Cement and Concrete Research 112 (2018) 66–75

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Digital in situ fabrication - Challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond

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ABSTRACT

While a consensus exists that advanced digital and mechatronic technology is on the cusp of profoundly impacting virtually every manufacturing and industry sector, there are some industries that seem to have profited far less from this ongoing ‘revolution’. One prominent example of this is the construction sector and, in particular, building construction. In this paper, we aim at discussing some of the reasons for this apparent lack, and some reasons why this might change in the near future. We introduce the problem of digital in situ fabrication as both a significant challenge and a huge opportunity. We support the discussion with an example of a robotically-fabricated digital concrete wall. Overall, we find that solving in situ fabrication constitutes an inherently multidisciplinary challenge.

1. In situ fabrication

Considering which industries have profited greatly from automation and more recent advances in production technology, such as Additive Manufacturing technologies (AM), a clear pattern emerges: industries that can rely on manufacturing processes in which the workpieces can be moved around a manufacturing plant have benefited most from automation technology [28]. To elucidate the reasoning leading to this insight, we analyze the wide-reaching impact of this apparently simple statement in more detail.

The fact that one can keep tooling equipment fixed and in a well-defined environment offers a number of critical technological advantages. It simplifies, or even eliminates, many difficult engineering problems. For example, if one can ensure that the workpiece is fed to a machine in a precise and repeatable manner, the machine does not have to localize it. Moreover, if the machine is bolted to the ground, it does not need to localize and understand itself in the environment. If the machine is in a fixed location, one can also shield it behind safety cages, which means that it does not have to deal with unexpected circumstances, such as humans or other machines entering its workspace. Not having to design machines with these challenges in mind greatly simplifies design, programming, and deployment. Finally, simpler designs are more robust designs, and are thus easier to operate and maintain [25].

In short, smart domain-specific solutions to these problems have enabled all of the success of automation in the last decades. Accordingly, an entire industry is specialized in analyzing and breaking down a given manufacturing requirement, and mapping it to available automation and manufacturing capabilities [26,27].

However, this approach possesses some major limitations. To understand these, it is necessary to consider industries that produce final products that are too large to be efficiently moved around a factory and require numerous additional assembly steps at the final location where the ‘product’ will be used. Examples of this are ship building, aircraft manufacturing, building of energy infrastructure (production facilities and networks), and civil engineering and building construction [29]. Typically, these industries have benefitted far less from automation. In fact, on numerous levels, the overall manufacturing processes and logistics closely resemble those from many decades, if not centuries, ago.

Thus, the fundamental challenge is one of ‘logistics’ of tooling, or more generally, manipulation and manufacturing capability in 3D space. In other words, in any of these industries, a need exists to ‘get things done’ in a certain place, where localization of this place is not negotiable or at least heavily constrained due to fundamental requirements of the nature of the process and the product. Consider, for example, placing the final nuts on bolts that lock the blades of a large wind turbine in place, joining a prefabricated roof structure to the supporting structure of the building or filling concrete into a mould to build a wall. Invariably, in such situations, we have to rely on humans to get the tools there, and the necessary manufacturing steps are performed *in place*.

Nevertheless, it is important to realize that in all of these industries tremendous technological advances have been made, but they remain sub-domain specific and do not translate into fundamental changes in

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https://doi.org/10.1016/j.cemconres.2018.05.013
Received 7 January 2018; Received in revised form 10 May 2018; Accepted 15 May 2018
Available online 14 July 2018

Fig. 1. (top row) Construction site in 1906 and today. (Bottom row) Shipyard 100 years ago and today. Both are industries involving manufacturing of 'large products', and hence require tools to be brought to the workpiece, instead of vice versa, as is prevalent in traditional highly automated production processes. Similar scenes can be found in any industry with large-scale products (aerospace, energy systems, etc.).

the overall process (see Fig. 1). Examples in the construction domain that illustrate this point are innovations, such as self-compacting concrete, laser measurements, radio-controlled cranes, and radio and cell phone communication. These advancements have made certain parts of the overall product manufacturing chain easier, but the final tooling and manufacturing steps must still be completed by a person. The reason is that determining precisely how to bring complex tooling capability to a certain point in 3D space without having to rely on an extrinsic infrastructure remains an unsolved challenge. Currently, the best way to solve this challenge is still to give a person a tool and have this person take the physical actions necessary to complete the manufacturing steps (e.g., welding, bolting, concreting, building a brick wall, etc.).

We distill this insight into the formulation of a central challenge for advanced manufacturing of large-scale structures, i.e., what we refer to as the '*in situ* fabrication (IF) challenge'. To summarize, it constitutes the following question: *"How can we enable 'arbitrary' autonomous mechatronics tooling capability, anywhere in 3D space, in 'arbitrary' environments without relying on fixed installations?"*

It is worth noting that even though the assembly might occur in a given 'sheltered' location, e.g., a hangar of an aircraft manufacturing plant or a shipyard, the problems that arise are still a part of the IF challenge [14].

Opportunities for solving the IF challenge are immense. The technology that will solve this challenge will enable more efficient processes and 'products' in many domains that require sophisticated assembly and tooling in large workspaces. In turn, this will help in addressing some pressing needs of society. For example, the cost of building and maintaining an adequate infrastructure would decrease dramatically. The time required for the planning and implementation of infrastructure will greatly decrease, and we will achieve more agile societies that can address evolving and urgent needs more rapidly and in a more targeted fashion, enabling much lower costs and use of resources [12].

Interestingly, the domains that struggle with automation are also industries that struggle significantly with worker health and safety concerns. On a relatively short time-scale, however, we will witness many benefits for the health and safety of workers in these domains. Furthermore, IF technology will act as an enabler for traditionally underrepresented groups in the workforce. For example, if physical strength or agility is not a fundamental requirement to complete a particular manufacturing job, that position will be available to a broader demographic of age, gender, and physical ability. On the other hand, we will also have to take action to ensure that the education of our workforce remains adequate, as well as strive for technology that facilitates non-specialist use. There are certainly wider implications of the development of digital technology in construction and they require a discussion of other domain experts and stakeholders. Such are questions around regulation, education and preparation for a changed work profile, the role of government in facilitating and regulating the developments, and the interplay and adaption of building regulations and code. A discussion of these important topics is beyond the scope of this article both for reasons of required depth and expertise.

2. Digital fabrication with concrete

Many of the challenges of in situ fabrication directly apply to the task of building with concrete. Concrete structures are a perfect example of a product which fundamentally needs to be assembled in the place of their final application. It is certainly possible to partially prefabricate concrete structures off-site, but due to logistics limitations a larger structure still needs to be assembled in-situ. The most prevalent approaches to attempt digital in-situ fabrication with concrete to date have been variants of contour crafting (see [38] and references therein), whereby a large-scale robotic device leads a nozzle through space to build up a concrete structure layer by layer. A discussion of advantages and disadvantages of contour crafting can be found in [8] and research challenges are discussed in [38]. Below we show an example of an alternative approach that, for the first time, allows to digitally fabricate steel reinforced concrete and thus fully load bearing walls (see also [39] for a discussion of the aspects of reinforcement). However, both approaches have many of the basic digital fabrication challenges, in common, i.e. localization against global frames and workpieces, precision of material deposition, process inherent constraints [38] on the mechatronics of the production system etc. In particular, to date most applications of contour crafting use the idea of mechanical devices that are significantly larger than the structure they build (i.e. ‘a printer’, rather than an IF system). Contour crafting deploys an additional simplification, namely avoiding the complexity of placing a steel reinforced, structurally sound (i.e. welded or bound) steel cage. As we will see below, adding this aspect to digital concrete requires special care and significant interdisciplinary process- and mechatronic engineering effort [8,13] to develop a specific digital concrete building process enabled by a special purpose robotic tool head. We believe that such in situ fabrication specific tool heads and materials processes are a fundamental aspect of addressing many in situ fabrication challenges and opening fundamentally novel possibilities with in situ fabrication.

2.1. Technological bottlenecks in solving the in situ fabrication challenge

However, before we can derive all the potential benefits of in situ fabrication, we must surmount very difficult problems in order to solve the IF challenge. In fact, the challenges are not only of a technological nature, but many of them have their origin in industry as a socio-economic system.

2.2. The ‘hard problems’ of robotics

As mentioned in the introduction, there are important technological reasons why IF capabilities remain elusive. However, attempting IF in the construction domain offers unique opportunities to advance the technological state-of-the-art. Many of the challenges that we face constitute ‘hard problems of robotics’. The basic problem at the core of in situ fabrication, i.e., getting around a complex environment and ‘getting things done’, is of course at the core of the vision of the overall purpose and versatility of robotic technology, and has inspired much research in robotics. Solving this requires addressing a variety of technological challenges, ranging from system theory, algorithmic solutions, and design and systems challenges. In the following, we briefly highlight the most important challenges.

2.3. Design challenges

Current robotic and automation technology and solutions are often not general, but are instead rather domain-specific. Moreover, this specificity is not limited to required domain-specific elements, such as handling interfaces, but often penetrates deeply into the innermost and most basic design decisions, tools, and solutions. The engineering answer to generality, versatility, and reusability are (design) abstraction, modularity, and clearly defined interfaces. However, accurately defining such questions is difficult and typically occurs in a process that resembles an evolutionary process within a larger engineering community rather than a targeted effort of a few decision-makers. One can find numerous examples and lessons of such in the evolution of computer science and engineering. Indeed, as a community, we have managed to layer hugely complex functionalities in a way that it is available to non-domain-experts. For example, one does not have to be a network expert to implement a sophisticated networked application, thus freeing the application designer to consider the functional requirements for their application domain (e.g., in a peer-to-peer payment system, the designer can focus on the design of the financial transaction algorithms, rather than the underlying communication infrastructure). Such abstraction has made rapid progress and scaling in the computer science domain possible. In contrast, current advanced mechatronic systems are frequently quite monolithic in terms of both their hardware and the software utilized to operate them.

2.4. Functional integration

Sophisticated robotic systems require a tight integration of an enormous range of functionalities across numerous domains. For instance, they necessitate expertise in mechanics, electronics, materials, manufacturing disciplines, and many other fields. In addition, for each application, relatively deep knowledge of the details of manufacturing processes are required to design the tool heads/handling interfaces. Each functionality and requirement also presents a host of corresponding challenges, e.g., mechanical requirements, volume and weight constraints, communication buses, electrical and communications interfaces, thermal management, battery or other prime energy sources, etc. Comparing the functional integration of our most advanced mechatronic designs with the dense, multi-scale integration of biological systems reveals that we are still very far from mastering advanced integrated multi-domain designs. The current state-of-the-art is more akin to attempting ‘compressing’ non-integrated designs together. Until we have solved this issue in a more fundamental way and possess tools that enable us to master this complexity, robotics technology will not scale for widespread use as IF technology.

2.5. Systems theoretical challenges

Generally, there are three high-level algorithmic steps that an IF has to solve. First, it must localize itself, workpieces, and other items of interest. This might mean determining their mutual position in space, its own position in a ‘world’ coordinate system, elements on the workpiece, such as holes, attachment points, orientation and other state information of the workpiece, etc.

Second, it has to understand and deduce the optimal action or sequence of actions given the state of the robot itself, the workpiece, the environment, as well as input from the planning/guiding software.

Third, it must execute these actions in a robust, predictable, and dependable manner. It needs to be able to control interaction forces in unknown environments. This requires fast multi-modal reasoning, efficiently and rapidly combining sensing streams from cameras, and position, rate and force sensors into action for the actuators. These are very hard, data- and computationally intensive processes. Often it is difficult to even specify the problem that has to be algorithmically solved.

Finally, in the IF setting, we encounter difficult and deep system theoretical challenges in all of these steps. In the first step, these challenges concern sensory fusion, scene understanding, context interpretation, etc. In the second step, these constitute challenges of reasoning, planning and control under uncertainty, as well as understanding how to algorithmically tie the solutions into a larger framework (e.g., how and in what form does the 'architect' instruct the machine about what to do). In addition, sensory streams will be multimodal and of high bandwidth (e.g., combining camera pictures, laser scans, force and position sensing, etc.). In the third step, the challenges comprise movement control, reasoning, and controlling the position and force of the machine 'itself' as well as the workpiece(s).It is also the case that these three steps often have to be run in a tight loop, further increasing algorithmic and software design complexity. All these are not fully solved scientific and engineering challenges, which define the current frontier of robotics research.

2.6. The problem of the 'corner' case - advanced/flexible intelligence required

Without engaging in a deep discussion of what intelligence means and its many definitions, a machine moving around a complex, open environment, such as a construction site, has to exhibit sensible behavior. Such a behavior we could depict as having a minimal machine intelligence to deal with complexity of situations arising in an intelligent, and most importantly, safe and predictable way. In fact, the number of 'corner cases', 'ill defined' problems, and 'fuzzy rules and targets' exponentially increases with the complexity of the machine and its environment. Unfortunately, traditional engineering is particularly ill-suited in handling such amorphous, fuzzy problems and many complex corner cases. One of the first golden rules that any engineer will apply is to ensure that he or she can control the setup of the challenge in a way to make it better defined, less fuzzy, and comprising fewer corner cases. This is precisely what occurs when we bolt robots to the floor of a factory hall, put them behind cages, and make sure that they receive workpieces in very well-defined ways. While this is a very powerful way to solve problems, there are certain classes of problems in which this approach simply does not scale. The IF challenge is, to the best of our knowledge, a perfect example of this.

This same issue also leads to extremely slow and expensive R&D cycles in the domains that face these challenges, and the construction domain is a prime example. Combined with the fact that these industries often already run on small margins and experience high demands on the performance and dependability of their final products, this may be why we have not seen major breakthroughs in the IF challenge domain thus far. In essence, the industry is facing a Catch 22. Specifically, employing standard processes and a person to handle the tools allows tight and robust calculation and planning based on a large body of previous experience. On the other hand, employing novel processes introduces a high degree of uncertainty regarding time and resource budgets. In the last Section, we will present a convincing reason why we believe that this is about to change dramatically.

2.7. Requirement for feedback-controlled processes

There are two major reasons why an IF process will require substantially more feedback and process control than standard automated manufacturing. First, most AM processes have inherent reasons why the outcome is significantly different than the plan that went into creating it [29]. Such reasons are, for example, due to settling of material, residual stresses, etc. [13]. Second, by definition, an IF process is implemented in a less tightly controlled environment than standard automated manufacturing [1,8,13,29]. Therefore, the need exists to sense quantities, e.g., such as the position within a defined a global reference frame (localization) [30,31] or in respect to a workpiece [32] in order be able to follow a building plan, the presence of humans or obstacles to be able to avoid collisions etc. [30]. The additional requirement for feedback control is accompanied by an added burden for sensing and algorithmic development and deployment. This is due to the fact that the process of computing the required quantities from raw sensory information often requires sophisticated algorithms with substantial need for computational power and time (e.g. such as in localization). This fact is well illustrated in the example below. On the upside, the generated data are very rich and can be harnessed for other requirements, such as quality assurance, documentation, statistical monitoring, early failure detection, etc.

2.8. Robotics and automation require a great amount of expertise

Robots are complex machines and currently require deep expertise in all steps of their life-cycle, from design to building, to programming, operation, and maintenance. This introduces a prohibitively large overhead in domains that have a small series, high-mix nature, such as architecture, in which one cannot offset these investments and costs with a favorable cost scaling in high volume series production. In order to enable certain domains, such as building construction, to use complex robotic technology we have to be able to significantly lower this overhead. This will be achieved through providing versatile, modular, and reusable solutions on all levels (design to software). Once we are able to reduce this overhead, the community can utilize it to experiment and identify best practices within their own domain (as we are currently witnessing in the 'maker community' and larger digital fabrication domain).

2.9. The construction process is immensely complex, but allows scalable autonomy

The 'entirety' of a digital building construction process constitutes an even harder challenge to solve than other, already very difficult, robotics problems, e.g., autonomous driving. The construction site, however, offers the opportunity of a scalable challenge that is not present in autonomous driving and other targeted robotics applications, such as household robotics. Even though fundamentally a complex, non-stationary environment, the construction site is a 'semi closed/controlled' environment in which professionals operate that are used to working with and around demanding and hazardous machines and processes. Essentially, they are accustomed to following certain procedures. To simplify certain aspects, one can temporarily control parts of the construction site environment, e.g., fence it off and create certain required environmental conditions (light, humidity, access control, etc.). Construction itself comprises a heavily structured process, and novel manufacturing processes can be weaved into this process a top-down manner.

However, we also would like to emphasize that a fully automatic construction site is very likely not a desirable goal, neither for social nor economic reasons. Importantly, solving the in situ fabrication challenge should not be a mere challenge of automating current work flows. Quite the contrary, to fully unlock all of the advantages of novel digital methods, opportunities of digital fabrication have been discussed on a production system level and in a holistic way. As our example below illustrates, it is not feasible to build digital steel-reinforced concrete in situ by copying and 'automating' the existing materials and construction system. In fact, the materials-enabled opportunity of removing the mould both requires *and* facilitates novel ways to automatically assemble the mesh. This mesh process is then enabled by targeted innovation in mechatronics and robotics. Finally, the novel materials system requires new ways of assimilating it into the architectural planning and production process due to inherent process variations.

2.10. Digital fabrication and construction robotics as a socioeconomic system

We now discuss limitations and bottlenecks in the development and adaptation of IF technology which are not of a technical nature.

2.11. Non-technological bottlenecks

While we have discussed numerous technological challenges in designing and deploying IF technology, numerous bottlenecks exist that are not primarily technological. While the background of the authors might not be fully appropriate to discuss the challenges in required breadth and depth, we have experienced their importance. Due to their fundamental nature, one needs to examine the IF challenge in this larger context. In short, a successful deployment of technology must be discussed in the larger socio-economic system of the given industry.

First, a fundamental initial bootstrapping problem exists in applying IF processes to the construction domain. Specifically, opportunities shift with capabilities, and use cases are unclear and business cases are even more so (among others, it might require a type of company that is not normally present in building ecosystems). A large, complex, strong, and tight interdependence exists across many disciplines, but especially regarding the materials process and mechatronics solutions utilized to apply these.

Compared to particularly innovative industries (e.g., computer science, electronics, materials science, etc.), the construction industry does not possess a deep and significant R&D culture and resources, leading to a technology lock-in effect. In addition, on a very pragmatic level, a company aiming to move in this direction might not know where to start, and have no direct and clear access to knowledge and experts. The state-of-the-art is currently unclear, and a common understanding is lacking due to overhyping certain developments and underutilization of other already existing technologies. In short, the construction domain expert has a difficult time answering the initial question 'What can digital technology do for me'?

Furthermore, even though significant actors in the field are investing great efforts to address these issues, in large parts of the world the industry at large still benefits from the availability of cheap labor, and poor employment and workplace standards and enforcement. This fact tilts the cost/benefit analysis too much towards entrenched 'traditional' building processes and makes new technology prohibitively expensive.

Finally, the building industry has high entry hurdles for new actors who could possibly introduce major changes. For example, complex legal constraints and boundary conditions exist, as well as demands on performance guarantees (e.g., a building needs to be safe, and fulfill a large number of other legal and formal boundary constraints). Successful building construction requires very local networks and knowledge, and a medium-to large-building project typically involves hundreds of actors.

2.12. In situ fabrication is not 'just a digital technology, robotics or mechatronics' challenge

While many of the challenges that need to be solved fall within the domain of digital technologies, robotics or mechatronics, successfully guiding the development, and in particular the deployment, of IF processes constitutes a multi-disciplinary, cross-domain challenge. It also requires a systems-view and subsequent optimization over the entire process. The steps of this process are certainly not mutually independent. In other words, innovation in this domain cannot be solved in a sequential manner (i.e., an architect conceptualizes a futuristic design, an engineer translates it into a technical design and requirements, engineering offices execute the design, etc.). The solution is the result of a trade-off between many multi-domain inputs, requirements, and boundary constraints. Finding such a solution is a complex, *iterative* process. In order to innovate, the ecosystem must allow such interactions. Lessons can be learned from other industries with complex design tradeoffs, yet high performance requirements (e.g., the aircraft industry). In our example, we will see that the successful innovation of an IF steel-reinforced concrete process required the interactions and innovations of experts in numerous domains over a prolonged time and over several maturation steps.

2.13. Innovation requires experimentation

Innovation fundamentally necessitates experimentation and frequently the ability to learn by 'trial and error'. Other industries that have fast innovation cycles can literally perform experiments 'on the product', e.g., fine-tuning the parameters of a search engine, or an adword algorithm for a small set of their users and observe the outcome and impact.

Thus, we need to be able to 'experiment' on the job, learning by doing in the domain of in situ fabrication for building construction. In this domain, stringent safety, reliability, and dependability of the final product are often requisite. Thus, precisely how do we address and resolve this apparent conflict? And, what does trial and error in a building construction domain mean? Even though it would be absurd to assert that a final, inhabited building could be the result only of a trial and error process, it is still possible to enable such innovation cycles closer to the product in certain industries, such as the construction industry. However, this requires an R&D and innovation ecosystem that currently does not exist.

Certain types of experimentation can be accomplished 'in the lab', on prototypes or small-scale models, and pavilions. However, it is critical that one be able to experiment with 1:1 scale prototypical products, and the experiments must be realistic. Thus, we have to create an research, development and innovation (RDI) ecosystem, in which all of these opportunities exist. In turn, this means that all actors must identify roadmaps and windows of opportunity to contribute in the direction of developing IF technology.

Although large research initiatives, such as the Swiss NCCR Digital Fabrication [15], constitute a step in adding to this required ecosystem, they are not sufficient in and of themselves. 'Experimental' building projects, such as the NEST project [19] and the DFAB House, a prototypical module therein [20], are another element. The ambitions driving NEST is to overcome precisely this barrier of 1:1 experience with innovation in construction. However, to be successful in changing the innovation dynamics in the construction industry requires a much broader engagement of the many actors in this industry to engage in an open, productive RDI ecosystem. We emphasize the importance of an open ecosystem, as only such openness can lead to the required emergence of agreed standards and interfaces to ultimately enable scaling such complex technologies beyond academia and occasional experiments on construction sites. A strong precedent and justification for this argument can be found in the development of other complex technologies, primarily in the computer science and electronics domains. Clearly, the domain is too large and complex for a sole actor to innovate all of the required elements.

3. Example in situ fabrication process: Mesh mould metal

In the remainder of this article, we discuss an example that illustrates some of the points made in the previous section. We have recently built a load-bearing steel-reinforced concrete wall using an in situ fabrication process. The development and the final system reflects, to the best of our knowledge, one of the most comprehensive IF processes in the building construction domain. It allowed, for the first time, to robotically build a fully load capable steel-reinforced concrete wall, in-situ, on a real construction site, i.e., the NEST building in Dübendorf, Switzerland.

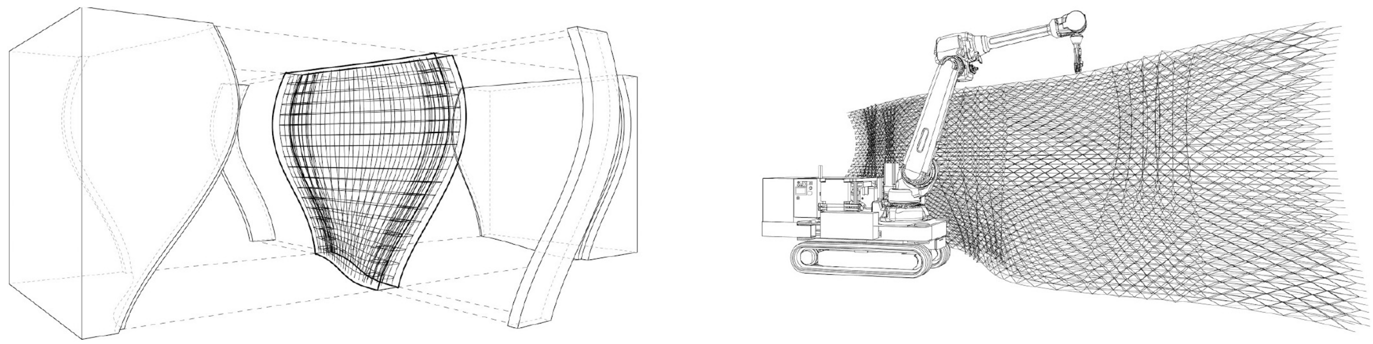

Fig. 2. (left) Illustration of the standard way to produce doubly-curved steel-reinforced concrete walls using formwork and rebar cages. (right) Illustration of the concept behind the mesh mould, in which an in situ fabricator builds a dense reinforcement mesh directly on site. The mesh serves as a lost formwork.

3.1. Mesh mould metal in situ fabrication process

The mesh mould metal (M3) process is a novel construction technique for fabricating steel- reinforced concrete structures, which is based on innovation in materials science, structural engineering, and mechatronics [8]. The development of the M3 process and its successful testing required experts in several disciplines to work very closely together. The involved disciplines are architecture, structural engineering, materials science, and robotics.

The key concept in M3 is using the reinforcement mesh as a lost formwork (Fig. 2). The mesh is built more densely than traditional steel-reinforced concrete rebar cages, and thus the yield stress (cohesion) of the concrete mix keeps the concrete from flowing through the mesh [9].

The complexity of the denser mesh is enabled by a robotic fabrication process [11], in which a mobile robot, the in situ fabricator (IF), guides a special purpose tool head [10] mounted on a robotic arm through 3D space (Figs. 3 and 4). The tool head feeds two sets of reinforcement-grade steel rods and performs a series of functions both for material processing and local positioning required for building the mesh.

The M3 process relies on a special concrete mix [8] and the yield stress [22] of the concrete mix for it to remain confined within the metal mesh. The assembly of the mesh and the filling with concrete occurs directly on the construction site, i.e., in the final position of the wall. The outer side of the meshes are later covered with concrete typically applied by spraying and then surface finished by being manually troweled. The composition and thickness of this layer should be selected in regard to expected durability and exposure conditions.

To facilitate the construction of the mesh, in addition to the process-specific M3 tooling, the IF is equipped with additional sensors needed to support the building process (Fig. 5). In order to build the mesh accurately on-site, the IF must not only sense its position within the construction site, but also be able to measure the contour of the mesh during construction. This information is used to adaptively construct the mesh, compensating for deflections in the mesh as they build up over repeated bending and welding operations [13].

3.2. M3 @ NEST

Using the M3 process, we built an undulated steel-reinforced concrete wall for the DFAB house on the NEST building at EMPA in Switzerland. The wall is 12 m long and 2.8 m high. The required mesh consisted of over 20,000 welding points, which were built with an average deviation of 9.5 mm and maximum deviation of 38 mm from the planned design (Figs. 6 and 7). When finished, the wall will carry a structural live load of more than 100 t.

3.3. Architectural design principles and algorithms

The design of the wall is implemented as an algorithm which parametrically generates a CAD design of the 3D mesh, using the

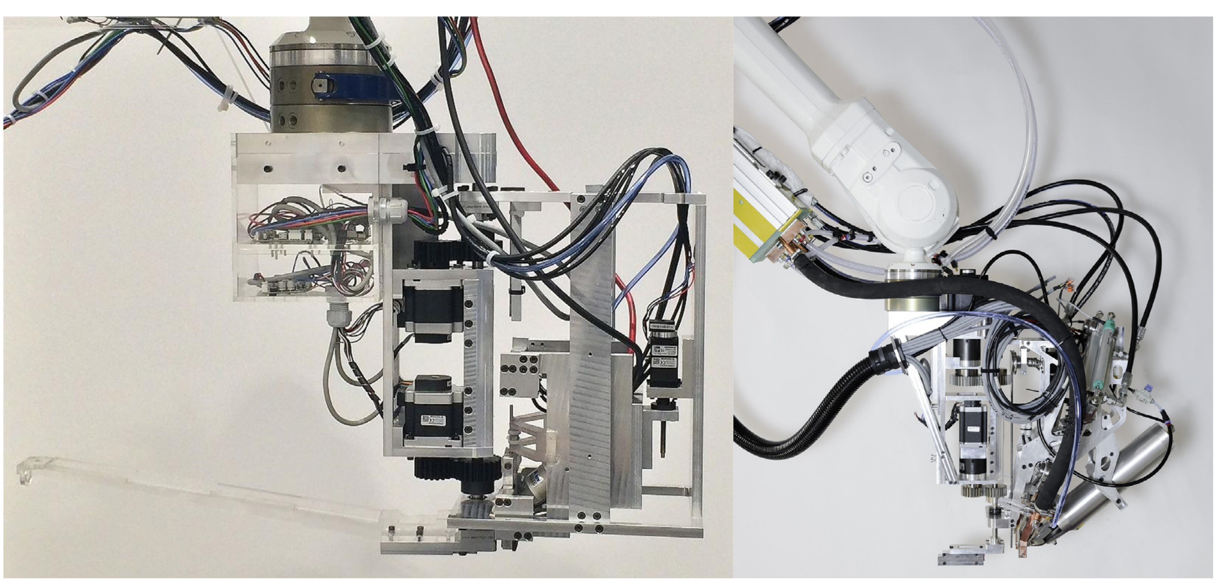

Fig. 3. Two versions of the mesh mould tool head. (a) An earlier electrically actuated version for steel diameters up to 2 mm. (b) Improved head with a hydraulic welding clamp and pneumatic cutting unit. This version is able to process reinforcement steel of up to 6 mm in diameter.

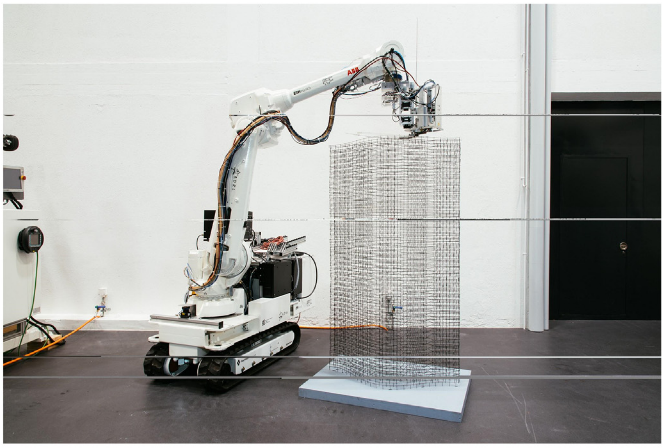

Fig. 4. IF building a mesh prototype. (b) Filled steel-reinforced wall prototype.

Grasshopper plugin for the Rhino 3D design environment (Fig. 6) [4]. The principle behind the architectural design algorithm is to use less material for concrete by building thinner walls and incorporating undulations to stiffen them as required for the live load. The design algorithm maintains important design constraints, e.g., such as positions of attachments to ground and ceiling elements and error tolerances to maintain structural integrity. From this design, the sequence of building operations, specifying the sequence of IF building positions and the sequence of tool head operations, is automatically generated. Individual building operations are sent to the robot via a TCP/IP interface. Through this same interface, feedback from the IF (e.g., localization, registration of the mesh contour) is received. This acquired information is used to generate an updated building plan for the subsequent process steps, thus utilizing online feedback in the construction process to achieve the final product [29].

3.4. Software architecture

The SW architecture of the IF- and M3-specific sensing profits from the development of generic SW building blocks for control and sensing of advanced mobile robots [36,37]. It runs software that is also used on very different types of mobile robotics systems, such as quadcopters or legged robots. The sensing software is designed in such a way that it uses a thin application-specific layer interfacing with generic mathematical sensory fusion algorithms. Again, these algorithms are used for other projects due to their generic implementation and modularity. Many of the used software layers are developed as part of our research and are available open source or to be released as open source soon [3,23,24]. They build on other openly available tools, such as ROS [33], Eigen [35], OpenCV [34] etc. The amount of customization required of course varies. Sometimes the need of a specific project will motivate adaptations or tweaks in the core algorithms. However, often it boils down to developing the required interfaces to 3rd party libraries and drivers to provide the data in the right format for the numerical core algorithms.

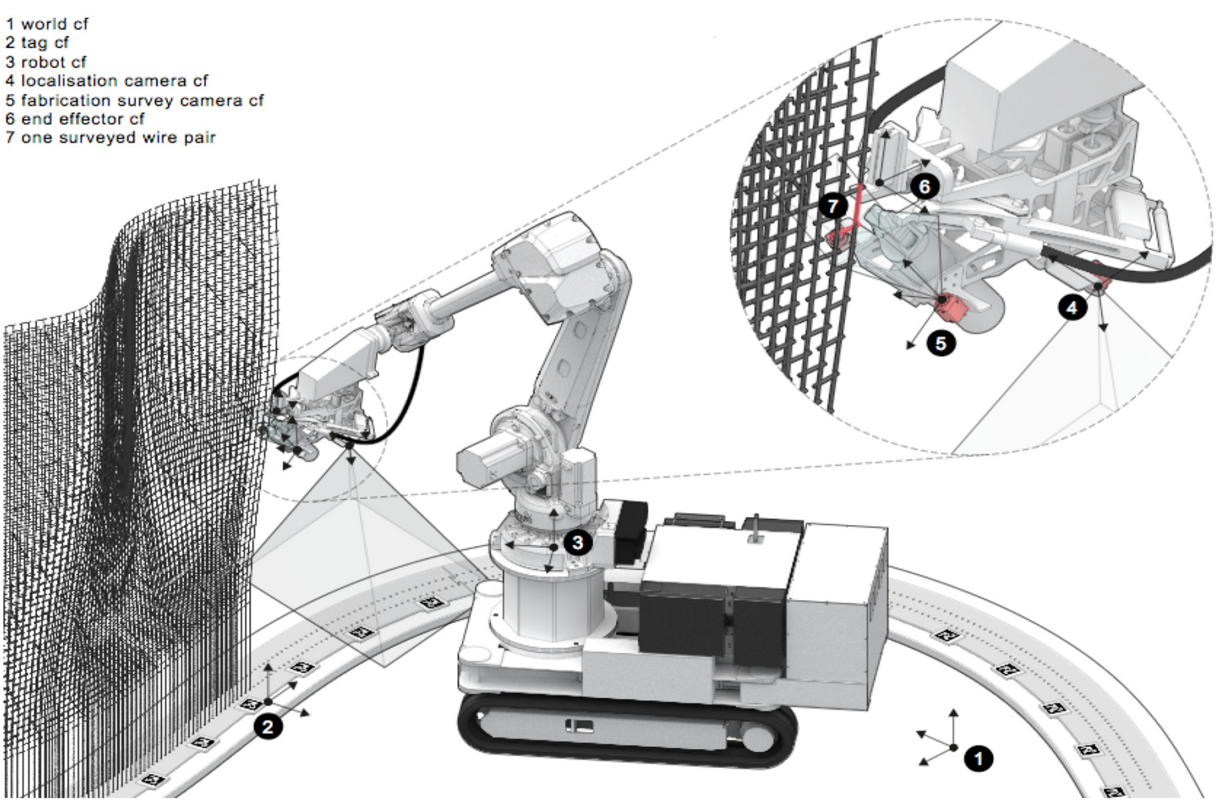

Fig. 5. Illustration of the two sensing systems employed.

Fig. 6. (a) The IF constructing the steel-reinforced reinforcement mesh at the NEST construction site. (b) Screenshot of the CAD integration of the M3/IF production system.

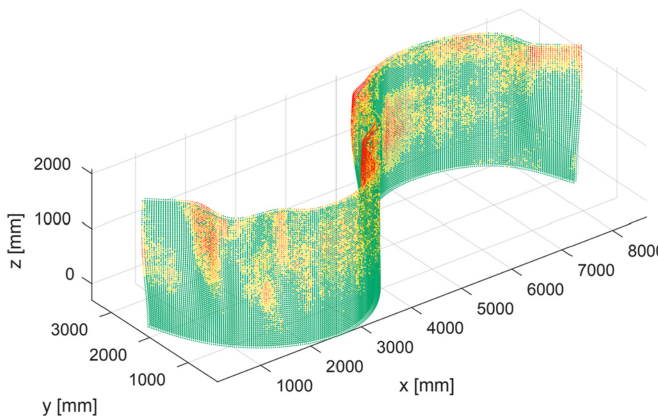

Fig. 7. Error plot of the built wall. The colors represent regions with errors in the following ranges. The percent of the structure falling in that range is also given in parentheses. Red (2.1%) ≥ 20 mm > dark orange (2.5%) ≥ 16.67 mm > orange (7.8%) ≥ 13.33 mm > yellow (20.4%) ≥ 10 mm > green (67.1%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.5. *The M3 tool head*

The tool head for the MM3 process and the robotic fabrication process itself is a result of an iterative experimentation process. In this process, a compromise has been achieved between necessary functions to automatically build a metal mesh and the necessity to be compact, lightweight, and portable enough to be deployed as a mobile end-effector. It is a fully customized design integrating several functions both for material processing and local positioning of the reinforcement-grade steel rods required to fabricate a metal mesh. The tool head, by design, performs local referencing to align two sets of rods to form cross-wire connections in order to weld them, in addition to bending, welding, cutting, and feeding operations. The first iteration end-effector (Fig. 3 a) was a feasibility study for the robotic fabrication process, whereas the second iteration end-effector (Fig. 3 b) incorporated major changes, such as design of a custom hydraulic gripper through algorithmic design optimization and integration of a different resistive welding technology. These changes were required to adapt the robotic fabrication process from 2 mm steel wires (first iteration) to reinforcement-grade steel rods of 6 mm diameter (second iteration) necessary for real-world applications. It currently allows for a cycle time of 5 s per welding node. In our deployment on NEST this allowed to place 0.76 t of steel in 125 h. In first order, the amount of steel needed per m3 of concrete is independent of the steel bar diameter. This means that for a given structural function, the number of welding points scales with the fourth power of the steel diameter. As welding is a rate limited step, there is a huge benefit in increasing the steel diameter. M3 is characterized by using steel with diameters about 3 times larger as compared to the process with the first version of the toolhead, which leads to a time saving factor of about 80. Thus, with the redesign of the tool head, the time saving factor is close to two orders of magnitude. This exemplifies how, in early stages of technological developments, major gains in efficiency can be obtained. It also underlines the need to defer cost calculations of promising technologies to later development stages, or to properly take into account that potential gains can be extremely large.

An architecture re-design of the tool head with regards to mechatronic integration along with usage of additive metal AM processes for manufacturing, as for IF, will enable an even more performant, lighter, compact, and easily adaptable M3 head in the future, as we aim for even higher goals.

3.6. *The in situ fabricator*

The mobile robot deploying the M3 tool head is the in situ fabricator [1]. An IF is a novel class of versatile mobile robots specifically designed for in situ fabrication tasks on construction sites. This novel class of machine is best defined using a set of requirements that an on-site construction robot needs to fulfill. This includes high positioning accuracy at the end effector (1–5 mm), mobility in non-flat terrains, and transportability by common means of logistics. The robot can be equipped with different tools and end effectors to accomplish a wide range of building tasks. Naturally, it requires a sufficient payload to be able to operate heavy construction tools and specially-designed digital fabrication tool heads. Ideally, the robot can operate in non-ventilated spaces and has sufficient on-board power to function independently from main power for a couple of hours. An IF can also provide essential process information to operators and to architectural planning and design environments in real-time, and enables the functionality to be operated by a non-robotics expert. It is worth noting that this definition is tailored for a machine that focuses on the fabrication aspect of a building process. To date, we intentionally neglect the fields of automatic logistics and supply management.

Our current IF (IF1) is built from standard components, a tracked base, and an ABB IRB 4600 manipulator arm with 2.55 m reach and a payload of 40 kg [1,36,37]. It is fully self-contained and provides battery power for 3–4 h of autonomous operation on construction sites. For the M3 application, additional external power supplies for the welding process were integrated into the system.

To accurately build the mesh on-site, the IF is equipped with two complementary on-board sensing systems. For localization within the construction site, a camera mounted on the end-effector of the robot is used to detect the position of reference markers mounted along the base plate of the wall. After the IF is moved to a new building position, this system is used to determine the new location of its base. The second sensing system consists of a stereo camera pair centered at the M3 tooltip. By sweeping the arm over the last layer of the mesh that has been built, this system can measure the contour of the mesh, providing the information required to adapt the building plan to accumulated material deflections. Although this sensing system is process-specific, it utilizes standard computer vision methods which are then integrated into the IF software system through generic and modular tools for calibration and optimization.

4. Vision and outlook

Given the initial discussion, attaining practical IF technology in the near future might seem infeasible. However, we think that several current streams of technological and economic developments are conspiring to fundamentally challenge this contention. In short, these powerful developments constitute the recent advent of cheap, but very high performing sensors, computation and algorithmic breakthroughs in the field of estimation, and control and data- driven robotics. We thus believe that widespread, sophisticated, and versatile IF capabilities are attainable within one to two decades if conducive socio-economic boundary conditions can be achieved.

In this light, we would like to identify some current important development trends that are critical key technologies to enable IF technology.

- Localization: A mature topic in robotics and currently on the cusp of enabling a new wave of applications, from autonomous driving to novel mapping capabilities. However, for application in the IF domain, the methods need additional flexibility and adaptation. Furthermore, the construction processes often require higher accuracy than the current state-of-the art affords.
- Functions integration and advanced mechatronic design: Current advances in mechatronics manufacturing enables increasing integration density significantly, while simultaneously allowing for more optimal and compact designs (e.g., SLS-based hydraulic actuators [1,5], gecko feet [6], robot bees [7], etc.). Usage and development of algorithmic design optimization methods lead to easily adaptable, reconfigurable novel mechanism designs converting higher-level functions integration to the mechatronics level (actuators, sensors, transmission, etc.).
- Modularity: Advanced design flows, exploiting state-of-the-art digital tools, facilitate modularity and reusability in mechatronic designs.
- Domain-specific modelling in the software domain allows building domain-specific, easy to use, and well maintainable yet highly performant, SW frameworks [2,3].
- Increasingly advanced openly available SW 'libraries', e.g., sensing [23,24,36,37] and control [3], allow the quick adaptation of state-of-the-art methods in novel robot designs.
- The robotics community is currently developing strategies to ensure safety and reliability of advanced robotics systems in complex, unstructured environments (e.g., autonomous cars and drones). As such, they can partially profit from a rich body of experience and knowledge in other fields (e.g., aircraft, energy), but complement them with new elements (e.g., statistical safety considerations for data-driven components within the control architectures). As we have identified, the advantage of the construction domain comprises the possibility to partially structure the environment and not have to deal with as strict requirements or as complex of a situation as, for example, a household robot would need to.

We believe that it will ultimately be possible to build generic machines to support in situ fabrication, which we refer to as in situ *fabricators*. Just like printers and 3D printers, their design will be generic to a large degree. However, they will come in many different forms and shapes, and with domain-specific modifications.

We have built a first version of an in situ *fabricator* for medium payloads and targeting finished building shells. In other words, the robot can be used in closed rooms, and be able to enter and exit through standard doors. However, while the current IF constitutes a first step towards autonomous IF processes and a very productive machine to obtain first insights into IF processes, its hardware possesses a few significant limitations, mostly stemming from the fact that the available COTS hardware is not designed for this application domain and not highly integrated. Novel integrated actuator design and other innovations, such as modular high-performance designs, together with state-of-the-art optimal and learning control software, will enable more suitable and flexible IF hardware [1,36,37].

Nevertheless, we are witnessing an exhilarating first wave of robotic technology and advanced measurement technology entering the building industries, in bespoke prefabrication [16–18] and other related fields [14,21], which constitutes a proving ground for many technologies that will help solve the IF challenge.

Acknowledgements

Research and development into the mesh mould metal and the in situ fabricator, and the realization on the NEST site are interdisciplinary research projects. The results are a collaborative achievement of a large group of individuals, including the following:

Marco Baur	Nitish Kumar
Jonas Buchli	Julio Lopez
Kathrin Dörfler	Manuel Lussi
Robert Flatt	Jaime Mata Falcón
Philippe Fleischmann	Michael Lyrenmann
Markus Giftthaler	Rosali Pyun
Konrad Graser	Andreas Reusser
Fabio Gramazio	Timothy Sandy
Norman Hack	Joseph Schwartz
Volker Helm	Lukas Stadelmann
Walter Kaufmann	Alexander N. Walzer
Matthias Kohler	Timothy Wangler

We would like to thank Norman Hack, Kathrin Döfler, and Michael Lyrenmann for the photos and illustrations of the IF/MMM process.

This research was supported by the Swiss National Science Foundation through the National Centre of Competence in Research (NCCR) Digital Fabrication (Agreement #51NF40 141853), a Professorship Award to Jonas Buchli (Agreement #PP00P2 138920 and PP00P2 166163), and a Research Equipment Grant.

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