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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 [A7]. 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 [A4].

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 [A5, A6].

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 [A8]. 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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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