 4.0 and cyber-physical systems, providing deep integration of software components with mechanical and electronic parts, are well established and elaborated, the counterpart for robotized construction sites remains largely undeveloped. Valid approaches towards representing, processing, and handling information are still missing, considering the specific challenges that distinguish building construction from production in other industries. To overcome this deficiency, the authors propose concepts and architectures of an information backbone, enabling communication with and across heterogeneous robotic construction fleets.

Table 1: Overview on adoptable methods and technologies, and needs for innovation

Method or technology	Comment
Sensors and drives	These components are mostly available for rough conditions from industries like chemical processing, mining, automotive or naval engineering. Still, mechanical protection might be required.
Control platforms	Fundamental concepts such as redundant and failure-tolerant network protocols, client-server or peer-to-peer architectures as well as robot control systems are available and proven. Real-time buses and protocols are available
Robot systems	Conventional industrial robots are sold in millions and both cheap and reliable. However, they are typically not prepared for rough site conditions and need additional protection. The workspaces of robots available of-the-shelf are typically small compared to building structures, which raises the needs for additional motion axes such as movable platforms. Novel architectures such as drones or cable-driven robots need to be validated.
Navigation	Autonomous navigation in unstructured environments is mostly driven my academic research. Other industries typically provide known and fixed production conditions, well-structured regarding temporal sequences and geometrical conditions. However, Industry 4.0 concepts are providing foundations to handle this which yet have to be validated.
Digital Toolchain	Tools for mechanical or electrical engineering used in other industries typically support a fully digital data flow from requirements engineering to CAD/CAM and even quality management. First implementations for the construction industry have been proposed, but holistic implementations are yet to be implemented.

2 State of the art

Construction robotics have been in the focus of researchers and industries since almost half a century. Early in-situ robotic construction systems for high-rise buildings had been introduced in Japan (Bock, 2006; Bock, 2014) in the 1980's. These large-scale vertically moving robotic construction systems provided a fully enclosed, well-defined, and systematized working envelope. Several other on-site implementations have been demonstrated since by academic and commercial parties (see, for example, Arai et al., 2011; Detert et al., 2017, Charaf Eddine et al., 2017; Bruckmann et al., 2016; Bruckmann et al., 2018; Sousa et al., 2016; Pinto et al., 2016; Doerfler et al., 2019) and on European (Bots2ReC, P2Endure) and other international research projects (ROCCO, ESPRIT, BRONCO). Further academic and industrial research efforts, some of which are summarized in Table 1, focus on automating single, isolated production steps, such as digging, jointing, coating, or spraying (Siciliano,

2008) using mobile robotic systems. Bock, for example, lists about 400 demonstrators for specific purposes (Bock, 2006).

Table 1: Recent examples of robot-supported construction work prototypes developed in academia.

Renovation/ maintenance	Cutting robot for contaminated structural decommissioning and maintenance	(Matteucci & Cepolina, 2015)
	Robotic spraying of exterior insulation for energy-efficient building renovation	(Cebollada et al., 2018)
	Robot-assisted deconstruction of multi-layered façade constructions	(Lublasser et al., 2017)
Painting and finishing	Robotic painting for decorative features	(Seriani et al., 2015)
	Contour crafting robot for walls	(Omid Davtalab et al., 2018)
	Robotic application of foam concrete	(Lublasser et al., 2018)
Wall construction	Drone-based robotic masonry	(Latteur 2016; Bonwetsch 2016)
	Automated unilateral walls	(Więckowski, 2017)
	Robotic construction of double-curved reinforced concrete walls	(Hack et al. 2017)
	Automated masonry using cable robots	(Bruckmann et al., 2016)
Additive manufacturing	Concrete printing	(Bos et al., 2016)
Preparation for commissioning	Floor-cleaning robot to prepare buildings for commissioning	(Prabakaran, 2018)
Earth and site works	Robotic excavation	(Kim et al., 2018) (Johns et al. 2020)

Many of the early practical attempts of integrating robotics into the building industry have led to expensive factory-like construction sites with limited flexibility or highly specialized robots for single tasks, eventually hardly adopted by the industries. Construction automation specialists agree that stand-alone automation of isolated processes is not conductive (Linner, 2013; Helm, 2012). Instead, several construction tasks need to be conducted in a well-defined spatio-temporal order that requires complex coordination (Petersen et al. 2019). Construction robots will be mobile (Dörfler et al. 2016; Giftthaler et al. 2017; Buchli et al. 2018); they will need to account for complex temporary dependencies, and they will need to be able to adapt to changes (Vasey et al. 2014; Dörfler et al. 2019). The ability to perform multiple construction tasks will be key feature for future robot concepts. Finally, considering that many tasks are still conducted by humans on site, robots and humans will need to work together safely, productively, and collaboratively, and eventually form a hybrid human-robot team.

Many early projects had not only envisioned the robotic building site, but they had also foreseen an integrated system from planning to construction to facilitate their workflow. This integrated information management system – referred to as the Computer-Integrated Construction (CIC) concept (Gambao, 2000) – included the planning of logistics in regards to all resources (e.g., material supply, robotic machinery, operators), the setting up of the machinery on site, as well as the development of operator interfaces (e.g., planning and simulating robot actions, controlling the robotic processes on site). Recently, several studies have started to shed light on some of these early envisioned aspects, albeit still in an isolated manner. For example, building upon the work described above, researchers have shown that robots can be directly controlled out of CAD and BIM environments (Brell-Cokcan and Braumann, 2011; Dörfler et al. 2012; Menges 2015) and integrated already in the early phases of design modeling (Gramazio et al. 2008; Menges 2012; Gramazio et al. 2013). Novel computational tools such as COMPAS, a framework for computational research in architecture and structures aim to integrate aspects of design, structural engineering and digital fabrication into one unified planning tool (Van Mele et al. 2017). To bring robots to a broader spectrum of users and directly to the construction site different human-robot collaboration scenarios have been explored for individualized assembly tasks (Stumm et al., 2016; Kyjanek et al. 2019), and conceptual studies into topics of advanced robotic control, such as haptic programming, have been conducted. However, like many of the early efforts to implement isolated robots on construction sites, these studies still mainly focus on specific tasks or construction methods. This also applies to first investigations towards cyber-physical construction that also only focuses on isolated fabrication methods such as timber construction (Wagner et al. 2020). Still, recent analyses emphasize the meaning of a dedicated coordination system (Melenbrink et al. 2020). An overarching research effort into concepts of cyber-physical construction and the underlying information backbone is still very much required to provide a solid foundation for future developments in the field. While progress has been shown in many compartmentalized areas, an overarching concept for information modeling, communication and processing in the context of robotic construction is still missing.

3 The information backbone of robotized construction

In this paper, the authors propose the concept of the "information backbone" of a cyber-physical architecture that allows to simulate, optimize and coordinate the robotic construction site in all relevant facets. It consists of various abstraction layers comprising process- and product-oriented representations of the construction project including Digital Twins, define interfaces and data models to provide connection points for sensing, actuating and steering nodes and allow to integrate various processing chains and automation models (Figure 1).

The final goal is to conceive and develop a plug-and-play architecture that allows integrating new robots, sensors, processing units, and software components into the cyber-physical construction system in a seamless manner, thus realizing the vision of an inhomogeneous, but well-coordinated human-robot fleet on site while considering the high development dynamics in this field. With the aforementioned features, the information backbone is expected to support simulating and optimizing the robotic employment on site, while considering the building design and novel construction methods. Explicitly, the information backbone will allow to seamlessly step from site planning and simulation to site control and monitoring, following a digital toolchain.

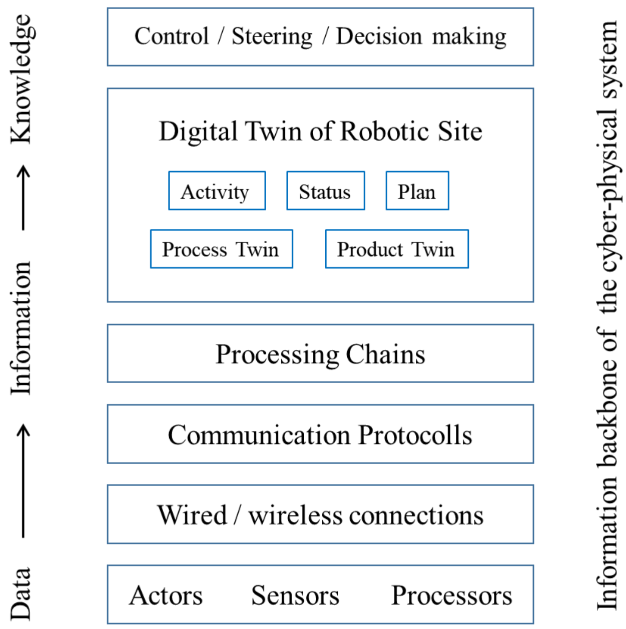

Figure 2: The components of the cyber-physical information backbone

In analogy to the Reference Architectural Model Industry (RAMI) 4.0, the Industry 4.0 reference architecture defined for the stationary industry, the developed information backbone will serve as the foundation of a future reference architecture for robotized construction. The authors are convinced that coordinated research activities are required to close the gap, develop the principles and architectures of the information backbone and thus provide the basis for robotized construction. The core research questions to be answered are:

- What are the formal requirements to be fulfilled by the information backbone for supporting and enabling robotized construction?
- What are suitable software architectures capable to support the various aspects of robotized construction?

- How can the information backbone be designed to support both the planning and simulation as well as the actual execution of robotized construction?
- How can data models and interfaces be designed to realize open and interoperable cyber-physical systems of robotized construction?
- How can dynamic digital twin representations of construction sites be conceived to provide all required information for planning and steering robotic construction?

For jointly developing the system architectures, data models, and protocols that make up the information backbone, the envisioned research activities should interface with domain experts and knowledge holders and jointly develop methods for simulating the dynamics of the robotic construction process and the involved information flows on the backbone synthesizing and overarching all individual approaches and projects.

The information backbone should be based on modern paradigms of distributed computing, providing proper interfaces and communication standards that allow to involve multiple modeling paradigms, simulation environments and control platforms. Doing so would then, in turn, enable and enforce the collaboration across the individual projects and coordinate their contributions to the common information backbone. In addition, it will provide a solid, long-term foundation for innovative research in the field of robotic construction.

4 Outline of research activities necessary to establish an information backbone for robotized construction

The challenging goal of robotizing construction sites can only be achieved on the basis of a comprehensive research roadmap that we aim to outline here. Future developments must concentrate on providing suitable digital representations of the facility under construction, the interacting robotic systems and the construction methods. Major emphasis must be put on specifying a framework for conducting virtual experiments of robotized construction sites to allow for the development and application of Digital Twins, mirroring their physical counterparts on site.

Initially, research can focus on virtual experiments that significantly increase the insights in the research domain and enable the development of new methods and approaches to address the issues identified. As discussed above, simulation environments based on existing concepts, techniques, and software libraries may include modules of physics engines and robot simulators and do not have to be developed from scratch. Based on a successful validation of robotic systems in virtual experiments, subsequent research can conduct real-world tests in physical environments, thus realizing a two-stage validation concept.

Research will also need to focus on formal modeling approaches for buildings using advanced building information modeling (BIM), ontology modeling, and process modeling formalisms. Examples for such formalisms are product modeling in UML, the development of ontological models in first-order logic, formal descriptions of systems using SysML, or the development of deterministic or stochastic process descriptions using process modeling methods, such as BPMN or UML. The simulation models developed are expected to be based on methods such as discrete event simulations or agent-based simulations, ideally integrating complex spatial (3D) and temporal aspects. The development of advanced visualization methods for concepts in 3D graphical representations of large data simulations are another important topic for research. Beyond providing this digital basis, all projects will influence and shape the development of the cyber-physical architecture, and employ it to simulate and clearly validate the feasibility of the explored automated construction processes.

The domains depicted in Figure 2 are of particular importance for conceiving the information backbone. In the following, the expected contributions from these domains to conceiving and designing the information backbone for cyber-physical construction are outlined.

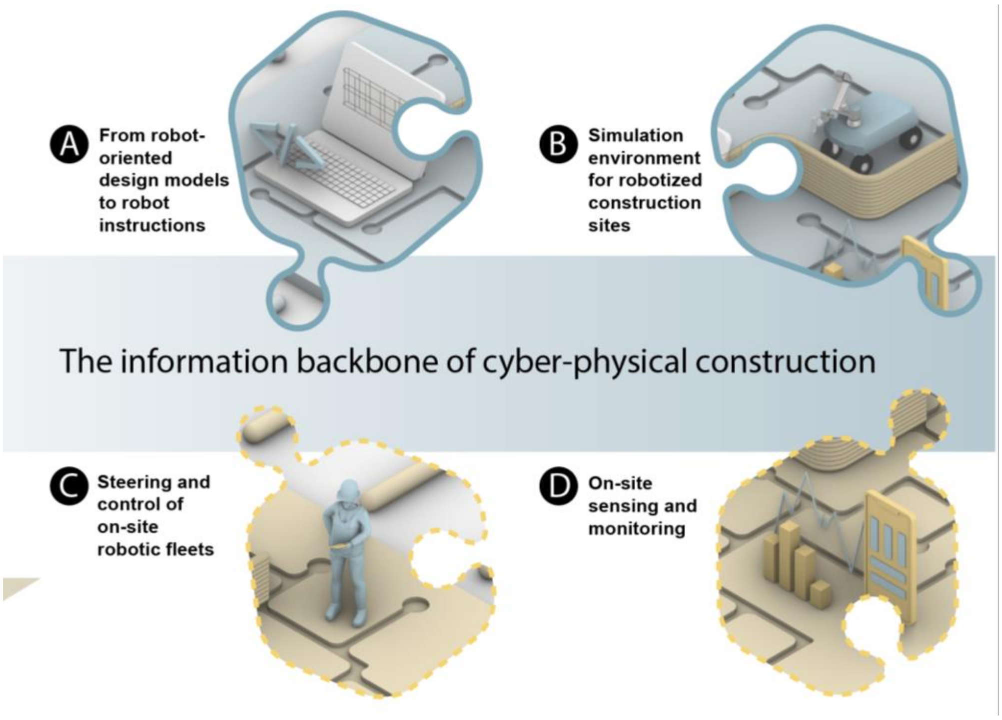

Figure 3: The domains to be considered for developing the cyber-physical information backbone of robotic construction site.

A: Multi-abstraction models: From robot-oriented design models to robot instructions

Conventional construction methods are oriented to fit the capabilities and limitations of human workers on site. As robots have completely different capabilities and limitations, conventional construction methods and consequently, the design and engineering of buildings, needs to be rethought to fit the needs and logics of robotized construction. To allow architects and building engineers to consider robotized fabrication methods during design, a new approach to design support considering robotized construction methods is required. While building information modeling (BIM) is a well-established method for the digital design of buildings, current use of BIM for the robotized construction phase is very limited. To this end, the notion of fabrication information models (FIM) has been established (Slepicka 2021), that provide a much more fine-grained representation of building components and integrate processual production information. On the machine level, even more detailed, concrete instructions are required to actually control the robot. Researchers from this domain are expected to contribute knowledge on robotized construction methods and contribute to the information backbone the relevant abstractions and data models for representing capabilities and constraints of specific fabrication methods. On that basis, research projects will have to jointly develop the information models and computational processing methods that enable robot-oriented architectural design and planning tools. They should conceive and elaborate the formal representation of the features and required capabilities that need to be represented in the information backbone. Researchers from this domain need to advance the relevant data structures, geometric-semantic transformation algorithms and communication protocols that will subsequently form an integral part of the information backbone of robotic construction.

B: Simulation environment for robotized construction sites

A main functionality of the information backbone is the capability of simulating the production process of the collaborative human-robot fleet before construction start. To allow architects and building engineers to simulate the robotized construction site, a new approach to robot production simulation considering robotized construction methods on various temporal and spatial scales is required. While robot fabrication simulation of single processes is possible to date, a generalized representation for robots in building construction is required, to simulate the robots' capabilities to operate within different building projects and in cooperation with other robots and human labor crews. Additionally, an accurate model of the behavior of robots in the real-world environment of building construction is required, taking uncertainty and unreliability into account. Projects contributing from this domain will enable the information backbone to handle different levels of abstraction regarding the process and product view of a simulated building site and allow a seamless and consistent transition from one level to the other based on formal patterns reflecting detailed fabrication knowledge. This includes also the formal representation and simulation of otherwise compartmentalized construction processes on various temporal and spatial scales. Clearly, the developed models have to be validated in experiments. Furthermore, they form the base for Digital Twins that reflect the robotized processes on the physical site accurately.

C: Steering and control of on-site robotic fleets
On future robotic construction sites, the information backbone will play a major role in steering and controlling the inhomogeneous robotic fleets on site whose collaboration has to be coordinated. Accordingly, research is required to conceive the respective components of the information backbone for realizing a cyber-physical production system under consideration of the specific boundary conditions of construction. First research steps still can use a pure simulation basis to explore and verify concepts. In consecutive phases, however, setups with real physical robots need to be investigated and corresponding field experiments have to be performed to validate developed functionalities. To allow for a seamless transition to the experimental phase, the simulations should be designed as Digital Twins of the real robots as introduced, allowing to exchange virtual and physical robots easily. This domain will impose important requirements on the backbone that have to be resolved by a proper architecture, capable for real-time, secure and reliable data exchange and robot coordination. Interfaces need to be carefully designed, following open standards and norms where appropriate. Research is required to investigate interface requirements to interconnect robot-specific control systems and the information backbone. The goal must be to not only synthesize generic communication protocols and interfaces as well as data distribution and storage strategies, but also control schemes to steer and control the behavior of each robot fleet member, ensuring a coordinated work execution on site.

D: On-site sensing and monitoring
Sensors form an integral part of robotic systems in construction automation as they provide up-to-date real-time information on the status of the production process, including faults and quality measures, allowing an immediate reaction by the robotic system to achieve production goals. In recent years, substantial advancements have been made with respect to automated monitoring of construction processes using auto-ID, photos, photogrammetry and laser-scanning including the respective post-processing. Contributions are necessary with a focus on integrating data from multiple sensing techniques into global site observation information and combine it with process data provided by the robots. Here, additional research is required to fuse data from different sources and to create a high-quality digital twin of the construction site that is constantly kept up-to-date. While the development of low-level sensor data processing algorithms (image recognition, point cloud creation, etc.) is progressing, data models and processing pipelines into the information backbone are required to refine the multi-layered architecture of the overall cyber-physical system.

This structure will allow to propose an overarching framework for future construction sites with flexible human assistance systems and co-working robots that account for the entire delivery lifecycle of a built facility. The framework will be composed of interfaces and information flow definitions between individual domain-related elements of geometric-semantic product representation, process simulation as well as sensor processing and data fusion.

5 Summary

In this paper, we have described the motivation, vision and concept of the information backbone for robotized construction. The information backbone is required to coordinate and steer heterogeneous human-robot fleets on future construction sites. It thus and serves as the fundament of a cyber-physical architecture that will comprise and connect all kinds of actors and sensors on site. The paper has outlined the functionalities and components of the information backbone and has outlines the research required for conceiving and developing it.

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