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Strategies for Robotic In situ Fabrication

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Abstract

Since the construction industry has begun deploying robotic technologies for digital fabrication processes, this direction has mostly been focused on integrating industrial-type robots into off-site prefabrication processes. By contrast, no enabling robotic technology exists today that allows robotic systems to be integrated into in situ construction processes right on the building site. This is mainly because in comparison with robotic prefabrication, robotic in situ fabrication faces fundamental technological challenges. First, buildings are large in scale. In contrast to prefabricating sub-assemblies of a building with stationary robotic systems off-site, in situ robotic systems must be able to fabricate large-scale assemblies at their final location. Second, building sites are poorly structured. As opposed to operate within structured factory conditions, in situ robotic systems must be able to accurately fabricate large-scale assemblies—irrespective of the uncertainties prevalent on-site.

To firstly address the challenges imposed by the building scale, this thesis explores the mobile robotic fabrication of continuous and monolithic architectural-scale building components on-site. To further respond to the challenges imposed by the unstructured nature of building sites, and by the uncertainties related to the site, the fabrication, and the material, this thesis investigates the integration of robotic sensing solutions and the implementation of adaptive fabrication control techniques. For the purpose of validating the developed methods and strategies for robotic in situ fabrication, three subsequent case studies are implemented. Each of them utilises a different robotic set-up, once a stationary and twice a mobile, and applies a distinctive material system—that is, loam, bricks, and steel rebar. The research culminates in the third experiment, namely the mobile robotic fabrication of a doubly-curved steel rebar mesh for a reinforced concrete wall. This demonstration provides the unique opportunity to present robotic situ fabrication not only as a future vision, but applied in the context of a real construction project.

Zusammenfassung

Der Einsatz von Robotern für digitale Bauprozesse beschränkt sich heute fast ausschliesslich auf die Integration von Industrierobotern in der Vorfabrikation. Im Gegensatz dazu existiert heute faktisch keine roboterbasierte Technologie, die den Einsatz von Robotern direkt auf der Baustelle erlaubt. Diese ungleiche Entwicklung ist darauf zurückzuführen, dass die roboterbasierte In situ Fabrikation im Vergleich mit der robotischen Vorfabrikation fundamentale technologische Herausforderungen bewältigen muss. Eine davon ist der Gebäudemassstab. Ein grossmassstäbliches Objekt als Ganzes an Ort und Stelle zu fabrizieren ist weitaus komplexer, als Teile eines Gebäudes mit stationären Robotern in der Vorfabrikation. Eine weitere Herausforderung ist die kaum strukturierte Umgebung von Baustellen. Die roboterbasierte In situ Fabrikation muss Methoden integrieren, die es einem Roboter erlauben trotz schwach strukturierter Bedingungen ein Bauteil präzise und seinem digitalen Modell entsprechend zu fabrizieren.

In Hinblick auf diese zwei massgeblichen Herausforderungen untersucht diese Dissertation 1) die Fabrikation von monolithischen und grossmassstäblichen Bauelementen mit einem mobilen Roboter direkt auf der Baustelle, und 2) die Integration von Sensorik und die Implementierung von adaptiven Kontrollalgorithmen zur Steuerung eines Roboters. Um die entwickelten Methoden und Strategien zu validieren, werden drei Versuchsstudien durchgeführt. In diesen Studien kommen zwei unterschiedliche robotische Set-ups, ein stationäres und ein mobiles, und drei verschiedene Materialsysteme, nämlich Lehm, Ziegel und Bewehrungsstahl für Stahlbeton, zur Verwendung. Die Forschungsergebnisse kulminieren in der Realisierung eines Baudemonstrators im Rahmen der dritten Studie—nämlich der mobilen robotischen In situ Fabrikation eines doppelt gekrümmten Bewehrungskorbes für eine frei geformte Stahlbetonwand. Diese Demonstration gibt die Gelegenheit, robotische In Situ Fabrikation nicht alleine innerhalb der Forschung sondern im Rahmen eines tatsächlich realisierten Bauprojektes—dem DFAB HOUSE auf dem NEST Forschungsgebäude der Empa—zu präsentieren.

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After almost five years of research, today is the day that I can finally write this note of thanks as the finishing touch on my dissertation. This dissertation has been a journey of intense learning for me, not only in the scientific arena, but also on a personal level. I would like to thank all the people who have been on this wonderful journey with me, and who have brought me to where I am now.

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Contents

1 Introduction

1.1 Motivation

Automation has become an essential and indispensable component to a highly efficient and digital production workflow in the classical manufacturing industries. For example, in the today's automotive industry, the entire process from the design to the production of single parts and up to the final assembly is almost fully automated [1] (see Fig. 1.1). In the field of building construction, however, the level of automation is comparably low to date [2]. While significant efforts have been made to increase automation in this area since the 1980s [3], these efforts have been rendered difficult on a multitude of levels. One key reason is that the typical mechanisms known from economies of scale do not apply to the construction industry modes of production [4]. In contrast to standardised products that run down assembly lines, every building is considered a unique artefact that is embedded in a specific context at a particular site. Therefore, the process of building has to be individually adapted in each case. Moreover, due to the building's scale, such a product cannot be fully assembled off-site and in line with the manufacturing industries' production ways. The final assembly of a building has to happen *in situ*[1]—directly at its final and definite location.

Despite the latter reason, many efforts in implementing digital fabrication workflows for construction have been focused on prefabrication until this point in time. Some of these efforts—initiated within research in architecture in the last decade [5] and lately adopted by the construction industry—have included the appropriation of industrial-type robots to perform architectural-scale additive fabrication processes in dedicated off-site construction factories. That is, because construction factories for prefabrication facilitate the implementation of robotic fabrication processes on many levels—with the most important one being the ability to provide a controlled and fully structured environment. One such prominent and recent example from the construction industry is seen with the Swiss building contractor company ERNE AG Holzbau. They installed a large-scale gantry robot for the prefabrication of complex timber constructions at one of its plants in 2015 [6, 7].[2]

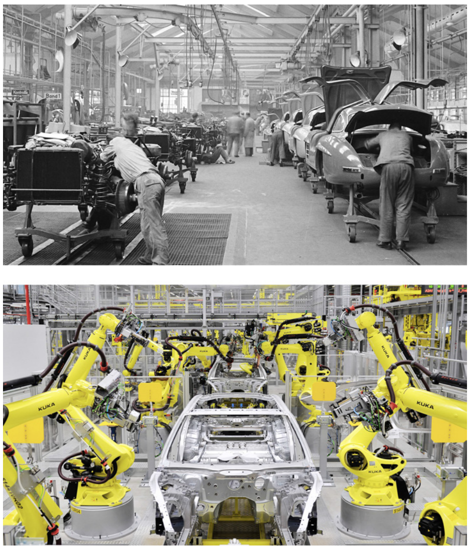

Figure 1.1: The level of automation in the automotive industries has radically increased. This can e.g. be seen by comparing the manual assembly line at the Daimler-Benz A.G. production plant in Sindelfingen, 1954 (top), with a robotic chassis fabrication at a Porsche production plant in Leipzig, 2018 (bottom).

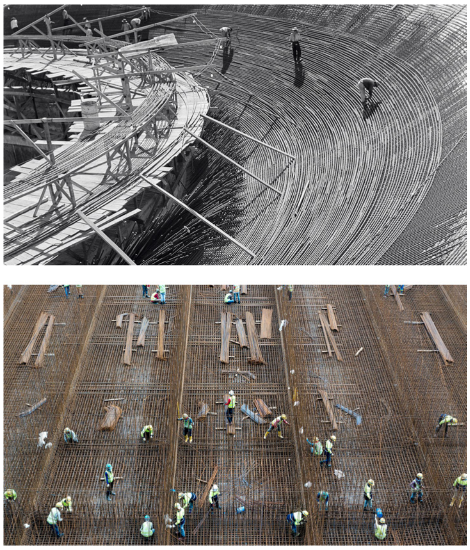

Figure 1.2: Manual assembly processes on building sites are still heavily dependent on manual labour, as seen e.g. by comparing the manual process of rebar assembly for the National Congress Palace in Brasilia in 1959 (top) with the manual caisson construction on a building site in Singapore in 2018 (bottom).

By contrast, no enabling robotic technology exists to date that allows robotic systems to be integrated into in situ construction processes. Fundamental technological challenges, many of them caused by the poorly structured conditions on building sites, have thus far hindered the automated assembly of building elements directly on construction sites. Hence, the assembly of building components at their final location on-site is still mainly dependent on manual labour, and these final and manual assembly processes on the building site are thus interrupting the continuous digital process chain[3] from design to construction [8] (see Fig. 1.2).

While prefabrication certainly provides many benefits—particular in terms of simplifying the integration of automated processes into assembly workflows—prefabrication also imposes a number of important limitations in the architectural and construction-related context. Since prefabricated building components are not produced at their final location, the question of transportation limits the overall scope of applications. It first implies that material has to be transported twice—once as feedstock material to the intermediate location of the factory, and from there in a pre-assembled state to the construction site. The extents of these prefabricated components are limited by the size and weight permitted for transportation and lifting into the final position. Furthermore, prefabricated components need to be able to sustain the forces acting on them during transportation and final assembly. In cases where these components are assemblies with a loose material compound that cannot sustain high tensile forces, transportation may not be possible, or may require temporary bracing or other types of support structures. Thus, the use of material systems such as bricks or building stones for masonry construction [9], or earth and loam for adobe construction [10, 11] depend on in situ assembly processes at their final location.[4] Moreover, the production of prefabricated building components generally refers to sub-assemblies of a building and therefore parts of a larger whole. These sub-assemblies pose the challenge of joints and interfaces in between them during their final assembly on the building site. It requires prefabricated sub-assemblies to be fabricated with a high accuracy, since adjustments that are potentially necessary, can only take place in the connections and joints between them. Furthermore, these components must be joined in such a way that the connections allow for a structurally sound structure as a whole. This question of joining again limits prefabrication to certain types of construction and material systems that allow for such joint connections; such systems may include timber module construction, lightweight steel construction, or pre-cast concrete construction. By contrast, structures that need to be monolithic and continuous in order to be structurally sound—for example structures of complex geometry, or of high dynamic and alternating loads—can therefore not or only partially be produced on a modular basis off-site; examples of such structures are monolithic reinforced concrete structures [12].

With respect to these limitations, the questions that arise are as follows: As an alternative to robotic prefabrication—is it possible to robotically construct complex building components directly in situ? Can a sufficient fabrication accuracy be achieved using robots in a poorly structured construction site environment, as opposed to using robotic systems within structured factory conditions? What consequences follow and which alternative tectonics ascend if conventional and manual construction processes are redefined and augmented[5] with the support of robots on the building site? Moreover, can robotic in situ fabrication processes eventually allow production chains to be cut short?

1.2 Problem statement

The use of robots for digital fabrication has proven to be highly effective for a variety of reasons [5]. Solely by the customisation of the end effector, robots can carry out a wide range of construction processes using different types of building materials. Their use opens up the possibility to establish a continuous digital process chain through directly integrating digital design with construction workflows. In such a robotic fabrication process, a digital model is valid both as a definition of geometry and instructions to its production routines. Hence, these robotic fabrication processes allow computer-generated non-standard designs with complex geometries to be fabricated in a highly efficient manner. Through applying the principles of mass-customisation, serialised non-standard construction can thus be achieved at no additional cost [13, 14, 15, 4]. But in addition to that, machine-related fabrication logics and material-related constraints can become design drivers in the development of an architectural project [16, 17].

While the construction industry has begun exploiting the benefits of using robots and automation in prefabrication, in situ construction robotics has not advanced at the same pace. Even though initial attempts in mobile robotic bricklaying on building sites were undertaken more than 20 years ago [18, 19], it is only now that robotic systems for in situ building construction are moving closer to commercialisation. Examples of this can be seen with companies such as Fastbrick Robotics for automated mobile bricklaying [20] or nLink for the automation of drilling on-site [21]. There are a number of fundamental technological challenges that prevent the extensive deployment and utilisation of robotic systems performing fabrication tasks directly on building sites. These challenges can be summarised into two main points:

- *Architectural scale:* Many well-established methods in robotic prefabrication rely on fabricating sub-assemblies of a building within the stationary robotic work-cells of a factory. These sub-assemblies are typically smaller than the static workspace of a stationary robotic system used, and they can thus be positioned and fabricated within it. In the case of robotic in situ fabrication, however, the spatial relation between the assembly and the robotic system is reversed. A robot has to travel or be installed so as to reach the final location of assemblies on the building site. Such assemblies can no longer be segmented into smaller parts, but they must be robotically fabricated as one continuous structure right at their final location. Therefore, these large-scale assemblies typically exceed the static workspace of a robotic system used.
- *Accuracy:* Many approved processes in robotic prefabrication rely on structured conditions such as the complete knowledge of the factory environment and the perfect control of the stationary robotic systems used. Robotic in situ fabrication processes, however, lack a perfectly structured environment and lack a complete knowledge of the building site surroundings. Moreover, mobile robots are missing a fixed

> mechanical link with their environment. Hence, in situ construction robots depend on robust sensing and control solutions to be able to fabricate large-scale assemblies according to a digital building model—despite the uncertain conditions caused by a poorly structured building site environment. Such robots must be able to localise themselves and position their end effector within a globally consistent (i.e., absolute) workspace that covers the extents of the job site. Moreover, they must be able to sense and handle disparities between as-planned and as-built dimensions of the building site, unpredictability of construction material behaviour,[6] and fabrication-related tolerances during the assembly of a building structure.

Early attempts for implementing robotic systems on building sites in the 1980s had responded to these challenges by aiming to fully structure the construction site environment (see also Chapter 2). By taking the idea of factories for mass-production as a model, these previous approaches aimed at introducing a high level of standardisation as well as rigidly planned production routines to the whole building process—including the logistics, the prefabrication of parts, and the robotic processes on-site [22, 19]. With respect to the scale of buildings, these early approaches focused on one hand at developing large-scale robotic systems by turning the construction site into a vertical or horizontal factory. In such a system, a large-scale robotic installation was made capable to move along with the evolving building progress—e.g., by moving floor-wise along the vertical axis of a high-rise building.[7] On the other hand, there had been a parallel development that concentrated on small-scale robots. Yet, these small-scale robots were specialised and single-task systems that could operate only in perfectly prepared and structured on-site conditions. In short, early robotic systems lacked robustness and precision, but above all, they were deficient in flexibility and adaptability. Hence, it was very difficult for those systems to compete with the efficiency and versatility of manual labour. These reasons may have attributed to the fact that these first generation in situ construction robots were not adopted by the construction industries and did not find an entry to the market.

As an alternative to these previous approaches, today's development of in situ construction robotics must focus on integrating versatility and adaptability—both into the robot hardware system design and its respective control logic. Instead of structuring the job site, construction site robots must be equipped with robust sensing and control solutions that support their operation in poorly structured environments and under uncertain conditions.[8] With respect to these uncertainties, the robotic control for the fabrication can not follow a purely feedforward and predetermined approach. Instead, adaptive and feedback-driven robotic control approaches at several levels are necessary for robot operations to be carried out successfully. In the particular case of uncertainties that relate to the effective dimensions of the fabricated artefact, they must be perceived by the robot and the acquired information fed back to the architect's design and planning environment. As a consequence, this feedback would then allow for informed decision making processes to be automated directly in the environment of the building planners. Thus, a maximum flexibility and agility over a fabrication process and its desired outcome could be ensured.

In short, the successful integration of robotic systems into in situ construction processes relies on integrating architectural design, robotic operation planning, and fabrication into one unified system.

1.3 Research questions

This thesis explores how to extend the digital process chain from architectural design to the final assembly on a building site. It investigates, whether the robotic in situ fabrication of geometrically differentiated structures can become an alternative to the robotic prefabrication and the manual assembly on the job site. On the basis of experimentation, this research thus firstly explores how sensing and adaptive robotic control techniques can support to overcome the challenges imposed by various uncertainties caused by the poorly structured nature of a building site, and thereby to enable the accurate construction of architectural-scale building components beyond structured factory settings. Furthermore, this research investigates how a robotic system can fabricate continuous and architectural-scale assemblies on a building site that are larger than the static workspace of the robotic system employed. Finally, this research also considers the question of how to express the process of making—by involving the contextual characteristics together with the underlying logics of the fabrication system—in the architectural design of robotic in situ assemblies.

By enabling the integration of robots into in situ construction workflows, this thesis explores whether the present application space of additive robotic fabrication can eventually be expanded to on-site applications.

1.4 Method

The above-outlined subject matters require a synthetic and multi-disciplinary approach that can develop and consequently validate robotic in situ construction methods within the field of architecture and digital fabrication.

In this scope, several fundamental challenges must be addressed:

- ***Integration of robotic sensing technologies***: The design and implementation of the physical experiments require the integration of state-of-the-art robotic sensing technologies. They must perform sensing tasks for several purposes as follows:

    Mapping: This involves the integration of appropriate robotic sensing technologies for the perception of the building site environment.

    Localisation: This concerns the integration of appropriate robotic sensing technologies for robot localisation.

Fabrication survey: This involves the integration of appropriate robotic sensing technologies for locally surveying the performed manipulation tasks.

- ***Integration of design with adaptive fabrication control***: The integration of design with adaptive control methods for robotic in situ fabrication processes require the implementation of a computational tool-set embedded in the architectural design and planning environment. The implementation concerns both the development of adaptive fabrication control algorithms and the implementation of dedicated robot control interfaces.
- ***Mobile robotic fabrication***: To develop appropriate robotic in situ construction methods using a ground-based mobile robot, the fundamental potentials and limitations of mobile robotic fabrication must be investigated .
- ***Adoption of additive fabrication processes***: Additive fabrication techniques that have previously been developed in the laboratory must be adopted so that they comply with the requirements and fabrication logics of the respective in situ application.

This research aims to expand the current limitations of additive robotic fabrication by exploring the implementation of robotic processes directly on construction sites. For this purpose, this thesis has adopted an exemplary case study methodology, conducted with an interdisciplinary research team. The individual implementation of three different case studies serves to both identify their common challenges and develop integrated design and adaptive fabrication control techniques. The associated physical experiments serve to validate the proposed strategies and adaptive fabrication control methods. Each of the individual case studies utilises a different robotic set-up—once a stationary and twice a mobile—and deals with a different in situ material system—that is, loam, bricks, and steel rebar for reinforced concrete.

1.4.1 Experiments

In the scope of exploring fundamental challenges of robotic in situ fabrication, three different experiments are conducted. Each experiment individually addresses the common challenges of 1) building site mapping and robot localisation, 2) fabrication survey, and 3) the integration of design with adaptive fabrication control. The first case study of this thesis serves to investigate these topics by using a *stationary* robotic system on-site. Both the second and third case studies serve to explore robotic in situ fabrication challenges by utilising a *mobile* robotic construction unit—namely the *In situ Fabricator* (IF) [23] (see Section 1.4.3 and Appendix A for a detailed description).

A detailed description of the experiments is provided below:

Case study 1: Stationary in situ loam aggregation. The first case study describes the additive in situ fabrication method *Remote Material Deposition* (RMD) [24], and it showcases the method through the realisation of an architectural installation. RMD allows to construct large-scale and geometrically differentiated loam wall structures with a small-scale and stationary robotic system by throwing loam projectiles to a distant location. This method allows the commonly constrained workspace of a stationary robot to be radically expanded. It also offers a fundamentally new approach of materialising architecture. The remote deposition results in unique material morphologies that are a direct expression of a dynamic and adaptive fabrication process. RMD is presented as the first case study of this thesis, specifically because it provides critical insights into integrated material- and process-informed design and fabrication approaches—at a full architectural scale.

Case study 2: Mobile in situ brickwork assembly. The second case study—*Mobile Robotic Brickwork* [25]—explores the mobile assembly of a free-form double-leaf dry brick wall by deploying the mobile construction robot IF within a mock-up construction site environment. This experiment allows the focus to be put on the development and integration of three basic functionalities of the IF. First, it includes the integration of a sensing solution that enables the mobile robot to map and perceive disparities between the ideal dimensions in the CAD model and the as-built dimensions found on-site. This feature is to show the benefits of a robot being able to adapt the CAD model of the building component so that it accurately fits the dimensions of the encompassing architecture—directly at the place of assembly. Second, it involves the integration of sensing solutions for localisation. The localisation capability allows the IF to assemble brickwork while moving along the wall; consequently, the robot assembles a wall longer than the static reach of the machine. Third, it includes the automated generation of discrete assembly sequences for the mobile fabrication of brickwork, with the number of robot relocation procedures being minimised.

Case study 3: Mobile in situ rebar assembly. The final experiment of this thesis describes the mobile in situ fabrication of a doubly-curved steel rebar mesh by using IF on an actual building site. The IF applies the novel construction system named Mesh Mould [26, 27] for realising a slender, load-bearing reinforced concrete wall, situated in the ground floor of the DFAB HOUSE[9] [28, 29]. This concluding case study allows all the know-how gained from the previous two case studies to be merged—namely the one attained in adaptive fabrication control with the one attained in mobile fabrication. Moreover, this experiment negotiates within the boundaries of a real architectural project; that is, the design intentions, the structural integrity, and the constraints of the fabrication system applied. Finally, the realisation of this case study serves to provide evidence on the efficiency of robotic in situ fabrication with respect to the integrated design-to-fabrication workflow.

1.4.2 Computational tool-set for in situ robotic fabrication

In situ robotic fabrication processes are challenged by uncertainties of different nature, such as prevalent building site tolerances, robot state estimation and robot system inaccuracies, or the unpredictability of construction material during deposition.[10] To deal with the uncertainties occurring during fabrication on a job site, this study proposes the establishment of an adaptive fabrication control system. In such a system, robotic procedures are not fully planned beforehand; they require a respective control system to generate a control action in reaction to the sensory input collected during assembly.

To create accessible interfaces for architects and designers to study complex robotic control operations, architectural design and robotic execution control need to be integrated in one system. For this purpose, a high-level computational tool-set for in situ robotic fabrication processes is implemented and integrated directly within the architectural design and planning environment.[11] This tool-set comprises a design tool for in situ robotic fabrication processes with an adaptive fabrication control system. The individual customisation of this tool enables the realisation of the respective physical experiments and demonstrators conducted throughout this thesis. This eventually serves to test and validate the robotic in situ fabrication strategies and adaptive control algorithms proposed. Thus, the underlying methods implemented within this tool-set are briefly described as a preamble to the experiments in the beginning of Chapter 3.

1.4.3 Interdisciplinary approach

The interdisciplinary approach specifically relates to the experiments conducted with the mobile construction robot IF (see Appendix A for a technical description of the robot). The development of IF at a hardware and software level is a collaboration between the groups of Gramazio Kohler Research (GKR) and the Agile and Dexterous Robotics Lab (ADRL) of Professor Jonas Buchli at the Institute of Robotics and Intelligent Systems, embedded within the NCCR Digital Fabrication. This collaboration enables the conception and development of the prototypical robotic machinery—that is, the IF—as a generic, context-aware, mobile fabrication robot for real-world construction sites. In the context of the research of this thesis, the mobile robot serves as an experimental test bed for the realisation of construction experiments. Through this interdisciplinary approach, the advancement of in situ building processes and building methodologies could be closely connected with the development of complementary robotic technologies. In the field of robotics, in situ fabrication processes are particularly challenging because they pose the hard problems of autonomous navigation and high accuracy localisation of the end-effector in the poorly structured and gradually evolving building site environment. In the architectural and construction related context however—which is the subject of this thesis—the major challenges are the development of building strategies for using a mobile robotic system on the job site, the integration of such a machinery into a high-level planning environment, and the development of respective control interfaces.

The exploratory implementations and studies using IF are conducted in close collaboration with two PhD students from ADRL, Markus Giftthaler and Timothy Sandy (see also Appendix B for project credits). Giftthaler's research focuses on controller and planner generation for arbitrary articulated robots. His work is incorporated into the IF prototype in order to enable remote-controlled as well as autonomous driving routines [30]. The research conducted by Sandy investigates sensing and control methods, which allow mobile manipulators (robots with one or more arms mounted onto a mobile base) to perform dynamic manipulation tasks accurately even in the presence of base motion, environmental disturbances, and unpredictable end-effector loading [31]. His research directly supported the realisation of the second and the third experiment of this thesis.

1.5 Structure of the thesis

This thesis is composed of four chapters and complemented by two appendices.

After this introductory chapter, Chapter 2 contextualises the research of this thesis. It contains a historic survey on the first generation of construction site robots and an outline of the differences to the approaches of today. It argues that novel approaches are enabled once by a progress in robotic technologies, but also by a conceptual shift. This is then followed by a literature review of state-of-the-art examples of in situ robotic construction systems, both from academia and industry. The chapter concludes with the relevant points extracted from the literature review that are used to draw out the areas of focus for this thesis.

Chapter 3 begins with an introduction to the computational tool-set for adaptive robotic control that was developed to realise the robotic fabrication processes on-site. Subsequently, this chapter describes the experiments that were conducted throughout this research. All case studies presented are structured to first give an overview on the robotic set-up and the material system used. This is followed by the description of the respective design tools and the illustration of the underlying in situ robotic fabrication strategies. Finally, in order to review the developed strategies, it concludes with a discussion of the experimental results and their validation. Highlighted in this chapter is Case study 3. The experiment not only combines all the know-how gained in the previous studies, but distinguishes itself from the prior experiments by describing the deployment of an in situ robotic fabrication process in the context of a real building project.

In Chapter 4 presents the overall conclusion. It begins with a summary of the results of all case studies. It then highlights the fundamental lessons learned from the exploratory work. It identifies the contributions, as well as limitations of the research and provides an outlook for future work in this field.

Appendix A gives an overview on the concept for the mobile construction robot IF and its technical components.

Appendix B summarises all project credits and acknowledgements for the realisation of the individual experiments.

Notes

[1] This means *locally*, *on-site*, or *in place*.

[2] Further examples include emerging start-ups with a general focus on developing digitally produced building products, e.g., the Danish formwork technology developer Odico [32] founded in 2012, or the Dutch production company Aectual [33] founded in 2017.

[3] The digital process chain is a continuous digital organisation process that starts with the digital design of a product and then continues through a digitally controlled fabrication process of a physical artefact with minimal or no human involvement. In the case of robotic fabrication, it is implied that planning data no longer needs to be interpreted by a human (e.g., for the assembly of parts); design datasets are interpreted by the digitally controlled machinery only, serving to steer the execution of robot tasks.

[4]The material systems that require to be assembled at their final location are therefore referred to as *in situ material systems*.

[5] The term augmentation refers to the possibility of implementing one singular robotic process among a number of manual processes in contrast to fully automating all processes of a work site.

[6] Assembly processes of physical artefacts have certain types that are characterised by the fact that the fabricated structure can deform in unexpected ways during material assembly processes. This is caused by uncertain material behaviour and can include inducements such as the expansion under heat, or the shrinking through hardening.

[7] This relates to one prominent example from the 1980s found in high-rise building construction in Japan. In this example, a one-storey robotic factory installation could move up vertically with the construction of each floor [22].

[8] Since in situ construction robots are exposed to an environment that is poorly structured and constantly changing, these robots share much of the technological challenges of field robotics in relation to robot localisation, navigation, planning, and control [34]. Field robotics deals with the automation of mobile platforms operating in harsh unstructured environments for outdoor applications, such as mining, rescue, agriculture, underwater exploration, and exploitation. These applications require advanced robotics principles in sensing, control, and reasoning to be applied.

[9] The DFAB HOUSE is a collaborative demonstrator of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication in the NEST building of Empa and Eawag [28, 29]

[10] Uncertain material behaviour contributes to material-related tolerances during fabrication. While also in prefabrication, robotic processes need to be able to cope with unpredictable material behaviour during build up, certain factors increase the probability of materially induced tolerances on the building site. Such factors can be the prevalence of dirt and temperature changes.

[11] The computational tool-set is implemented in Python within the design and planning environment Grasshopper/Rhino [35].

2 Context

This objective of this chapter is to contextualise the research of this thesis—both historically and in the context of state-of-the-art examples, and it concludes by introducing the areas of focus of this research.

Firstly, Section 2.1 outlines the differences between the first-generation construction site robotics, starting in the 1980s, and the approaches of today. It argues that previous attempts of implementing robotic machinery on construction sites had conceptually been moulded by the principles of the mechanic age (see Section 2.1). Following the trend of standardisation and specialisation, their aim had been to structure the building site environment and fully specify the building process. Yet, these early attempts had not been able to establish themselves and gain traction. As an alternative to the automation logics rooting in the 20$^{\text{th}}$ century industrialisation, the recent rise of the reprogrammable robot in architecture and digital fabrication has caused a disruptive change. The use of robots has allowed architects to explore the principles of the non-standard to be applied to the serial modes of production—at the full architectural scale. Meanwhile—enabled by faster, smarter, and more affordable sensor and actuation technologies—the latest developed robotic systems no longer depend on fully structured conditions. In combination with advances in dynamic control, these robots can cope with unstructured surroundings and uncertainties in their environment. In short, the section discusses that these various advancements and their integration with each other should enable an entirely different approach of implementing robots on construction sites today.

Next, Section 2.2 reviews state-of-the-art examples of robotic systems for in situ robotic construction—both from academia and the construction industry. This section compares the different approaches by categorising them into stationary and mobile robotic systems.

In closing, Section 2.3 discusses that the broad landscape of recent examples does not reveal a one-size-fits-all solution on how to successfully integrate robots into in situ construction processes. Thus, the conclusion of this section serves to render the current limitations and the common fundamental technological challenges of robotic in situ fabrication. The section then closes by introducing the areas of focus of this research.

2.1 From the structured towards the unstructured

2.1.1 Principles of mechanisation in early construction robotics

The early developments of in situ construction automation had been initiated by large contracting companies with the goal to increase the sector's efficiency and productivity. These first approaches had evolved out of the motivation to recreate a prefabrication factory's well-structured environment directly on the building site. It had been assumed that highly structured surroundings and strictly planned production routines could provide the necessary means for robotic systems to be implemented within [36, 37].

2.1.1.1 Mechanised in situ construction factories

Examples of these successfully integrated construction automation systems had been the Obayashi Corporation's Automated Building Construction System (ABCS) [38, 39, 40] (see Fig. 2.1) and the Big-Canopy [22] system, or the Shimizu Corporation's Manufacturing System by Advanced Robotics Technology (SMART) [41]—developed from on the 1980s for the robotic construction of high-rise buildings in Japan. These vertically moving in situ construction factories provided a fully enclosed, well-defined, and systematised working envelope. Automated overhead crane systems integrated in a massive scaffolding structure were used for the in situ assembly of structural members and prefabricated sub-assemblies. These components were lifted up automatically from the unloading area in the ground floor. For the organisation, a central information management system allowed for the whole process to be monitored and coordinated.

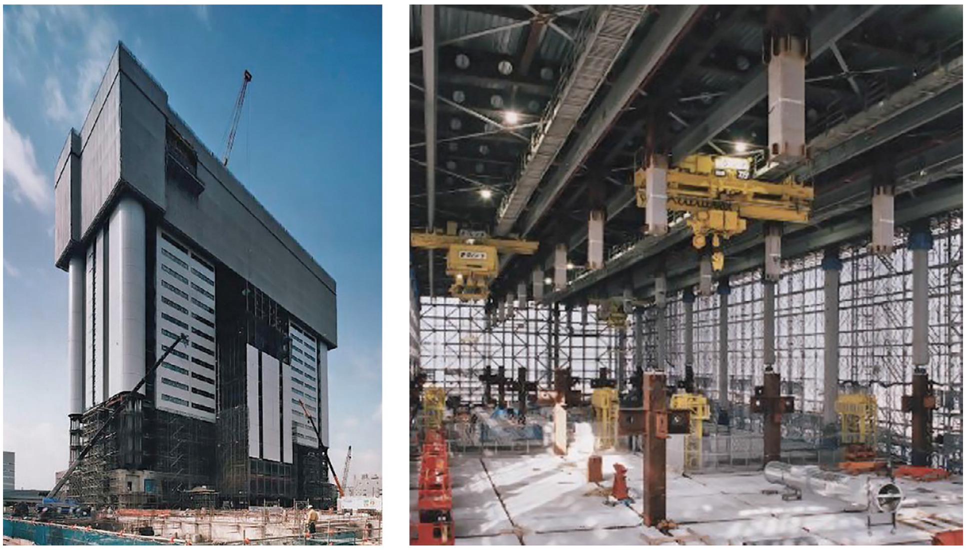

Figure 2.1: The Automated Building Construction System *(ABCS)—developed by the Obayashi Corporation in the 1990s—is on prominent example for mechanised in situ construction systems. The two images show the construction of the 28-storey NEC building in Tamagawa Renaissance City, completed in 2000 [38, 39]; the left image shows a view from outside onto the ABCS, the right image shows a view from the inside—the large-scale robotic system can rather be categorised as a factory than a construction site.*

Remarkably, these early projects had already envisioned not only the robotic machinery on the building site, but they had rather foreseen a complete integrated system from planning to construction to facilitate their workflow. This integrated information management system was referred to as the Computer-Integrated Construction (CIC) concept. The CIC—as an approach to assist contractors in introducing digital technologies—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) [41, 1, 42].

2.1.1.2 Semi-mobile robots for in situ block assembly

As an alternative to stationary robotic systems, the EU Robot Assembly System for Computer Integrated Construction (ROCCO) [42] and the Bricklaying Robot for Use on the Construction Site (BRONCO) [19] were among the earliest projects that had developed semi-mobile and autonomous robotic technologies for construction sites (see Fig. 2.2). In accordance with the CIC concept, these large-range robotic systems were intended for the automation of block assembly with respect to a building plan. The respective experimental assembly robot prototypes were hydraulically actuated systems, for reasons of a high power-to-weight ratio[12]; such as seen with ROCCO that had a payload limit of 350 kg.

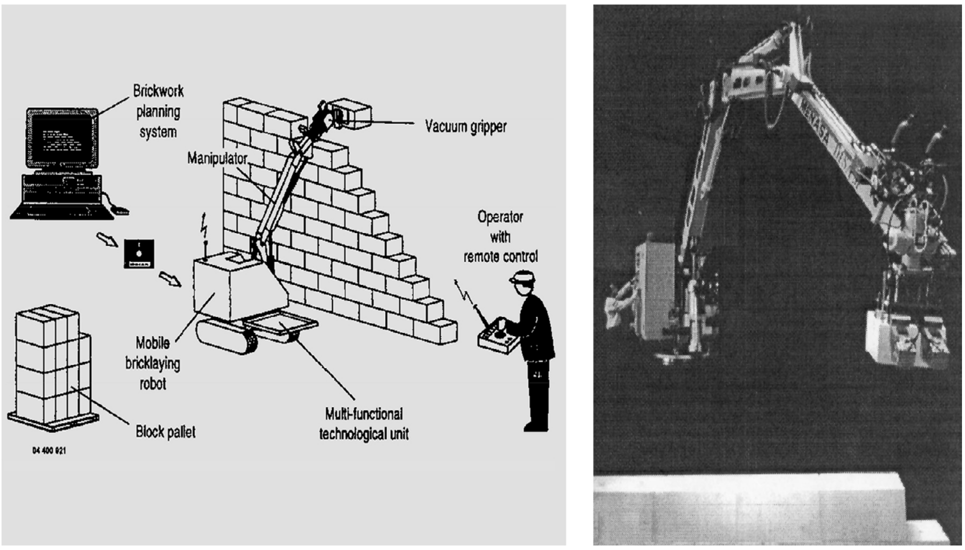

Figure 2.2: The in 1996 developed automated block assembly systems for on-site construction: ROCCO [19] (left) shows a scenario of a man-machine-system for automated bricklaying on the job site. The semi-mobile bricklaying robot BRONCO [42] (right) has a working range of 8.5 m.

Due to the low precision of the hydraulic actuators, however, the robotic control needed to be supported by an external laser tracking system. While the tracking enabled the robot to eventually achieve a end effector positioning accuracy of approximately ± 20 mm, an additional passive compliance device mounted on the custom pneumatic gripper was necessary. This device allowed for a self-alignment of the assembled blocks in support of the process.

Overall, the cycle time for the pick and place routine of one block added up to be around 30 s in total—including the laser tracking cycle time of 8 s to 10 s)—that is, the process was very slow.

2.1.1.3 Specialisation proves ineffective

Many initial attempts of integrating robotics into the building industry in the 1980s and 1990s had led to either expensive factory-like construction sites with limited flexibility [37], to highly specialised robots, or to heavy-duty and thus slow robotic machinery. For example, the weight of such a large-scale factory-like robotic installation, including the robots and cranes, amounted to approximately 2000 t. It turned out to be too expensive or even impossible to customise these robotic construction systems for a variety of building typologies, different from those demonstrated high-rise buildings. Moreover, it had apparently also proven difficult to customise highly specialised robotic systems to carry out different building tasks. The emphasis of these early systems on rationalisation and standardisation—characteristics which are inherent to the traditional schemes of mass production—had created a too rigid system for the architectural purpose. The combination of these reasons may have contributed to the lack of impact and the wider adoption of these early robotic systems by the industries.

2.1.2 The reprogrammable machine in architecture and digital fabrication

2.1.2.1 Economising the bespoke

The fragmentation of the architectural practice between the act of design and the production of buildings had been well anchored in the industrialisations' principles of specialisation and segmentation [43]. While architects had become used to design a building as a finished product, their thinking had become detached from the ones of the builders and contractors. Builders, on the contrary, had always understood a building as a sequence of actions, for example, as a sequence of building the foundation, walls, slabs, and roof [44]. The progress of digital fabrication at the turn of the 21st century, and in particular additive robotic fabrication from on its beginnings in architectural research in 2005, has marked a complete paradigm shift in that regard. The utilisation of the generic and reprogrammable machine has opened up the possibility for architects to engage in a transformation of the architectural representation. Primarily, this has allowed architects to represent a geometric shape as much as the means of its production [43]. Thus, digital fabrication and the use of robots have enabled the design knowledge flow to be explicit, and a novel convergence of design computation and the fabrication process of a physical artefact [5]. Additionally, it has allowed architects to create and fabricate in a design space with infinite variations. On the brink of linking back to pre-industrial modes of production, the process of making in architecture could once again be explored beyond the corset of standardisation—yet moreover, in economising the bespoke [4].

2.1.2.2 Reciprocal information flow between the digital and the material domain

Triggered and facilitated by digital tools and robotic fabrication, architects have rediscovered their interest with modes of production. Associated therewith comes a strong focus on the material and its behavioural and performance-related domains.[13] Yet, in comparison with the digital domain, material processes are inherently messy. During a robotic manipulation procedure, material behaviour can be uncertain and hard to anticipate [24, 45, 46].

In many cases, this uncertainty proves a purely model based approach to fabrication—unless it is probabilistic—ineffective [47, 48]. However, a robotic system is not restricted to let the information flow only in one direction, that is, from the computational model to the material domain. With the use of sensors, information can also flow vice versa [49, 50, 51], culminating in a reciprocal exchange of information. In a feedback-driven fabrication process, sensing data is collected during the on-going fabrication process and utilised to inform a robotic control. This approach enables robotic procedures to be adapted to the material behaviour in accordance with a desired output as the fabrication proceeds. In this way, a *material-aware* fabrication process can be established. Rather than specifying a formation process of a physical artefact in every detail from the top-down, adaptive strategies allow for the mediation between the intention of a design objective and the uncertainty of the material domain [49, 52]. In so doing, the robotic fabrication process becomes malleable to material stimuli and—next to solely understanding it as a way to achieve accuracy—it also allows to unleash the generative character of an integrated design and fabrication process [53, 54, 55, 56].

2.1.2.3 Robotic fabrication in uncertain environments

In the context of robotic in situ fabrication, the robotic processes are challenged by a variety of external influences and uncertainties in their immediate environment. The cause of such uncertainties are manifold. For example, in comparison with their digital blueprint, building site environments often exhibit deviations and dimensional tolerances. Such a discrepancy may occur if the digital model of a building site does not capture a very accurate and detailed depiction of the actual as-built conditions, e.g., because an entity was not constructed exactly as the planning foresaw [57]. The exposure of building sites to the outer climate may also cause the occurrence of deflections in constituent building elements, and hence, cause deviations to their digital blueprint—solely through the expansion or retraction of material caused by temperature changes prevalent in unprotected environments. Besides, building sites are not static, but evolve over time and constantly change with the ongoing progress of construction.

The potential of unpredictability of the physical domain interferes with the predetermination of a digital building plan. However, in the end it is precisely this dilemma that drives the architectural research in this domain. In the context of robotic in situ fabrication, robotic sensing technologies must allow these robots to perform fabrication processes that are both material-aware and additionally aware of the *site*. This means that robots must be able to perceive their immediate environment to support the fabrication process with all the necessary information—right at the place being.

2.2 State-of-the-art robotic systems for in situ fabrication in architecture

This section introduces the recent generation of robots for construction sites. The presented robotic systems comprise additive robotic fabrication processes with robotic machinery that can perform the fabrication tasks directly on the building site. They are described and their approaches compared with respect to two major challenges of robotic in situ fabrication: First, to the challenge of architectural scale—how to robotically fabricate large-scale building components directly on the job site, and second, to the challenge of accuracy—how to guarantee the accurate fabrication of these components with respect to their digital blueprint.

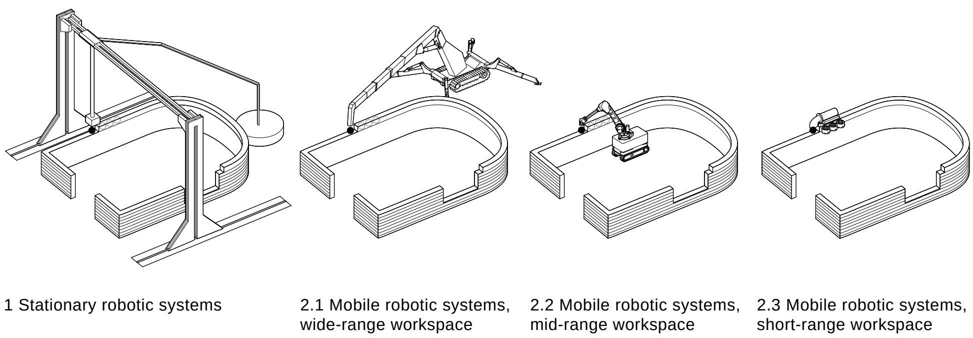

Figure 2.3: Taxonomy of robotic systems, categorised into 1) stationary robotic systems, and 2) mobile robotic systems.

The main categorisation of this section relates to the challenge of scale. Hence, two main categories of robotic systems are distinguished, namely 1) stationary robotic systems, and 2) mobile robotic systems (see also categorisations published in [58, 59, 60]); this division is irrespective of the robotic system's customisation for tasks-specific operations, or the material system used (see Fig. 2.3).

The challenge of accuracy in robotic in situ building construction directly correlates with the type of robotic system used. The fabrication of a building component in relation to a CAD model typically requires absolute positioning of the robot's end effector in one global workspace. This allows for the material to be deposited at an absolute location, and thus, the fabricated component to be consistent with the CAD model. This review aims to show that different methods exist on how to address the challenge of absolute positioning—depending on the type of the robotic system used.

It is important to consider in this context that accuracy requirements in fabrication may vary, for example in relation to a respective robotic building task, or to permitted tolerances in construction; the latter are subject to respective standards, depending on the size and measurement distance of a building element, or depending on if the element is part of a shell construction or an exposed finishing element.[14] Moreover, a particular material system used may have a direct impact on the precision requirements for the robotic actuation. For example, material that is compliant and can adapt itself to the underground has different accuracy requirements during deposition than the assembly process of rigid building components. Depending on the design objective, relative positioning with respect to the location of the fabricated artefact as opposed to absolute positioning may sometimes also be sufficient for the execution of a robot task. Hence, these different methods are therefore illustrated using the examples throughout the following review.

2.2.1 Stationary robotic systems

Stationary robotic systems are usually comprised of a gantry system. A gantry system has the advantage that fixed mechanical links exist throughout the system. This allows for absolute positioning of the end effector within the work space and simple operation in terms of control. Even if such a gantry system lacks a certain stiffness, in most cases the mechanical links still allow for a model-based and analytical approach in calibrating the system towards accuracy.

Figure 2.4: The Building on Demand (BOD) demonstrator object of the company Printhuset in 2017 is fabricated by utilising a large-scale gantry system set up on the building site performing a concrete extrusion process [61].

In recent years, the additive fabrication technology Contour Crafting has been adopted by a number of firms and integrated into stationary robotic set-ups for in situ construction purposes. Originally invented by Khoshnevis et al. at the University of Southern California in 2004 [62], the layer-based material extrusion process can be used to construct large-scale structures such as houses, using clay or concrete. The system promises a waste-free, cheap, and fast automated construction method for non-standard wall structures. It declares the simple integration of openings or utility conduits such as plumbing in the extruded structure—all without the need for additional human intervention—and thus for maximum architectural flexibility in planning and execution.

The first example of such a layer-based concrete extrusion process being integrated into a stationary robotic system for in situ construction has been shown in 2017 by Printhuset [61] (see Fig. 2.4). Their demonstrator object Building On Demand (BOD) shows the fabrication of the bare structure for a $50\,\mathrm{m}^2$ office hotel. The building is fabricated in layers by extruding concrete through a nozzle. This nozzle is carried by a large-scale gantry system with a work space of $8\,\mathrm{m} \times 8\,\mathrm{m} \times 6\,\mathrm{m}$, set up on the building site. The printing speed is 2.5 m/min, the layer width is approximately 50 mm to 70 mm, and the layer height is approximately 20 mm. The extruded structure is double-leaf and hollow, and can thus be filled with other types of material at a later stage, such as for the purpose of improving insulation or structural performance.

The project ApisCor [63] utilises the same type of additive fabrication method. However, in this example, the nozzle is mounted onto a 6.5 m long arm of a stationary robotic system, installed in the center of the building to be fabricated (see Fig. 2.4). In their first demonstrator shown in 2017, the company realised the bare construction for a small-scale living unit processing fibre concrete. In comparison with using a gantry system as shown before in the BOD, this robot only rests on one central pillar. Thus, it needs less effort in being set up on the job site.

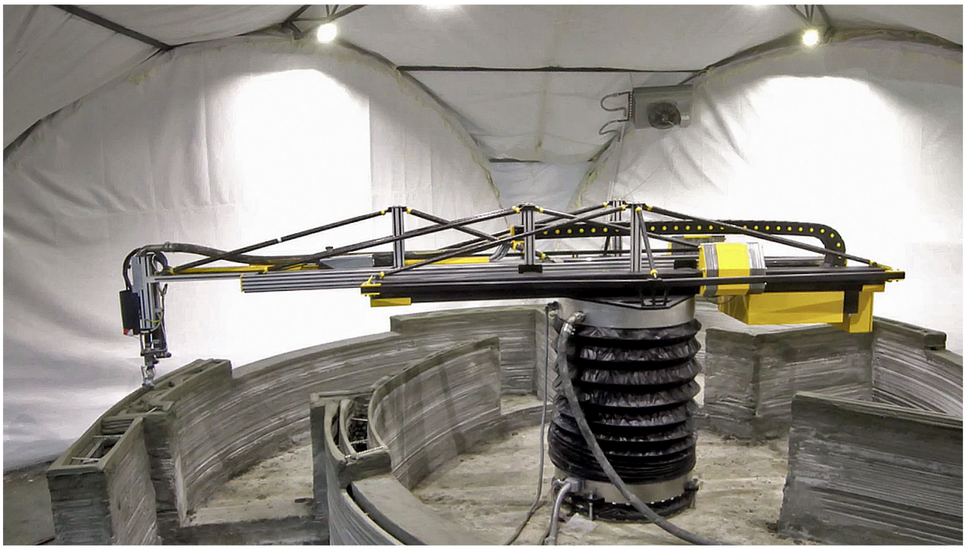

Figure 2.5: The company ApisCor developed a stationary rotational robotic system for constructing buildings using concrete extrusion in 2017 [63].

A third approach for robotic in situ material extrusion is shown by the WASP BigDelta clay extrusion robot [64] (see Fig. 2.6). An outdoor demonstration of the robot in 2016 shows the wall construction of a small building. A delta robot with the dimensions of 6 m in diameter and 12 m in height is set up on a field in open air. The stationary robot is used for the layer-based extrusion of a soil and straw material mix. With a layer height of around 20 mm and including the waiting period necessary for the drying time of the material, the system allows for a building speed of around 600 mm/d.

Figure 2.6: A large scale delta robot—the WASP BigDelta—is set up on a field during summer 2016 for fabricating the bare walls of a conical-shaped loam building [64].

These three examples—Printhuset, ApisCor, and the WASP BigDelta—showed the in situ production of mono-material structures using a stationary robotic system. The fabricated structures are a direct translation of a given digital model that had been designed within the range of the material system's constraints. However, these large-scale stationary robotic systems are characterised by the fact that their static workspace needs to be bigger than the structures being fabricated—just like the workspace of any small-scale 3D printer too. Hence, the size of the robotic system eventually constrains the size of the workpiece. Furthermore, these robotic systems are seen to provide only limited degrees of freedom (i.e., three). This is suitable for horizontal layer-based extrusion processes, however, hardly sufficient to make the robotic systems apt for more complex robot manipulation tasks, such as positioning material spatially. Aside to these limitations, setting up large-scale stationary robotic systems on the job site generally requires extensive manual effort [62, 65, 66].

2.2.2 Mobile robotic systems

In comparison to the limited workspace of stationary robotic systems, mobile robots can fabricate structures bigger than their own static workspace. Their mobility can be categorised as ground-based or aerial. Since aerial robots provide mobility in all three dimensions, as their mobility is not bound to the ground, their features have already been studied for construction purposes, for example in Mirjan et al. [67]. Yet, they are limited first by low payload capabilities and limited degrees of freedom, limited robustness in view of environmental influences (such as wind or rain), and further by a high energy consumption, to make these systems convenient for construction robotics in general. Ground-based mobile robots, on the other hand, can meet both the requirements of dexterity and agility as well as the high payload demands for performing construction tasks. They can travel on the job site, and in some cases even on the structures they are fabricating. In contrast to stationary systems, they also do not require extensive efforts for setting them up on-site.

However, unlike stationary robotic systems that have fixed mechanical links throughout their set-up, mobile robotic systems lack a mechanical referential point. Therefore, mobile robots depend on advanced sensing and control solutions to achieve global positioning accuracy [58, 68]. One possibility is to use externally located and stationary tracking system (such as for example the laser-based Leica Tracker [69]). Such trackers can locate the robot end effector within their range of visibility. Another possibility is to use sensing solutions on-board of the robot. On-board sensing solutions can be laser- or vision-based, and can perceive and register features in the robot's surroundings.They allow the robot to obtain its own location relative to the registered features.

2.2.2.1 Wide-range semi-mobile robotic systems

Wide-range semi-mobile robotic systems consist of an extended manipulator and a mobile base. The mobile base allows these robots to drive to the building site. However, due to their wide-range static workspace that can cover the size of a building, they are eventually used as stationary and fixed-base robots.

Hadrian 105 and its successor Hadrian X are developed since 2015 by the company Fastbrick Robotics [20] (see Fig. 2.7). The robot promises to provide a fully automated brick deposition system for fabricating structurally sound walls. These brick walls can be produced flexibly in the plan layout. The robot features a 30 m boom mounted on a truck. It includes a feeding system at the very end, said to be capable of placing bricks at a rate of 1000 bricks per hour. For tracking the end effector location within the workspace to compensate for the boom compliance, the robotic system utilises an externally mounted laser-based referencing systems. However, no statement is made about the type, speed, and accuracy of the system. Moreover, the system has not been shown being relocated during construction.

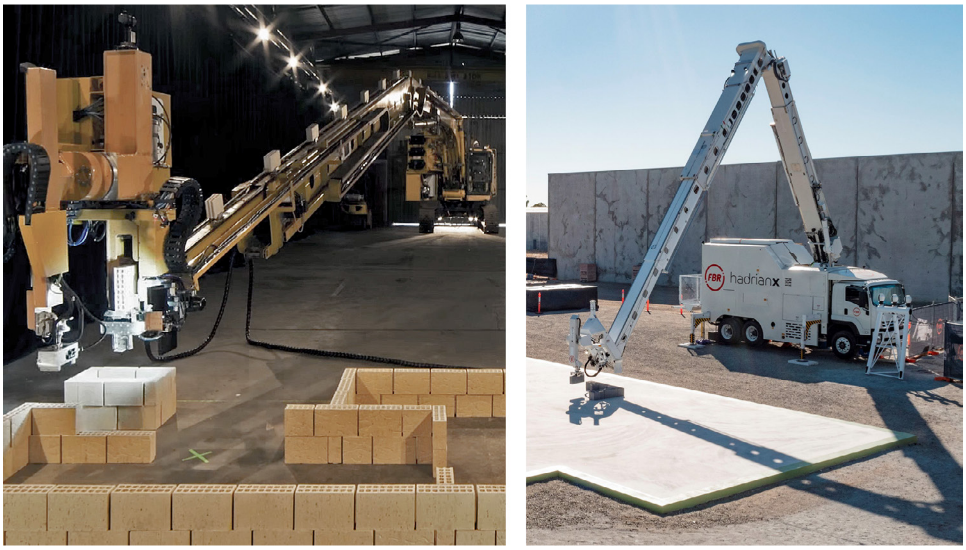

Figure 2.7: The in 2016 presented Hadrian 105 prototype (left) and the in 2018 presented successor version of it—the Hadrian X (right) by Fastbrick Robotics [20]: a one-armed robot for the construction of structurally sound brick walls on site.

The Digital Construction Platform (DCP) [70, 60], developed at the MIT Media Lab, shows a similar approach. The large-range robotic machinery comprises a 6 m long hydraulic boom with an industrial-type arm attached at its end. This compound robotic arm system is mounted onto a track-based mobile platform. The boom is utilised for gross positioning, while the robotic arm is utilised for the fine positioning. The motion control for the arm is guided by an external laser tracking system, similar to the one discussed above. This allows the robot arm to compensate for occurring oscillations during actuation. A scoop mounted at the end of the hydraulic arm illustrates the possibility of using excavated material from the building site.[15] Furthermore, solar panels mounted on the rear side illustrate the aim to achieve energy autonomy. This autonomy would enable mobile robotic systems to operate in environments without access to electric energy, such as unexploited terrestrial or extraterrestrial spaces. One demonstrator in 2017 showcased the fabrication of an insulating stay-in-place formwork for an open dome structure with a diameter of 14.6 m (see Fig. 2.8). To produce this structure, a foam extrusion process was applied. However, the case study demonstrated the system also as a fixed-base robot—positioned once in the center of the work site and fabricating the structure within the static reach of the boom.

Figure 2.8: The DCP (Digital Construction Platform) [70, 60] is equipped with a dual robotic arm system on a tracked base, solar panels and a scoop (left). In 2017, the system fabricated a stay-in-place formwork for an open dome-like structure with a 14.6 m diameter (right).

2.2.2.2 Mid-range mobile robotic systems

Mid-range mobile robotic systems are characterised by using a arm-based manipulator mounted onto a mobile base. They are utilised for fabricating structures exceeding their own static workspace through relocation.

One pioneering representative of such an arm-based mobile robot was seen with the Gramazio Kohler Research group in 2012, named DimRob [8] (see Fig. 2.9). The system was developed to explore robotic brick assembly processes that were previously developed for prefabrication directly on-site.

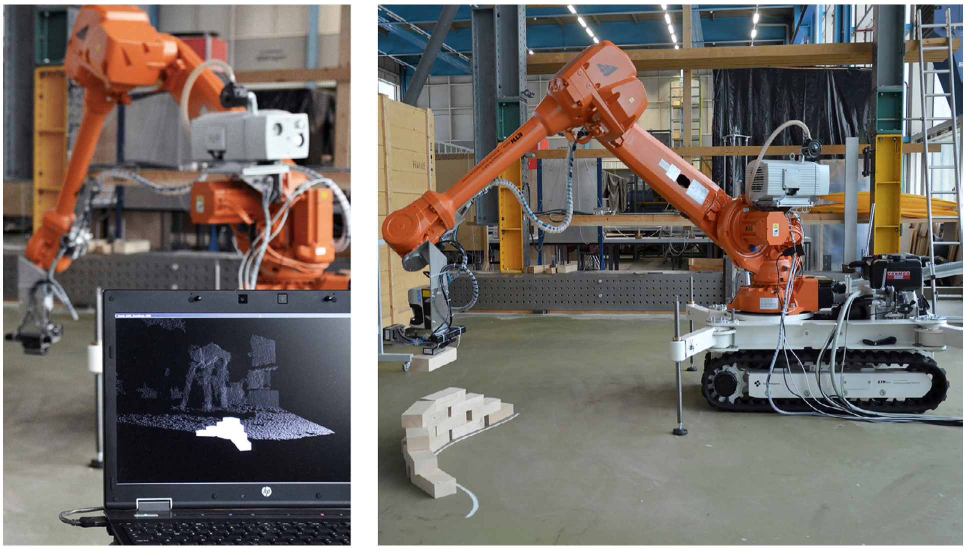

Figure 2.9: DimRob, the first mobile construction robot prototype of Gramazio Kohler Research was presented in 2012 [8]. The robot can assemble a brick wall that is generated on the basis of a Kinect-tracked visual instruction by a human operator.

DimRob comprised an industrial robot arm with a tracked mobile base. The base was powered by a Diesel engine and could be steered manually. The end effector was equipped with a vacuum gripper for pick-and-place tasks, and was additionally outfitted with sensors such as a laser range finder or a Kinect camera. This allowed the system to sense and react to material tolerances during a brick assembly process. Instead of relying on external tracking devices, the project also laid out the concept for localising the robot with on-board sensors scanning its environment. This capability was presented in a case study through scanning specially prepared discs on the ground with a

Kinect camera. The registered location of two discs served to estimate the robot pose relative to them. Moreover, the project explored the opportunities of integrating human cognitive skills with machine skills in relation to precision and endurance [8]. This feature was shown in a case study, in which the geometry of a brick wall was generated in response to visual instructions by a human operator. DimRob then assembled the brick wall according to the shape of the tracked movement (see also Fig. 2.9).

The most resembling project of DimRob aiming to reach a commercial stage can be been seen with the company CyBe Construction. They have been developing a mobile robotic system for in situ concrete extrusion since 2013 [71]. The CyBe RC 3Dp consists of a tracked mobile base that can lift its undercarriage to reach a working range of up to 4.5 m in height. The integrated concrete extrusion system allows for an average printing speed of 200 mm per second, with a layer height of around 20 mm. They showcased a first application using the mobile robot in 2017 by fabricating a drone laboratory in Dubai, and a second one in 2018 by producing the walls for a house of 100 m^2 at the Milan Design Week 2018. However, no information is published by the company that gives details about the robotic system's precision, automated robot localisation methods or the overall building accuracy.

Figure 2.10: The mobile construction robot CyBe RC 3Dp fabricating a drone laboratory by applying a concrete extrusion process on a job site in Dubai in 2017 [71].

Another approach to achieve mobility is seen with the mid-range mobile robot SAM100 (short for Semi-Automated Mason) [72], which has been developed by the company Construction Robotics since 2015. SAM100 is a semi-automated system for the construction of of straight extruded brick façades. This robot uses existing scaffolding systems generally found around the construction site as a rail system to move along. With this system, the company claims to surpass manually performed brick-laying processes in costs and speed.

Figure 2.11: SAM100 [72], the in 2015 presented semi-automated system for the in situ construction of standard brick façades.

SAM100 consists of an industrial-type arm that is mounted onto a wheeled base. The system can be lifted onto the existing scaffolding and then move along it over the full length of the wall (see Fig. 2.11). Before construction, one operator has to measure in and calibrate the system's workspace according to the required data needed by the control software. This is done by the use of an externally mounted linear laser tracking system. These a priori measurements allow for example the coursing value in between the block elements to be adjusted over the length of the wall. The precise assembly of the brick elements along a straight line is enabled by utilising the same linear laser tracking system. Enabled by the external tracking, the robot can compensate for the imprecise location of its mobile base. One operator must support the assembly process by feeding the conveyor belt, filling the bucket of the mortar pump, and relocating the robot. Although a number of projects have been realised in recent years, the developed technology is still limited to buildings with straight façade geometries. This limited geometric freedom for fabrication can also be attributed to the constrained robot mobility tied to the scaffolding structure.

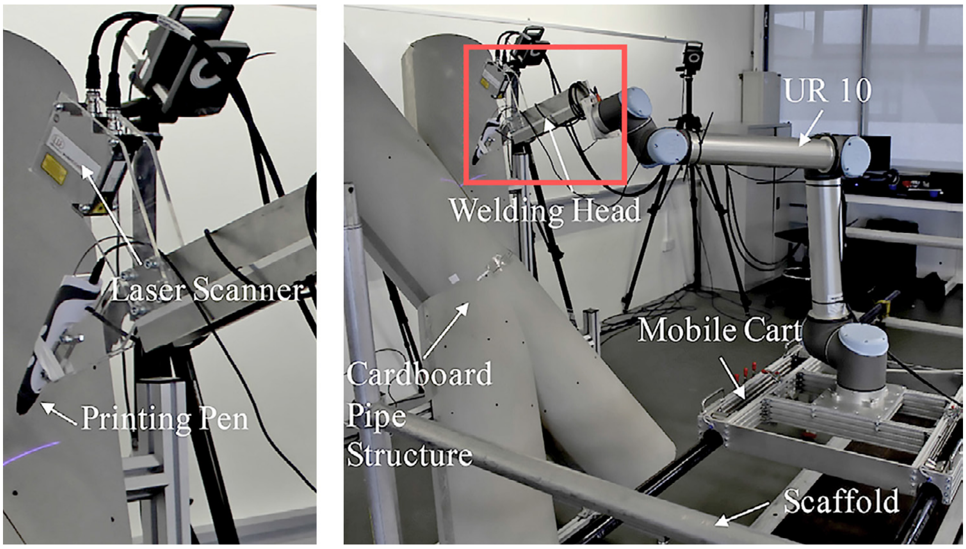

Figure 2.12: Lab set-up of a portable in situ robotic welding system [73, 59, 74] that consists of a robot arm mounted on scaffold transoms and a dummy welding end effector equipped with a 2D laser scanner. The system was tested in 2017 on a 1:1 scale mock-up of a jack-up oil rig pipe structure.

Dharmawan et al. [73, 59, 74] have presented a similar concept. The robot also utilises the building site scaffolding to act as a rail system for the robot's mobile platform. The portable mobile platform includes an installation mechanism to be mounted to the transoms and can carry a lightweight industrial robot arm. This allows the robot to reach the elevated heights of a construction site. The system is demonstrated simulating the in situ welding of jack-up oil rig structural components (see Fig. 2.12). Since one welding task is limited to a defined local area, the robotic system solely depends on relative positioning in respect to the tracked pipe welding seam. Therefore, the project focuses firstly on refining the positioning accuracy of the robot end effector in relation to the supporting rails (scaffold transoms). By defining the transoms as the mechanical link to the robot's base, the authors developed an analytical model to estimate the deformation of the scaffold transoms due to the robot weight, and thus, to compensate for the compliant behaviour of the rail system. Secondly, the project focuses on localising the pipes and tracking the weld seam with a laser scanning system mounted on the robot end effector [74].

2.2.2.3 Short-range mobile robotic systems

This category describes mobile robotic fabrication systems radically small in scale. While these short-range robots are limited by their low payload capability, they can autonomously climb a structure as it is being fabricated. By leveraging the potential to move with the expansion of the fabricated structure, these robots can reach elevated heights without the need for an extra scaffolding aside.

Figure 2.13: Harvard's TERMES swarm robots project, presented in 2014 [75]: Independent autonomous robots with purely on-board sensing work collectively on predefined structures utilising emergent behaviour.

One famous example of such small-scale and short-range mobile fabrication robots is the Harvard's TERMES [75] project, presented in 2014 (see Fig. 2.13). The project shows distributed and decentralised networks of small robotic machineries. They act as agents and can assemble a desired structure structure in a cooperative manner by utilising the emergent behaviour of a distributed system.[16] As opposed to using a global blueprint for controlling the robotic agents for fabrication, the authors proposed a bottom-up method for the on-board robotic control—referred to as stigmergy.[17] The proposed system automatically generates low-level rules for independent agents that guarantee the production of a globally desired structure. This approach allows the small climbing robots to use only local sensing and coordinate their activity via the shared environment.

However, discrete assembly processes (i.e., pick and place routines) are not the most suitable option for the exploitation of small-scale mobile robots for construction purposes. Payload limitations massively effect their applicability. Instead, they can be utilised for other types of fabrication processes in which the scale of the machine can be used more effectively and payload limitations can be bypassed.

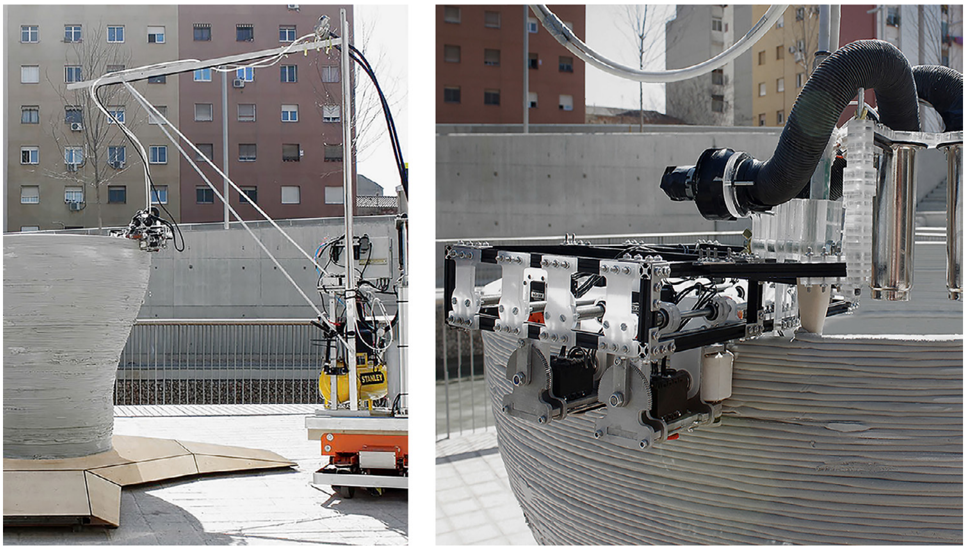

Figure 2.14: The Minibuilders project [76] in 2015 shows compact mobile robotic units with a clay extrusion nozzle. These mobile robotic devices can fabricate a 3-dimensional structure independent of their own size. The image shows the gripping robot, which attaches to the structure by clamping it in between 4 rollers, and climbs the structure while fabricating it.

For example, the Minibuilders project [76]—developed at the IAAC Barcelona in 2015—shows the utilisation of small-scale mobile robots for a continuous clay extrusion process. A structure is fabricated through depositing clay material through a nozzle that is carried by a small mobile robot. Moreover, such a robot is climbing the structure while actually fabricating it. This allows it to build structures substantially larger than itself. First, a mobile foundation robot is depositing the ground layers of the clay material by tracking and following a curve previously marked on the ground. After this, a gripping robot is attached to the fabricated foundation layers and continues the material deposition process while climbing the structure. Through positioning the nozzle of the mobile robot sideways relative to the layers underneath, the system also allows to produce slightly doubly-curved geometries.

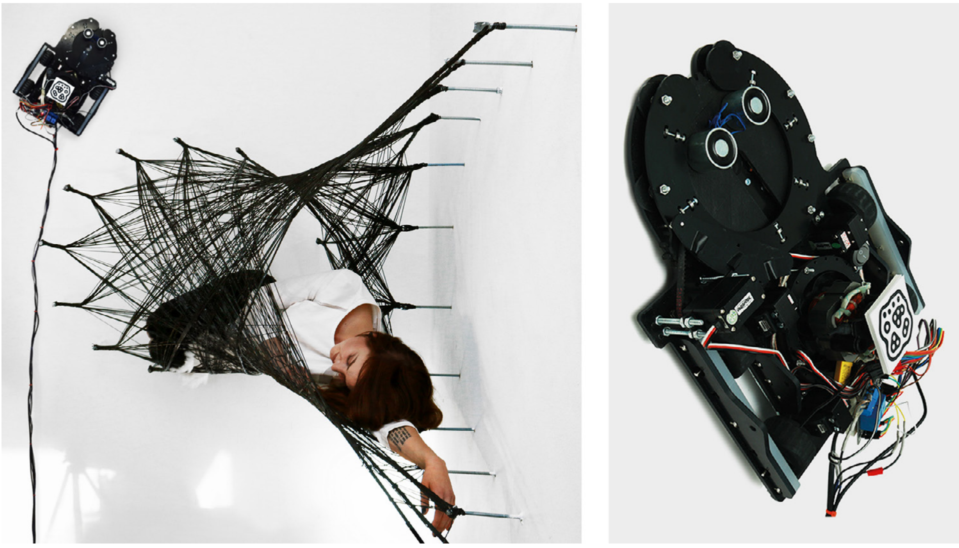

Figure 2.15: Mobile robotic fabrication system for filament structures presented in 2016 [77]: Two wall climbing filament winding robots are fabricating a structure in between two walls meeting in a corner through winding filaments around metal pins.

Finally, the project Mobile Robotic Fabrication System for Filament Structures [77]—developed at the ICD Stuttgart—shows a mobile application for winding filament into a spatial structure. The winding is performed by two small-scale robots that can climb on walls with a flat surface (see Fig. 2.15). Despite the limited payload capabilities of these small-scale robots, the low weight of the filament coil together with the winding technique allows them to fabricate structures in an architecturally relevant scale.[18] As opposed to the prior shown relative positioning system of the Minibuilders, here, the robots are positioned with the support of an external camera system by tracking fiducial markers mounted on them.

2.3 Conclusion

2.3.1 Summary and conclusion

The reviewed examples demonstrate that robotic in situ fabrication exhibits great potential to extend the field of application for digital fabrication. It can fundamentally change construction site workflows and production chains as we know them today. Although the analysed robotic systems are still in an early experimental state, the in situ approach shows many advantages in comparison to prefabrication. Since the fabrication takes place at the location where the structure remains, there is no need for a factory elsewhere. Transportation expenditures of building material can be reduced, primarily because feedstock material can be transported from the producer directly to the building site, without having to be brought to an interim destination for prefabrication. Also, feedstock material may be packed more densely than if being pre-assembled to a voluminous building component. Finally, in situ material systems that cannot be used in prefabrication and that to date depend exclusively on manual labour derive particular benefits from the possibility of automating building process using such material systems directly on site.

In the context of construction, robotic systems are required which payload capacities, reach, and flexibility fit the requirements of manipulation and assembly tasks at an architectural scale. Thus, mid-range mobile robotic systems using an industrial-type robot arm and a tracked mobile base have some clear advantages over large-scale stationary or semi-mobile wide-range robotic machinery. They outperform them in relation to flexibility and dexterity and also require only minimal effort in being set up on-site. A tracked mobile base allows the robot to travel freely on site, which has clear benefits over other systems such as using scaffolding as sliding rails for linear motion, which constrains the overall mobility. As exemplified in the review, mobile robotic systems using an industrial-type robot arm are also more applicable to construction tasks compared to small-scale mobile robots. Both short-range and small-scale ground-based and aerial robots typically provide limited degrees of freedom (i.e., three) and quickly run into payload limitations for material deposition tasks. Moreover, a mobile robot using an industrial-type arm embodies a genericness that allows one system to be employed for a variety of additive fabrication processes—solely by customising the end effector for task specific operations.

The review further indicates that a construction site—despite the obvious challenges—also offers various features that can facilitate its robotic augmentation. Although the environment of a building site is not structured to the level of a factory and is also constantly evolving, it does provide some properties of structure and organisation. For example, a building generally contains areas that can be categorised into floors, walls, ceilings, pillars, rooms, and corridors. This holds the potential that a robot's sensing solutions can perceive and automatically register such areas, and store them into a topological structure accordingly. Furthermore, building sites contain defined and controlled areas for operation, depending on the building task. Hence, a construction site may be categorised as a semi-structured environment.[19] Additionally, the existence of a defined digital blueprint of a building site and the element to be fabricated is considered a-priori knowledge. The same accounts for knowledge of material properties and behaviour, which thus can be modelled beforehand as required for the manipulation of it. This a-priori knowledge plays an important role in the design of the high-level fabrication control algorithms of the robotic systems operating on-site. In many cases, both the task planning and the sensing and decision making processes can therefore be facilitated and limited to defined and local areas. Also, the process of perceiving the environment and interpreting the acquired information can be enhanced by using this a-priori knowledge. And last, many of the examples suggest that human presence on site can be employed to assist robot procedures—particularly those which require cognitive skills—and thus facilitate the integration of robots into existing construction workflows. Such manual assistance can refer to setting up a robotic system on the job site, or measuring in and calibrating the workspace. Also, relocating a robot between different operations may be human assisted, especially if robot relocation is an occasional event in the overall workflow. Finally, the delivery of feedstock material close to the robotic system mostly depends on manual support (e.g., by lifting it onto a construction platform using a crane). Once being close, the material can be processed further robotically (e.g., via automated pick and place or feeding routines for material assembly, or pumping routines for material extrusion processes).

2.3.2 Current limitations and challenges of robotic in situ fabrication systems

Despite the number of potentials and prospects, robotic in situ fabrication still faces a number of major technological challenges. These challenges are limiting their wide-range impact and so far successful adoption of either stationary or mobile robotic systems for in situ fabrication by the construction industries. They are identified and summarised into four distinct areas as follows:

2.3.2.1 Robot localisation

Robotic systems for in situ fabrication are utilised for the production of building assemblies on the job site with reference to a digital blueprint. This requires the systems to be capable of precisely localising and positioning the end effector with absolute accuracy across the entire job site. Mobile robots, which in comparison with stationary systems, lack a fixed mechanical link with their environment, therefore rely on sensing solutions to localise themselves on site and position the end effector accurately within a global workspace.[20] Externally mounted tracking systems such as single-beam laser-based referencing systems locating the robot are one possible solution to the problem (as it has been shown in the projects of SAM100 [72], Hadrian [20], and MIT's DCP [70]). However, despite the fact that these sensors can provide absolute location information with very high accuracy, the use of these sensors is limited by a few key aspects. They have to be set up in such a way to ensure a constant line of sight to the points being tracked. To maintain a clear visibility space without occlusion can, however, causes difficulties, especially in the case of constructing non-standard and geometrically differentiated structures. Also, visibility constraints limit the overall size of the workspace. To overcome these limitations, vision- or laser-based sensing solutions for localisation can be integrated on-board of a robot. Avoiding dependencies on external installations can support the autonomy and flexibility of a mobile robotic system at large. The potentials of on-board sensing for robot localisation have been shown for example in the DimRob project using a Kinect camera scanning landmarks [78], or in Dharmawan et al. [74] for referencing the robot location relative to a workpiece using a laser range finder. These shown methods, however, are not sufficiently precise to support construction processes to their full extent. Also, they did not show multiple localisation procedures within one absolute reference frame across the entire job site; i.e, they only showed relative movement and the localisation from one position to the next. Hence, extensive research is necessary in developing custom on-board sensing solutions for localising a robotic system on the building site. For this reason, the integration of on-board sensing solutions comprising commodity sensors and process-specific software, and their validation, are a major part of this thesis. The interdisciplinary research on this topic is presented using the individual case studies within Chapter 3.

2.3.2.2 Site-specific operation: Awareness of the building site environment

To enable a robust and accurate building process, a robot for in situ construction needs to be able to deal with the imperfect nature of a building site. It requires to support the adjustment of an existing digital blueprint to dimensional tolerances generally found on construction sites. Thus, it needs to be able to sense the building site environment, using vision- or laser-based sensing solutions, and build a *map* of it prior to fabrication. The creation of such a map relates to obtaining a set of images (using vision-based sensors) or laser range measurements (using laser range finders) and then fusing this data to construct a 3D representation of the measured space. Features of an existing CAD model of the building site can then automatically be aligned with this map. If necessary, the expected ideal dimensions of the CAD model can be adapted to the effectively found geometric information of the obtained map.[21] For example, the parametric model of a brick wall allows the courses of bricks to be adapted to fit certain dimensions found on-site. Such an adaptive feature has been shown in basic terms by the bricklaying robot SAM100 [72], however, by using an external sensing device and manual input procedures. None of the above discussed systems shows the potential of automating this important feature by utilising robotic sensing procedures for *site-specific* operations. For this reason, considerable research is necessary in this area. Such solutions towards recognition of the effective building site geometry—later referred to as mapping and alignment—are presented in the experimental section of this thesis in Chapter 3.

In addition to sensing and creating a geometric map, in situ construction robots should also be able to obtain semantic features of their surroundings. This would open up the possibility to automatically detect what is a floor, a wall, a ceiling, or an opening of a building, and thus support the alignment process between a CAD model and a robotically obtained map. It would also allow for automatically detecting obstacles or moving objects (e.g., human workers) in the robot's immediate surroundings. While the approach of detecting semantic features is not covered within this thesis, it would eventually allow a robot to base planning and decision making processes to be extended by using this additional information.

2.3.2.3 In-process survey: Awareness of the fabricated structure

To further support the goal of robustness and accuracy during fabrication, robotic in situ fabrication systems need to provide in-process sensing and adaptive control strategies. This allows the robotic system to compensate for material- and fabrication related tolerances, such that local errors in a global workspace do not add up. Most of the existing systems presented in the review only concentrate on robot localisation and end effector positioning, and do not address the challenges caused by uncertain material processes. Therefore, this thesis presents strategies that specifically address this issue. These strategies—later referred to as fabrication survey—are described based on the experiments in Chapter 3.

2.3.2.4 Integration of design with in situ robotic fabrication processes

To date, architectural planning software merely focuses on the geometric definition of building components and their spatial relationships. Conventionally, this geometric data is then interpreted and augmented by construction companies according to the specific parameters of their production workflow. Robotic fabrication, however, demands for a close integration of the design with the construction process. This extends the reach of design towards the definition of construction logics and the sequence of robotic tasks.[22] Well-established techniques in robotic fabrication (i.e., in robotic prefabrication) rely on perfect knowledge of material processes, and perfect control of the environment. This allows a robotic procedure to be planned and executed in a feed-forward approach, with the assumption that the related robotic actions succeed reliably. For robotic in situ construction processes, however, this approach is not sufficient. Instead, the in situ approach requires design intentions to be integrated directly with physical processes. The incomplete knowledge of the environment has to be completed by perceiving uncertain factors related to the material, the site, and fabrication. This includes that the effect of robotic actions on the fabricated artefact has to be monitored continuously. Acquired sensing data can then inform automated decision making processes in an on-going fabrication process to achieve a desired design.

To integrate design with robotic in situ fabrication, a computational tool-set is developed within the scope of this research. The tool-set aims to enable designers to explore sensor feedback and complex robotic control operations, and it integrates the following aspects: First, it provides communication interfaces that allow for a seamless data exchange between robotic components (i.e., sensors and actuators) and the design environment. Second, it integrates design with fabrication control algorithms for adaptive and feedback-driven fabrication procedures. Explorations in the domain of feedback-driven fabrication procedures as well as their validations are thus also presented in Chapter 3.

Notes

[12] The ratio of power-to-weight is the correlation between the amount of torque a robot's drive system provides compared to the weight of that robot. Hydraulic systems have a higher power-to-weight ratio than electric systems. This is also due to the fact that the power unit (hydraulic pump) of a hydraulic actuator can be stationary and placed somewhere away from the robot itself, powering the robot via an umbilical hose.

[13] In this context, the notion of *digital materiality* [79] has been constituted as the object of interest for architectural explorations.

[14] The Swiss norm for permissible tolerances in construction (SIA 414/10) stipulates for example the following permitted deviations for horizontal slabs, which vary in relation to the distance of measurement:

Distance:		4		10		20		40	[m]
Socket concrete:	±	12	:	16	:	20	:	25	[mm]
Floor screed:	±	6	:	8	:	10	:	12	[mm]
Exposed concrete:	±	8	:	12	:	16	:	20	[mm]

[15] Both the NASA and European Space Agency (ESA) refer to this as in-situ resource utilisation (ISRU) [80]. ISRU can avoid the transportation of raw material, since local resources can be exploited instead.

[16] Emergent behaviour describes the phenomenon that complex structures can emerge from actions of many independent agents using only simple rules and local information.

[17] Stigmergy is the indirect coordination of actions through modification of the environment by the agents. The principle is that the trace left in the environment by an action stimulates the performance of a next action, by the same or a different agent.

[18] Such an approach has also been shown in an applications with flying robots in Mirjan et al. [81]

[19] Semi-structured environment have certain rules that define them, while still being characterised by the prevalence of uncertainties.

[20] Localisation of mobile robots is the process of obtaining the accurate position and orientation of the robot relative to an absolute world frame.

[21]As a result, also the CAD model of the physical artefact to be fabricated can be updated in relation to the obtained information to eventually fit the effectively measured distances of a job site envelope.

[22] Extending the reach of design towards the definition of construction logics brings the designer again closer to construction, a progress which links back to the pre-industrial era.

3 Experiments

3.1 Introduction

This chapter describes three case studies that have been conducted during the scope of this thesis. As a preamble to the case studies in Section 3.2, this chapter also discusses a computational tool-set that incorporates the fabrication strategies and computational methods applied for their realisation. This tool-set aims to integrate design with adaptive fabrication control for robotic in situ fabrication processes. The subsequent experimental part forms the core work of this thesis, and it is used for validating the developed integrated design- and fabrication-strategies and adaptive control methods associated with the computational tool-set.

Case Study 1 of this thesis investigates an additive in situ process for fabricating loam wall structures using a *stationary* robotic system. One part of this stationary system consists of a custom robotic launching device for throwing loam projectiles. Throwing the material and depositing it at a remote location allows a stationary robot's static workspace to be radically extended. However, this remote material deposition process also involves a number of uncertainties. Therefore, the stationary launching machinery needs to be complemented with a sensing solution and an adaptive fabrication control method. It is only with this complement that the remote deposition method for the construction of architectural-scale loam wall structures can be achieved. This first experiment has a singular position when compared with the subsequent two. However, due to the intricacies of the construction method, this experiment has been specifically chosen because it can best illustrate why a feedback-based approach to in situ fabrication is necessary and inevitable. In contrast to using a stationary robotic system, the fabrication scenarios presented as Case Study 2 and 3 of this thesis are realised utilising a mobile robot named the *In situ Fabricator* (IF) (see Appendix A for a detailed description of the robot). The IF is employed to investigate the construction of architectural-scale building components that exceed the robots own static workspace through mobile robotic fabrication. In both experiments, different custom developed on-board sensing solutions are explored; these solutions allow the robot to localise itself and at the same time to deal with uncertain conditions of a building site. Case Study 2 explores the mobile robotic assembly process of brickwork structures using the IF in a simulated construction site environment. Case Study 3 describes the deployment of the IF on a real construction site, and the study showcases the accurate in situ fabrication of a large-scale steel rebar mesh for a cast-in-place reinforced concrete wall.

Taking the robotic systems directly to construction sites have allowed these systems to be exposed to actual site conditions (e.g., dirt, temperature changes, non-flat grounds), to real world logistical circumstances (e.g., transport, energy supply, feedstock material supply), and to material processing challenges. The characteristics of the construction systems and the resistance of the materials have prompted the need for adjustments of certain methods various times during the course of the thesis. This exposure has led to an integrative understanding of all parameters involved and has thus guided the advancement of this research at large.

The description of each experiment is structured into 1) the definition of an objective that contextualises the study in the broader slope of the thesis, 2) an introduction giving an overview on the experiment, 3) the technical description of the robotic system used on the building site, 4) the description of the building material system used, 5) the design logic and the generative tools applied, 6) methods for the mapping and alignment of the building site environment and for the localisation of the robotic set-up, 7) the in-process fabrication surveying and the adaptive fabrication control method,

8) a discussion of the results and their validation, and finally concludes with 9), an assessment of the applied strategies.

Appendix B outlines the project credits including a short summary of the individual contributions for each experiment.

3.2 Computational tool-set for adaptive robotic control

Processes in robotic prefabrication typically rely on the perfect knowledge of their environment, that is, highly structured factory conditions and the perfect control of stationary robotic systems. These structured conditions make the accurate robotic prefabrication of building components straightforward to attain. Processes in robotic in situ fabrication, however, are challenged by the lack of perfect knowledge and various uncertainties. Such incomplete knowledge is caused by the poorly structured nature of construction site environments and the challenging control of a robotic system on-site—which is typically mobile and not tied to one location. Various sources of uncertainty thus complicate the accurate robotic in situ fabrication of building components with low tolerances in relation to their digital design. With respect to such poorly structured conditions, a robotic system must both complete the missing knowledge with the use of sensors and apply advanced control strategies. Thus, this thesis proposes to establish an adaptive fabrication control system. Sensing in combination with adaptive fabrication methods should allow a robotic system to be in constant interaction with its surroundings, and thus, to deal with uncertainties induced from multiple sources during fabrication.

The computational tool-set for adaptive fabrication control is embedded within the architectural design and planning environment.[23] This approach aims to expand digital design methods into the domain of fabrication in a coherent way. The purpose is to create accessible interfaces for architects and designers to handle complex robotic control operations and enable their explicit access to the materialisation and construction of architecture.

In regards to the implementation of such a tool-set, the adaptive fabrication firstly requires certain sensing and control strategies, which are introduced in Section 3.2.2. These control strategies define the type and the sequence of actuation and sensing requests, geometry processing and computation, and decision making processes during fabrication. Furthermore, the adaptive fabrication control requires custom communication interfaces to all distributed components of a robotic system used. This communication system is described in Section 3.2.2.

3.2.1 Geometric-based closed-loop control

3.2.1.1 Uncertainties in robotic in situ fabrication

An adaptive fabrication control system aims to iteratively detect uncertainties of a system by the use of sensors and to adapt the fabrication tasks according to defined performance criteria. Such a control method can relate to feedback loops on the low-level process stage (e.g., monitoring the feed rate of material and monitoring a hydraulic pressure state during gripping); yet, feedback loops at this stage can only indirectly influence the output of a fabrication task. This research, however, explores fabrication control strategies that allow the loop to be closed on a geometric level [82] by monitoring and estimating the entities that concern the geometry of the fabricated artefact within one globally consistent coordinate frame. With this approach, this research explores to achieve a desired level of control and accuracy for robotic fabrication processes being performed on construction sites, despite uncertainties induced from multiple sources.

Three of such crucial sources of uncertainty can be summarised as follows:

- ***Building site induced uncertainties***: A building component to be fabricated has to fit to its encompassing architecture (e.g., fit in between two attaching walls or fit to a floor with a certain slope). Such a component is planned accordingly based on a CAD model of these encompassing elements. However, building site environments often exhibit dimensional tolerances and can deviate substantially from their ideal dimensions in a CAD model. These deviations constitute the building site induced uncertainties.

- ***Localisation induced uncertainties***: In contrast to stationary robotic systems used in prefabrication, a robot on a building site has to travel on site and localise itself within it. The estimation accuracy of such a localisation procedure depends on various parameters, such as the sensing system used or the quality of such a system's calibration. Thus, the occurrence of slight inaccuracies and noise in the robot's estimated location cannot be ruled out, as this creates the localisation induced uncertainties.

- ***Materially induced uncertainties***: The uncertain behaviour of material during its assembly contributes to fabrication-related tolerances. While robotic processes need to be able to cope with unpredictable material behaviour during the assembly also in prefabrication, factors such as the prevalence of dirt and temperature changes increase the probability of materially induced uncertainties on site.

3.2.1.2 Sensing tasks for robotic in situ fabrication

With respect to various uncertainties on a building site, a robotic system for in situ construction must perform sensing tasks at several levels—first prior to fabrication and then during the ongoing fabrication process—as follows:

- ***Mapping and alignment***: Prior to fabrication, a respective robot's sensing system (i.e., vision-based or laser-based) has to obtain a set of measurements of the entire building site environment, or of certain entities within it. This acquired data is then fused to construct a 3D representation of the measured space, referred to as the reference map $\mathbf{S}_0$ (see Fig. 3.1).[24] In a one-time calibration step, this created map $\mathbf{S}_0$ is aligned with the CAD model of the building site, and the transformation $\boldsymbol{T}_{WS_0}$ between them is estimated accordingly. In the event that the CAD model or certain features within it substantially deviate from the robotically sensed and constructed map $\mathbf{S}_0$, the CAD model must be adapted to the effectively measured dimensions.

- ***Localisation***: During fabrication, the robot must sense and estimate its own location on the building site. For this localisation procedure, the reference map $\mathbf{S}_0$ that is created in the previous mapping step serves as the source of the information. This known map is used as the reference to estimate the transformation of the robot pose as $\boldsymbol{T}_{S_0R}$ or as $\boldsymbol{T}_{WR}$ respectively (see also Fig. 3.1).

- ***Fabrication survey***: During fabrication, the robot must also survey the structure it is building. Since the fabrication survey is local, it is always performed in the currently estimated robot pose. This survey allows the robot to sense uncertain material behaviour and register geometric deviations from the fabricated structure with respect to its reference geometry. This survey also allows the robot to register imprecisions in the current robot pose estimation and to refine end effector positioning locally.

An exemplary design set-up of such an in situ fabrication process including the geometric relationships between the building site, the robot, and the fabricated structure is shown in Fig. 3.1.

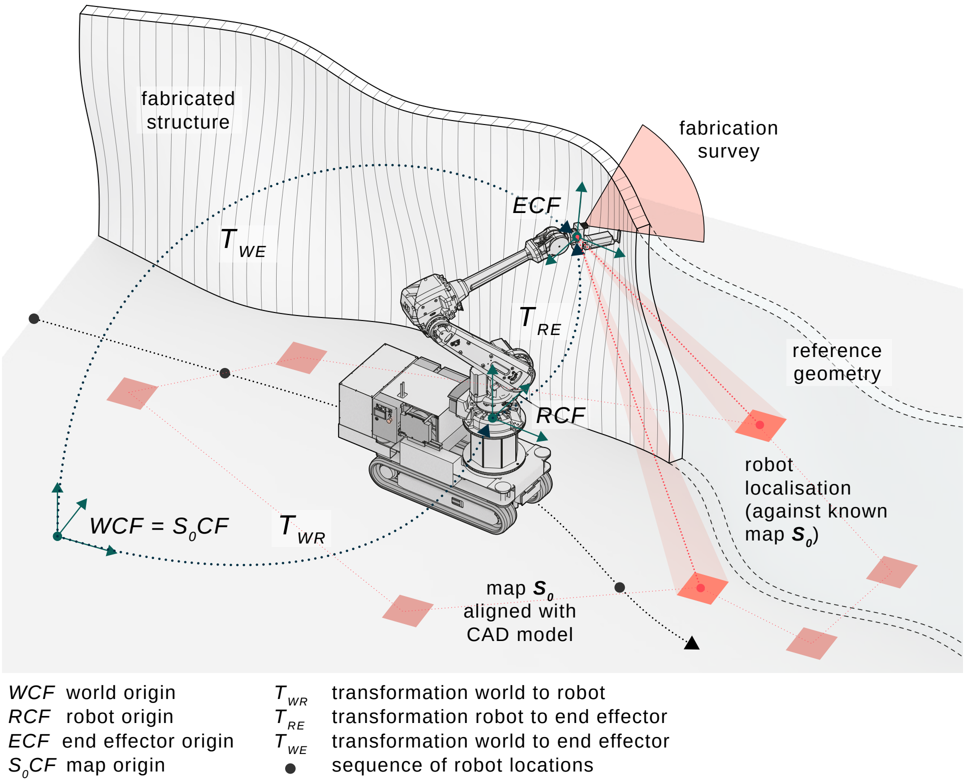

Figure 3.1: Depiction of one exemplary robotic in situ fabrication set-up. It represents 1) the CAD model of the building site and the reference geometry for fabrication; 2) a map $\mathbf{S}_0$ *of the building site that is created and aligned with the CAD model prior to fabrication; 3) a mobile robot that can localises itself on the building site by estimating perceived snapshots against the known map, fabricate a structure, and monitor if its actions succeeded reliably by surveying the development of the fabrication.*

3.2.1.3 Adaptive fabrication control

Subsequently, the acquired sensing data from multiple sources must be fed back to the design environment for the adaptive fabrication control (see Fig. 3.2).

Prior to fabrication, the feedback from the building site serves the purpose of calibrating the job site workspace so that the CAD model of the building site is made consistent with the conditions found on site. During fabrication, the fabrication controller monitors the difference between the desired dimensions (i.e., reference geometry) and estimated dimensions (i.e., sensor feedback) of the fabricated artefact with sensory information coming from

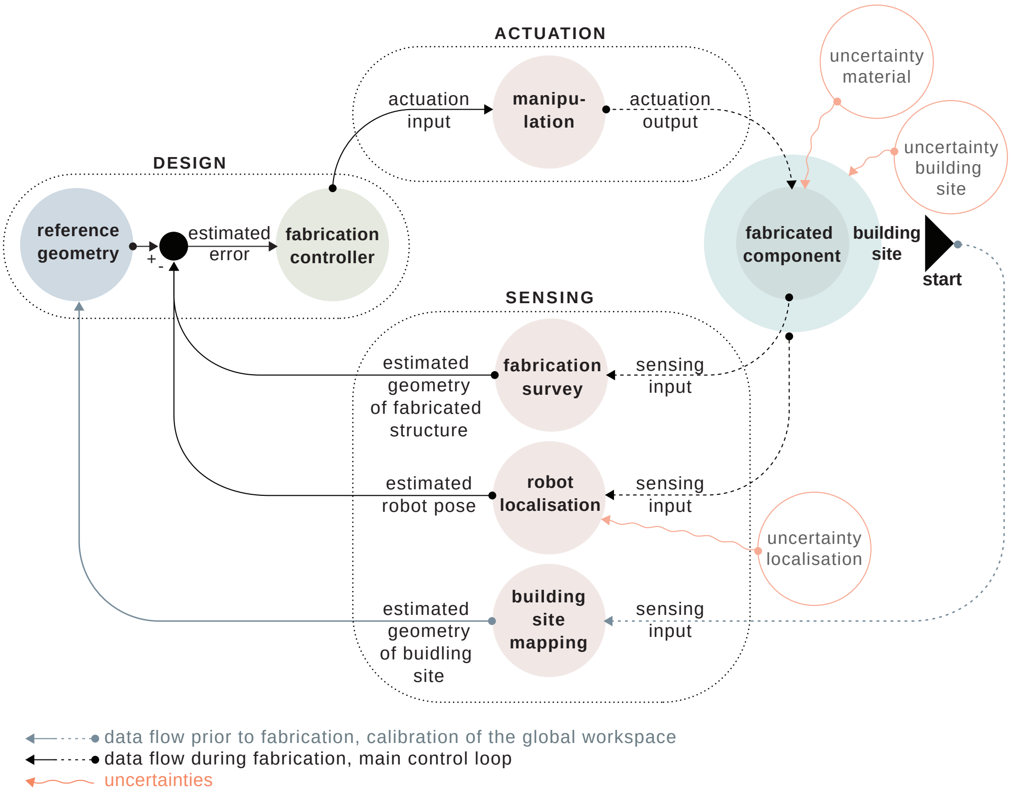

Figure 3.2: Diagram depicting the closed loop of a geometric-based adaptive fabrication control for robotic in situ fabrication. The fabrication controller serves to generate control actions to attain desired performance criteria.

multiple sources; here the sources are the estimations of both the robot pose and the fabricated geometry. The controller then serves to generate a control action to attain the desired performance criteria, and this control action allows robotic manipulation procedures to be incrementally adjusted towards a globally defined reference geometry. In the specific context of the experiments of this thesis, generating these control actions is not a time-sensitive process. Furthermore, the intervals in between sensing and manipulation are each adjusted to the respective experiment's construction and material system used.[25]

Furthermore, to sum up the concept of such a geometric-based closed-loop control, a high-level flowchart of such a process is depicted in Fig. 3.3. The individually integrated sensing solutions and methods and techniques developed for *mapping and alignment, localisation*, and *fabrication survey*, and how this sensing data is used in such a control loop are presented later in this chapter, in accordance with the case studies of this thesis.

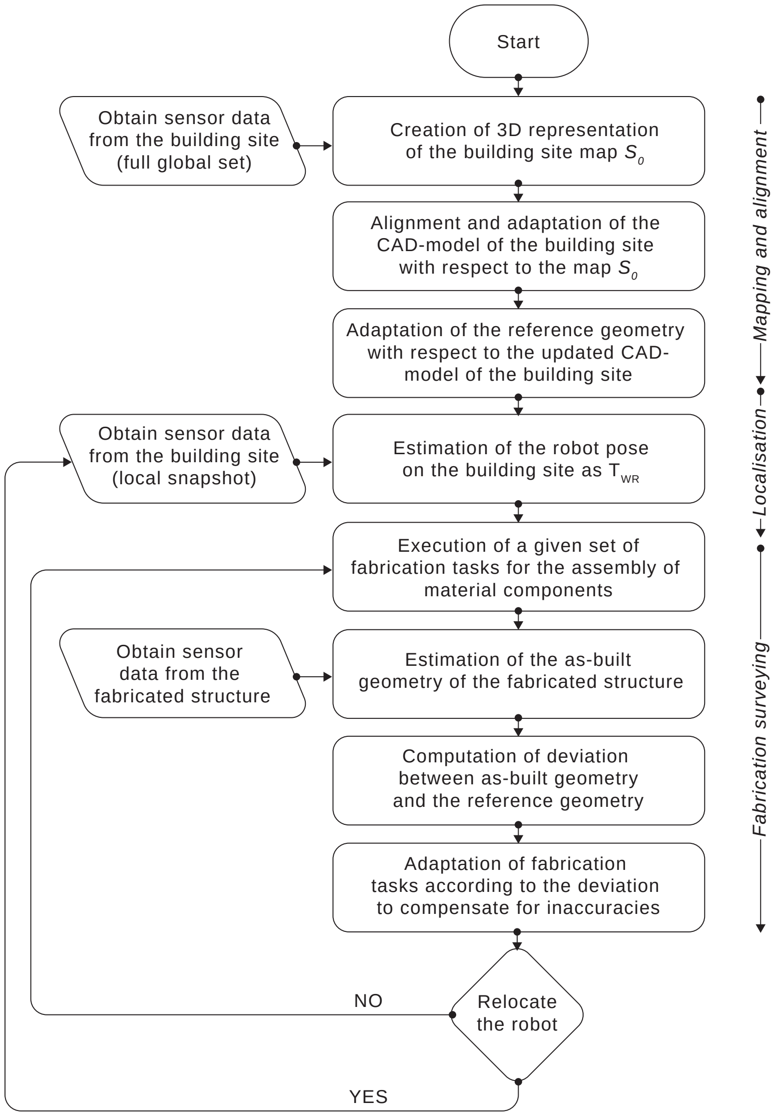

Figure 3.3: High-level flowchart of one exemplary robotic fabrication loop on a construction site using a mobile robotic set-up.

3.2.2 On-line communication system

The adaptive fabrication control requires an on-line communication system to be implemented, and it also requires this system to be integrated into the architectural design and planning environment. The custom communication interfaces allow data to be exchanged from within the design environment to distributed components—referred to as *nodes*—of a robotic system. These nodes can refer to controllers of manipulators (e.g., an industrial robot arm) or sensors (e.g., a camera or a laser range finder). They can also perform computational tasks (e.g., for localisation or for state estimation, or for feature detection) within an external platform such ROS (Robot Operating System) [83] or any other platform used. The number of nodes is interchangeable and extendible, and this number depends on the current construction task and the robotic set-up used.[26]

Although more advanced robotic control platforms exist in the field of robotics—the best example to date being ROS—they are not easily accessible for architects and designers. At a basic level, these platforms lack the functionality of high-level design and planning tools, such as geometry processing, geometry rationalisation, or fabrication process planning. The reason for this is that the software functionalities necessary for architectural design are not relevant in relation to the conventional field of robot applications (e.g., autonomous navigation, sorting of objects, and complex dynamic manipulation tasks). Embedding such a communication system into the design environment therefore allows for complex robotic control actions and at the same time for utilising the features of an architectural design and planning environment.[27]

3.2.2.1 Client/server model

A communication can be established from within the design environment to all involved nodes of a respective robotic system used. The communication is based on a client/server model, which in most cases relies on Ethernet TCP/IP. Applying this model means that all nodes act as servers in the system, and the clients that are implemented and running in the design environment can connect and disconnect to any of these servers as needed. This communication system thus presumes that the servers of a node must be running before starting a fabrication control loop.

As soon as a fabrication client has established a communication to a running server, the node's state is set to on-line, and formatted messages with a common protocol can be sent and received in between them. This data exchange can happen in two different modes: 1) in a streaming mode, or 2) in a service-based mode. In the first mode, a node transmits data continuously to a socket and the client can access this stream if needed; for example, the robot controller node streams the state of the robot's joint values, the sensing node streams the estimation of the robot origin. The latter refers to the client requesting a service from a specific node and waiting for a reply only once; for example, requesting a distance measurement value from a sensing node.

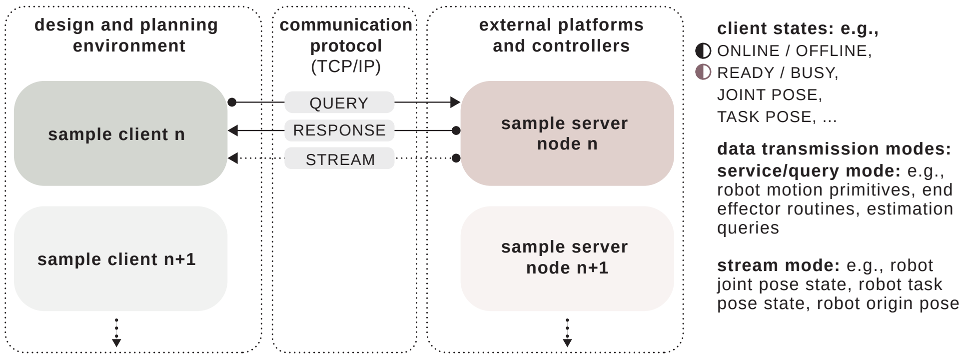

Figure 3.4: Communication system diagram showing three nodes of an exemplary robotic system (in this case: two nodes for actuation and one for sensing). Within each node, a server *is running and waiting for incoming connections by the clients that are implemented and running in the design and planning environment.*

Fig. 3.4 shows a diagram of the communication system; as seen in this diagram, the system allows to have an arbitrary number of nodes. The diagram exemplifies the data transmission modes between the clients and the servers of such nodes. For the purpose of synchronising the message transmissions, the nodes can be set to different states. The individual node set-up for the robotic systems used are described later in this chapter with respect to each experiment.

3.3 Case Study 1: Stationary in situ loam aggregation

3.3.1 Objective

The first case study describes the construction process of architectural-scale loam wall structures through the robotic throwing of loam projectiles, namely by launching and depositing them over distance. The novel additive robotic fabrication method, referred to as *Remote Material Deposition* (RMD)) [24] features a stationary robotic system that is set up on the building site. One part of this system consists of a robotic launching device for throwing the loam projectiles. This launching device operates in connection with an externally mounted laser-based sensing unit. Prior to the fabrication process, this sensing unit allows the effective geometry of the building site to be mapped; it is also possible to have the robotic launcher localised within this map and the remote material deposition method calibrated. During the fabrication, the sensing unit allows the material aggregation process to be surveyed, which informs the adaptive robotic control accordingly. In short, the robotic throwing of material radically extends the limited static workspace of a stationary robotic system (see Fig. 3.5). In this way, it offers a novel approach for an additive in situ construction process at an architectural scale.

3.3.2 Introduction

A successful implementation of the in situ loam aggregation process RMD needs to overcome a number of challenges. First, the remote material deposition process requires a simulation of the ballistic trajectory and a calibration of the trajectory through real world physical experiments. The experiments serve to provide empirical information about uncertain parameters of the equation underlying the trajectory simulation; one possible parameter is the launching speed of the projectiles. Second, the throwing of material projectiles and depositing them over distance requires a rethinking of the traditional

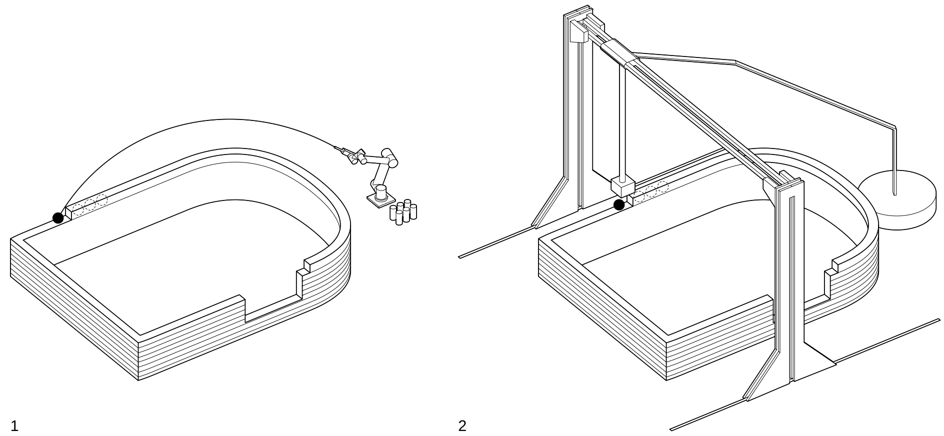

Figure 3.5: Schematic additive fabrication diagrams comparing 1) the RMD method with 2) a conventional large-scale gantry 3D-printing method.

notion of assembly, in which the position of each individual element and its interconnection to other elements is precisely defined in space. In RMD, when a projectile hits the already built structure, the impact causes a deformation and a compression of the material. These material aggregations result in a geometrically unpredictable but structurally sound bind with the previously built structure. Furthermore, due to inconsistencies in the launching system, material projectiles can occasionally miss their deposition targets. These uncertainties can only be managed by the robotically driven fabrication process being supported by a feedback system that provides a geometric survey of the as-built state of the structure as it is fabricated.

Figure 3.6: Close-up of the robotically aggregated loam structure of the RMD installation.

Therefore, the RMD fabrication control features a closed loop, integrating the following three process steps: 1) throwing loam projectiles along a pre-computed trajectory to a remote target, 2) scanning the aggregated structure and estimating the as-built geometry, and 3) successively adapting the next deposition targets in accordance with the acquired information (see Fig. 3.8).

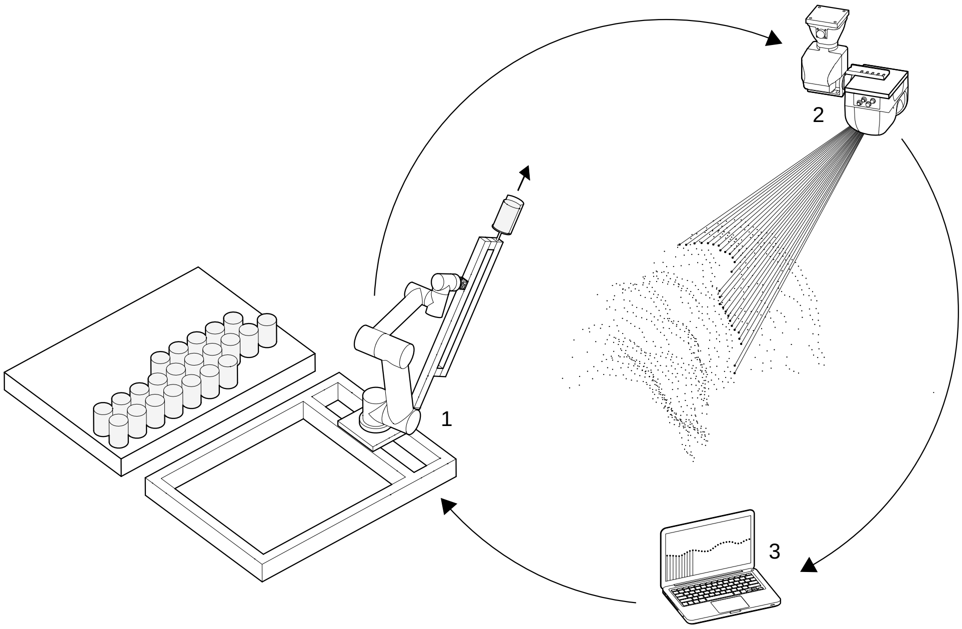

Figure 3.7: Adaptive fabrication control: 1) actuation: the lightweight robotic arm positions the pneumatically driven actuator and throw a projectile to hit a desired target; 2) sensing: 3D scanning of the material aggregation; 3) adaptation: computing the difference between the expected and the estimated structure's geometry allows subsequent deposition targets to be identified and corresponding machine instructions to be adapted accordingly.

With respect to the development and advancement of a hardware set-up as well as a computational tool-set for RMD fabrication processes on site, the fabrication system's constraints and structural morphologies are explored through subsequent modelling, prototyping and the conducting of empirical studies. Examples of these morphologies include the trajectories of ballistic bodies, the interdependencies between the robotic workspace and the ballistic range, ballistic shadows, good compressive but low tensile capacities of loam wall structures, scanning resolution, and scanning occlusion. This integrated approach allows for the development and exploration of the fabrication logics for the feedback-driven robotic process. Additionally, it enables the user to create a fundamental understanding of the design space of the entire in situ fabrication system for geometrically differentiated loam wall structures at an architectural scale.

The RMD process is demonstrated as an architecture installation in cooperation with the foundation of Sitterwerk St.Gallen [84]. In a four weeks' workshop format, a loam wall structure is designed and fabricated together with a group of students. This demonstration gives the opportunity to present RMD at full architectural scale. At the same time, the demonstration serves to validate the in situ fabrication strategies—such as the geometric-based feedback system and the adaptive fabrication control algorithm—that are developed within this research.

3.3.3 Experimental robotic set-up

As depicted in Fig. 3.8, the RMD fabrication process is demonstrated and performed in a large indoor space that measures $12\,\mathrm{m} \times 12\,\mathrm{m}$ and has a ceiling height of $7\,\mathrm{m}$. A lightweight robotic arm (Universal Robot UR 5) [85] is installed on a gallery adjacent to the space; this arm is equipped with a custom engineered pneumatically driven actuator for throwing the loam projectiles to defined target positions. The elevated position of the robotic launcher enlarges the system's static workspace and facilitates the access to far-off material target positions. The linear actuator with a length of $1.2\,\mathrm{m}$ is mounted with a 2-degrees-of-freedom passive joint mechanism to the base of the robotic set-up, while at the tip, the actuator is connected to the last link of the robotic arm. This mounting allows the actuator to be rotated around these joints to specified pan (horizontal) and tilt (vertical) angles using the robotic arm, and at the same time the actuator's recoils to be directed into the robot's foundation (see Fig. 3.9).

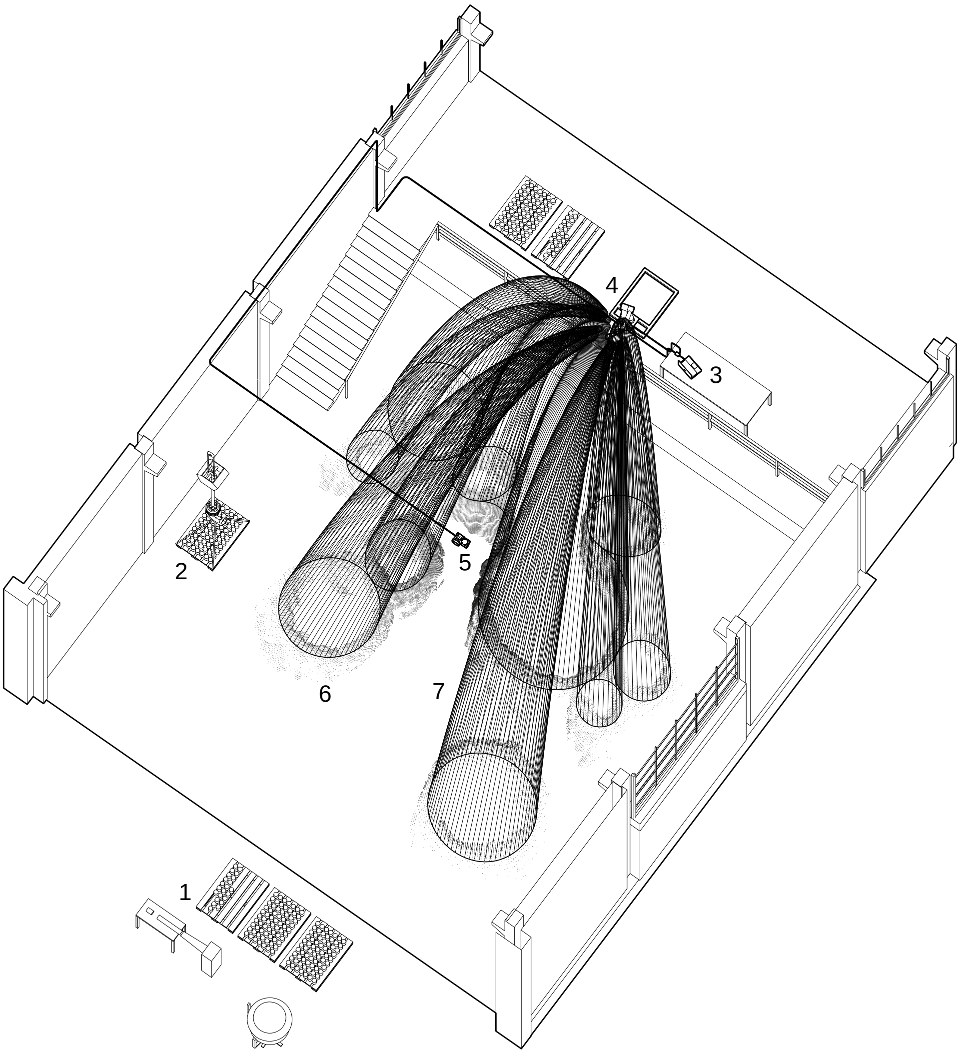

Figure 3.8: Fabrication setup and trajectory simulation of the RMD installation at Sitterwerk St.Gallen: 1) Production of loam projectiles, 2) Crane transportation of prepared material, 3) Laptop for computation and control, 4) Robotic arm with custom launching actuator for remote material deposition, 5. 3D scanning unit, fixed on the ceiling, 6) Point cloud of laser scan and 3D NURBS curve describing the target geometry, and 7) Simulated trajectories of the loam projectiles aiming at desired targets.

A scoop at the tip of the actuator can be loaded with a loam projectile. As soon as the loaded actuator is launched, the accelerated projectile flies off the scoop, following a ballistic trajectory. This trajectory is a function of the initial launching speed v_0 and a specified pan angle α of the actuator, while the launching speed v_0 is dependent on the air pressure that activates the launching mechanism, on the extension length of the linear actuator, and

Figure 3.9: A robotic lightweight arm is positioning a pneumatically driven actuator to desired pan (horizontal) and tilt (vertical) angles for remote material deposition. A scoop at the tip of the actuator serves to hold the material projectile during the launching process.

on the projectile's mass. It thus follows that the extended workspace of the stationary robotic system is constrained by the geometric boundary of the ballistic trajectories as a result of the maximum achieved launching speed.

For geometrically mapping the building site prior to fabrication and for surveying the on-going fabrication process, a 3D laser scanning unit is mounted on the ceiling, centrally above the building area (see Fig. 3.8). This scanning unit consists of a laser range finder (LRF) mounted onto a pan-tilt unit.[28] By rotating the LRF, a 360°-point cloud scan of the whole surrounding space can be retrieved. To map the entire workspace with an appropriate resolution, the scanner is rotated in steps of 0.5°, and its resolution is set to 0.1667° with an opening angle of $\sim$ 120°.

3.3.3.1 On-line communication system

As shown in Fig. 3.10, the on-line communication between the design environment and the robotic system for the RMD fabrication process allows for the exchanging of data with two nodes. With node 1, data is exchanged for actuation, which can be tasks such as moving the robot arm to a target pose or activating the pneumatic actuator for launching the loam projectiles. With node 2, data is exchanged for sensing tasks, that is for the mapping and the fabrication survey; this can include requests such as to obtain a point cloud with the 3D laser scanner, or to estimate the as-built geometry at defined locations in this point cloud.

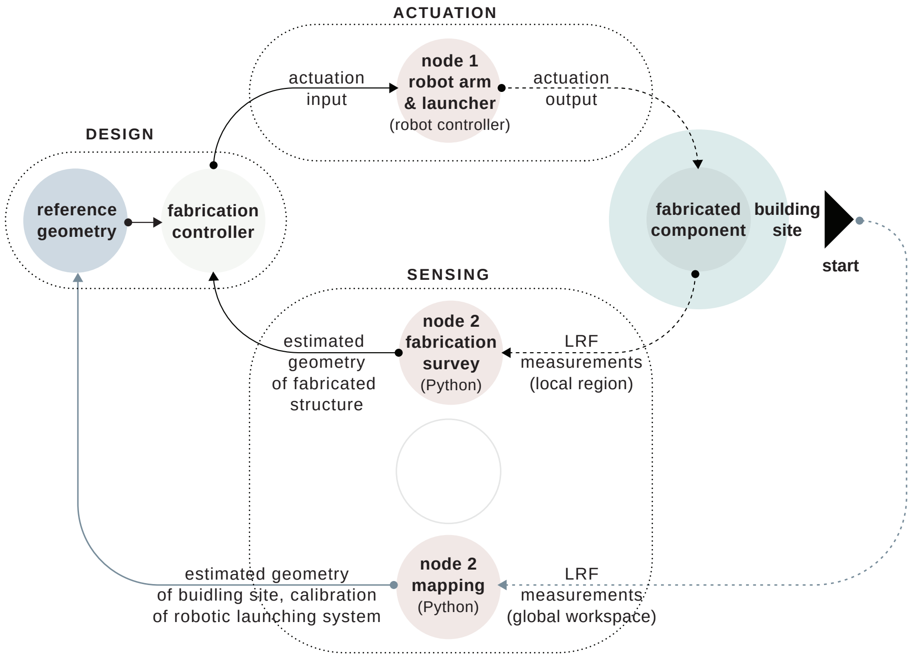

Figure 3.10: Diagram showing the on-line communication of the design environment with the robotic system for the RMD fabrication process, exchanging data with two nodes.

3.3.4 Building material system

There are two material property requirements defined for the RMD process. First, a material projectile must sustain the impact of hitting the already built structure (e.g., without falling apart). Second, this projectile must be able to create a structural material compound with it, such as through fusing or through interlocking. The choice of using the building material loam for this process has turned out to be compelling for a variety of reasons. Primarily, it is available locally. This geographic vicinity minimises both the effort in transportation and the cost of the raw building material to the building site (see also the local loam mine in Fig. 3.11). Furthermore, loam is easily processable. It is entirely recyclable solely by the use of water since the loam's hardening does not involve a chemical reaction, but the material is solely drying.

Figure 3.11: Loam mine (left) and loam processing (right) of a local brick factory.

The robotic process of aggregating loam material portions to a structural material compound resembles an ancient manual technique, named *Zabour* [86, pp. 270-271]. This technique refers to loam structures being constructed through the subsequent throwing of soft material portions in a layer-based manner from an altitude of about 1.8 m. The plasticity of the raw material—something between solid and liquid—allows the impact force of the projectiles and their deformability to be utilised for establishing a structurally sound bonding of newly deposited material with the already built structure. This process implies that certain drying times inherent to the material need to be considered during the fabrication. A viable structural capacity of the constructive system can be achieved only if the last layer of loam is already hard enough to sustain the impact of new material but still fresh enough to fuse with it. In short, this process facilitates the fabrication of extruded single- or slightly doubly-curved loam wall structures with a thickness between 30 cm to 60 cm without the use of formwork or scaffolding.

3.3.4.1 Loam mixture

The identification of an appropriate loam mixture for the RMD process are carried out empirically through a series of material launching studies in collaboration with Sitterwerk, with which the requirements to the material properties are examined. For example, a material projectile has to be solid enough to sustain being launched and flying along a trajectory without falling apart, yet it also needs to be soft enough to create a viable compound with the previously deposited material solely through the impact force. Additionally, the surface of the projectiles should remain smooth and plain, after having been deformed by the impact (see Fig. 3.12). Moreover, the material should be dry within a reasonable time frame, since the time needed to gain the load-bearing capacity of the material have an elementary influence to the achievable building speed.

Figure 3.12: Material studies and identification of an appropriate loam mixture for the RMD fabrication method.

The finally selected loam material mixture contains the following components—a ready-made-mix provided by a local brick factory [87] that contains 45% clay, 10% sand, 40% silt, and 5% lime is complemented by 30% crushed sand, 10% cellulose, and 10% wood chips (percentage as volume). These latter components are added for the purpose of increasing the structural performance of the hardened material but also to accelerate the drying time, and to have less shrinking and therefore fewer cracks. Together with using construction dehumidifiers at the building site, this mixture allows for a daily construction height of around 20 cm.

3.3.4.2 Material processing

To keep the degree of uncertainty low, the ballistic aggregation process of RMD requires the production of loam projectiles with a consistent mass and geometry. This consistency is achieved by a manually assisted production process, situated outdoors next to the building site venue where the raw loam mixture is stored. It involves the intermixing of the material components described above in a pug mill mixer with the addition of 7% of water (percentage as weight). As shown in Fig. 3.13, the mixed material mass is then subsequently extruded through the pug mill and portioned with the aid of a cutting harp, which leads to cylindrically shaped projectiles with a height of 150 mm and a diameter of 83 mm. The density of the extruded cylinders in their plastic state (i.e., before drying and becoming hard) is approximately $2\,t/m^3$. These prepared projectiles then have to be prevented from drying out (e.g., by covering them with plastic foil) and processed within a limited range of hours for the construction. This is done firstly to ensure a proper bonding in between the layers and secondly to ensure an even humidity rate and consistency of the projectile's weight.

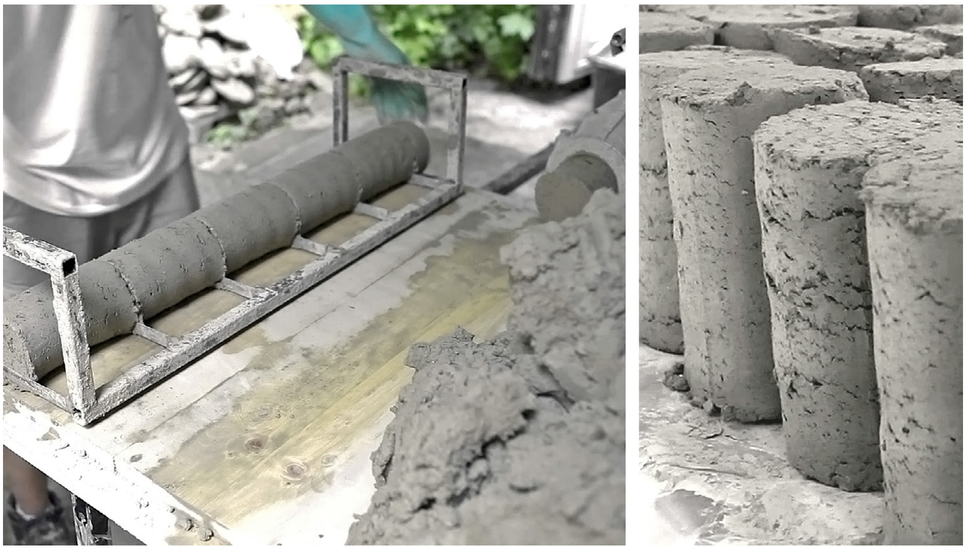

Figure 3.13: The preparation process of the projectiles involves the intermixing and extruding of the material with a pug mill, and further cutting them into same sized pieces with a cutting harp.

A crane system serves to transport and lift palettes with prepared projectiles up the gallery to store them next to the robotic launching mechanism, from which the material has to be fed manually to the robotic set-up for fabrication (see also Fig. 3.8).

3.3.5 Design objective and generative tools

3.3.5.1 Installation design

The design for the architectural installation is developed together with students within a two-day hands-on workshop. The objective of the workshop is to build models in the scale of 1:20 with the same loam material later used for the RMD process, so that the students would develop a sense of the general material properties. The students are also encouraged to incorporate certain process-based geometric constraints into their design explorations; such constraints can be minimum and maximum curvature ranges, bifurcations to stabilise the structure, ballistic workspace boundaries, ballistic shadows, or the total available amount of 25 t of raw material.

As depicted in Fig. 3.14, the final design concept is based on a circle-packing pattern in the horizontal section. It is expected that extruding these closed circular geometries to generate wall structures provides a higher structural integrity in comparison to extruding open forms.[29] Further differentiation of the design is explored by varying the circle density, radii, and the extruded wall's height profile.

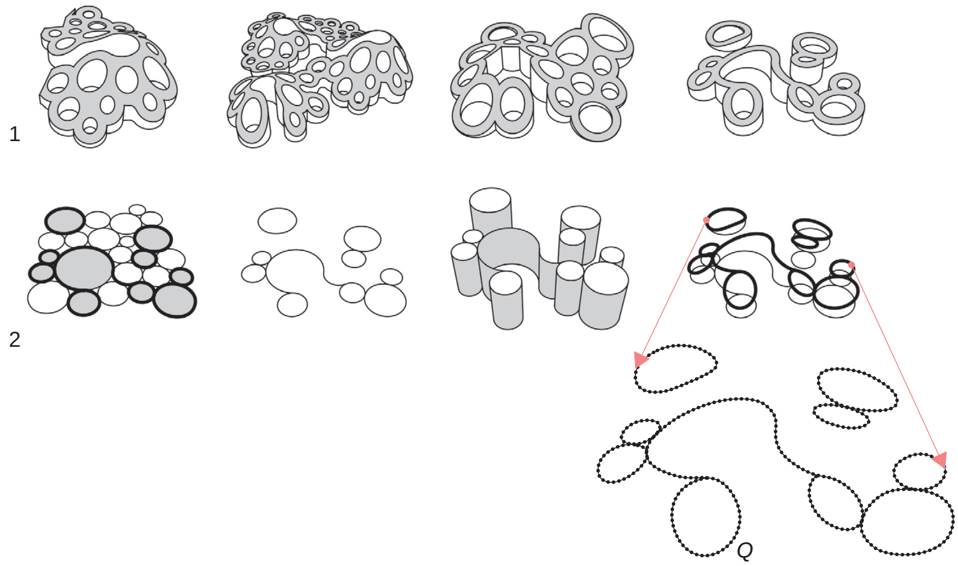

*Figure 3.14: The upper row in 1) shows design variations generated on the basis of a circle-packing algorithm, with the objective to populate the installation space with circular extruded wall structures with varying parameters such as the density, the radii and the wall's height profile. Below in 2), the design principle is illustrated. The zoomed-in diagram shows the reference geometry of the design for fabrication, which is represented by a list of 3D point locations **Q** (with the sequence being defined by the order of the list entries).*

After having defined the desired target geometry, the generation of the fabrication data involves solely representing the upper border as a set of 3D NURBS curves within the global workspace (see also Fig. 3.14). Since the building process is inherently discrete, these curves are further subdivided into a set of 3D point locations $\mathbf{Q}$ with an equidistant spacing of 9 cm to one another; this spacing has been considered optimal after having conducted a series of empirical studies. Eventually, these 3D points $\mathbf{Q}$ serve as the reference geometry within the fabrication data structure to guide the entire fabrication process. More broadly, the integrated design and fabrication method of RMD also allows for exploring the possibility of adapting certain parameters of the reference geometry during fabrication. For example, while the horizontal plot (xy-coordinate of the points in **Q**) is fixed because the material system requires the walls to be extruded straight, the height profile of the reference geometry (z-coordinate of the points in **Q**) can be adjusted at a later stage in the process [56].

3.3.5.2 Ballistic trajectory simulation

As depicted in Fig. 3.15, the desired target position for a single loam projectile is specified as a target point $\mathbf{Q_i}$, expressed in the robot coordinate frame RCF. First, the actuator needs to be rotated around a pan angle β to point towards the target point $\mathbf{Q_i}$. Then, in order to derive the respective actuator's tilt angle α for the projectile to hit a desired target point at a given distance b, a modelling of the physical process is required. For the RMD method, the influence of air resistance and other complex phenomena affecting the trajectory can be neglected, since the ballistic bodies—in this case the loam projectiles—are characterised by a high mass, and they travel at relatively low speed. Therefore, the basic equation of motion is sufficient to model the accurate ballistic trajectory. In this equation, each projectile is represented as a point of mass m, which is assumed to be launched with a constant speed at a given direction, and the projectile is affected only by the constant negative vertical acceleration $\vec{a}$ which is caused by gravity.

The above can be formulated with the following second order differential equation:

$$m\frac{d^2R(t)}{dt^2} = m\vec{a}$$

which leads to the general solution of:

$$R(t) = 1/2\vec{a}t^2 + \vec{v_0}t + R(t_0)$$

with the following boundary conditions:

$|\vec{v_0}| = v$ (the constant launch velocity, ~ 9 m/s)

$R(t_0) = P = O + l\frac{\vec{v_0}}{|\vec{v_0}|}$ (the launch point O and the actuator length l parallel to $\vec{v_0}$)

$R(t_1) = \mathbf{Q_i}$ (the target point hit at time t_1)

These three independent equations can be solved for the three unknown variables $\vec{v_0}$, P and t_1. The solution for P, and accordingly the actuator's tilt angle α, is solved numerically.

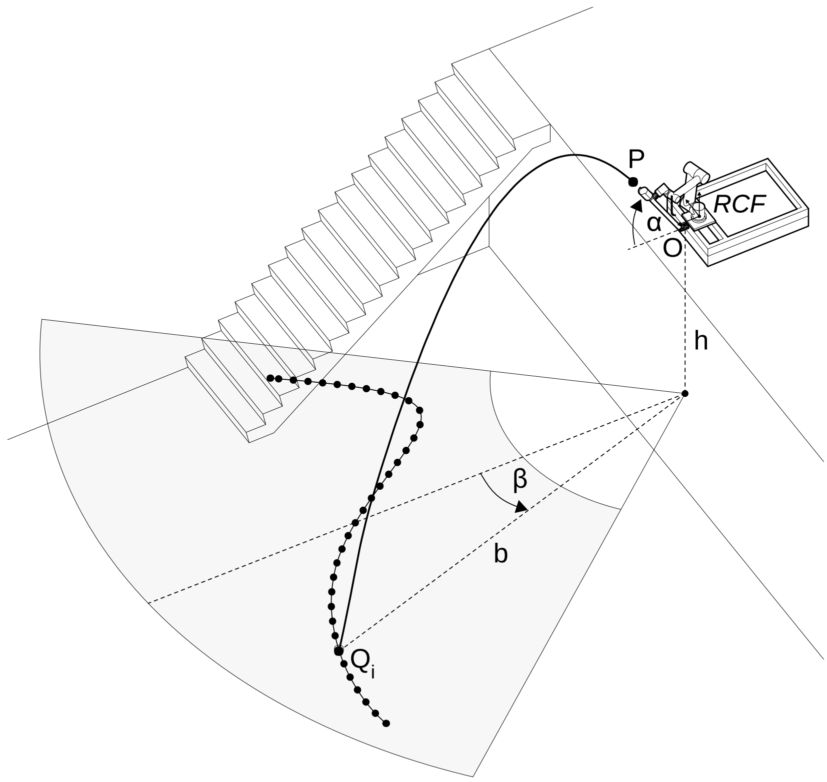

Figure 3.15: Visualisation of the fabrication set-up: Pan (β) and tilt (α) position of the launching actuator simulating a projectile to hit the target point $\mathbf{Q_i}$ within the robot's static workspace.

3.3.6 Mapping, alignment and localisation

Before starting the fabrication, the distance measurements retrieved from the rotating laser scanning unit allow for creating a structured point cloud reference map $\mathbf{S}_0$ of the job site (i.e. the global workspace). This map is then aligned with the CAD model, and the origin of the scanning unit SCF is located in reference to the robotic set-up RCF as $\boldsymbol{T}_{RS_0}$.[30] The alignment and robot localisation process is done manually within the design and planning environment. Since the robotic set-up in this experiment is stationary, this step has to be done only once.

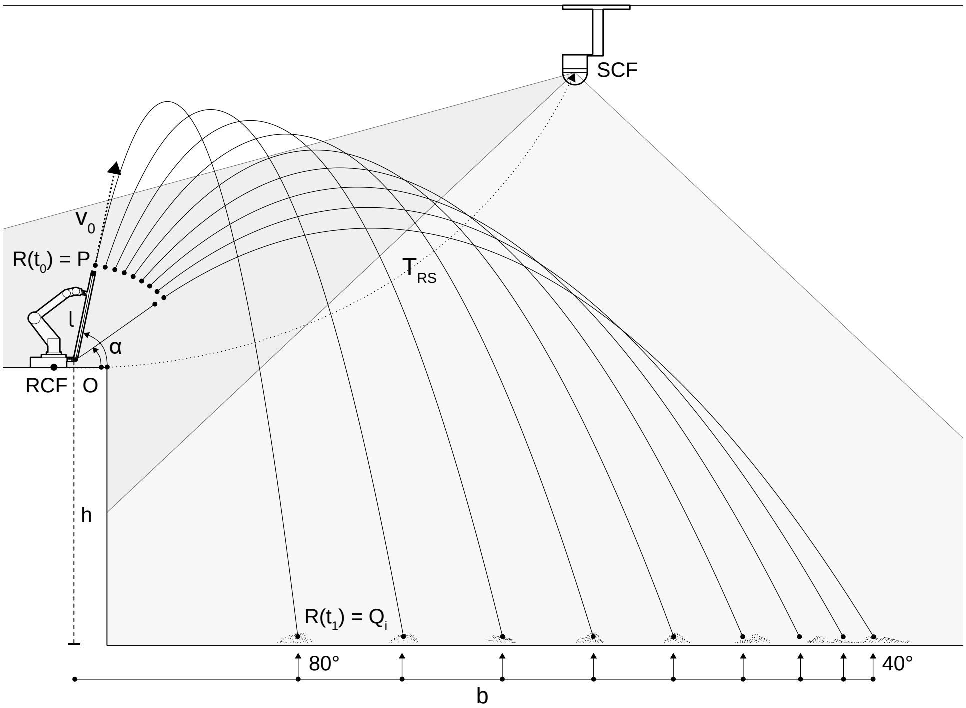

Figure 3.16: Side view of the robotic set up: The origin of the laser scanning unit is identified in reference to the robot location as $\boldsymbol{T}_{RS}$. The launching speed v_0 is derived from the ballistic equation by matching a range of vertical (tilt) angles α of the launching actuator from 40° to 80° with the estimated centre points of the 3D scanned targets.

Retrieving a structured point cloud of the building site prior to fabrication also serves to calibrate the developed simulation tool for the ballistic trajectories; specifically, it means to determine the initial launching speed $\vec{v_0}$ of the prior obtained equations. This calibration is achieved by comparing expected landing locations of a sequence of launched projectiles with their estimated locations, namely the estimated centre points of the 3D scanned landed projectiles (see Fig. 3.16). As a result, the simulation of the ballistic trajectory matches the effectively measured and estimated data, and it can be used for generating the data for the fabrication.[31]

3.3.7 Fabrication surveying and adaptive control

The remote deposition and consequent aggregation of loam projectiles lead to a unique material expression. In contrast to assembly systems with building components of known geometry and precise interconnection, "aggregates materially compute their overall constructional configurations and shape as spatio-temporal behavioural patterns" [88, 89]. The RMD process shows an inherent complex, non-linear and noisy behaviour, within which it is impossible to predict the very precise landing location of single projectiles or the extent of the material deformation caused by the impact. Thus, closing the loop between sensing and actuation allows the process to be open to these uncertainties and to take account for disturbances in the system. For this purpose, a feedback-system is introduced that allows geometric information about aggregated material to be upstreamed to the digital domain during the fabrication process [90, 82]. The developed system is different than a purely model-based feed-forward approach, which would involve refining the system's behavioural model or introducing probabilistic methods into the simulation. Here, the developed fabrication system introduces adaptive mechanisms that allow the material aggregation to be registered geometrically at each discrete building step. By iteratively measuring the fabricated output and generating the current fabrication steps according to the analysis of the previous ones, it is eventually possible to achieve overall robustness and stability, despite the uncertainties in the system. In fact, due to the feedback-driven fabrication process, the RMD method to build a complex architectural structure is dependent neither on an exact geometrical description of the structure to be built nor on a high fidelity simulation of the underlying process physics [91, 49].

3.3.7.1 Adaptive fabrication control loop

The sensing procedure takes place each time before computing and depositing a set of material deposition targets for one entire layer j of the structure (see flowchart in Fig. 3.17 and illustration of the target computation in Fig. 3.18).

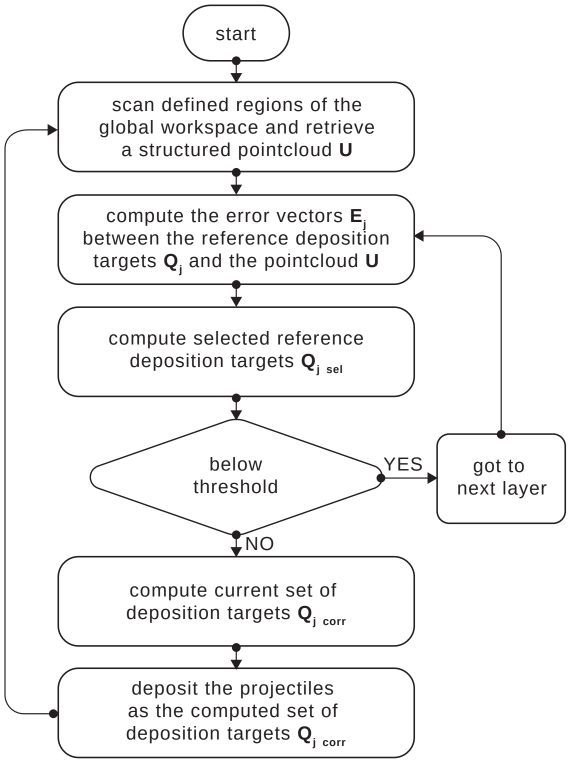

Figure 3.17: Flowchart of one iteration of the adaptive fabrication control loop.

When the sensing procedure is called, a scan of defined regions of the global workspace is performed. This procedure returns a structured point cloud $\mathbf{U_j}$ representing the as-built state of the entire structure at the job site.[32] For each reference deposition target $\mathbf{Q_{ij}}$ in $\mathbf{Q_j}$, a height error vector $\mathbf{E_{ij}}$ is calculated as the difference between the expected and the estimated height at the given layer j:

$$\mathbf{E_{ij}}(z) = \mathbf{Q_{ij}}(z) - \mathbf{T_{ij}}(z)$$

where $\mathbf{E_{ij}}(z)$ is the error vector, $\mathbf{Q_{ij}}(z)$ is the height of the reference target point location, and $\mathbf{T_{ij}}(z)$ is the estimated height of the fabricated structure. $\mathbf{T_{ij}}(z)$ is calculated as the weighted median height of all scanned neighbour points of $\mathbf{U_j}$ within a certain distance in the xy-plane of the deposition target $\mathbf{Q_{ij}}$ in question. After having computed the error vectors $\mathbf{E_j}$, a set of targets

$\mathbf{Q_{jsel}}$ are selected from the reference deposition targets $\mathbf{Q_j}$ by choosing the ones with the highest error rate and above a certain threshold k. Finally, the z-value of each target in $\mathbf{Q_{jsel}}$ is adjusted to the actual estimated height at that location and stored as $\mathbf{Q_{jcorr}}$. After this, the newly computed set $\mathbf{Q_{jcorr}}$ can be deposited, and a new iteration starts. The iterative cycle continues to the next layer $j+1$ if less than five error vectors[33] are below the defined threshold k. The adaptive fabrication algorithm can also be designed with more complexity—that is, the error vectors can represent not only an error in height but also in the horizontal direction for estimating the wall width. However, it is shown here in the simplest form for the purpose of explaining the basic algorithmic concept.

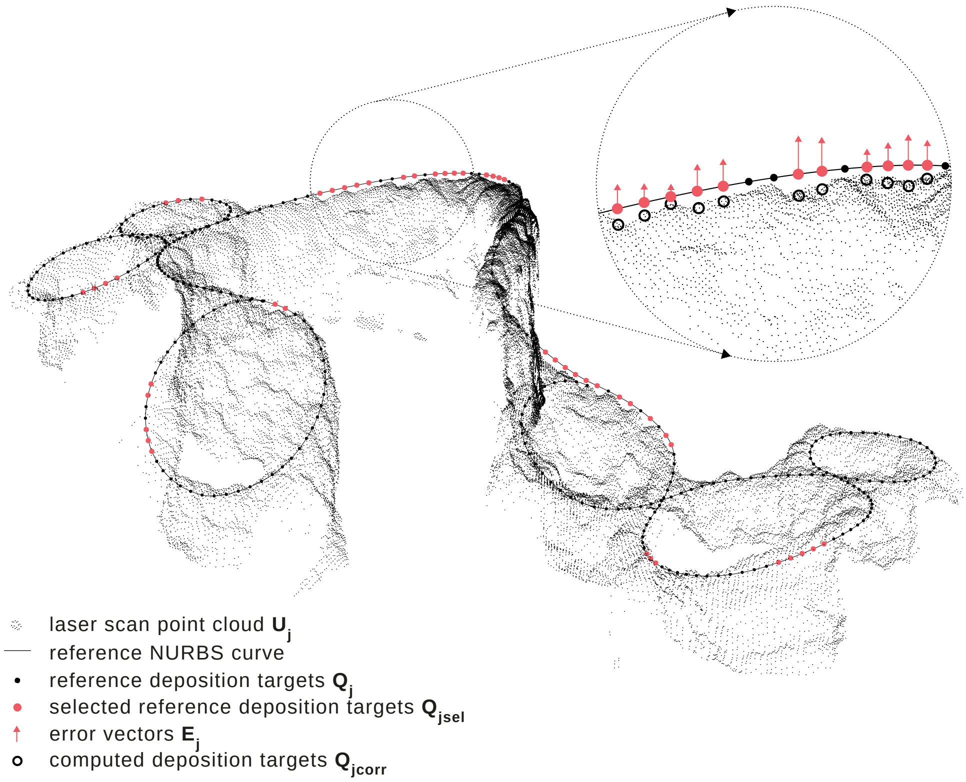

Figure 3.18: Principle of computing material deposition targets based on the laser scanning data: The black dots represent the reference deposition targets $\mathbf{Q_j}$, whereas the red dots represent the selected targets $\mathbf{Q_{jsel}}$; at these locations, the height of the structure does not meet the reference height, which is resulting in an error vector above a certain threshold, represented by red arrows. The new set of material deposition targets $\mathbf{Q_{jcorr}}$ can then be computed with respect to the estimated height values of the structure.

3.3.8 Results and validation

3.3.8.1 Results

The resultant loam wall structure had a measurement of 10 m × 10 m, with a varying building height between 0.8 m and 2.0 m, and with a wall thickness in between 25 cm to 40 cm; it consisted of 13,000 individually deposited material projectiles, which in sum weighted approximately 20 t. As depicted in Fig. 3.19, the fabrication of the structure took 2 weeks. The fabrication speed of a maximum 20 cm of building height per day was not primarily determined by the launching or scanning procedures but by the drying and hardening time of the material. This wait time was necessary in order to avoid having the structure collapse under its own weight.

Figure 3.19: Snapshots of fabricating the loam wall structure: Complying to strict drying times of the loam, the architectural artefact was constructed within a two weeks period of building time, in steps of max. 20 cm *building height/day.*

3.3.8.2 Validation

In computing the ballistic trajectories, there were uncertainties that could be caused by various possibilities, such as the unsteadiness of the pneumatic launching device, the presence of a sticky launching scoop leading to friction, or a slightly varying density and mass of the loam projectiles due to the manual preparation. Despite having these uncertainties, the reached accuracy was sufficient to enable a stable construction of slender loam wall structures up to a height of 2 m. The final launching speed $\vec{v_0}$ of 9 m/s for projectiles with an average weight of 1.8 kg—together with mounting the actuator at a height of 2.1 m above the ground—allowed the ballistic system to achieve an operating range between a 1.8 m and a 10.0 m distance from the actuator's origin.

Figure 3.20: View during a walk through the architectural installation.

Generally, the accuracy increased for short distance shots with a steep tilt angle α, and it decreased for long distance targets with a shallow tilt angle α. The inaccuracies in meeting predefined targets could be estimated about $\pm$ 15 cm in the area closer to the robotic actuator and up to $\pm$ 40 cm in the one that is more distant, which had an effect on the thickness of the wall. These differences in accuracy resulted in a slender wall thickness (25 cm) that was closer to the robotic launching mechanism, as well as a slightly higher one (45 cm) more distant to it. Moreover, inaccuracies in meeting predefined targets could be accommodated better in those regions of the structure which had a direction that coincided with being radiant to the actuators origin, as opposed to the ones being in a 90° angle to these rays. However, the overall accuracy remained well within the boundary values necessary for the fabrication of slender vertical loam wall structures.

The stationary ceiling-mounted sensing system was used for mapping the building site prior to fabrication. This map allowed the CAD model to be aligned to it, and the robot to be localised within. Furthermore, the mapping of a range of launched projectiles allowed the parameters for the ballistic trajectory simulation to be calibrated. During fabrication, the sensing system was used for surveying the aggregation process. While the alignment, localisation, and calibration have been performed by manually aligning the CAD model with the point cloud data, the fabrication survey for the feedback loop was performed autonomously. The sensing accuracy met the requirements of the material system used, and it enabled a reliable and robust construction of the structure according to a defined reference geometry.

3.3.9 Discussion

RMD represents an additive in situ construction process performed with a stationary robotic system. This system consists of an actuation device and a separately installed sensing and surveying station.[34] The RMD setup allowed sensing and actuation strategies—which are imperative in the context of robotic in situ fabrication—to be successfully implemented. These strategies included the following aspects: 1) mapping the site-specific geometry and adapting the fabrication data to the as-built geometry of the work site, 2) localising the robot within the surveyed workspace, and 3) adaptive fabrication methods which allow fabrication data to be iteratively adapted in dependence of the unfolding of the structure's shape.

The materialisation process of RMD illustratively shows the divergence between the digital domain of precise number processing, and the physical domain characterised by contingency, interference and emergence. It was

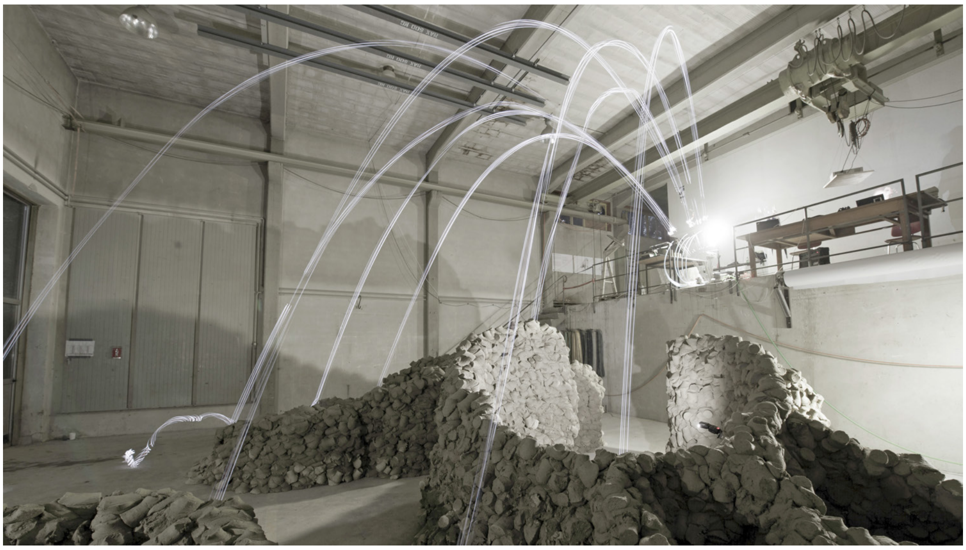

Figure 3.21: Ballistic trajectories of light projectiles, captured by bulb exposure.

found that the RMD fabrication method, together with the developed adaptive fabrication strategies, offered the distinct opportunity of synthesising digital form generation together with physical processes in a bi-directional fashion. The features set by the ballistic system, the inherent material behaviour, and the established feedback loop became an integral and explicit part of the architectural formation process and the expression of the fabricated structure.

In contrast to closed-loop feedback systems handling independent low-level parameters that only have an indirect influence on the fabricated geometry (e.g., regulating the air pressure supplying the linear actuator), the proposed feedback mechanism monitors the material behaviour and registers its unfolding geometry on a local as well as global scale. Despite the discrete sampling nature of the laser scan (subject to the scanning unit's resolution, see also Fig. 3.22), the obtained geometric information is still sufficient to be used for controlling the process and attaining the fabrication of a desired reference geometry. Aside from this, since the sensor information is directly available within the architectural design and planning environment, this availability allows a control algorithm or a designer to also directly adapt the reference geometry during the on-going process. This can be necessary in reaction to an unexpected development of the structure, or to design intents originating in experiencing its spatial and physical qualities on a 1:1 scale. This possibility, however, was only explored marginally within this experiment.

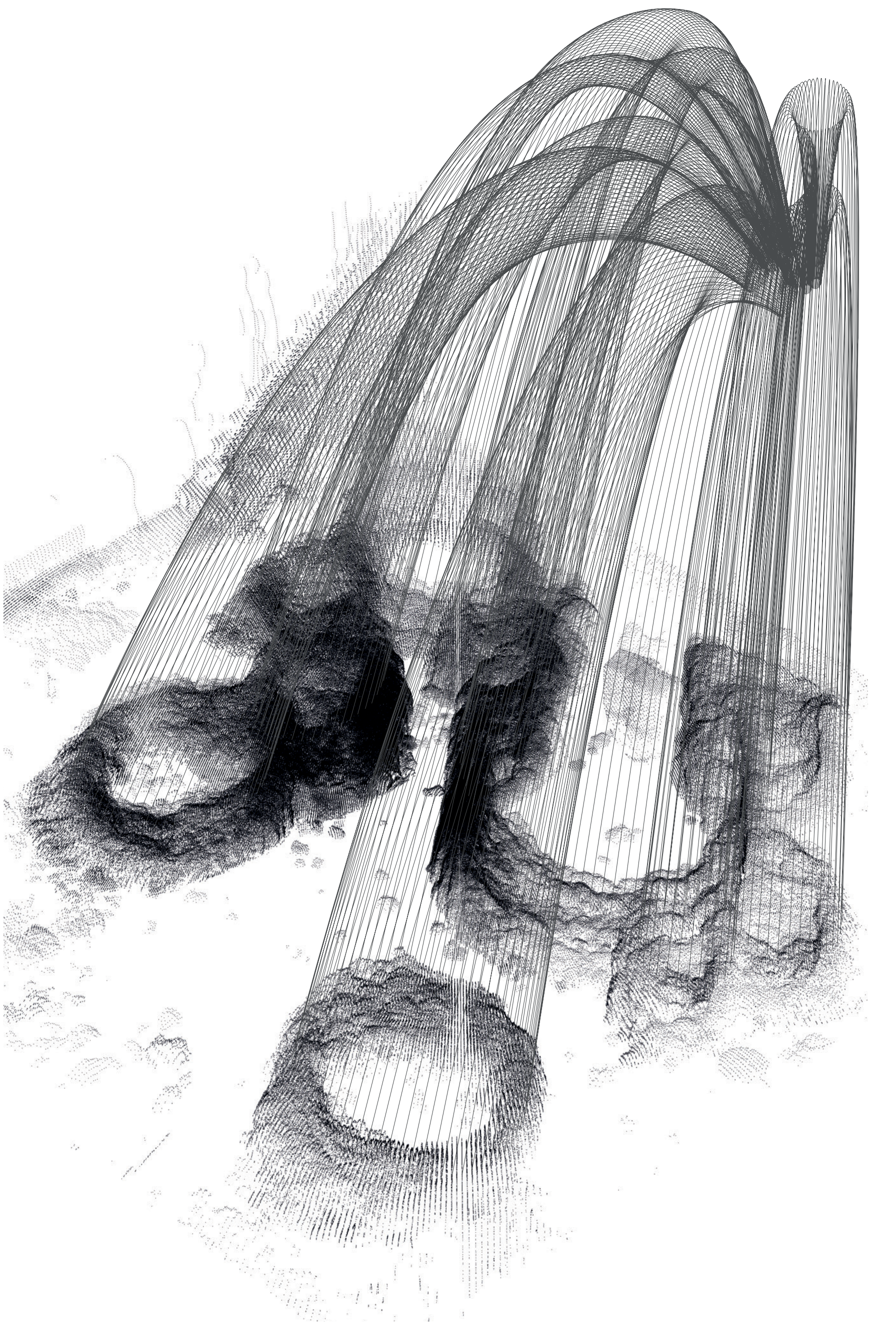

Figure 3.22: Point cloud of the scanned structure and ballistic trajectories for a set of remote deposition targets of the RMD installation.

In conclusion, the selection of the building material loam and the experimental reinterpretation of an ancient manual production process into a robotic one proved to be intriguing on multiple levels. Firstly, the architectural installation physically embodied and displayed the history of its own making by its intricate and highly articulated surface texture, as well as its process-inherent accumulated patterns. Furthermore, RMD expresses the notion of *digital materiality* in its very core[35] [79], as RMD features the particular interlacing of design, articulated materiality and the means of production.

3.4 Case Study 2: Mobile in situ brickwork assembly

3.4.1 Objective

Case Study 2 describes the first application scenario of the mobile construction robot, the IF (see Appendix A for a technical description of the IF). The study discusses the fabrication of an undulated double-leaf dry stacked brick wall in between two pillars that is performed in a lab environment set up to mimic a construction site [25] (see Fig. 3.23). This experiment serves as the entry point for investigating mobile robotic fabrication, and it explores the assembly of continuous building components that exceed the robot's static workspace. Moreover, the experiment explores mobile fabrication by using only on-board sensing systems so that the robot is not dependent on an external sensing device. Thus, the layer-based assembly method for the construction of brickwork is specifically chosen so that the complexity and the barriers to enter such explorations are kept at a low level. This approach allows the implementation of three basic functionalities of a mobile robotic fabrication process to become the focus of this experiment. Firstly, this experiment focuses on the integration of automated methods for sensing and registering the as-built dimensions of a building site and adapting the geometry of the parametric brick wall model to the site. Second, it aims to integrate and validate an on-board localisation system in order for the robot to perform assembly tasks from multiple locations. Lastly, the experiment focuses on the development of an assembly strategy and discrete assembly sequences for the mobile fabrication of brickwork structures.

3.4.2 Introduction

The implementation of this case study—that is, mobile in situ brickwork assembly—aims to expand the field of applications for additive non-standard fabrication technologies. In order to develop and validate methods, and explore the potentials for mobile robotic fabrication, this experiment is conducted with an interdisciplinary team of architects and robotics scientists (see also projects credits in Appendix B). By integrating custom robotic sensing technologies, this experiment explores the possibilities of constructing architectural-scale continuous structures that exceed a robot's own static workspace. It further investigates how the logics of an assembly sequence can substantially be redefined with respect to the mobility of the machinery. Thus, this experiment seeks to foster new forms of flexible, adaptable, and robust building strategies in the field of robotic in situ production of architecture.

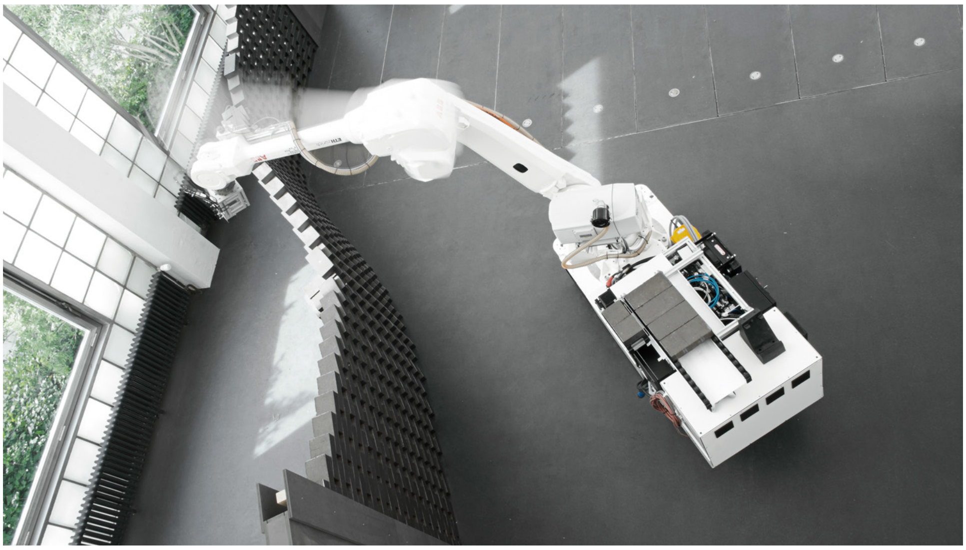

Figure 3.23: The in situ fabrication of a continuous dry stacked brick wall is performed with the IF in a lab environment set up to mimic a construction site.

3.4.3 Experimental robotic set-up

For the prototypical fabrication of dry stacked brick walls, the IF is equipped with an end effector consisting of a vacuum gripper for performing pick and place routines[36] (see Fig. 3.24). The base of the IF carries a vacuum pump that supplies the suction cups at the end effector. A small brick feeder is mounted at the rear side of the base. This feeder can carry six bricks at a time and has to be manually refilled.

For performing the sensing tasks, a laser range finder (LRF) [92] is mounted on the robot's end effector (see Fig. 3.24). By executing a sweeping motion with the last link of the robot arm, the system can obtain a point cloud of its surroundings. Additionally, an inertial measurement unit (IMU) is mounted at the robot's base frame. This sensor is used to detect and eventually compensate for the robot's tilting behaviour, which can occur during an arm movement routine caused by the change of the robot's centre of mass.[37]

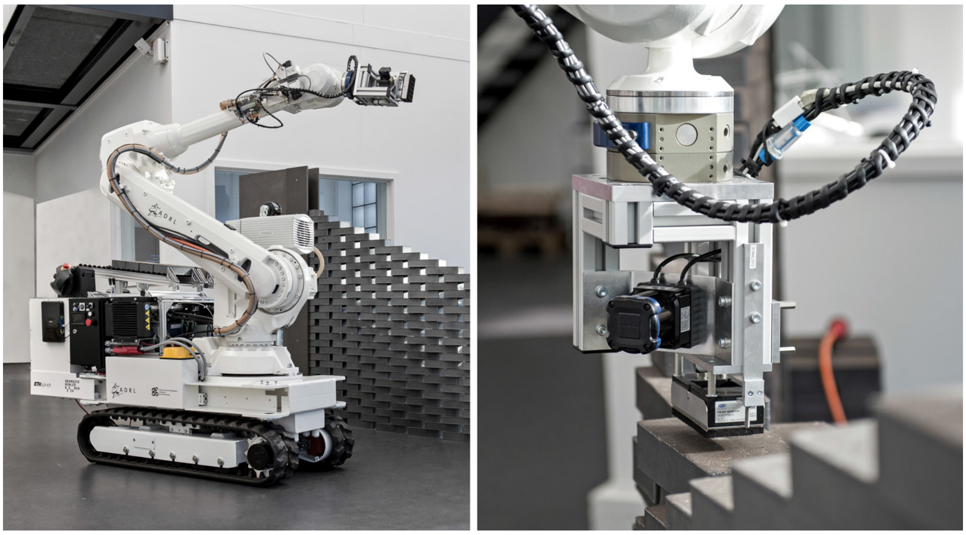

Figure 3.24: The image shows the mobile robotic set-up IF, customised for the fabrication of dry stacked brick walls. For this purpose, the IF is equipped with an end effector consisting of a vacuum gripper for pick and place routines and a laser range finder for sensing.

The experimental mobile fabrication case study is performed in a lab space of the NCCR Digital Fabrication, and this space is set up to mimic a construction site.

3.4.3.1 On-line communication system

As shown in Fig. 3.25, the in situ robotic assembly process requires communication to take place with two of the IF's nodes from within the architectural design and planning environment. Node 1 is running on the robot arm controller, and it can receive requests for performing actuation primitives (e.g., arm movement routines, pick and place routines, arm sweeping routines for scanning).[38] Node 2 is running within ROS, and it can receive requests for sensing, that is, for the building site mapping and the robot localisation (e.g., obtaining a full point cloud map of its surroundings, IMU angular values, estimation of robot origin).

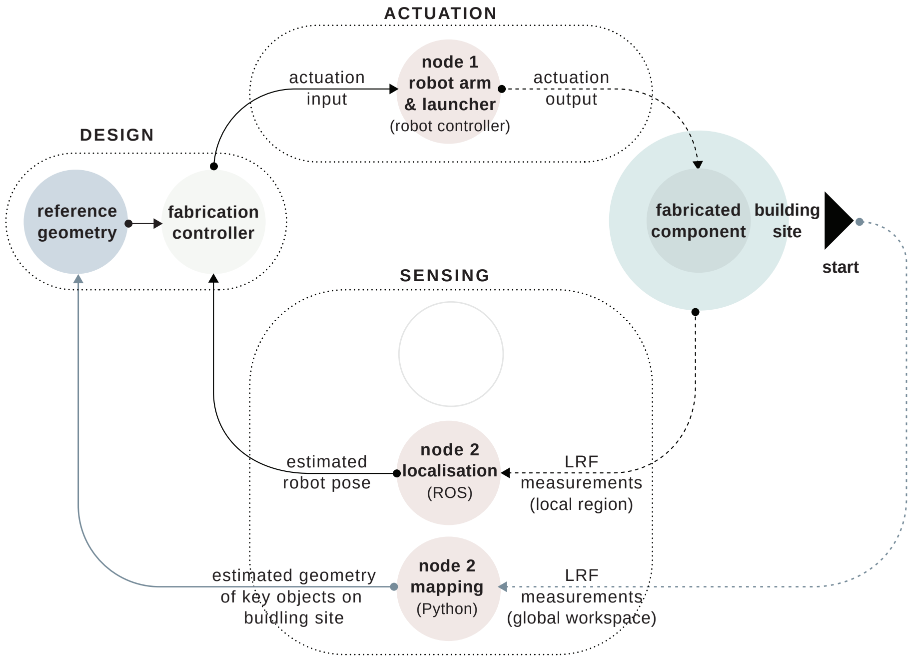

Figure 3.25: For the fabrication control, a communication to two of the IF's nodes needs to be established: 1) to a node running on the ABB arm controller for actuation, and 2) to a node running within ROS for performing the sensing tasks, that is, building site mapping and robot localisation.

3.4.4 Building material system

The building material system for the prototypical brickwork consists of dry stacked bricks, also known as clinker stones. In brickwork, perpends may not be contiguous across courses. Thus, rows of bricks—called courses—are laid on top of one another, arranged in a horizontally staggered masonry bond to build a structure such as a brick wall. The selected masonry bond for this experiment is the simple Stretcher bond, with the bricks in each successive course staggered by half a stretcher. This bond results in a wall with the thickness of only one-half of a brick. At the beginning of each alternating stretching course, a cut-in-half brick is used to achieve the necessary offset for the bond.

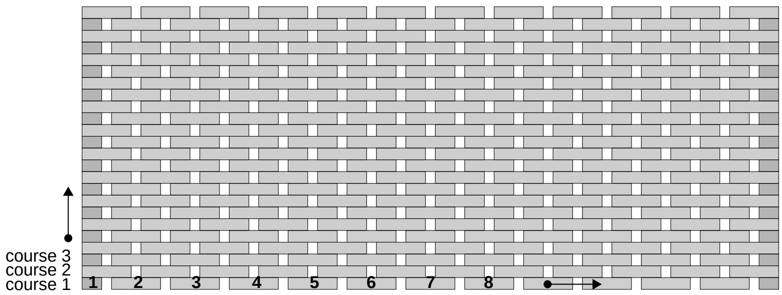

Figure 3.26: This diagram shows the Stretcher bond for one leaf of the brickwork wall. Layers of bricks—called courses—are laid on top of one another in a horizontally staggered Stretcher bond, with the bricks in each successive course staggered by half a stretcher.

3.4.5 Design objective and generative tools

For this case study, the wall is designed to be a double-leaf, and the leaves are crossed-over at two locations in order to increase the wall's stability. This increased stability allows a 2-m building height to be reached without any bonding—such as mortar or glue—needed between the courses; the bricks are solely dry stacked. The wall's design is stored within the fabrication data structure. This data structure is built upon a graph, within which the nodes of the graph represent the individual bricks—including their parameters, such as position, rotation, neighbourhood, and the built-state. In addition, the graph allows the discrete assembly sequences to be computed from it.

3.4.5.1 Fabrication sequence for mobile fabrication

If the full length of the brick wall exceeds the robot's static workspace, this wall needs to be fabricated from multiple locations. Due to the staggered pattern of the masonry bond, however, only a limited number of bricks can be laid down at one robot location. Thus, the assembly logics of the Stretcher bond in combination with the dimensions of the robot's static workspace result in an assembly sequence of trapeze-like patches, in which each patch is fabricated from a different robot location (see Fig. 3.27).

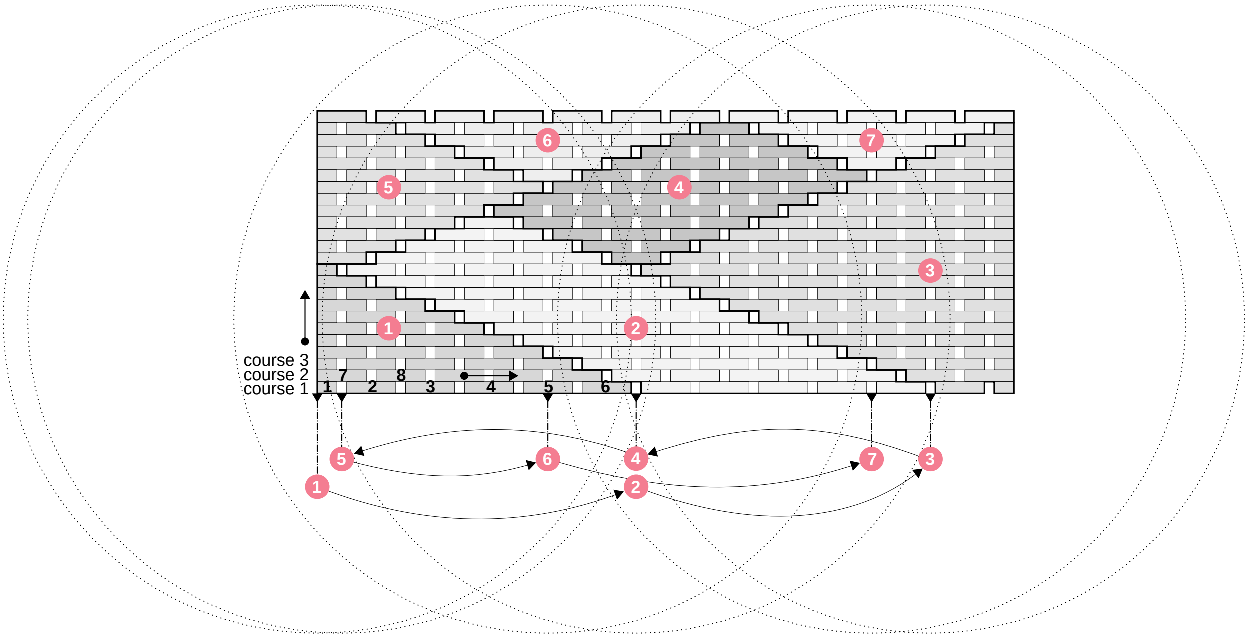

Figure 3.27: This diagram shows the generated trapeze-like patches for the assembly sequence of a brick wall with 300 bricks from seven different robot locations. These patches are computed in relation to the robot's reachability constraints and the logics of the Stretcher bond.

For the computation of such an assembly sequence from multiple locations, the wall model's underlying graph firstly allows single patches of bricks to be generated in relation to the robot's workspace dimensions and its given location anywhere along the wall (see Fig. 3.28). This feature enables the robot to be steered to an arbitrary location along the wall to be fabricated, after which the machinery can interactively generate the assembly sequence at its current location and within its static reach. Moreover, this procedure also allows an optimal sequence with a minimised number of robot relocations to be generated and thus be precomputed for the fabrication of the full length of the wall.

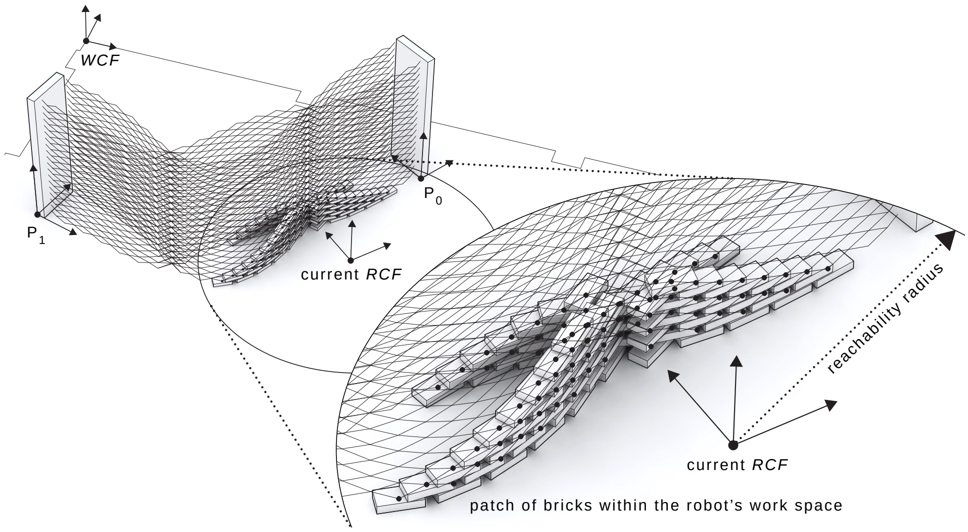

Figure 3.28: The patch of bricks within the robot's work space can be derived from the brick wall model's underlying graph, given both the robot location and its reachability constraints as an input.

Building the double-leaf dry brick wall with the dimensions of 6.5 m in length and 2.0 m in height and the use of 1600 bricks requires at least 15 consecutive robot relocations (see Fig. 3.29). As a consequence of the constructive logic, the robot can never place all the bricks that would be reachable from its current location; it can only place the ones which comply with the rules of the staggered bond. Thus, in order to fulfil the construction of the entire wall, the machine needs to traverse back and forth a path along the wall multiple times.

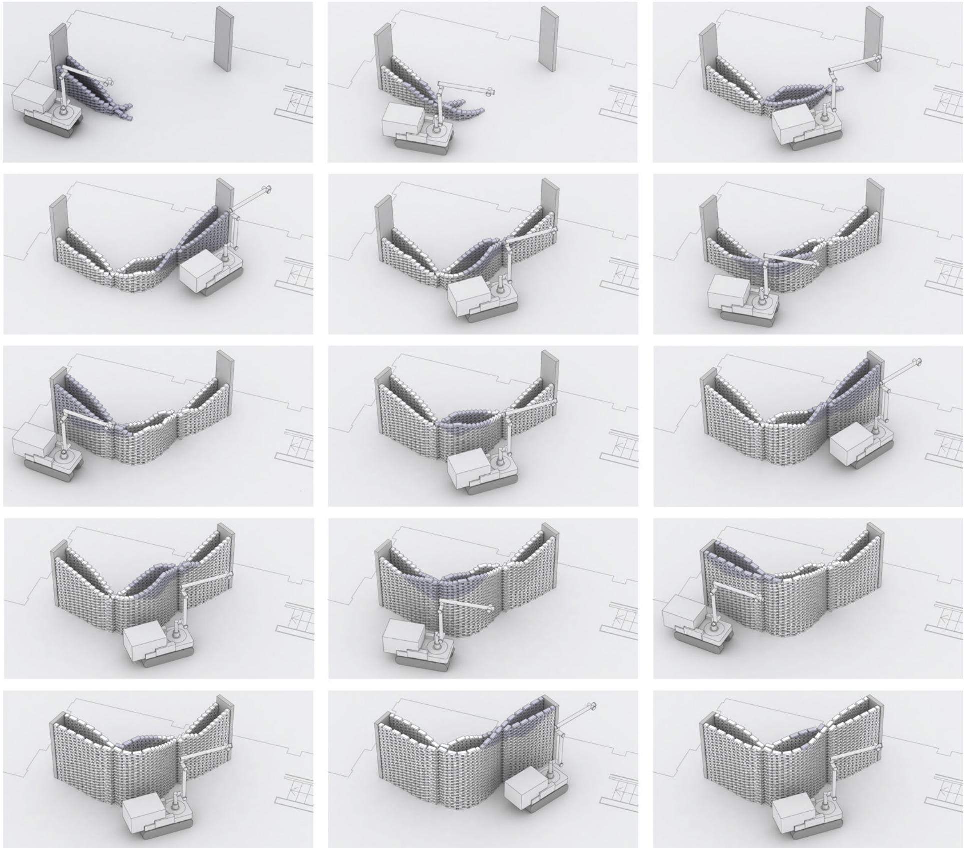

Figure 3.29: Snapshots of an exemplary brickwork fabrication sequence, shown from top left to bottom right. Since the bricks are layered horizontally forming a Stretcher bond, the fabrication sequence has to comply to the staggered pattern arrangement of the bricks. Even though the number of relocation procedures is minimised in relation to the current brick-laying task, the robot needs to traverse a path along the wall multiple times.

3.4.6 Mapping, alignment and localisation

3.4.6.1 Mapping and alignment

Before starting the fabrication process, the building site needs to be mapped by the robot from a central location. This mapping is achieved by calling a routine from the IF's sensing node, which captures an initial point cloud $\mathbf{S}_0$ (also referred to as *reference point cloud*) by executing sweeping motions with the LRF that is mounted onto the robot end effector. In the following step, the existing CAD model of the construction site needs to be automatically aligned with the reference point cloud, and their transformation is identified as $\boldsymbol{T}_{WS_0}$.

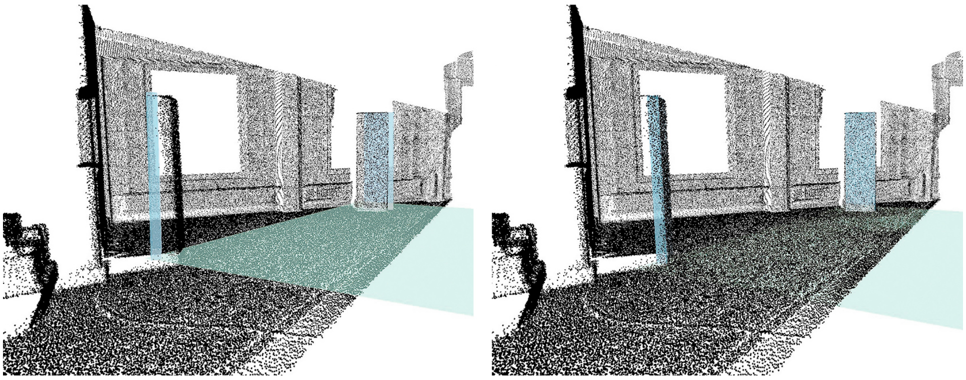

Figure 3.30: Mapping and alignment of the building site environment by using the on-board sensing set-up of the IF: Prior to fabrication, the CAD model is aligned and adapted to the reference point cloud, captured by the IF. In the picture to the left, the initial guess of the location of key objects within the building site (here: blue attachment pillars, green floor) is slightly off the point cloud data, whereas in the picture to the right, their location matches the point cloud.

In this experiment, special attention is given to the fact that the as-built dimensions of the construction site can generally deviate from their ideal dimensions in a CAD model. These deviations have an effect on whether or not a building component to be fabricated (i.e., the brick wall in this experiment) effectively *fits* to the true dimensions of its encompassing architecture. Thus, true dimensions have to be registered and taken into account for the robotic in situ fabrication process. In the scope of this experiment, the encompassing architecture is represented by the brick wall's two attachment pillars and the floor, and they are named *key objects* of the building site. Locating the geometric representation of these key objects within the 3D reference point cloud allows their true as-built locations to be estimated individually (see Fig. 3.30). For the purpose of the automated registration, the geometry of these key objects is represented as parametrically defined geometric primitives,[39] such as an infinite plane that represents the ground of the construction site, as well as polygonal faces grouped into rigid objects that represent the pillars. The registration of the location—also called the pose—of each object to the reference point cloud is formulated as a non-linear least squares optimisation problem, in which the optimal set of object poses is found by minimising the sum of squared point distance errors. A precondition for finding the objects' true poses is a sufficiently good initial guess (refer to Sandy et al. [93] and Dörfler et al. [25] for details on the implementation of the algorithm). Finally, the feedback of the as-built poses of these key objects into the architectural design and planning environment enables the CAD model of the building site to be updated. Subsequently, the brick wall's geometry can be adapted in relation to their true dimensions (see for example the poses P_0 and P_1 of the two pillars marked in blue in Fig. 3.31).

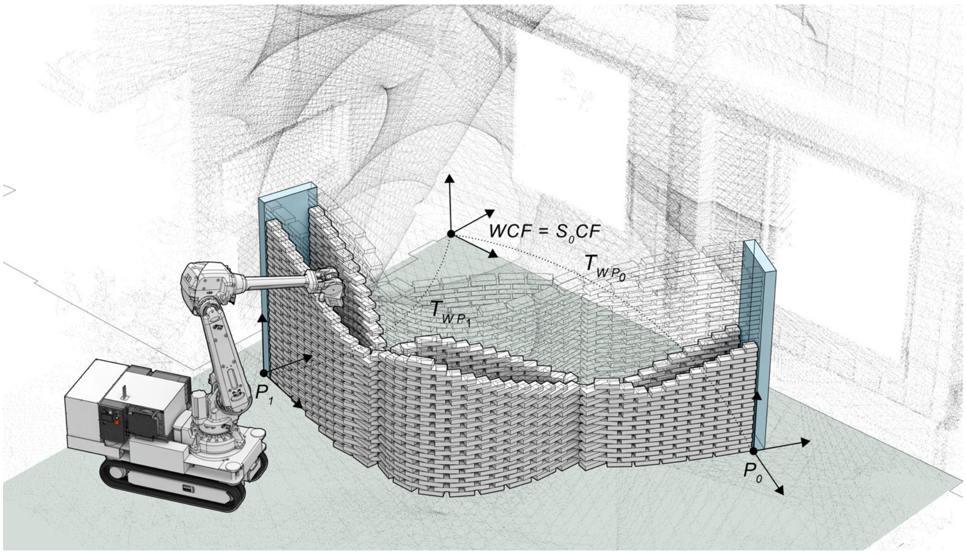

Figure 3.31: The brick wall design must be adapted to match the true dimensions of the building site—in this case the estimated location P_0 and P_1 of the attachment pillars.

The locations of the bricks within the wall's overall geometry are represented and stored by a mesh geometry. This format allows a mesh relaxation algorithm[40] to be applied; it also allows the individual brick's position, orientation and spacing to be adapted in relation to the prior estimated transformations $\boldsymbol{T}_{WP_0}$ and $\boldsymbol{T}_{WP_1}$ of the two attachment pillars (see Fig. 3.32). In the particular case of the 6.5 m long wall, the measured as-built pose of one pillar could deviate up to 30 cm and 2° from its planned location, before the changed dimension of the wall would require the number of bricks in one layer to be increased or reduced accordingly.

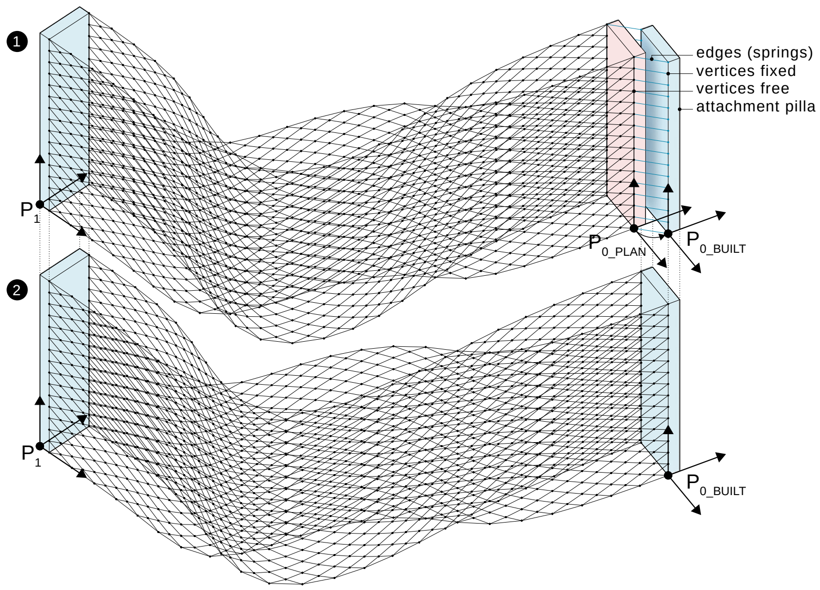

Figure 3.32: This exemplary diagram shows a mesh relaxation algorithm being performed in relation to the true location of one attachment pillar's pose P_{0_BUILT}. The algorithm pulls the sides of the mesh (the according edges are marked in blue) to the pillar and equalises the remaining edges' length and orientation in the xy-plane. The upper diagram (1) shows the mesh before the relaxation algorithm is performed, and the lower (2) shows the equalised mesh.

3.4.6.2 Localisation

To localise the robot's origin after a relocation procedure, a new point cloud $\mathbf{S}_i$ needs to be obtained each time. This point cloud $\mathbf{S}_i$ is registered relative to the initially retrieved reference point cloud $\mathbf{S}_0$. The obtained relative transformation $\boldsymbol{T}_{S_0 S_i}$, together with the prior defined $\boldsymbol{T}_{W S_0}$, eventually allows the robot pose to be estimated by the transformation $\boldsymbol{T}_{WR}$ (see Fig. 3.33, and refer to Dörfler et al. [25] for details on the implementation).

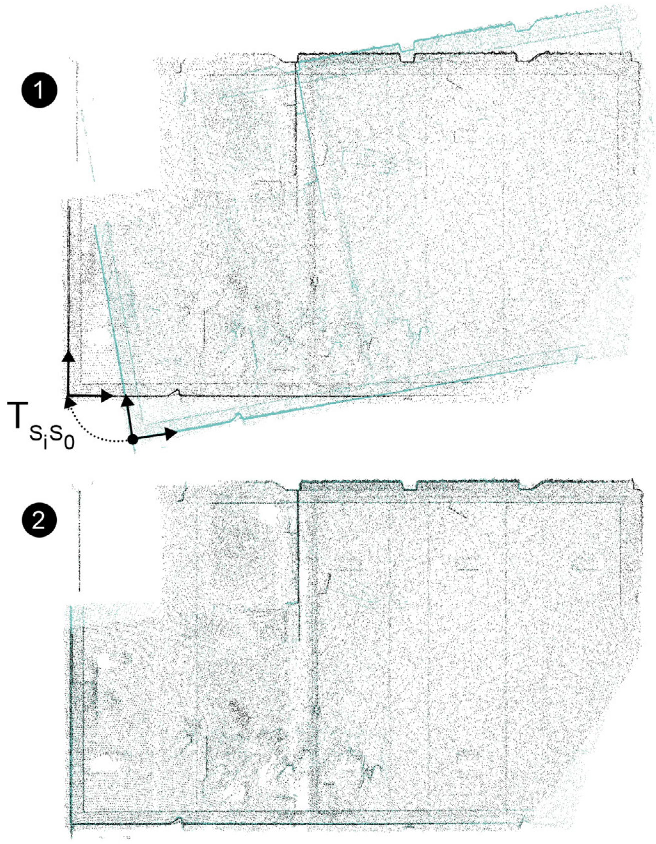

Figure 3.33: Robot localisation: Point clouds before (1) and after registration (2). The point clouds are used to find the relative transformation from the current robot map $\mathbf{S}_i$ to the reference robot map $\mathbf{S}_0$ as $\boldsymbol{T}_{S_0 S_i}$. The robot origin can then be obtained as $\boldsymbol{T}_{WR} = \boldsymbol{T}_{WS_0}\boldsymbol{T}_{S_0 S_i}$.

3.4.7 Adaptive control

After the above described workspace calibration process through mapping and alignment, and the subsequent adjustment of the final brick wall's geometry, the fabrication process can begin. To start off, the IF is manually steered by using a remote control to a first building position. Then, the calling of a 3D scan procedure by the fabrication controller allows the exact robot location to be obtained from the IF's sensing node (see Section 3.4.6.2). In relation to the obtained current location, the effective brick-laying sequence is derived from the brick wall's data structure. Subsequently, the assembly process of one patch of bricks can be performed. During the placement of the bricks, the angular value feedback of the IMU is used to compensate for the robot's tilting behaviour, which is merely a slight rotation of the robot's base. This whole process repeats after having finished the construction of each patch of bricks; the robot needs to be relocated manually, after which it automatically localises itself and then continues the construction from this new location.

The following flowchart outlines this high level fabrication control loop, which controls the low-level robotic nodes for accomplishing the wall's fabrication (see Fig. 3.34):

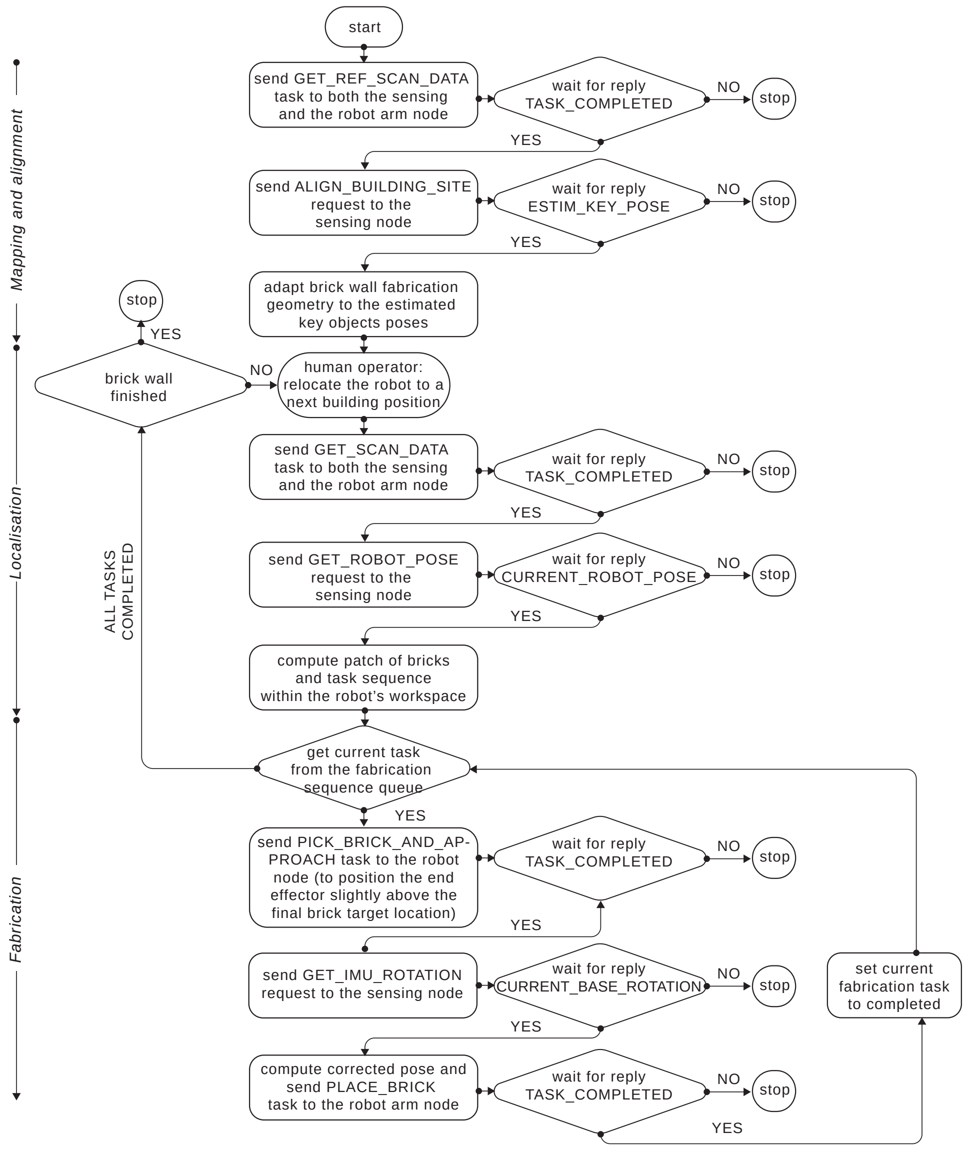

Figure 3.34: High level flow chart for the brick wall's fabrication control loop.

3.4.8 Results and validation

3.4.8.1 Results

The double-leaf brick wall was constructed from 14 successive robot locations (see Fig. 3.35) by assembling 1324 of the total number of 1600 bricks of the wall design.

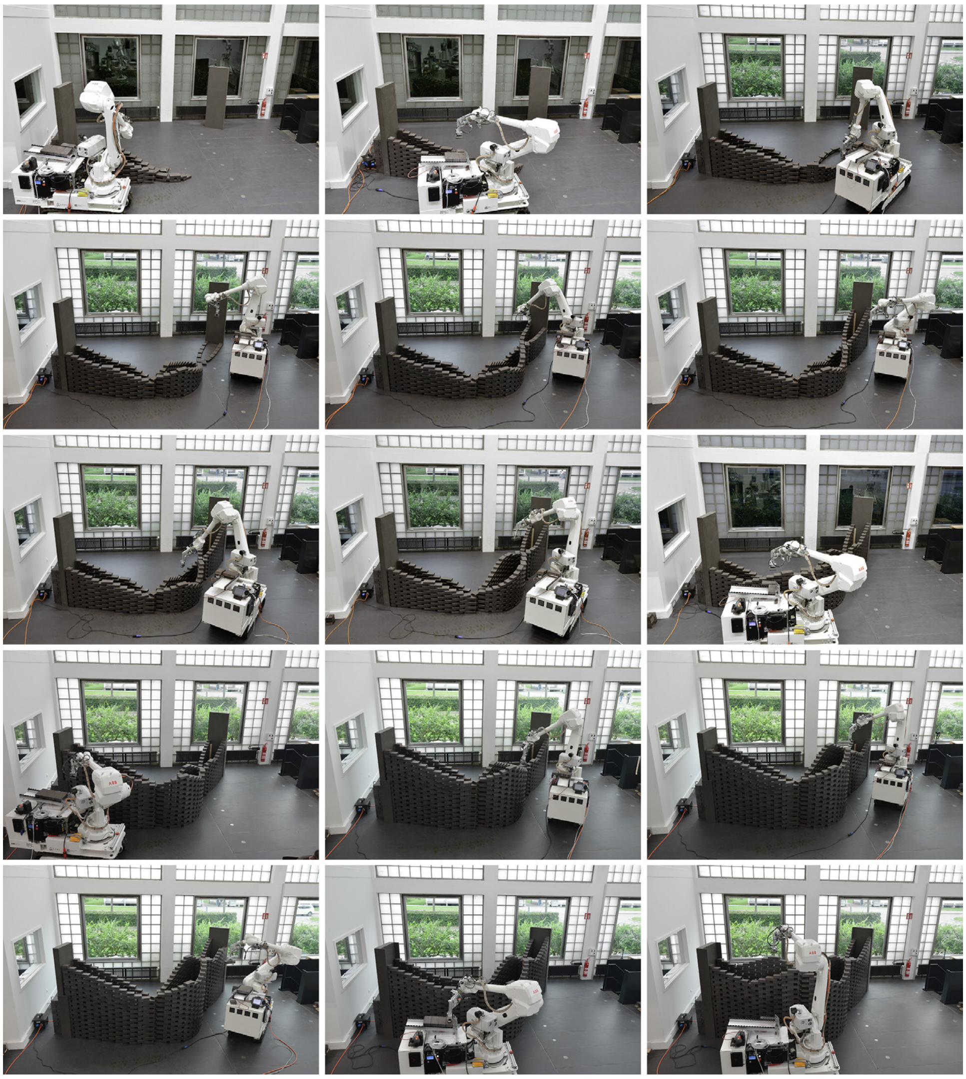

Figure 3.35: Snapshots of the mobile robotic assembly process from 14 different robot locations.

Despite the possibility to precompute an optimal sequence of robot locations and steer the robot sequentially to these locations—such as by marking them on the floor prior to fabrication—the mobile robot in this experiment was steered by an operator to an arbitrary position somewhere close along the wall to be fabricated. After this step, the robot could automatically sense and obtain its exact location, generate a respective brick-laying sequence within its static reach, and continue building with no further human intervention involved. Hence, it was possible to derive the production sequence interactively, solely depending at which exact location the operator had positioned the robot. However, due to the deliberate non-precise and therefore non-optimal human positioning of the mobile robot during construction, the number of relocations necessary for fulfilling the entire wall's fabrication increased.

Motivated by a design decision during construction, the wall was not entirely finished. This allowed the dented upper border of the brick wall—which effectively is a consequence of the logics of the assembly sequence—to remain visible after fabrication. In relation to the production speed, the average gross duration for the laying of one single brick was measured to be around 40 seconds. This gross duration included the time that was needed for relocating and localising the robotic unit. In sum, it took around 15 h to finish the full production (see also Table 3.1).

production speed	
wall height	2.0 m
wall length	6.5 m
brick size	24.0 cm × 11.5 cm × 5.0 cm
number of bricks laid	1324
number of robot relocations	14
time required for one robot relocation (incl. remote controlled driving and automated localising)	30 min
net fabrication time (pick and place) of one brick	22 sec
gross fabrication time of one brick (incl. interventions such as the manual robot relocation, automated scanning and localisation)	40 sec
percentage of time required for automated procedures versus the manual interventions	54% vs 46%
total fabrication time	15 h
robustness and accuracy	
estimated accuracy of the end effector positioning in the global workspace	± 8 mm

Table 3.1: Table of numbers relating to the production of the double-leaf brick wall.

3.4.8.2 Validation

The accuracy of the robotic sensing system for localisation was evaluated by measuring the position of placed bricks from one patch relative to its neighbour patches. In between these connecting patches, a translational error of maximum ± 8 mm between the bricks could be observed. Additionally, it was observed how accurately the wall attached to the second pillar opposite from where the robot started to build. The attaching column of bricks was measured to be off by 7 mm from the expected location. The localisation method also indicated that errors do not accumulate over the course of the building site, since each localisation scan was registered against the same *reference* scan S_0.

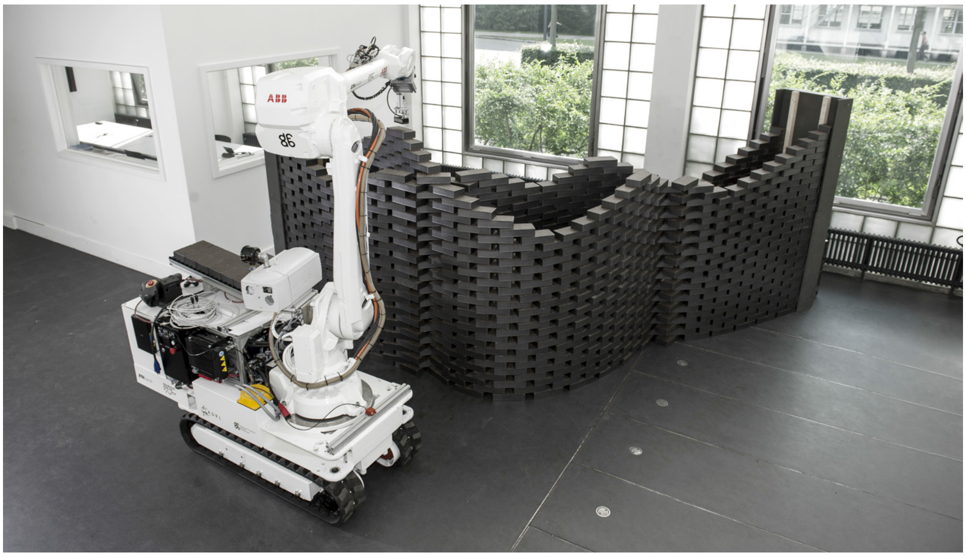

Figure 3.36: The finished double-leaf brick wall fabricated by the IF.

3.4.9 Discussion

This initial experiment of using the IF for the in situ assembly of brickwork was enabled by the multidisciplinary approach of bringing together novel robotic technologies and architecture. Its successful implementation marked a step forward towards the integration of robotic fabrication processes into construction sites. The accomplishments of the experiment can be summarised as follows: First, the developed sensing system enabled the building site to be mapped and the CAD model of the brick wall to be adapted to the true dimensions found on site. Second, the sensing system also enabled the robot to localise itself and accurately position the end effector across the entire building space with a sufficient accuracy for the chosen building task. Thus, the continuous and architectural-scale brick wall could be fabricated accurately from multiple robot locations. And third, the developed mobile assembly strategy for brick walls with a Stretcher bond allow such a wall to be fabricated continuously and with a minimum number of robot relocations.

The chosen mapping and alignment process prior to fabrication was sufficient to support this experiment. However, the process also showed its limitations. For example, the alignment required a user's specific definition, specifically which objects on the building site are defined as the key objects that need to be registered within the obtained point cloud map. Furthermore, in order for the applied automated alignment method to function properly, a good initial guess was necessary, in which the key objects are already close to their expected location. Further developments in these directions would need to support both the automated recognition of what is defined as a key object or a key feature in the environment and the segmentation of such objects into semantically meaningful pre-determined classes (e.g., wall, floor, pillar, window, door, and obstacles).

With respect to the chosen method for localisation using a laser range finder, one advantage turned out to be that the scanning and registration method requires no assumptions about the structure of the robot's surroundings a priori. Furthermore, errors did not accumulate, since all new obtained point clouds were registered in relation to the same initially obtained *reference point cloud*. However, this method required the surroundings to remain more or less unchanged, which does not fully comply with construction sites being an environment of constant changes. Since this limitation could challenge the robustness of a real-world application, attempts were made to therefore scan only the work piece instead of the surroundings (as presented in one publication by Sandy et al. [93]). However, for several technical reasons, this approach showed severe limitations, such as the wide distance requirements between a LRF and the measured object. It also proved to be unsuitable to provide the desired accuracy.

Moreover, a robot does not only need to know of its location, but it also has to be aware of the structure it is fabricating. This additional feature implies the implementation of local surveying methods that can feed information on fabrication- and material-related tolerances back to the fabrication control system. In this way, materials with more unpredictable behaviour can also be handled. The implementation of such local fabrication surveying methods has turned out to be essential for the realisation of Case Study 3 of this thesis, and this is presented in the following section.

3.5 Case Study 3: Mobile in situ rebar assembly

3.5.1 Objective

Case Study 3 describes the in situ fabrication of a steel rebar mesh for a slender doubly-curved reinforced concrete wall by deploying the IF on a real construction site. The implementation of this experiment allowed all the know-how gained from the previous two case studies to be brought together—namely the know-how obtained in adaptive fabrication control with respect to uncertain material behaviour, and the one obtained in mobile fabrication. The research objectives of this experiment can be summarised in four main points. The first objective involves the implementation of a robust sensing system that supports both the robot's mapping and localisation features, and a fabrication survey. The second relates to the development of an adaptive fabrication control method that allows for the compensation of system inaccuracies and material deformations of the structure during fabrication. The third involves the development of an integrated design and rationalisation tool for the mobile fabrication of continuous and undulated rebar mesh geometries. The fourth objective aims at the validation of strategies that have previously been developed in the lab environment and have now been transferred to a real construction site.

In short, this final case study seeks to prove that in situ robotic fabrication is not merely a future vision but that it is ready to be applied successfully in real-world construction scenarios (see Fig. 3.37).

3.5.2 Introduction

The robotic in situ fabrication process for steel rebar meshes applies a novel construction system for reinforced concrete structures named Mesh Mould [26, 27]. The system consists of robotically fabricating a double-sided steel rebar mesh on the building site. Later, this hollow mesh effectively acts both as formwork for concrete to be filled in and reinforcement after the concrete has hardened. Thus, the process facilitates the construction of geometrically differentiated, structurally informed, and monolithic and continuous structures in a material- and labour-efficient way. The construction system has specifically been chosen to demonstrate best the potentials of robotic in situ fabrication in a real world project—firstly due to the system's load bearing capabilities, and then secondly due to its applicability for mobile fabrication.

Figure 3.37: The IF fabricating the last layers of the steel rebar mesh on the DFAB HOUSE construction site.

The case study implements the in situ fabrication of an undulated 12 m-long reinforced concrete wall using the IF. This load-bearing building component is a part of the residential unit DFAB HOUSE in the Empa NEST building [29, 28].

The DFAB HOUSE is initiated to serve as a research demonstrator and driver for novel digital building technologies [94]. As depicted in Fig. 3.38, the Mesh Mould wall is situated in the ground floor of the unit. The doubly-curved building element divides the space into different zones and, at the same time, it supports a cantilevering pre-stressed concrete floor slab with a two-storey timber structure on top. In total, this wall needs to carry a load of 100 t. The design of the wall seeks to demonstrate that the structural capacity of such

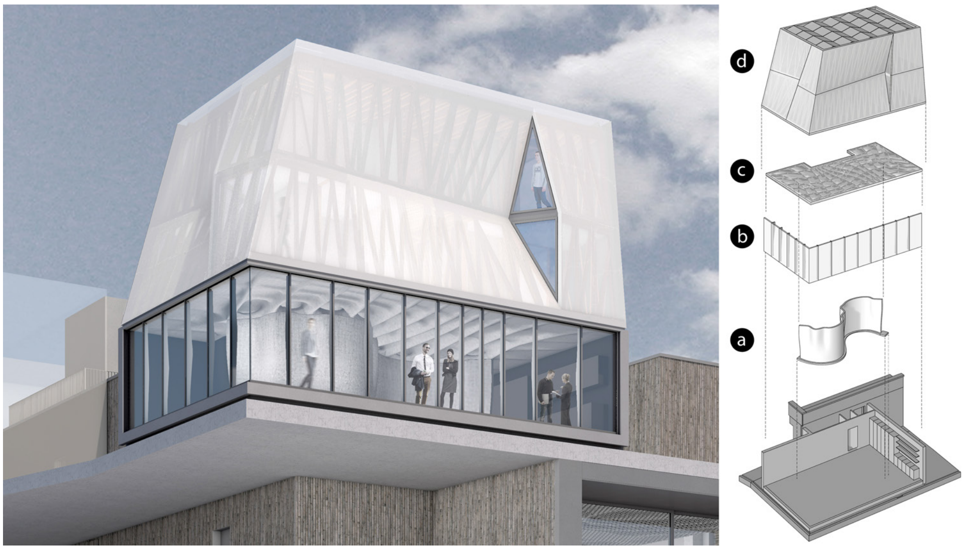

Figure 3.38: Visualisation of the DFAB HOUSE [94] of the Empa NEST building, which showcases four different innovation objects aiming to advance digital fabrication techniques: a) In situ Fabricator and Mesh Mould, b) Smart Dynamic Casting, c) Smart Slab and d) Spatial Timber Structures.

a wall can be increased by optimising its geometric shape; one possibility is by introducing double curvature at specific locations. As a result, the thickness and the material consumption of this wall can be reduced. Such a complex geometry would be very expensive and labour-intense if it was built using traditional formwork, but it would be much more efficient for the IF to apply the Mesh Mould technology. Thus, it is central for this research to demonstrate that the differentiated geometry of the steel rebar mesh can be fabricated accurately using a mobile construction robot—irrespective of the uncertain conditions of a construction site.

The multi-disciplinary nature of the case study demanded the involvement of researchers from different fields—namely those of material science, structural engineering, robotics, and architecture—plus project architects and engineers, all putting together their intense efforts in realising this pioneering project (see also projects credits in Appendix B).

3.5.3 Experimental robotic set-up

For the purpose of fabricating the steel rebar mesh, the IF is equipped with a custom developed robotic end effector able to place and weld ribbed steel rebar with a diameter of up to 6 mm. This end effector is a second generation development of the one end effector shown in Kumar et al. [27], in which the incorporated components for actuation such as feeding, cutting, and welding the steel rebar have been substantially scaled up. This up-scaling has been done to comply with the structural requirements of the on-site application, that is, the end effector needs to be able to process ribbed steel rebar up to a diameter of 6 mm (as the first generation end effector has been able to process solely steel wire with a 2 mm diameter).[41]

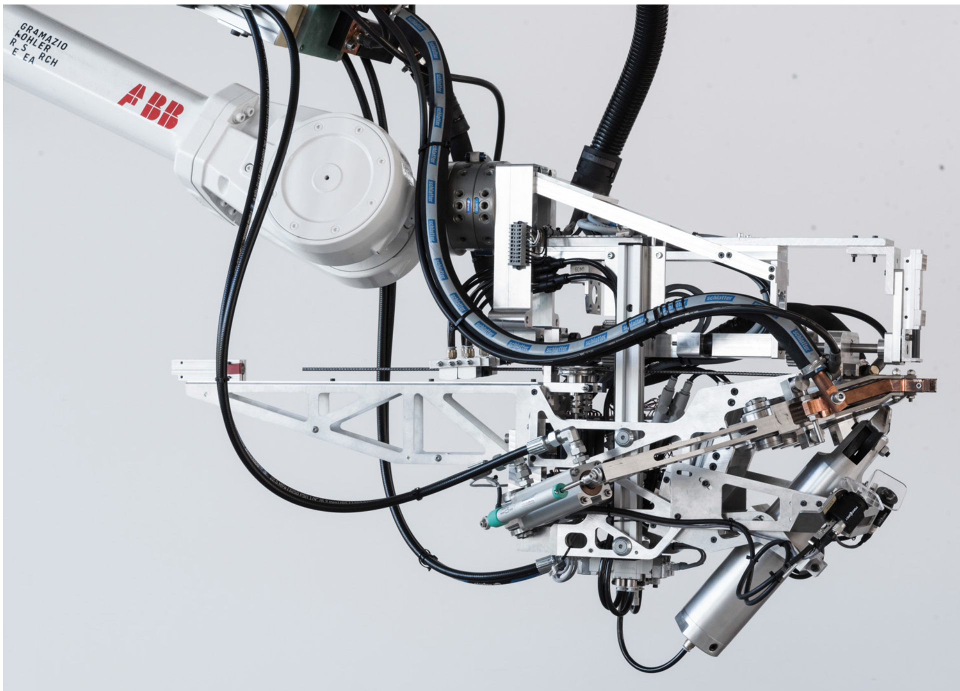

Figure 3.39: For the purpose of fabricating the steel rebar mesh, the IF is equipped with a custom developed robotic end effector.

The end effector is additionally augmented with a vision-based sensing system [95] (see Fig. 3.39) that consists both of one camera for localisation (2448 × 2048 pixel PointGrey Blackfly camera with a 8 mm fixed focal length lens) and a pair of wide-baseline stereo cameras for the fabrication survey (808 × 608 pixel PointGrey Blackfly camera with a 6 mm fixed focal length lens).

The robot's own on-board energy supply provides the necessary power for the arm and the tracks, as well as the sensing components. However, the end effector actuation components such as a hydraulic four-bar gripping mechanism or an electric welding system need to be powered from external sources.

To not impede the IF's mobility, all peripheral components are packed onto two separate pallets (see Fig. 3.40) and connected to the robot by one large cable tube with a length of 7 m. While the robot can be repositioned automatically, the peripheral components need to be moved manually as soon as the distance to the robot exceeds the length of this 7 m.

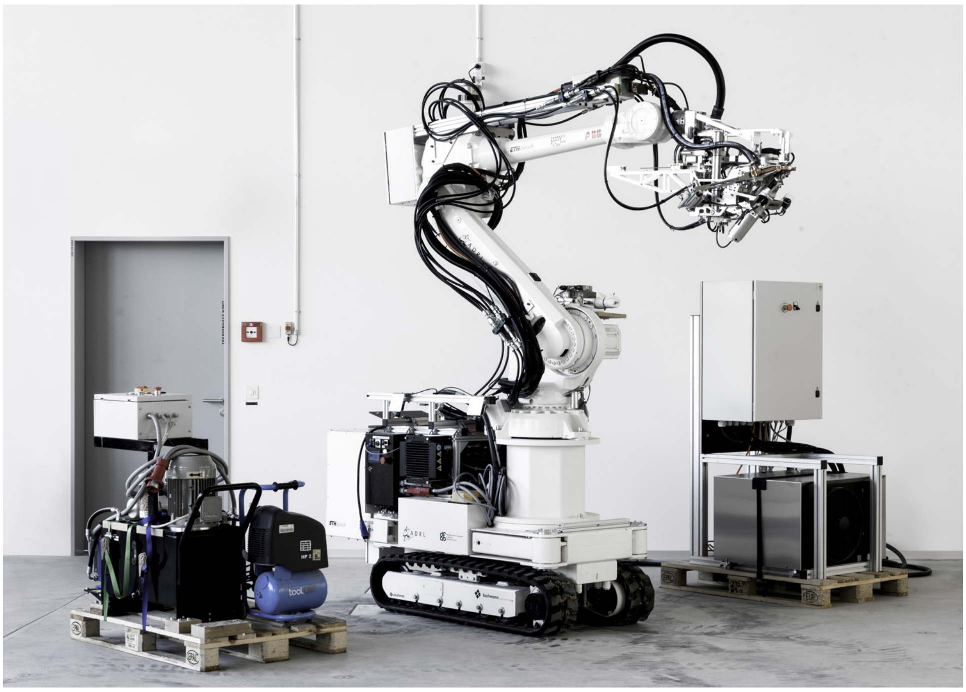

Figure 3.40: The periphery for supplying the end effector with the necessary sources of energy consists of an electronic control cabinet, water cooling (left), as well as a hydraulic and a pneumatic pump (right). A second electronic control cabinet is mounted on axis 3 of the robot arm.

As depicted in Fig. 3.41, the construction site venue—situated on the 3rd level floor slab of the NEST building—is protected by a scaffolding that shelters the robotic machinery and the material from harsh weather conditions during the time of construction. For the power supply of the robot, a building site's customary power connection of 400 V with 63 A is provided at the spot. The IF is transported inside a container and lifted up with a crane to the job site. Also, the feedstock material is delivered to the same location and stored inside the protected area; this material consists of (6 mm straightened ribbed rebar with a length of 4.0 m, and 4.5 mm straightened ribbed steel rebar with a length of 2.5 m).

Figure 3.41: The DFAB HOUSE building site on the 3rd level of NEST is weather-protected with a scaffolding covered by tarpaulins. The IF and its periphery are transported inside a container to the building site and lifted onto the same level.

3.5.3.1 On-line communication system

As shown in Fig. 3.42, controlling the in situ robotic mesh fabrication process requires communicating with four of the IF's nodes from within the architectural design and planning environment. Node 1 running on the robot arm controller can receive task primitives for movement routines such as end effector poses. Node 2 is running on an Arduino micro controller [96] that controls the robotic end effector, and it can receive actuation primitives such as closing or opening the welding gripper, feeding the rebar, activating the cutting scissors, and welding. Node 3 and node 4 are running within ROS and can receive requests for sensing, that is, mapping, robot localisation, or fabrication survey requests.

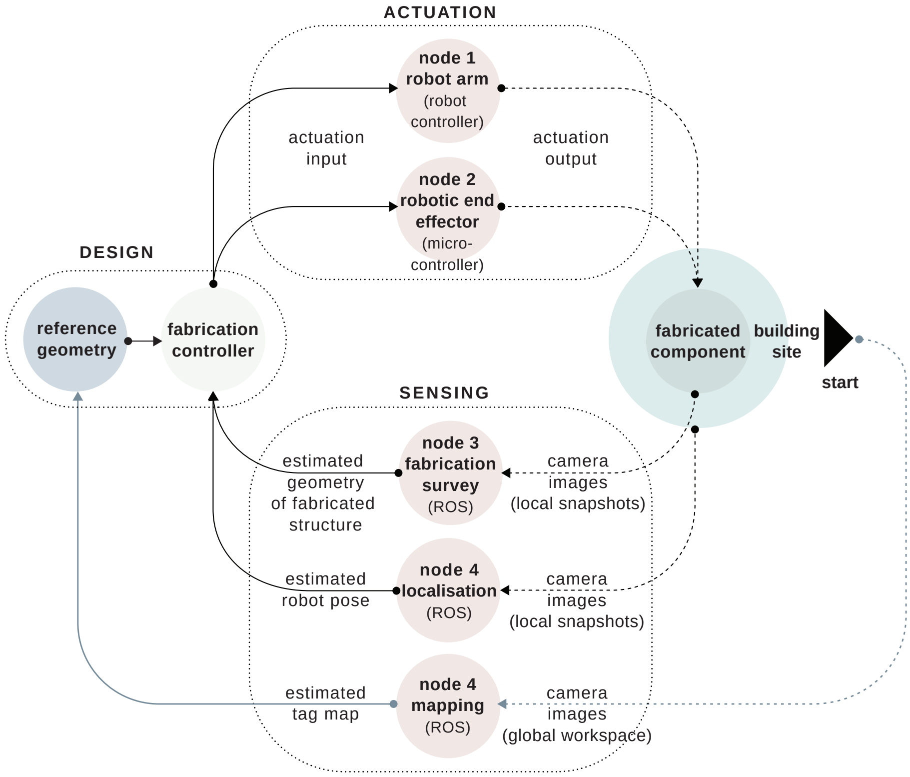

Figure 3.42: For the adaptive fabrication control, a communication to four if the IF's nodes needs to be established: 1) to the robot arm controller, 2) to the micro controller of the robotic end effector and 3) to two sensing nodes running within ROS.

3.5.4 Building material system

The Mesh Mould technology permits the construction of double-sided steel reinforcement meshes with a differentiated geometry; this can be a varying cross-section in between the sides or a double curvature of the mesh surface geometry. A custom developed end effector can position, bend, cut, and weld steel rebar and thereby fabricate a 3D mesh in a layer-based fashion. The layout of the steel rebar incorporates requirements derived by structural considerations as well as constraints imposed by the mesh filling process (for further details refer to Kumar et al. and Hack et al. [27, 26]). The mechatronic design of the robotic end effector is therefore designed in such a way that it allows for a maximum geometric flexibility in the mesh fabrication and complies with the given requirements. Hence, the development of an integrated design and fabrication method for the in situ fabrication of steel rebar meshes using a mobile robot requires the implementation of a geometry rationalisation tool, which would take into account all the fabrication- and site-related boundary conditions. The principles applied for this process are described in the following sections.

3.5.4.1 Mesh topology and fabrication constraints

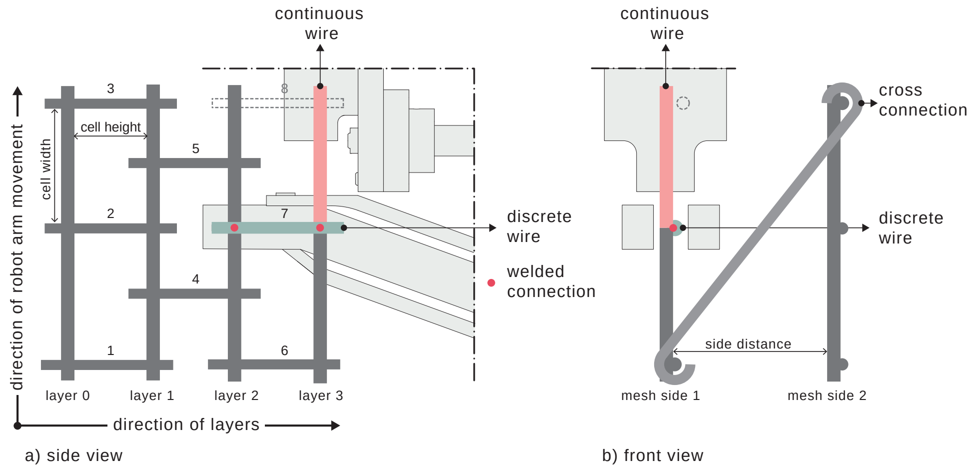

Figure 3.43: This diagram shows the mesh topology and a silhouette of the end effector in the background. In a), the side view of successive layers of continuous rebar being connected by short discrete rebar elements through a cross wire welding connection are shown. One process step of the fabrication is represented by both the lines of a continuous (red) and a discrete (blue) rebar element, and the two points of the welded connection (marked as red dots). The numbers indicate the sequence of the process steps of the layer-based fabrication; b) shows the front view of the double-sided mesh. The two mesh sides are coupled to each other at a few locations by manually inserted cross connectors.

As shown in the side view in Fig. 3.43, the mesh topology is non-uniform, and it consists of a *continuous* and a *discrete* direction. Layers of long continuous ribbed steel rebar with 6 mm in diameter are successively welded with short discrete elements of ribbed steel rebar with 4.5 mm in diameter in order to form a stable reinforcement mesh. One process step of this fabrication process is marked in colour. The front view in this diagram shows the two robotically constructed sides of the mesh. These mesh sides are connected to each other with cross connections that need to be inserted manually at a few locations (e.g., each fifth welding node in every fourth layer).[42] A curvature in the continuous direction is achieved by bending the continuous rebar with the end effector at successive locations within the range of its elastic deformability. The welded connections at these locations with the short discrete rebar elements keep the elastic deformation in place. This curvature, together with the angle of the short discrete rebar elements between two consecutive layers result in the desired double curvature of the mesh.

The geometry of the end effector generates a number of geometric constraints for the mesh. The distance between the two sides of the mesh can vary; however, in order to avoid a collision between the end effector and the mesh, a minimum distance of 75 mm between them needs to be kept. The cell height is the distance between the layers of continuous rebar, which can vary in between 28 mm and 42 mm; the cell width is the distance between the short discrete rebar elements, which cannot be less than 35 mm. With respect to the material behaviour, only one significant constraint matters: Since the continuous rebar is deformed elastically while bending and not plastically, a maximum curvature radius of 1.8 m has been defined heuristically through a number of tests.

3.5.4.2 Geometry rationalisation for mobile fabrication

To allow for a continuous fabrication with the least number of robot relocation routines along the wall, it is optimal if the mesh expands horizontally along the mobile robot's path. As a consequence, the mesh has to be constructed in vertical layers, as opposed to the horizontal layers that are known from conventional 3D printing processes. This method results in the continuous rebar being oriented in the vertical direction. The vertical orientation of the continuous rebar elements has the further advantage of complying with the predominant vertical direction of the forces acting on the wall.

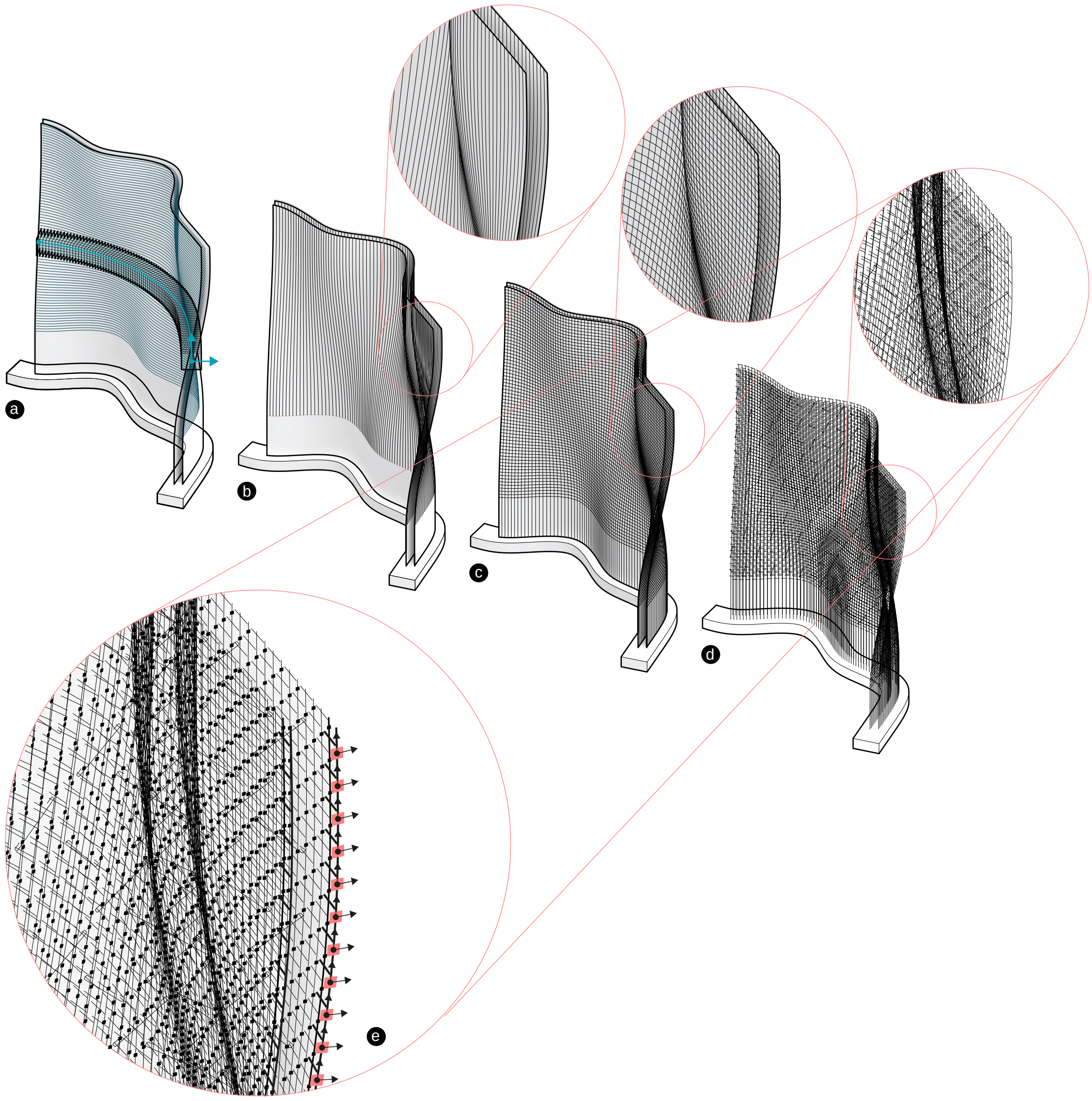

Figure 3.44: Rationalisation process of a surface geometry into a Mesh Mould mesh, containing all necessary information for fabrication.

The rationalisation of a given surface geometry (NURBS surface) for fabrication with respect to the system's boundary conditions is accomplished as follows: In order to generate the vertical layers for the mesh, a surface geometry is first sliced vertically with a sequence of planes perpendicular to a horizontal slicing curve (marked in blue in Fig. 3.44 a). This horizontal slicing curve is calculated as a weighted average curve from a set of curves that slice the surface geometry horizontally (marked in darker blue) in such a way that the cell heights in the horizontal direction are distributed evenly in between the range of the defined height constraints. The optimal even distribution is found by using an incremental search algorithm that searches through a sequence of weight parameters for averaging these curves. The resulting vertical slicing curves (see Fig. 3.44 b) are then the basis for generating a mesh geometry according to a defined cell width (see Fig. 3.44 c). In the final step, the created mesh is used for calculating both the actual fabrication data and the final steel rebar mesh geometry. The vertical cell edges of the mesh represent the continuous rebar, while every second horizontal cell edge (alternating layer-wise) represents a discrete rebar element. In this way, all necessary information for fabrication are derived from the mesh geometry (see Fig. 3.44 d); this information can include the end effector poses for positioning the continuous rebar or the angles for inserting the discrete rebar elements. Consequently, in Fig. 3.44 e, a sequence of robot end effector poses on one side of the generated steel rebar mesh is shown and marked in red.

3.5.4.3 Constructive constraints

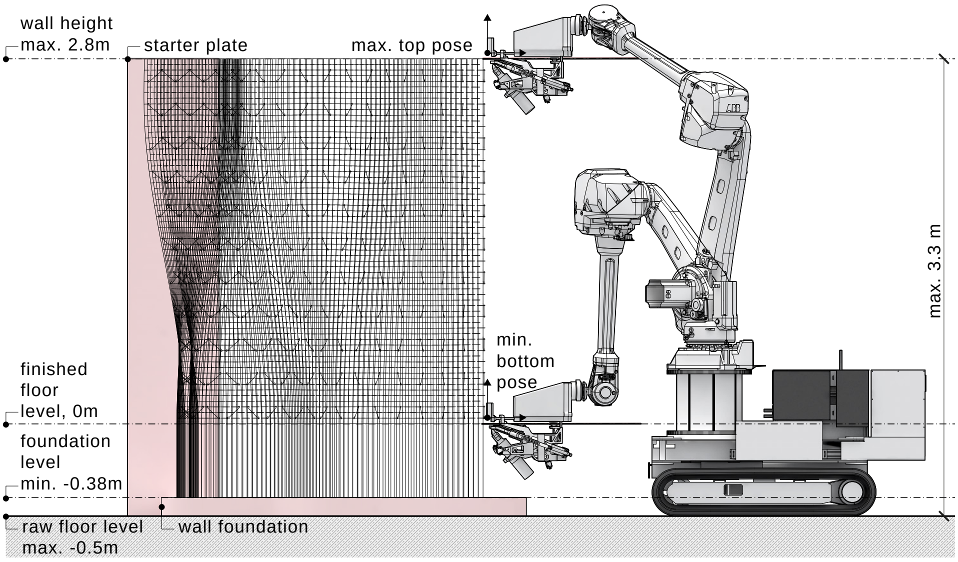

Figure 3.45: Side view showing the construction-specific constraints in relation to the wall height and foundation.

To be able to fabricate the mesh directly on the building site, a few additional constraints have to be taken into account (see Fig. 3.45). First, the end effector geometry does not allow the fabrication to be started directly from the ground up. In order to avoid a collision with the floor, a minimum height of 380 mm of the first welding pose has to be guaranteed (see bottom end effector pose in Fig. 3.45). This minimum distance implies that the steel rebar mesh geometry can only be curved above that required height. However, for the wall in the DFAB HOUSE, this constraint is not of a particular issue, since the finished floor level is installed above. Second, the maximum wall height, which is constrained by the robot's kinematic reachability, needs to be below 3300 mm (see top end effector pose in Fig. 3.45). Third, fabricating in vertical layers requires an installation of a vertical support structure from which the fabrication can start from, referred later to as the *starter plate.* As soon as a section of the steel rebar mesh is fabricated and is standing stable by itself, this starter plate can be removed.

3.5.5 Design objective and generative tools

3.5.5.1 Design tool

To enable the exploration of possible wall geometries that take into account the constraints of the Mesh Mould material system as well as the boundary conditions of the mobile robotic fabrication, a custom computational design tool was developed. In essence, the concept for the wall's geometry generation follows the assumption that local undulations in the global surface geometry increase the wall's stiffness and load bearing capacity. Therefore, the wall's thickness and overall material consumption can be reduced. With respect to that logic, this tool allowed an oscillating surface geometry to be generated on the basis of the following input parameters: 1) a 2D base curve; 2) a wall height and thickness; 3) an amplitude, a frequency, and weight parameters or attractor points for influencing the amplitude of the oscillations; and 4) a set of wall undulation typologies (see Fig. 3.46).

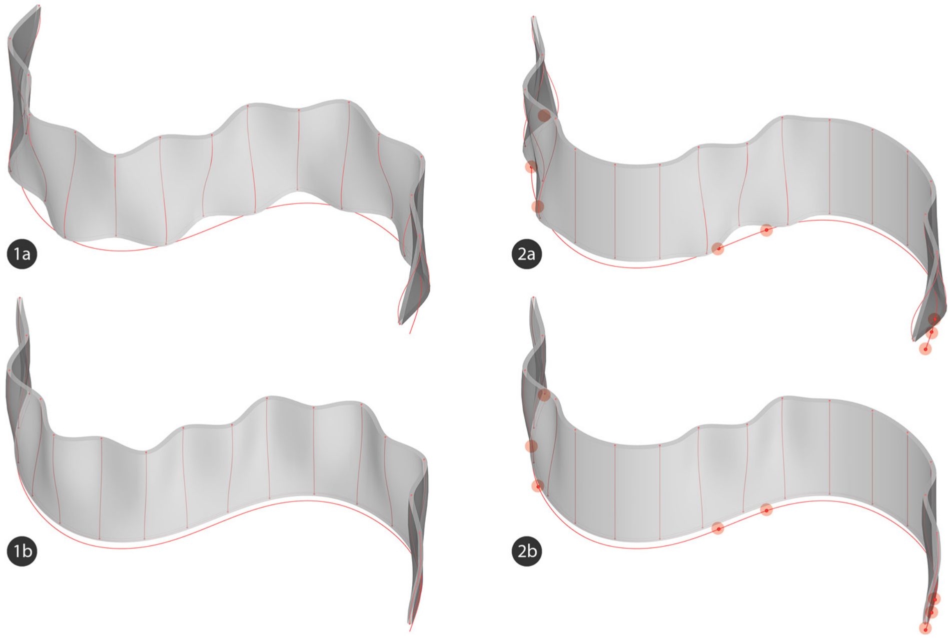

Figure 3.46: In 1a and 1b, the image shows two typologies of wall undulations generated on the basis of an input curve and an equally distributed frequency and amplitude. In 1a, the wall typology 'undulated top and bottom' is shown, and in 1b, the wall typology 'undulated top'. In 2a and 2b, the image shows how attractor points on the input curve can influence the weight parameters for the height of the amplitude. The wall undulations can thus be differentiated locally, depending on the attractor points' location.

The design tool allows the generated wall geometry to be rationalised for fabrication and also to be verified if the geometry exceeds certain fabrication constraints or causes collisions with the end effector; this constraints can be curvature values in the continuous or discrete rebar direction, the cell width and height, or the distance between the two sides of the mesh. Regions of the wall that violate certain design limitations and cannot be fabricated are subsequently marked in red. The display of this information allows the designer to iteratively refine the design until all the parameters are satisfied and the wall can then be built (see Fig. 3.47).

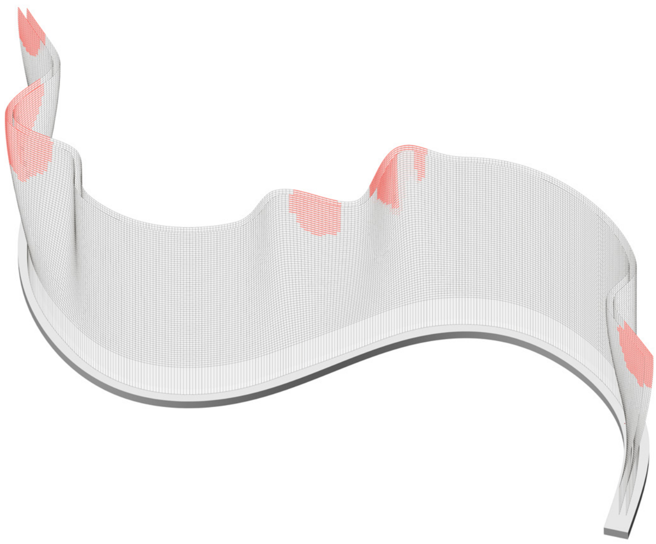

Figure 3.47: The design tool for the wall allows the designer to be informed about the fabrication constraints. As illustrated by this example, a too high amplitude results in exceeding the limits for the cell height constraints at certain regions of the mesh. These regions are marked in red accordingly.

3.5.5.2 Design evaluation

To explore and physically evaluate the different design variations, a number of generated geometries is 3D printed in 1:25 models (see Fig. 3.48).

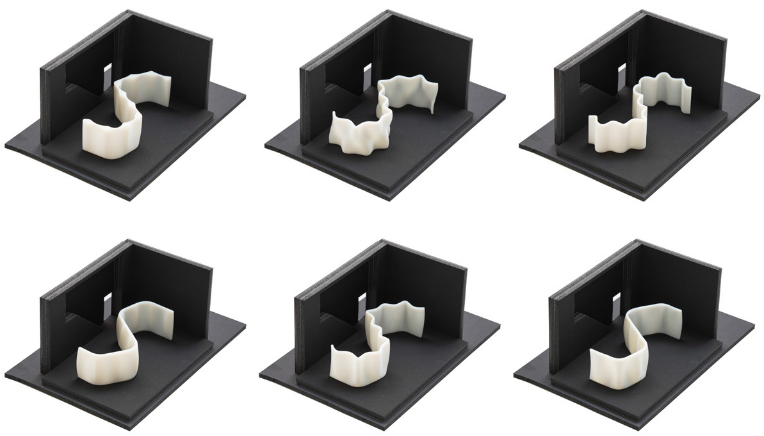

Figure 3.48: A set of generated design outputs are 3D printed in the scale of 1:25, in order to explore and physically evaluate their spatial qualities.

A deliberate selection is also checked and evaluated in relation to the wall's structural performance. For this structural evaluation, a simplified FEM elastic model based on structural tests of the Mesh Mould material system (for details of the structural load tests, refer to Hack et al. [26]) is implemented.[43] The computational framework COMPAS [97] allows an interface to be established to the FEM tool Abaqus, and thus different variations can be automatically evaluated in a comparative fashion from within the architectural design and planning environment. As shown in Fig. 3.49, the output confirmed the assumption that the wall is likely to increase its structural performance through local undulations.

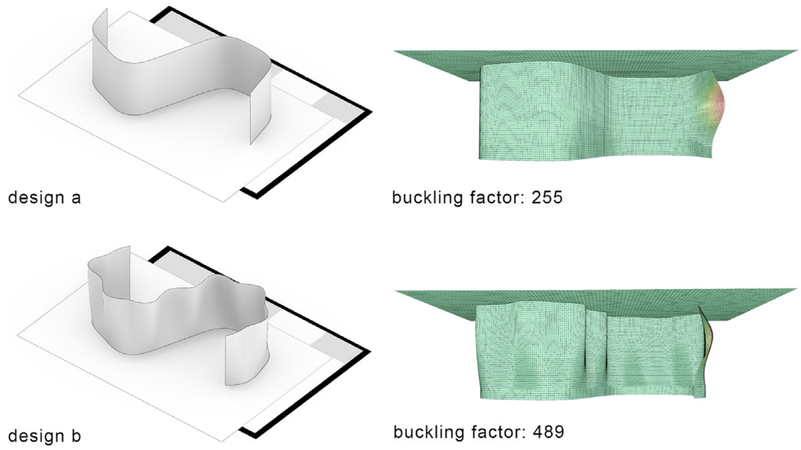

Figure 3.49: Structural evaluation: If the wall is locally undulated, an increase in the buckling factor can be observed. The numbers indicate that in comparison to the straight extruded wall, the undulated wall may buckle only under double the compressive load.

The final chosen design undulates only those regions of the wall, in which this intervention has the most effect on the structural performance—namely the ones with a low curvature of the input curve. This low curvature applies to both the ends of the wall and the middle part, while the other regions thus remain single curved. Aside from this, the wall is only undulated at the higher up region. The lower region (up to a height of 1.2 m) remains untouched and single curved in order to offer the future inhabitants an inviting space in which they can reside along the wall freely.

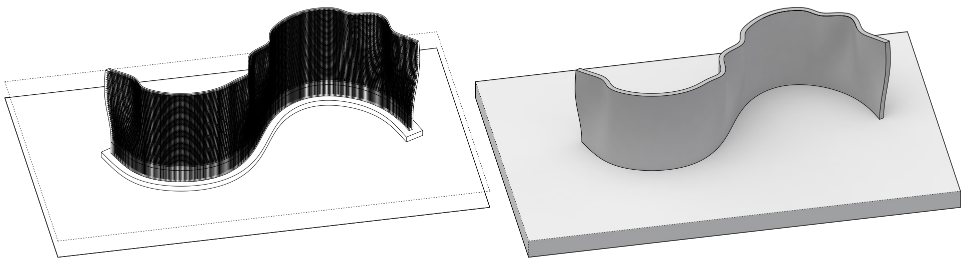

Figure 3.50: Final design for the Mesh Mould wall: The mesh foundation area disappears later below the finished floor level.

3.5.5.3 Fabrication sequence for mobile fabrication

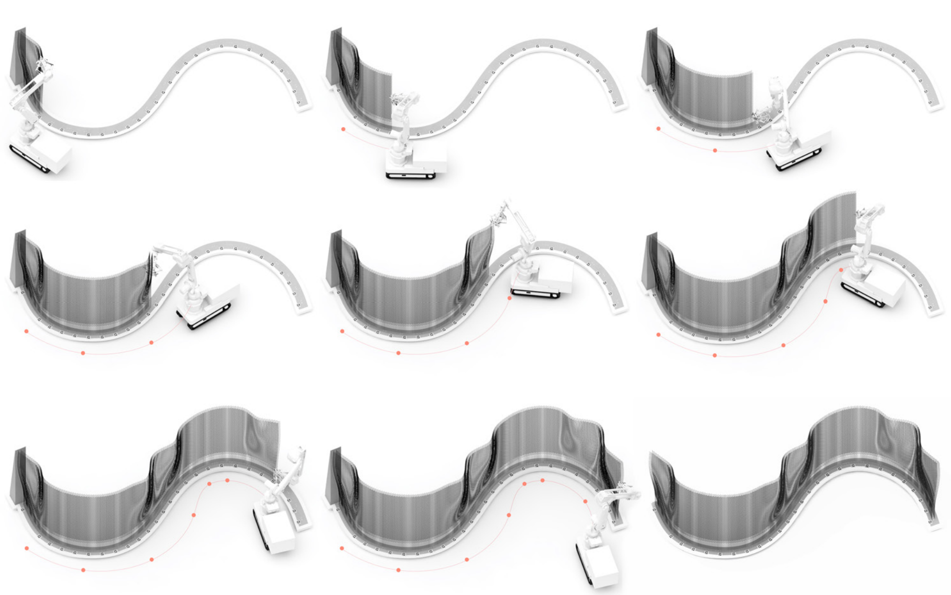

Figure 3.51: Visualisation of the mesh fabrication sequence from eight robot locations, which are needed to complete the wall's construction. The mesh is fabricated to its full height in vertical layers, which allows the geometry to expand horizontally along the mobile robot's path.

The steel rebar mesh can be produced continuously in vertical layers, which subsequently expand along the mobile robot's path. This fabrication logic allows the IF to construct the full 2.8 m height of the wall at once and to complete the 12.0 m long wall by relocating only 8 times (see Fig. 3.51).[44]

3.5.5.4 Connection details

Finally, as shown in Fig. 3.52, the robotically fabricated steel rebar mesh needs to be complemented by a set of connection details, and these are manually installed prior and during the robotic fabrication process. These complementary details of the mesh attend the wall's foundation, the open endings of the sides, and connection to the ceiling; their manual installation points towards a synergistic human-machine collaboration of such a process.

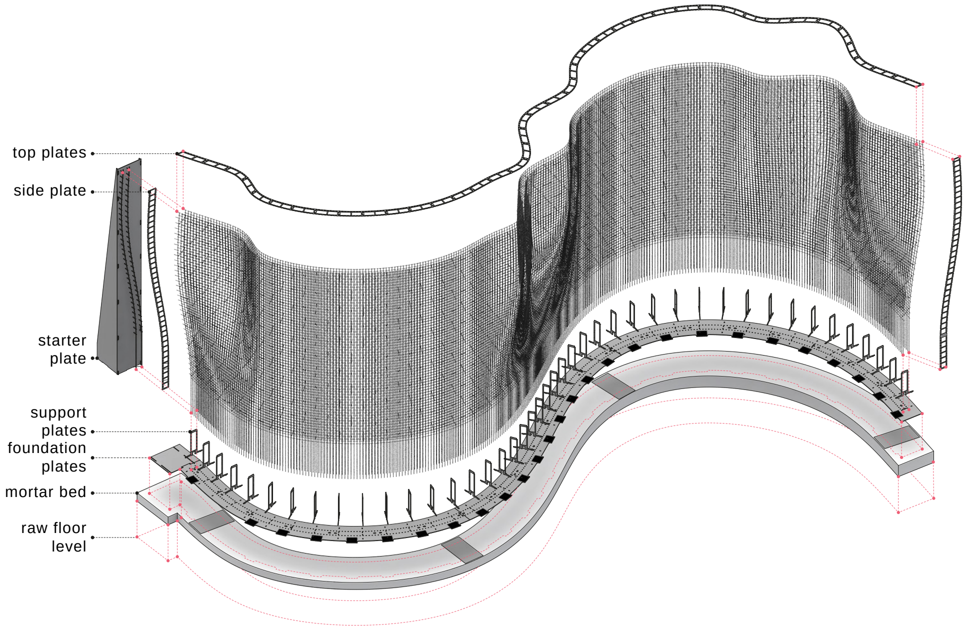

Figure 3.52: Visualisation of the NEST floor slab building site, showing an explosion graphic of the wall's foundation, the robotically fabricated steel rebar mesh and all laser-cut steel plates covering the open ends of the mesh.

As illustrated in Fig. 3.53, both the wall's foundation and the starter plate are installed prior to the robotic fabrication process. The foundation consists of a 6 mm thick laser-cut steel plate that is mounted on top of a levelled mortar bed, which rests on the inclined raw concrete floor slab. In order to absorb shear forces, this plate is fixed with a set of 20 mm anchors placed in pairs with a distance of 400 mm to the slab. The plate also has a sequence of holes, into which the 6 mm continuous rebar of the mesh can successively be inserted and welded during fabrication. Additionally, it carries a set of AprilTag fiducial markers for the robot's localisation (as described later in 3.5.6.2). The starter plate is mounted perpendicular to the base plate and holds the first layer of steel rebar, from which the robot can start off the fabrication. Fig. 3.52 also shows a set of 6 mm thick laser-cut steel frames that reinforce the open top, the open sides, as well as the foundation area; the frames are placed and welded manually to the steel rebar mesh during fabrication.[45]

Figure 3.53: The wall's foundation and the starter plate are installed manually prior to the robotic fabrication.

3.5.6 Mapping, alignment and localisation

For localising the robot's pose on the construction site, a camera mounted at the robotic end effector recognizes AprilTag [98] fiducial markers (later referred to as tags) that are distributed across the entire job site (see Fig. 3.56). The tags are stuck close to the work piece onto the foundation plate of the wall (see Fig. 3.54). This proximity has the advantage in that no occlusion between the tags and the robot can occur. Thus, the sensing and localisation during fabrication does not interfere with other actions taking place at the building site.

Figure 3.54: AprilTag fiducial markers [98] are stuck to the foundation plate of the wall. A camera at the end effector of the mobile robot IF detects the the transformations of multiple tag poses as $\boldsymbol{T}_{WS_i}$, which allows the robot to identify the transformation of its pose to the world origin as $\boldsymbol{T}_{WR} = \boldsymbol{T}_{RS_i}\boldsymbol{T}_{WS_i}$.

3.5.6.1 Mapping and alignment

For creating the tag map $\mathbf{S}_0$ prior to fabrication, a sequence of images taken by the localisation camera from various positions along the wall needs to capture the full number of tags (each having a unique ID) on the building site. This sequence of images can then be merged to construct the 3D representation of the set of tags on the site as map $\mathbf{S}_0$. A limited number of tags serves as *reference tags*; in this described use case, there are five. These reference tags need to be placed with absolute accuracy according to their location in the CAD model and are thus placed and measured in with the assistance of a total station. The rest of the tags are placed arbitrarily with a distance of around 30 cm to 40 cm to each other. Then, in a one-time workspace calibration step, this tag map is aligned with the CAD model by knowing the absolute position of the reference tags. As shown in Fig. 3.55, this allows the map's transformation to the world coordinate frame to be identified as $\boldsymbol{T}_{WS_0}$.

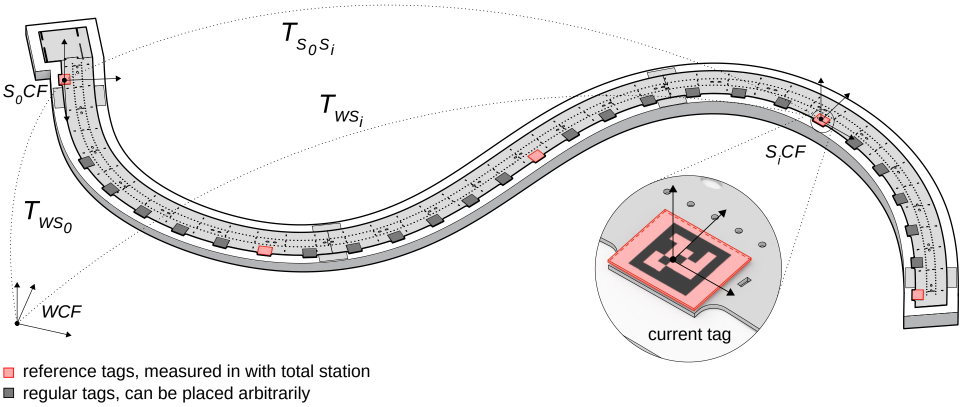

Figure 3.55: The tag map captured by the camera prior to fabrication is aligned with the CAD model by knowing the absolute position of a number of references tags (coloured in red). As a result, the transformation from the world origin pose to the origin of the tag map can be identified as $\boldsymbol{T}_{WS_0}$, and accordingly, every tag within the map as $\boldsymbol{T}_{WS_i}$.

3.5.6.2 Localisation

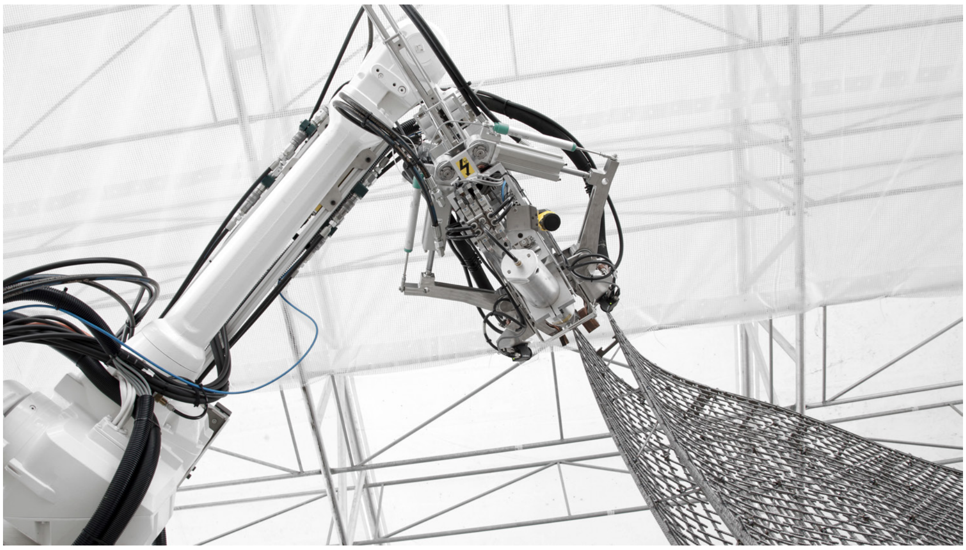

Figure 3.56: The Mesh Mould end effector is outfitted with a vision based sensing system. One camera of this system points downwards and serves to recognize tags for localising the robot at the building site. Two more cameras point towards the built structure and can thus survey the fabrication.

Over the course of the construction, the robot can estimate its own pose solely from images taken by the localisation camera on the end effector pointing downwards. By recognizing the poses of the tags that are stuck to the foundation plate, the transformation of the robot's pose $\boldsymbol{T}_{WR}$ can be obtained at any location along the wall (see Fig. 3.55 and see Lussi et al. [95] for details on the implementation).

3.5.7 Fabrication surveying and adaptive control

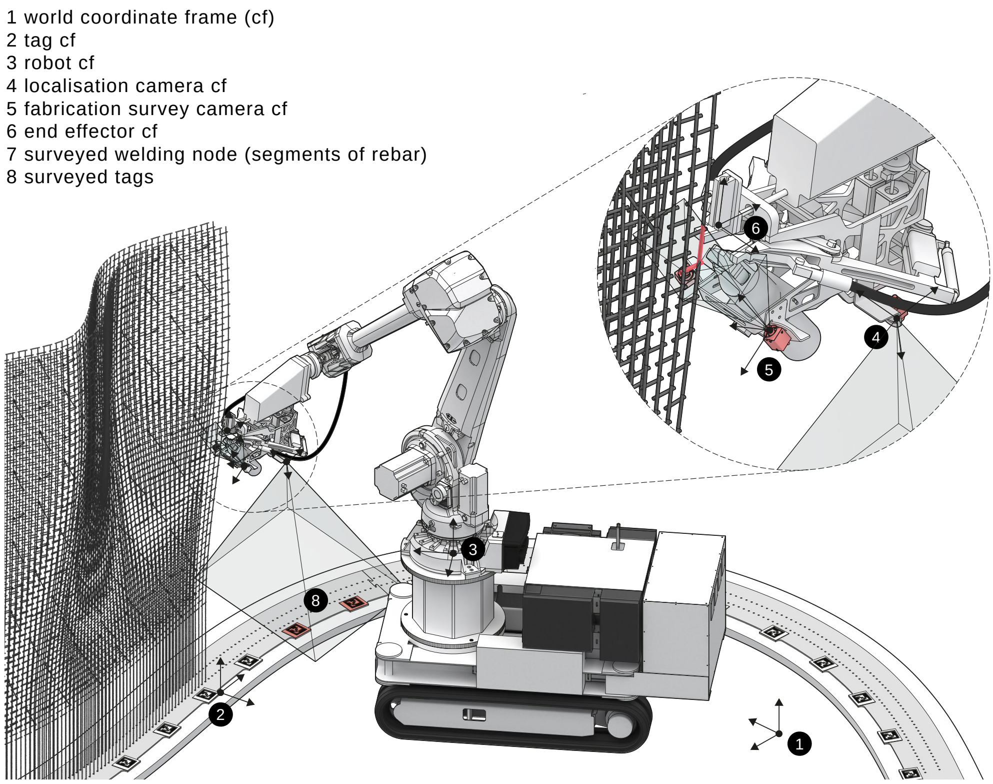

Figure 3.57: Illustration of the IF's complementary vision system with one camera at the end effector used for the detection of the tags, and two more for the in-process detection of the rebar mesh. The image also shows the various coordinate frames (CF) used in the sensing system.

In addition to estimating the robot location on site with an on-board vision system, complementary sensing solutions are necessary, which allow the fabrication process itself to be surveyed (see Fig. 3.57 for the complementary sensing system set-up). Since the in situ mesh fabrication is characterised both by numerous process uncertainties (e.g., deformations due to inner forces caused by the rebar's elastic deformation, deformations caused by welding heat) and by estimation inaccuracies in the robot's localisation, deflections in the mesh can occur during fabrication. These deflections not only lead to a mesh not meeting the accuracy requirements, but they can also cause major collisions between the end effector and the mesh when positioning and welding the discrete rebar elements. Because these deflections are almost impossible to model and anticipate, the chosen strategy is to observe the actual deformation and to locally compensate for deflections while building. This proceeding is similar to the way the fabrication has been surveyed and adaptively controlled in Case Study 1. However, there are some differences in this experiment, namely the accuracy requirements for the in-process survey are increased and lie in the range of $\pm$ 5 mm. Additionally, this survey is performed with an on-board sensing solution integrated into the IF.

3.5.7.1 Fabrication survey

For the in-process fabrication survey, a pair of cameras is mounted on the sides of the robotic end effector, forming a wide-baseline stereo vision system. To be able to occlude and shield away the background while taking measurements, two blinders are additionally mounted on the sides. By moving the end effector along the continuous vertical rebar, the sensing system can successively estimate the 3D position of each welding node and express it in the current robot pose $\boldsymbol{T}_{WR}$ (see Fig. 3.58, and refer to [95] for implementation details).

This procedure, which is referred to as *scanning*, allows the continuous wire contour of one full layer to be extracted. It is important to mention, that this scanning process cannot take place while fabricating one layer because the end effector is attached to the mesh and tends to pull the mesh into its direction. Therefore, the scanning process happens after the fabrication of one layer, at a point when the mesh is in a tension-free condition. Additionally, it has been observed that it is sufficient to scan only one side of the mesh. Since both mesh sides form a strong structural compound activated by the cross connections, the deflection occurs in both sides by the same amount.

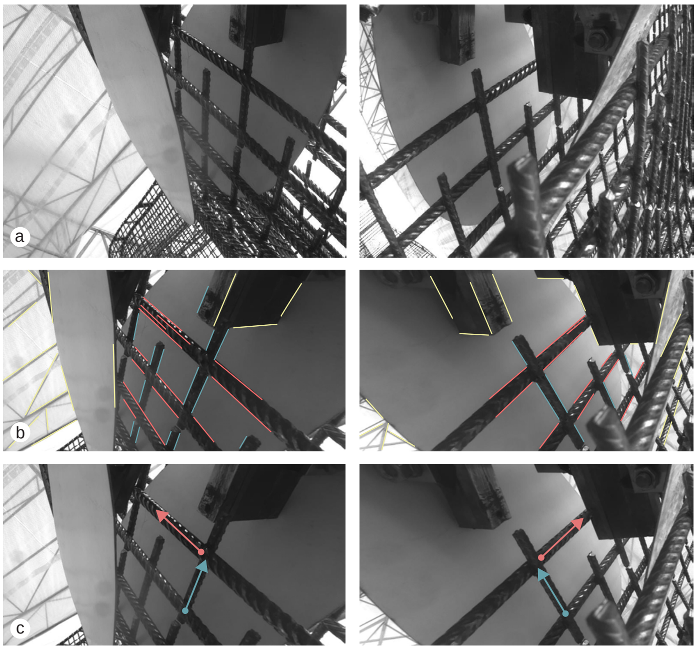

Figure 3.58: Steel rebar mesh detection enabled by the onboard vision system of the IF: In a), the image shows the camera view while surveying one welding node along the continuous rebar's contour. In b), lines are recognized in the rectified camera image, and subsequently filtered to identify the lines of one welding node. In c), the location of this welding node is then represented by a pair of two lines, one for the continuous (red) and one for the discrete (blue) direction of the rebar elements.

3.5.7.2 In-process adaptation of fabrication data

After scanning, the deformation of the mesh is calculated by comparing the expected reference location (given by the CAD model) and the estimated location (recognized by the sensing system) of each segment of the continuous rebar contour. Fig. 3.59 shows a sequence of steel rebar layers with their effective contours; each layer consists of 34 estimated wire segments. The deviation values are obtained by comparing the midpoints of the estimated line segments of one welding node to their expected location in the CAD model.

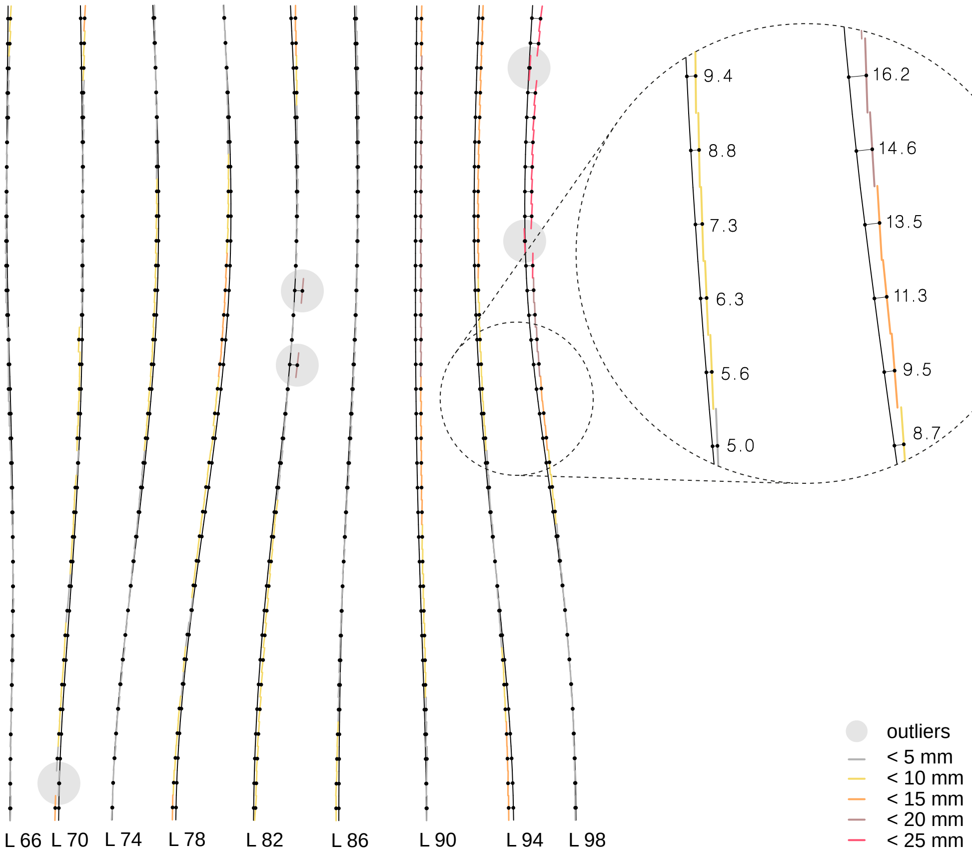

Figure 3.59: Sequence of estimated continuous rebar contours that are compared to their expected location in the CAD model. A color code indicates the amount of deviation (distance from midpoint to midpoint of the estimated and expected line segments), and outliers are marked with a grey circle. If the deviation exceeds 25 mm, the steel mesh detection tends to fail. In this selection of 297 estimations taken from the experiment, 5 outliers have been identified. The deviation values of these outliers then need to be estimated by interpolating their neighbour values.

Finally, to compensate for the estimated deviations and to fabricate the mesh according to the reference geometry, a correction value is calculated for the welding angle α of the discrete short rebar elements that connects the two subsequent layers. This compensation method has been developed empirically, and it was found to be the most effective one after a series of tests. During this testing time, other strategies to counteract the mesh deflections have also been tested, for example, by correcting the locations of the continuous rebar segments instead of correcting the insertion angles of the discrete ones.

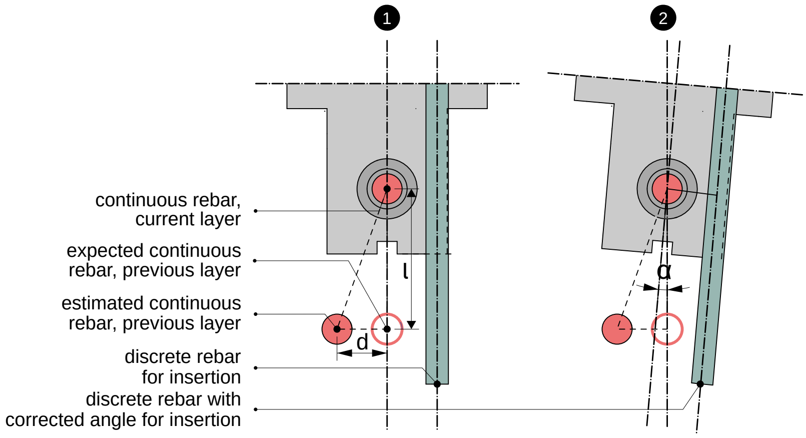

Figure 3.60: This diagram illustrates the in-process adaptation of the welding angle α for a single welding node, viewed in the direction of the continuous rebar: The observed error d in the left image generates the correction angle α in the right image. The mesh is reaching its desired corrected shape after n layers, in this image, $n = 4$ (and $f(c, h) = 1$).

The corrected angle α is calculated for each welding node as follows (see also Fig. 3.60 for illustration):

$$\alpha = \frac{\tan^{-1}(\frac{d}{l})}{n} f(c, h)$$

in which d is the distance between the expected continuous rebar and the estimated one in the previous layer, n is the number of layers taken into account for correcting the geometry, and l is the cell height (mentioned before as the distance between two subsequent layers). The function $f(c, h)$ is referred to as the correction factor and a weighting that adjusts the amount of correction, depending on the curvature value c of the steel wire and the z-value h of the welding node. A high dependence on these two parameters for the mesh deflection has already been observed while testing the fabrication process in the lab, and later also on the construction site.

3.5.7.3 Adaptive fabrication control loop

The entire steel rebar mesh is fabricated from only eight successive robot locations (see also Section 3.5.5.3). At each location, a patch of 40 to 80 layers can be fabricated; the number varies due to wall's geometry and the robot's workspace constraints. These robot locations are calculated a priori and marked on the floor accordingly. One relocation procedure is performed by manually steering the robot base with the remote control to a marked location (with an accuracy of approximately ± 20 cm and ± 5°). The supporting legs are then unfolded to stabilise the base,[46] and the arm is steered to a location from which the tag locations can be recognized by the sensing system and the robot pose estimated (see also Section 3.5.6.2).[47]

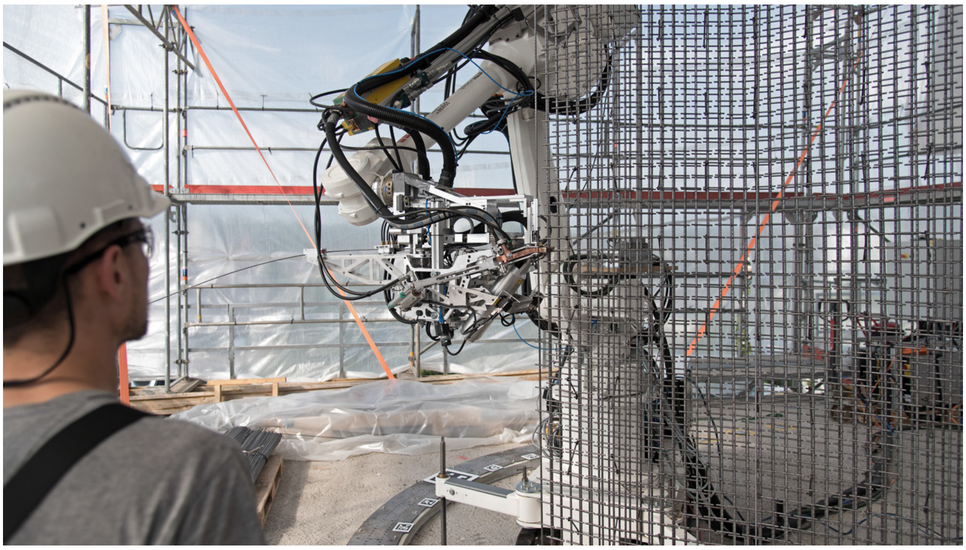

Figure 3.61: The IF fabricates the Mesh Mould steel rebar mesh on the DFAB HOUSE construction site.

As depicted in Fig. 3.61 and Fig. 3.62, the mesh fabrication consists of robotically fabricating both sides of the mesh in vertical layers. After each fourth layer fabricated, the steel mesh contour is autonomously surveyed by the on-board vision system for the purpose of compensating for unpredictable deformations in the mesh (see also 3.5.7.1 and 3.5.7.2).

The robotic fabrication process needs to be assisted by a few human interventions. These interventions include manually feeding both the steel rebar for the discrete and the continuous direction once for each layer. Additionally, every fourth layer, a number of prefabricated cross connections connecting the two sides of the mesh need to be inserted and welded manually (see Fig. 3.63). For every eighth layer, one steel plate supporting the foundation

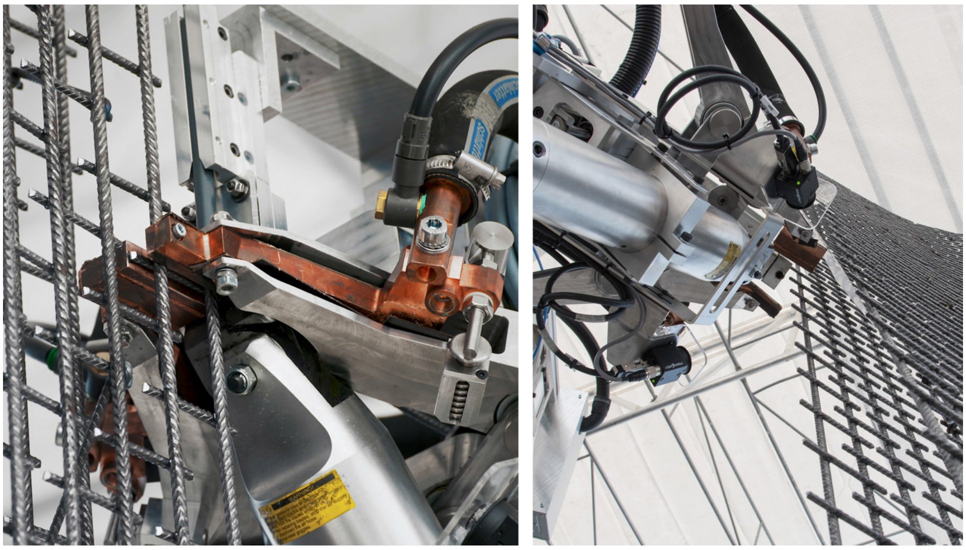

Figure 3.62: Close-up of the welding process (left): After the hydraulically actuated gripper with the welding electrodes is closed, the welding signal is triggered as soon as the required electrode pressure of 3kN is achieved in between them. View onto the steel mesh detection camera pair from below (right): The cameras are mounted at robotic end effector's rear side with their lenses pointing towards the mesh. They are additionally protected against weld spatters by a transparent shield.

area and one steel plate for completing the top are inserted manually and welded to the already fabricated steel rebar grid.

Figure 3.63: Manual welding of the cross connections (left), and view onto the manually inserted and welded top plates (right).

To sum up the whole process, a flowchart in Fig. 3.64 describes the complete high level fabrication control loop, which shows the control of the IF's low-level nodes for accomplishing the rebar mesh's fabrication.

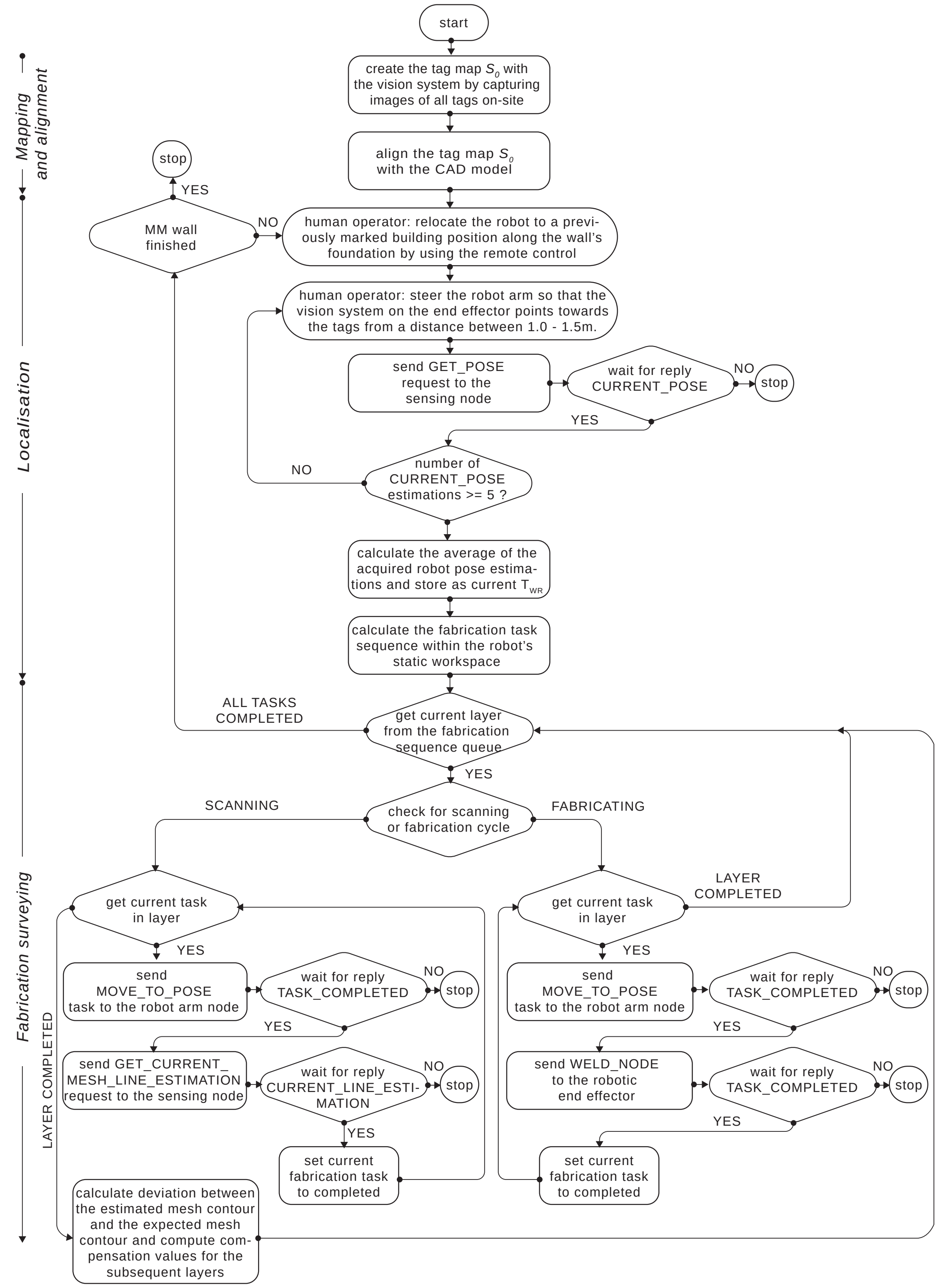

Figure 3.64: High level flow chart for the fabrication of the Mesh Mould steel rebar mesh using the IF and its on-board sensing system on the DFAB HOUSE construction site.

3.5.8 Results and validation

3.5.8.1 Results

The doubly-curved steel rebar mesh was successfully constructed at the DFAB HOUSE construction site from 8 different robot locations within roughly 125 h of production time (see Fig. 3.65 and the production video in [**MMIFMovie**]).

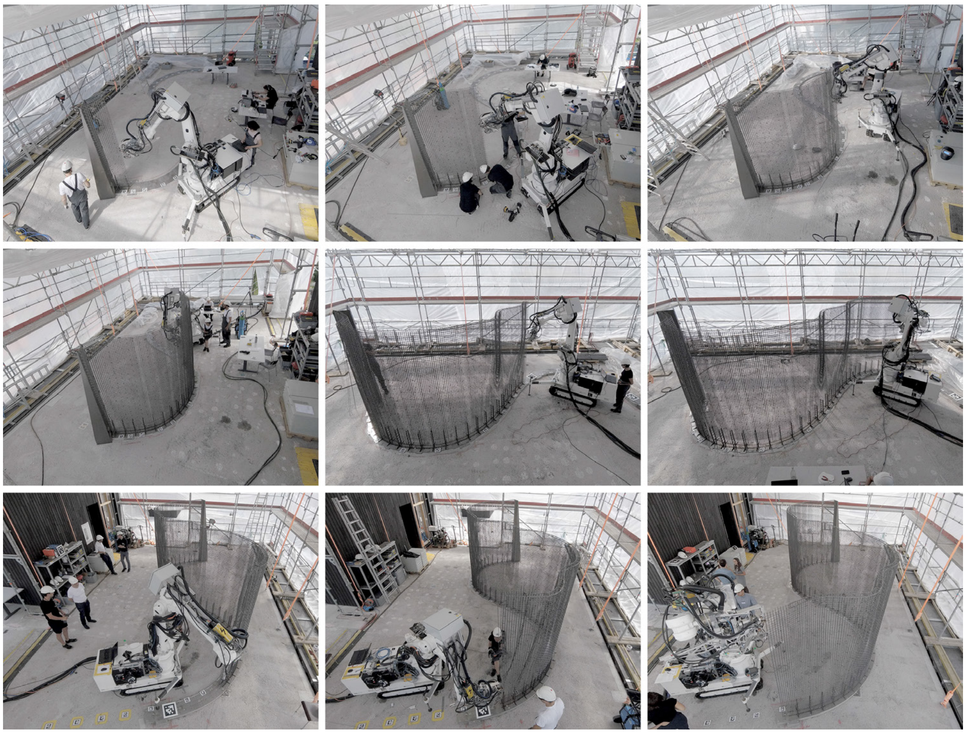

Figure 3.65: Snapshots of the production process over the course of three weeks.

The resulting 2.8-m high mesh structure consisted of 339 layers with more than 22000 welding nodes. The net cycle time measured for each welding node was around 5 s per node, but it was observed that the gross time observed was around 20 s per node. This time included several additional tasks, such as the visual survey of the mesh contour, the manual interventions such as material feeding, the insertion of the support elements (i.e., foundation plates, top plates, cross connections), and robot repositioning procedures. At this speed, each day on average 16 to 24 layers could be fabricated and the robot was relocated every second day (see also Table 3.2).

production speed	
wall height	2.8 m
wall length top/bottom	11.8 m / 11.4 m
sum of steel rebar length in direction: continuous / discrete / cross	2016 m / 1437 m / 1151 m
minimum/maximum discrete element length (= height of vertical layer)	31.0 mm / 40.1 mm
number of vertical layers	339
number of welding nodes	22374
number of welding nodes in one full double-sided layer	66/68 (one mesh side: 33/34)
number of robot positions	8
time required for robot relocation (incl. remote controlled driving, manually moving the robot's periphery and automated localisation)	1 h
visual survey time of one node / one side of one layer	4.3 sec / 2.5 min
net fabrication time of one node / full double-sided layer	5 sec / 5.5 min
gross fabrication time of one node (incl. visual fabrication survey and the manual interventions such as material feeding, insertion and welding of support elements (foundation plates, top plates, cross connections), robot relocation procedures) of one node / full double-sided layer	20 sec / 22 min
percentage of time required for automated procedures / manual interventions	33.3% / 66.6%
layers fabricated daily	16–24 layers
total gross fabrication time	125 h
robustness and accuracy	
estimated accuracy of end effector positioning in the global workspace	± 10 mm
estimated accuracy of the local mesh contour survey	± 5 mm
percentage of outliers in the mesh contour detection	1.6%

Table 3.2: Table of numbers relating to the production of the Mesh Mould wall for the DFAB house using IF.

The robot relocation procedures took around 1 h. The estimation method using the on-board vision system was refined and calibrated during the first five robot relocations. This calibration was achieved by additionally estimating the robot pose manually with a steel probe tip mounted onto the end effector. It was observed that the best estimation could be achieved by measuring the tags from the same distance and angle by which the tag map was created during the mapping process (from around a 1-m distance and an angle of 20° to 30°). For the last three robot locations only the tag estimation was used, and no additional manual measuring for comparing the results was necessary. After this refinement, an estimated end effector positioning accuracy of $\pm$ 10 mm in comparison with the pose estimation using the probe tip was achieved. The tag map, which was covering the full extents of the global workspace, ensured that errors do not accumulate (since each measurement was registered to the same initial tag map $\mathbf{S}_0$).

With respect to the visual fabrication survey, the scanning time (for one side of the mesh consisting of 34 welding nodes) required 2.5 min. The speed was limited not by the mesh estimation but it was limited by the time it takes to move the end effector from one welding node to the next. In the interest of the construction speed, the structure was scanned only after every fourth layer and additionally after each relocation procedure, though a better result could have been achieved by scanning and correcting after each layer.[48] By utilising the fabrication survey in combination with the adaptive control, no collisions between the mesh and the end effector occurred.

3.5.8.2 Validation

The performance of the localisation system before being integrated into the mobile robotic set-up was validated to be around $\pm$ 5 mm through ground truth measurements in the lab (for details, refer to Lussi et al. [95]). In the scope of validating the overall structure's accuracy, the welded steel rebar mesh was scanned with a Faro scanner after the fabrication was finished.[49] The captured point cloud was compared to the original CAD model of the mesh. In order to do this comparison, the captured point cloud was first box filtered, denoised and sampled down. The reduced point cloud was then fit to the CAD model through minimising the squared distance between the edge line elements of the CAD representation of the steel mesh and each point in the cloud. After this step, the average distance to the 10 nearest points in the point cloud was calculated for each welding node. The results are shown in Fig. 3.66.

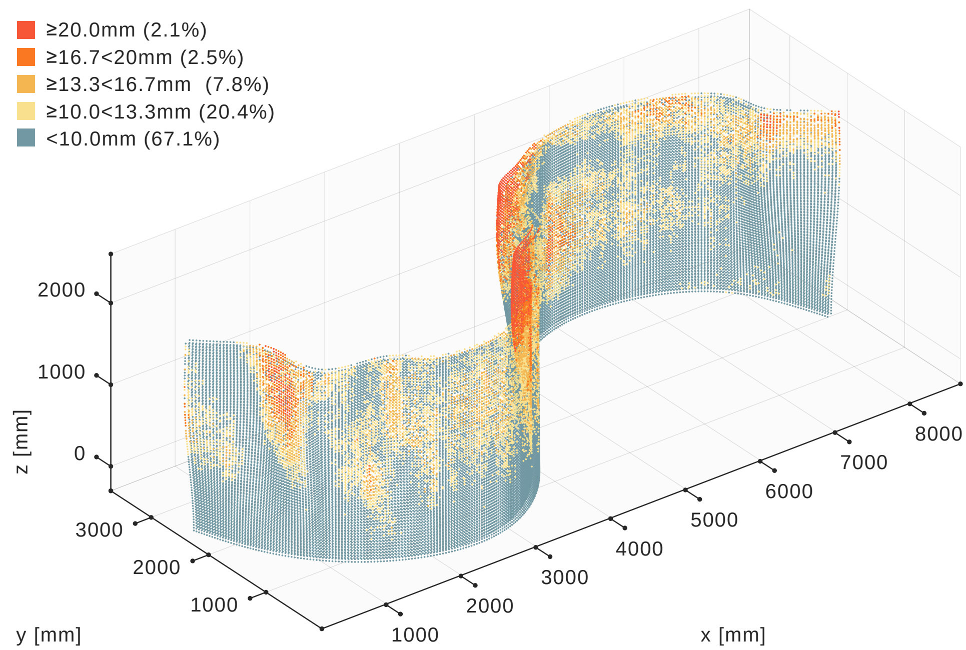

Figure 3.66: Ground truth error plot of the fabricated mesh: The colors represent regions with error ranges and percentage.

Two main sources of imprecisions could be identified: First, errors in the robot localisation created slightly visible gaps in between the layers in which the robot was repositioned; this is noticeable through the layer height being higher or lower than the neighbour layer heights, or not being completely parallel to the previous layer from the bottom to the top. Second, the springback behaviour of the steel rebar mesh caused deflections in the structure. Here, the Faro scan corresponded to the observations and measurements taken during fabrication, namely that deformations are higher towards the top of the mesh—as opposed to the bottom where the mesh is fixated to the base plate—and in regions of higher surface curvature. In the end, the deflections could not be controlled completely, even though in-process adaptation of the fabrication data within the range of the actuation capabilities of the robotic end effector was applied. They would have been significantly worse without correction, up to the point that the mesh would have needed to be held in place with a supporting scaffolding structure, which is a strategy that was tested in the lab on one of the prototypes before the local surveying was implemented. However, the remaining deflections indicate that there is still space for improvement.

Overall, the average measured ground truth error amounts to 0.47 mm, with a maximum error of 38.63 mm, and with 98% of the measurements being within the range of ± 20 mm. To conclude, the local correction allowed both the mesh deflections to be kept within the range of construction site tolerances and the mesh to be fabricated collision-free and as a free-standing structure.

Figure 3.67: The free standing mesh after completion of the robotic fabrication process.

3.5.9 Discussion

The deployment of the IF at the DFAB HOUSE construction site marks the culmination of the research objectives of this thesis. Within the scope of Case Study 3 it can be seen that it is possible to accurately fabricate a large-scale geometrically differentiated structure using a mobile robot on a real construction site.

3.5.9.1 Integrated design and fabrication workflow

The digital design tool for undulated Mesh Mould walls developed within this experiment incorporated the specific constraints of the fabrication process and can thus be characterised as a fabrication-aware design tool. This tool was used by the project architects of the DFAB HOUSE and allowed the team to explore the design space and the formal capabilities of the construction system in an intuitive way. During such explorations, the designers was visually informed regarding the fabrication-related constraints. This visual display allowed the designer to be directed towards choosing *fabricatable* design options. Once the design parameters were fixed, it was further demonstrated that all necessary data for fabrication (e.g., sequence of robot locations, sequence of end effector positions, and welding angles) could be generated from the same computational design model. Later during fabrication, this computational model also accommodated methods for the controller to adapt the fabrication data during the on-going process. This possibility eventually facilitated the robot to compensate for occurring deflections and fabrication tolerances in the mesh.

3.5.9.2 Sensing and adaptive control strategies

The complementary vision-based sensing systems developed for localisation and fabrication survey utilised off-the-shelf cameras and AprilTag fiducial markers. Yet, their use required the development and integration of process-specific software. To validate the robotic system's accuracy—that is, the robot localisation in combination with the fabrication surveying system—a high-resolution laser scan served to measure the constructed mesh. This validation allowed the performance of the system to be proven as consistent and predictable, and thus attaining construction industry standards.

While the local surveying method fully satisfied the requirements of the system, the method used for localisation has a few intrinsic problems. By using the vision system in combination with tag recognition for localisation, the building site needs to be prepared with these markers preceding the fabrication. If the vision system could apply featureless tracking to support the localisation with a sufficient accuracy and across a large-scale building space, the building site would not need to be prepared with them. However, this approach would require the sensing system to recognize other types of key objects than the tag poses in a map, so that this map can be referenced and aligned with a CAD model of the building site accordingly (e.g., compare with the alignment approach used in Case Study 2). Moreover, the tags needed to be registered from more or less the same camera pose as when the tag map was created, in order to return an accurate estimation of the robot pose. This indicates that the calibration of such a on-board sensing system for localisation is highly sensitive, and that its practicability for the use in construction site scenarios needs to be further explored.

3.5.9.3 In situ fabrication process of the steel rebar mesh

The Mesh Mould fabrication process was implemented and constantly refined towards the mobile application using the IF during a period of 1.5 years when highly interdisciplinary experiments were conducted. It took two generations of end effector designs to attain a robust process that is able to construct a structurally sound reinforcement mesh.

The mechatronic design of the end effector, together with the adaptive fabrication control strategy, allowed a highly robust process and a collision-free construction to be achieved. This design was adequate for the wall geometry of this experiment. However, for an expanded geometric freedom of the construction system, a bending mechanism for an effective plastic deformation of the steel rebar has to be integrated into the end effector design. This added feature could reduce the inner forces and resulting deformations of the fabricated mesh; it could also enable the robot to construct a tension-free mesh with a higher surface curvature and accuracy.

With respect to the speed of construction, the speed is mostly limited by the number and time required for manual interventions. Firstly, instead of steering the robot with a remote control across the job site, the integrated automated navigation features of the mobile robot would not require the desired locations to be manually marked on the ground and would allow for a more precise and speedier relocation of the robot. Second, several manual steps in the fabrication of the mesh slow down the production speed of the process. These steps include the manual feeding of the pre-straightened steel rebar material, the manual insertion of the cross connections, and the manual insertion of the supporting steel plates. In future developments, these manual assisted processes in the mesh fabrication—and in particular the automatic material feeding—need to become an integral part of the end effector mechatronic and process design.

In relation to the autonomy of the machinery, the integration of the Mesh Mould end effector required external power supplies due to the on-board sources not being sufficient to support certain processes (e.g., the resistance welding process). As a result, the mobility of the system is profoundly limited by the supply systems, which are composed of hydraulics, electric power, and compressed air. Although the supply systems were bundled and connected to the robot with a 7-m long cable strand, relocating the robot required some planning in the logistics, such as when and how to manually move these external components, as well as where to place them such that they do not interfere with the mobile robot's path. To support the autonomy of a mobile robot, the integration of an extra trailer robot for carrying extra components could be considered.

3.5.9.4 Mesh topology

The design of the mesh topology is a result of the robotic layer-based fabrication logics; the mesh topology consists of one continuous and one discrete

Figure 3.68: Due to structural requirements, the mesh required to be post reinforced at the open endings of the wall and the higher doubly curved areas. Moreover, to make sure to avoid major deformations of the steel rebar mesh during the subsequent concreting process, the mesh structure was diagonally braced using steel posts at a few locations.

direction, which does not fully satisfy the structural requirements for a reinforcement concrete structure. A structurally viable system requires continuity in both directions to be able to take tension forces in both directions of the mesh equally. For the application of the DFAB HOUSE, the finished mesh structure was therefore post-reinforced manually at locations where it was structurally required—that is, at regions that had a higher double curvature and both at the ends and the top of the wall. This was accomplished through fixating additional 6 mm steel rebar in the discrete direction of the mesh and also by adding stirrups at the free endings of the wall (see Fig. 3.68). Furthermore, at locations where load peaks of the floor slab resting on the wall occur, compressive reinforcement in the form of 20 mm steel rebar elements with a length of 1 m needed to be placed at 12 locations along the top contour of the wall.

To overcome these limitations in the future, a more fundamental rethinking of the robotic process is required. For example, in order to create a continuity of the mesh in both directions, the implementation of robotically placing and welding a secondary continuous rebar structure onto the already fabricated mesh could be introduced. Another alternative for such a secondary robotic process could be the robotic weaving of post-tensioning cables into the fabricated mesh.

Figure 3.69: The finished wall after having been manually filled with concrete and surface finished with a layer of shotcrete.

Notes

[23] The computational tool set is implemented in Python within the design and planning environment Grasshopper/Rhino [35].

[24] Such a map is a 3D representation of the building site, and it can be constructed by various methods. Using a vision system, for example, allows the map to be constructed by sensing and registering AprilTag fiducial markers spread out on the building site. Using a laser range finder, a map can be constructed by fusing the measurements to a point cloud.

[25] Usually, smaller intervals result in a higher accuracy, but they require more effort in sensing time and processing power. Furthermore, some materials may not be manipulated and sensed simultaneously because they need to set or dry.

[26] These custom communication interfaces allow a high-level fabrication control system to flexibly exchange data with computational sub-routines or low-level controllers of a robotic system. Thus, a distributed system is established, in which these external sub-routines can be implemented in ROS [83] or any other platform used. The platform-independent information exchange can also foster interdisciplinary collaboration, in which

different research groups can independently implement different sub-routines. Such a collaboration can be seen in the presented case studies—in these cases between designers and robotic scientists.)

[27] The developed library for the communication system builds upon a Python library developed within a collaborative master thesis by Romana Rust and the author of this thesis [100]; this was developed prior to this research. The software framework was advanced and refined alongside the implementation of the different case studies of this thesis.

[28] The 3D laser scanning unit consisted of the following technical components: a 2D Sick Laser Range Finder LMS511 [101] mounted on a rotating FLIR Pan-Tilt Unit-D100E [102]

[29] Having a bias towards closed-form structures over open forms was an informed decision, which was made based on prior knowledge gained through a number of material and fabrication experiments.

[30] In this case study, the origin of the global workspace is set into the base of the launching mechanism (i.e. $RCF = WCF$).

[31] This calibration has also been repeatedly performed during the two weeks fabrication process of the structure by throwing and estimating the landing position of a few sample projectiles. This procedure has been needed at certain times, such as after a new set of material projectiles has been produced with a slightly different density or after recognizable wear marks of the pneumatic actuator.

[32] To account for the inevitable holes and errors in the scan, the quality information for each point returned by the LRF was captured and extended by plausibility checks and stored in a list W_j.

[33] Experimentation showed that less than five error vectors remaining could as well be treated as part of the next layer of material deposition.

[34] In theory, it would have been possible to relocate the robotic actuation unit within the surveying range of the stationary laser scanning unit, and estimate its position in the point cloud as it was done once at the beginning of the fabrication process.

[35] "With the term digital materiality, we designate an emergent transformation in the expression of architecture. We recognize that materiality is increasingly being enriched with digital characteristics, and these characteristics significantly affect the material nature of built architecture. Digital materiality arises through the interaction between digital and material processes during design and construction. The synthesis of these two seemingly distinct worlds — the digital and the material — gives rise to new self-evident realities and sensualities. Data and material, programming and construction are woven into one another." [79]

[36] This vacuum gripper incorporated compliant features in the z-axis of the tool in the form of a 10 mm long spring to be able to account for slight inaccuracies in the end effector positioning during the placement of a single brick.

[37] While the robot's base can be additionally equipped with a pair of fold-out legs for stabilising the base and preventing tilting behaviour during moving routines, this limits the overall mobility of the machinery. Thus, it was explored in this experiment if the use of an inertial measurement unit (IMU) allows the tilting behaviour to be detected and compensated for on software level.

[38] For simulating arm movements or arm task routines, the node for controlling an ABB robot arm can also run on a simulated robot controller within ABB Robotstudio.

[39] The representation of geometric shapes can be distinguished between explicit versus implicit models, and parametric versus non-parametric ones. The explicit models refer to the shape of an object being encoded directly (e.g., a cylinder may be represented by a triangle mesh), while in implicit models, specific features may account for the whole shape (e.g., a histogram of surface normals). Explicit models may be parametric or non-parametric. Parametric models describe a shape using a small number of parameters (e.g. a cylinder may be represented by its radius and its heights), while the non-parametric models describe a shape explicitly, e.g., by a triangle mesh. In many cases, explicit models are well suited for the modelling of 3D shapes, while the implicit models are the preferred ones in 3D object recognition and classification [57].

[40] For this purpose, the constraint solver and Grasshopper plug-in Kangaroo [103] was used.

[41] Scaling up the end effector from the capacity to process a 2-mm steel wire so that it can process a 6-mm steel rebar involved for various tasks, such as to replace the electrical components of the gripper to hydraulic ones. This change has been done mainly because in hydraulic actuators the power unit can be mounted some place away from the end effector. Thus, the weight of the components integrated into the end effector can be reduced.

[42] Since the length of these cross connection varies in dependence of the mesh geometry, they need to be prefabricated accordingly.

[43] This model is implemented in the finite element analysis tool Abaqus.

[44] As opposed to the fabrication of brickwork in which the robot needs to traverse back and forth along the wall multiple times, the robot traverses the path along the wall only once in this experiment.

[45] While the installed top plates are not required structurally, they primarily make sure that the rebar mesh's top contour complies accurately with the planned data.

[46] For the use of the IF at the DFAB HOUSE construction site, it is necessary to use the fold out legs for additionally stabilising the robot during fabrication. This support helps to reduce disturbances and oscillations of the end effector due to the dynamics related to a few factors, namely 1) the movement speed of the arm; 2) the raw concrete floor, which has a very rough surface; and 3) the heavy weight of the end effector. Thus, a tilting of the base can be prevented, which eventually makes the use of an IMU (as used in Case Study 2) for this experiment obsolete.

[47] Additionally, the pose can be estimated by manually measuring a set of points previously engraved into the laser-cut foundation plate using a steel probe tip mounted at the end effector. These double measurements allow both the robot pose estimation values to be compared and the vision system to be calibrated during the first few robot locations.

[48] In order to locally deal with errors in the robot pose estimation, the full layer was also scanned after each relocation procedure. In this way, it was possible to locally react to inaccuracies in the global robot pose estimation.

[49] The scanner used was a Faro Focus3D X 330 laser scanner that could capture a point cloud with $\pm$ 2 mm precision and 0.4 mm standard deviation.

4 Conclusion

4.1 Summary of experiments

Through the realisation of three individual case studies, the findings show that it is possible to robotically fabricate architectural-scale and geometrically differentiated assemblies directly on a building site. The first experiment successfully demonstrated the in situ construction of a loam wall structure by employing a *stationary* robotic system that can throw material to a distant location. This throwing procedure allowed the static workspace of a stationary robot to be remarkably extended, and in this way the fabrication of architectural-scale assemblies can be achieved, even though the robotic system is small-scale and fixed to one location. While this experiment evidently stood apart from the subsequent two, it clearly illustrated the imperative nature for using feedback-based control methods for robotic in situ fabrication. A custom developed stationary sensing solution had to support the process; this support was done both prior to fabrication in mapping the building site and calibrating the robotic workspace and during fabrication in surveying the building progress. In contrast to this approach, the fabrication scenarios presented in Case Study 2 and 3 successfully demonstrated the utilisation of a *mobile* robotic system—the *In situ Fabricator* (IF)—for fabricating architectural-scale assemblies that exceed the robot's own static workspace. Moreover, through these two experiments it was also successfully demonstrated that such a mobile fabrication process can be performed on site using solely custom-developed sensing solutions on-board of the robot. These on-board sensing systems supported the fabrication process with their ability in several areas, namely to map and register the true dimensions of a building site, to localise the robot, and to survey the building progress. Within this scope, Case Study 2 demonstrated the robotic in situ assembly process of brickwork wall structures using IF in a simulated construction site environment. Finally, Case Study 3 allowed the deployment of IF to be showcased on an actual construction site, namely for the robotic in situ fabrication of a steel rebar mesh for a reinforced concrete wall. Hence, it can be seen within this thesis that robotic in situ fabrication processes allow the digital process chain to be extended from the design to the final assembly on site.

4.2 Strategies for robotic in situ fabrication

This thesis developed and experimentally validated strategies and techniques to overcome two major in situ fabrication challenges: the first one concerns the large scale of assemblies on a building site, and the second one concerns the required accuracy in building construction. The following conclusions can be drawn from the strategies applied.

4.2.1 Architectural scale

Many well-established methods in robotic prefabrication rely on the segmentation of architectural-scale assemblies into sub-assemblies so that these sub-assemblies can be brought to and fabricated within the static workspace of a stationary robotic system. Later in the process, these prefabricated sub-assemblies are transported to the building site where they are manually joined into a bigger structure. In the case of robotic in situ fabrication processes, the spatial relationship between the assemblies and the robotic system is reversed. Such an assembly can no longer be segmented into smaller parts, but it must be robotically fabricated as one continuous and monolithic building structure right at its final location. Thus, the robotic system must travel and reach this final location and fabricate the structure at the place where it remains. Two different methods that addressed this challenge of fabricating architectural-scale assemblies on site were shown within this research:

- ***Remote fabrication:*** Case Study 1 demonstrated the expansion of the static workspace of a stationary robot by throwing and depositing material at a remote location. Thus, the in situ fabrication of architectural-scale assemblies can be achieved, even though the robotic system is small-scale and fixed to one location.
- ***Mobile fabrication:*** Case Study 2 and 3 demonstrated the realisation of architectural-scale assemblies that exceed the robot's static workspace through mobile fabrication on a building site. In these experiments, a mobile robotic system fabricated these large-scale assemblies from multiple locations.

4.2.2 Accuracy

Many consolidated processes in robotic prefabrication rely on the perfect knowledge of the factory environment and perfect control of the stationary robotic systems. Robotic in situ fabrication processes, however, lack a perfectly structured environment and well controlled robotic systems. Furthermore, they are characterised as having an incomplete knowledge of the building site surroundings.

Despite these circumstances, the experiments of this thesis demonstrated that by using sensors, a robotic system could augment and complement this incomplete knowledge on different levels through

- ***mapping*** the geometry of the building site,
- ***localising*** the robot origin within it, and
- ***surveying*** the fabrication process.

Thus, the robotic system could stay in constant interaction with its environment and fabricate assemblies with the required accuracy directly on a building site.

With respect to these sensing tasks, this study has made a number of findings and achievements. Firstly, the mapping of the construction site allowed the robot to align and fit a CAD model of it to the true dimensions found on site. Furthermore, the localisation enabled the robot to travel on the job site and to position its end effector in one globally consistent world frame. Hence, the robot can fabricate structures that exceed its static workspace. Finally, the fabrication survey facilitated the robot to constantly monitor whether its actions succeeded reliably. In combination with the applied adaptive fabrication control method, this survey allowed the robot to locally deal with uncertain factors—including unpredictable material behaviour and imprecise robot localisation estimations—and eventually fabricate a structure accurately towards a defined reference geometry.

Within the scope of the cases studies, this thesis was able to explore two typologies of sensing systems:

- ***Stationary sensing systems:*** As shown in Case study 1, the externally mounted stationary sensing system—consisting of a laser range finder (LRF) on a rotating device—allowed both the extents of the building site to be mapped and the fabrication process to be surveyed. This system was sufficiently accurate to support the robotic fabrication of the loam wall structures. However, the visibility range of such a stationary sensing system can limit the size of the work piece. Furthermore, as the fabrication process progresses, certain regions can be occluded by the growing structure itself.

- ***Mobile sensing systems:*** Two different mobile sensing solutions were developed and integrated on-board of the IF. The first solution utilised a laser-based sensing system for mapping and localisation in support of Case study 2. However, it was replaced by a vision-based sensing solution in Case Study 3, mainly because the LRF showed its limitations both in the accuracy—particularly when it came to perceiving and registering objects close to the sensor—and in its reliance on more or less unchanging conditions on site. This vision-based sensing solution consisted of a primary system for mapping and localisation by registering AprilTag fiducial markers mounted on the job site. In comparison with the previously used laser-based system, the localisation accuracy could be improved. However, the high accuracy requirements of Case Study 3 also demanded this primary vision system to be complemented by a secondary vision system for surveying and registering the fabrication as it progresses. This complementary sensing solution allowed the precision of the end effector positioning to be locally increased. In short, all mobile on-board sensing systems have the advantage that they do not constrain the size of the work piece.

4.2.3 Discussion

The case studies demonstrated the far-reaching potential of fabrication robotics being implemented directly on building sites. The following sections discuss the contributions of this research to the field of robotic fabrication technologies in architecture.

4.2.3.1 Site- and material-aware fabrication methods

As both Mario Carpo and Tim Ingold argue, the hylomorphic model of creation has shaped our understanding in separating the intellectual act of design from the physical act of making [104, 44]. In this understanding, the material has solely been a passive receiver of a predetermined form in which the information has flown from design to assembly in a unidirectional way. Adaptive robotic fabrication challenges this notion of such a division. In the approach of introducing feedback loops on multiple levels, the material plays an active role in the physical formation process of an architectural artefact.

It could be demonstrated within this thesis that the implemented computational tool-set for adaptive fabrication control and its integration into the architectural design and planning environment allow design processes to be integrated with fabrication in a bi-directional way. The establishment of accessible interfaces to both robotic actuator and sensor components from within the design and planning environment opens up the possibility for designers to explore and take advantage of complex robotic control operations. While this integrated approach from design to fabrication challenges architects to be closely engaged with the logics of the robotic construction process, it also opens up new design possibilities and domains for optimisation. For example, adaptive fabrication fosters a bottom-up approach to design in which building components must be designed so that they are adaptable from planned dimensions in the CAD model to the true dimensions perceived by a robotic system on site. Moreover, the implemented adaptive fabrication control enables a robotic process to be open to disturbances and to involve uncertain factors while a fabrication process is ongoing. Thus, this adaptive control is vital for robotic fabrication processes to be performed also in a poorly structured and unpredictable environment such as a building site.

As exemplified in the case studies of this thesis, the feedback-based fabrication control leads to fabricated artefacts that are no longer a separate entity from the physical process of making. The process-flow becomes an integrated system that adapts and unfolds according to a number of factors, namely the design motives, the material behaviour, the fabrication constraints, and particularly also the found conditions on the site. In conclusion, the developed computational tool-set for adaptive fabrication control is also relevant for the wider field of additive fabrication processes in prefabrication, in particular for the ones that have to deal with uncertainties of unpredictable material behaviour during fabrication (as for example shown in the research of Rust et al., Johns et al., and Vasey et al. [49, 52, 45, 46].)

4.2.3.2 Mobile fabrication

The interdisciplinary set-up of this research has allowed the prototypical mobile construction robot IF to be developed as a generic, context-aware, mobile fabrication robot for real-world construction sites. The development of complementary robotic technologies—such as the on-board mapping, localisation, and fabrication survey—has given way to the implementation of adaptive fabrication control methods and their validation in the Case Studies 2 and 3. Featuring a mobile base, the IF showed the capacity to fabricate a geometrically differentiated structure larger than its static workspace from multiple locations. Such a mobile fabrication process of continuous structures was demonstrated across a large building space and with a minimum number of robot relocations. Prior to fabrication, the mapping features of the robot's sensing system supported the adapting of the planned dimensions in the CAD model to the true dimensions of the building site so that the structure to be fabricated could be adapted to its encompassing architecture (see Case Study 2). During the robotic fabrication process, the robot's global localisation on site was supported by a sensing solution to locally survey the fabrication (see Case Study 3). In this way, it was possible to locally compensate for both the prevalent uncertainties in the estimation of the robot pose and the deflections in the fabricated structure so that errors do not add up.

None of the reviewed mobile robotic system for in situ fabrication (see Chapter 2) demonstrated the combination of robot localisation with the ability of a fabrication survey. Furthermore, many systems using extended manipulators (e.g., Hadrian, DCP) showed the machineries as quasi-stationary systems without relocating the system while a structure is fabricated. Moreover, many of the discussed robotic systems have shown their dependency on external laser-based tracking systems for localisation (e.g., Hadrian, DCP, Sam100). The ones that used on-board sensing only showed robot localisation procedures either relative from one robot location to the next (DimRob) or relative to the work piece (Dharmawan et al.).

With the IF, the on-board mapping, localisation, and fabrication survey were performed in a complementary manner. Hence, right after the completion of the rebar mesh fabrication for the DFAB HOUSE in Case Study 3, robotic building construction start-ups approached the team to discuss the experiences with the developed system. This interest is a strong indication that the IF is preparing the grounds for the commercialisation of robotic in situ building technologies.

4.2.3.3 Logistics and productivity

With this research, it can be demonstrated that compared to robotic prefabrication, robotic in situ fabrication can simplify logistical efforts. For example, flat-packed feedstock material only needs to be transported once, namely from the material manufacturer to the building site. By contrast, in prefabrication, material must be transported twice, namely as feedstock to the intermediate location for prefabrication, and then from there in a pre-assembled and voluminous state to the building site. Furthermore, the robotic in situ fabrication process itself does not require any additional space other than the building site, and compact mobile robotic systems do not require extensive effort in setting up such a machinery on site. Additionally, production times can be predicted precisely, which facilitates the planning of the construction schedule and can ensure safe production time. In the particular case of the in situ production of the reinforced concrete wall for the DFAB HOUSE (Case Study 3), evidence was found that the robotically augmented fabrication showed a higher productivity than in the case of a conventional production process being applied for the realisation of such a complex-shaped building component.[50]

4.3 Future Work

Departing from the successful proof-of-concept demonstration of the case studies presented in this thesis (in particular Case Study 3), possible directions for future research can be identified as follows:

4.3.1 Mapping and alignment, localisation, and fabrication survey

The presented experiments demonstrated that the combination of mapping and alignment, localisation, and fabrication survey allowed a mobile robot to accurately fabricate assemblies on a building site despite the challenging uncertainties related to the building site, the fabrication system, and the material. However, these shown sensing solutions have been implemented prototypically and there is great room for extensively expanding the capabilities on a multitude of levels. With respect to future research for the process of mapping and alignment, the alignment and adaptation of an existing CAD model with an obtained map (e.g., through obtaining a point cloud) would require a more generic and fundamental approach for it to function fully autonomously and with a required precision. For example, through object- and context-based recognition, such a sensing system could automatically recognise key objects in the environment and hence support the alignment process with this information. This could be achieved by semantically segmenting the 3D data into meaningful pre-determined classes of a typical building site (e.g., wall, floor, pillar, openings, and obstacles). Here, the prior knowledge of the existing CAD model would serve to reduce the search space of object recognition algorithms. This knowledge can direct the process of recognising the relationship between data points and their belonging to specific entities in the scene. An even more advanced alternative to this could be an approach known from reverse engineering machined parts, in which a CAD model is reconstructed from scratch directly from the sensing data.[51] While such a reconstruction process may refer to finding a set of points to be a vertical plane, this process can also be enhanced by recognising such a plane as being a wall with an opening. Research on this topic has already existed for a while, as described for example in Tang et al. [57], or Yue et al. [105]. However, its methods need to be further developed so as to meet construction site accuracy requirements—namely to be fast and robust enough to be processed on site—and finally be integrated into one unified design and fabrication system. With respect to the speed of such a workflow, all sensing steps developed throughout this thesis have been performed sequentially. Future research must explore and integrate real-time approaches, such as the simultaneous mapping and localisation (SLAM) [106] techniques, which would allow both critical environmental information and localisation information to be obtained simultaneously and continually (see also Appendix A).[52] SLAM techniques in combination with local surveying and object recognition features would support both the autonomous navigation of a mobile robot and the performance of dynamic manipulation tasks. In this way, the techniques would eventually enable the robot to decouple the end effector positioning with the movement of its base.

4.3.2 Sensor feedback and adaptive fabrication control

The presented experiments demonstrated that the combined feedback of the geometric sensing data obtained from different sources (e.g., the robot map, localisation, and fabrication survey) allowed the fabrication control loop to be closed on a globally consistent level. This adaptive fabrication control enabled the robot to compensate for prevalent uncertainties on a building site and fabricate the building components in reference to a globally defined digital model. In the presented case studies, this digital model had acted as a reference that remained unchanged throughout the process, while the generation of the actual fabrication tasks did change each time according to the perceived external influences (e.g. found dimensions on site, robot localisation, and deflections in the built structure). After the completion of such a fabrication process, the built structure deviated locally from the dimensions of the prior defined digital reference model; in particularly, the local material formations did not look precisely the way as the model had foreseen. From the global perspective, however, the digital model and the built structure were consistent; in this case, deviations and errors had not added up.

Future research could also explore an open-ended design approach to fabricating buildings.[53] For example, this could relate to exploring the circumstances under which a robot may not only adapt its tasks in reference to prior defined performance criteria (i.e., the digital reference model) but may also adapt or generate new performance criteria at any point. Such design adjustments may be driven by monitoring and consequentially learning from unexpected environmental influences during an ongoing fabrication process. In an entirely open-ended fabrication process, however, a designer would need to abandon the idea of predicting the outcome, not just on the level of local details but also on the level of a globally defined design. Such a programmatic indeterminacy might firstly seem impractical for building construction, in which having a precise predictive model is essential for multiple reasons. One such reason can be the need to have multiple stakeholders involved in a building project who must agree on one common goal. Yet, the role of such a predictive model in an architectural project is not only to improve a design, but it is also closely related to how to maintain flexibility throughout the digital process chain so as to facilitate the workflow in practice. However, basic research in this direction is necessary to gain a better understanding on this subject.

4.3.3 Dynamic mobile fabrication strategies

In view of further optimising a mobile robot for in situ fabrication tasks with respect to various features (such as agility, dexterity, accuracy, speed, and safety), future research must aim at both real-time sensing and sophisticated dynamic whole body control approaches. Moreover, these advancements must be coupled with using lighter and more compact robotic machinery.[54] Future research has to investigate to which extent such lightweight systems using dynamic sensing and control can achieve the same payload and accuracy as for example the heavy and stiff ones used for the IF. A dynamic IF could perform dynamic manipulation tasks decoupled from the movement of its base[55] (as for example already shown prototypically in the research of Sandy et al. and Giftthaler et al. [31, 30]). While in the case studies of this thesis, mobile fabrication processes have been explored by performing fabrication and relocation procedures successively, a dynamic IF would allow exploring the potentials of performing these procedures simultaneously. Dynamic mobile manipulation capabilities would substantially expand the application space for in situ fabrication. For example, a dynamic IF would have the potential to expand the possibilities for adaptive fabrication by supporting the real-time adaptation of continuous building processes. In the specific case of the Mesh Mould technology, such a dynamic and adaptive process would enable the robot to perform the robotic application of the concrete onto the rebar mesh. Furthermore, dynamic control is also vital for force-controlled manipulation processes, such as drilling. In conclusion, future research on a dynamic IF needs to be continued with a multi-disciplinary team to address the challenges on both the hardware and software levels, as well as on the level of integrating such a system into in situ construction workflows.

Notes

[50] A study published by Hunhevicz et al. and Soto et al. [107, 108] investigated the effects of digital fabrication on productivity by analysing the cost and time required for the in situ construction of a robotically fabricated concrete wall (i.e., subject of Case Study 3) and by conducting a quantitative comparison to using conventional construction methods. The main conclusion of this comparison is that the robotically augmented process cannot compete in productivity with a conventional process for standardised and straight wall constructions. However, it showed a much higher productivity than a conventional process for the construction of complex and free-form building elements with differentiated geometry, as it was realised for the DFAB HOUSE.

[51] This refers to the process of reconstructing a simplified representation of the 3D shape of building components—such as walls, windows, and doors—from the existing point cloud data [57].

[52] Thus, SLAM techniques could also support a CAD model of the building site to be updated continuously throughout a fabrication process.

[53] An open-ended design means allowing room for a robotic system to continuously customise a design according to the changing context.

[54] The IF weighted 1.4 t.

[55] In the case of the IF, the hardware of the robotic set-up also limited further developments into the direction of dynamic control. The reasons for this have been presented in Giftthaler et al. [23]

A The In Situ Fabricator

A.1 Introduction

The mobile construction robot IF (In situ Fabricator) [23] is the result of an interdisciplinary research of both the Gramazio Kohler Research group (GKR) and the Agile and Dexterous Robotics Lab (ADRL) from 2014 to 2018 (see also section 1.4.3 in Chapter 1).

Figure A.1: The mobile construction robot IF (In situ Fabricator).

At the start of its development in 2014, a fundamental IF concept was developed, including the following defined core functional requirements:

- ***Mobility***: The robot needs to be able to move on the job site.

- ***Positioning***: The robot needs to be able to position an end effector with sub-centimetre accuracy in a global reference frame; this should be achieved with on-board sensing and without being dependent on external tracking devices.
- ***Survey***: The robot needs to survey its surroundings for the purpose of extracting geometric and semantic information; this allows the robot to react to uncertainties.
- ***Genericness***: The robot needs to be a generic system, that is able to perform an arbitrary construction task solely by exchanging the end effector.

These functional requirements are accompanied by operational requirements such as:

- Having a construction-compatible payload and workspace capacities
- Being self-contained
- Having a seamless integration into architectural planning tools
- Being able to be operated by a non-skilled operator

The IF hardware set-up builds upon its predecessor Dimrob[109], the first mobile construction robot prototype of Gramazio Kohler Research. For setting up the IF in this research, a major revision of the DimRob's hardware system was firstly undertaken, after which a set of digital tools of low-level algorithms for navigation, state estimation, planning and control was developed. These complementary robotic technologies were integrated into the architectural planning software in order to both support each of the fabrication experiments, and be validated throughout their applications. Thus, the first construction task utilising the IF and its features relates to the mobile construction of non-standard brickwork in a simulated construction site environment [25], presented as Case Study 2 of this thesis. Case Study 3 describes the employment of the IF on a real building site. This employment contributes to the construction of the DFAB HOUSE [94, 29, 28], in which the IF is utilised to fabricate a steel rebar mesh as part of the Mesh Mould construction process [110] for a load-bearing reinforced concrete wall.

In order to give a short systematic overview on the features and core aspects of the IF, the following sections describe 1) the hardware system set-up of the IF, 2) an identification of tectonic and architecture-related implications of using a mobile robot on a construction site, and 3) a summary of developed on-board sensing, estimation and control solutions that support the architectural applications.

A.2 Hardware set-up

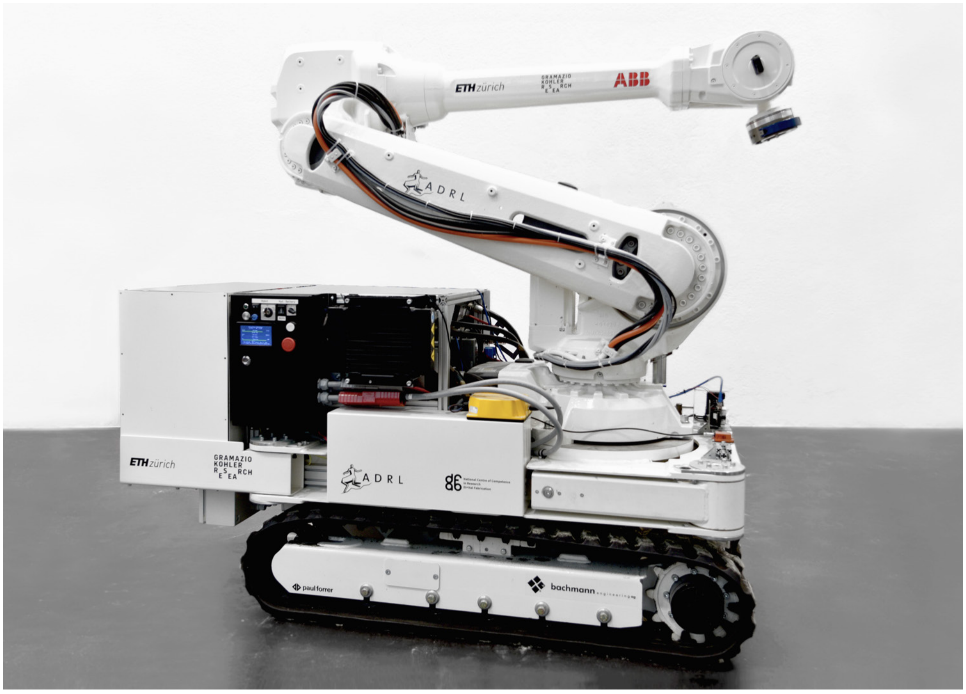

Figure A.2: The mobile construction robot IF being ready to be equipped with an end effector and with sensing solutions that are tailored to a specific fabrication process.

The basic hardware set-up of the mobile prototype machinery IF consists of the following commercially available off-the-shelf components. First, a tracked mobile base—powered by hydraulic motors—is equipped with an industrial robot arm (ABB IRB 4600, with a 2.55 m reach and 40 kg of payload limit), together with its compactly packed electronics from an ABB

IRC5 controller. The arm itself is position controlled, and a custom TCP/IP control interface allows the user to transmit arm commands such as simple movement routines (reference positions and velocities up to a rate of 250 Hz), or also more complex motion primitives such as placing a brick at a desired location. Both the arm components and the hydraulic system are powered by four on-board packs of Li-Ion batteries; this set-up allows the robot to be operated for around 3 h to 4 h autonomously and without the need to be plugged into an external power source. The robotic set-up provides an on-board charging system which can be plugged into standard mains power, as well as a power conversion system, which can convert currents from 5-48 V DC and 230-400 V AC at 50 Hz. The custom hydraulic system's core components are an AGNI DC electric motor which sustains a pump that can supply a pressure of 150 bar. Both the electric and the hydraulic power supplies can also serve additional components used at the respective end effector, for which a general set of power and data connections are provided at the fourth link of the arm.

The hydraulic system of the tracks is designed to enable the tracks to be driven with manual levers and to be operated automatically (either remote controlled or autonomously), controlled by the use of proportional valves. The system's architecture allows it to steer the robotic platform with a total weight of 1.4 t on non-flat ground or even soft terrain, as prevalent on building sites; with these conditions, a maximum driving speed of around 5 km/h can be achieved. The sensing and control tasks can be driven from an on-board computer (with an Intel i3-3220T processor with 2.8 GHz and 4 GB RAM), which runs ROS[111] on a hard real-time-enabled version of Linux Xenomai[112]. Apart from this, TCP/IP communications through ROS or custom interfaces allow the system to drive the controllers of the robotic components also from external computing stations.

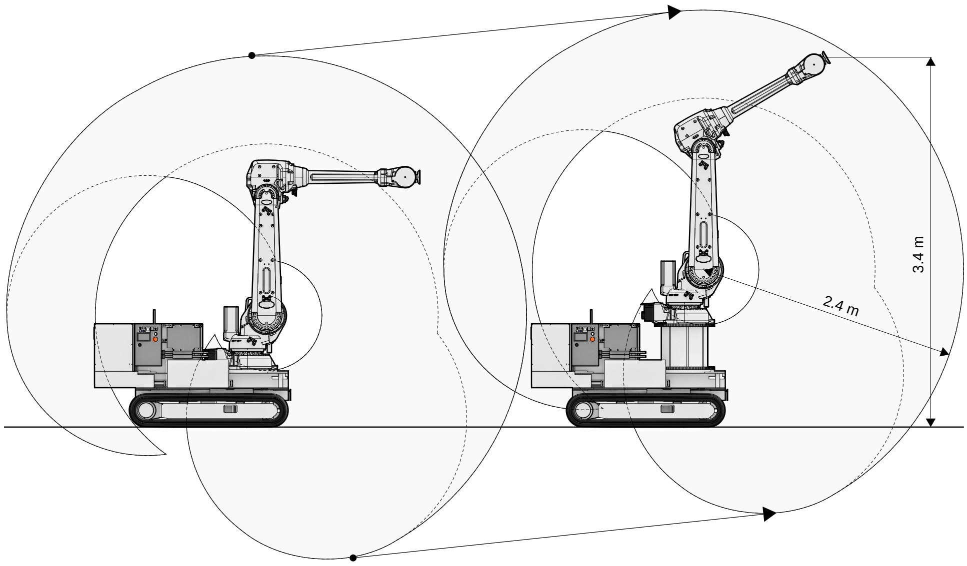

Figure A.3: Extension of the static workspace of IF: The mobile construction robot IF before and after being additionally equipped with a spacer between the tracked mobile base and the arm. This modification was undertaken in 2016 in order to further extend its workspace (i.e., the reachability in height for the fabrication of a wall above 3 m.)

The whole IF platform with a width of 80 cm can drive through a standard Swiss door, and it allows structures to be fabricated up to a height of 3.4 m (see Fig. A.3). This height is extendible also through the geometry of the end effector being used. The robot's base is equipped with the possibility to fold out a pair of legs in case the base needs to be additionally stabilised. For transportation purposes to the building site, the robot can be loaded onto a standard EPAL-pallet, it can also be steered into and out of a transportation container.

A.3 Tectonic implications

The major advantage of a ground-based mobile robot is the fact that the horizontal extents of the work piece are no longer constrained by the static workspace of the robot. Therefore, on the basis of the conducted experiments, the architectural implications of using a mobile robotic system for the fabrication of a physical artefact at the building site can be investigated as follows: Since a structure is fabricated at the place where it remains, its size is no longer subordinated to limitations imposed by transportation (e.g., the necessity to fabricate a larger piece in segments), but rather it can be fabricated as one continuous and monolithic structure.

Within the scope of this thesis, the robot's mobility is not a continuous one, but rather the relocation procedures are performed in discrete steps. The mobile robot performs construction tasks within its static reach while staying in one location, after which it travels and continues building from a new location. As this procedure should ideally be a continuous one (and so-called whole-body motions are also preliminarily shown in the research of Giftthaler et al. [113]), both the technical constraints of the robotic hardware set-up as well as very high precision requirements of the fabrication systems limit the development of simultaneous driving and construction-related manipulation procedures. As a consequence to this limitation, the attempt of this thesis is to minimise the number of relocation procedures of the mobile robot during construction. These machine-related constraints evoke a specific type of fabrication sequence and logic in which a structure can be constructed. These constraints must be integrated into the computational tool-set. Thus, optimised fabrication sequences are identified and developed in dependence of the actual construction task of the case study in question (see Sections 3.5.5.3 and 3.4.5.1 in Chapter 3).

A.4 Sensing, estimation and control solutions

A.4.1 Mapping, alignment and localisation

To utilise a robot's mobility for the purpose of fabrication, it is firstly necessary to have an accurate localisation system of the end effector in a globally consistent reference frame (below $\pm$ 10 mm). In the scope of the interdisciplinary development of IF, the aim was to achieve such a desired level of absolute positioning accuracy using only on-board solutions with commodity sensors. The on-board localisation, motion tracking, and mapping of the surroundings is commonly referred to as *simultaneous localisation and mapping* (SLAM). Even though extensive research exists within the robotics community in relation mobile robotic units performing SLAM [114, 115, 116], these methods can not be transferred directly to be used for mobile construction purposes. Construction tasks require a very high level of accuracy within a known and limited volume of building space. However, the main driver in SLAM is to achieve a much lower accuracy over the course of long trajectories in an unknown environment [117, 106] (as used e.g. in autonomous driving). Therefore, the existing methods must be extended so that the known geometric features of the building site environment (usually available in the form of CAD data) can be incorporated and used in the sensing system. This is expected to increase the system's accuracy and allow the robot to meet the demanding precision requirements.

Two different sensing solutions—each for the purpose of supporting the individual application scenarios of the case studies—are implemented and examined in regards to their capacity in achieving a sufficient global positioning accuracy. In support of Case Study 2, a laser range finder is utilised to map the building site and to localise the robot by registering point clouds against the prior constructed map (see Section 3.4.6). In support of Case Study 3, the laser range finder is replaced by the use of of a vision system. This system detects Apriltag fiducial markers distributed on the building site for the purpose of robot localisation (see Section 3.5.6).

A.4.2 Fabrication survey

A fabrication survey must complement the positioning system by monitoring the fabricated physical artefact. This is especially necessary in building processes in which unpredictable material behaviour can occur. This is the case in the mesh fabrication process of Case study 3. The sensing solution developed for this matter is described in Section 3.5.7.

A.4.3 Navigation

In the scope of the ongoing robotics research, automated navigation for the IF has been developed and tested within a number of experiments in the lab, as shown for example in Sandy at al. and Giftthaler et al. [93, 113]. However, for the architectural applications in this thesis, the IF is steered using a remote control to desired target locations.

B Project Credits

B.1 In Situ Fabricator (IF)

B.1.1 Collaboration

The initial concept for IF and the basic hardware platform originated from the DimRob project [109], which was initiated by Gramazio Kohler Research in 2011 and funded by the EU robotic research project ECHORD++. The development of IF was a collaborative project between the Agile and Dexterous Robotics Lab (ADRL), led by Prof. Dr. Jonas Buchli, and Gramazio Kohler Research (GKR), led by Prof. Fabio Gramazio and Prof. Matthias Kohler, funded by the R'Equip program of the Swiss National Science Foundation (SNSF) (see also Section 1.4.3 in Chapter 1). The preceding hardware development, taking place from 2013 to 2014, was undertaken by Timothy Sandy and Markus Giftthaler, both researchers of ADRL. From 2015 onward, the IF project has been integrated into the National Centre of Competence in Research (NCCR) Digital Fabrication. During this period, the PhD students Timothy Sandy, Markus Giftthaler, and the author of this thesis became the main collaborators. In the scope of Phase 1 of the NCCR (mainly in the 2015-2017 period), the low-level control software of IF was developed under the lead of the ADRL PhD students; the details of this can be found in the following papers: [23, 113, 93, 118]. In relation to the performed architectural application scenarios using IF (Case Study 2 and Case Study 3 of this thesis), the two sensing solutions directly supporting the experiments were developed by Timothy Sandy. In the scope of Case Study 3, Manual Lussi, a research assistant of ADRL, supported the development and implemented the software for the respective sensing solution.

B.1.2 Own contribution

From 2014 to 2017, the author of this thesis has undertaken the integration of the mobile robot machinery IF into the architectural design and planning environment. This led to the development of a set of computational tools to enable integrated design and fabrication processes using a mobile robot on a building site. It included enabling the generation of optimised mobile production sequences from within the architecture planning environment. Furthermore, it implied implementing a high-level communication system for the sensor and actuator components of the IF robot, as well as an adaptive fabrication control tool. Finally, it concluded in the conception and implementation of the architectural application scenarios presented as Case Study 2 and Case Study 3 of this thesis.

B.2 Case study 1

B.2.1 Collaboration

The realisation of the architectural installation *Remote Material Deposition* was enabled by Gramazio Kohler Research (GKR), led by Prof. Fabio Gramazio and Prof. Matthias Kohler, in collaboration with the foundation Sitterwerk and Kunstgiesserei, St.Gallen. The core team of Gramazio Kohler Research consisted of Sebastian Ernst (project lead), Luka Piškorec (teaching and workshop lead), and the author of this thesis (research lead). Some parts presented in this thesis are the result of a preliminary experimental study led by Sebastian Ernst in cooperation with Prof Robert J. Flatt, Prof. Hans J. Herrmann and Dr. Falk K. Wittel from the Institute for Building Materials, ETH Zurich. The project has been immensily supported by the whole team of the foundation Sitterwerk and Kunstgiesserei St.Gallen—in particular by Felix Lehner, Julia Lütolf, Laurin Schaub, and Ariane Roth. Their viable support enabled the realisation this exclusive architectural installation, as seen with them providing their know-how in the loam mix design, supporting the conception of the project, as well as housing the researchers and a group of students during the construction phase. Finally, also the students participating in both the elective course and the workshop contributed to successfully realising this pioneering experiment: Ralph Benker, Bo Cheng, Roberto Naboni, Pascal Ruckstuhl, Ivana Stiperski, Simone Stünzi, Anna Szabo, Andreas Thoma, Martin Thoma, Alexander Nikolas Walzer and James Yeo.

B.2.2 Own contribution

The main contributions for the realisation of this case study by the author of this thesis can be summarised in three points: First, a computational design tool for ballistic loam wall construction was developed, including the establishment of a ballistic trajectory simulation. Second, a sensing solution for the fabrication survey of the build-up was developed, together with the implementation of a high-level communication system for the sensor and actuator components of the robotic set-up. Third, an adaptive fabrication control strategy was both developed and validated in the scope of the fabrication of the architectural installation.

B.3 Case study 2

B.3.1 Collaboration

The implementation of this experiment has been supported by the Swiss National Science Foundation through the National Centre of Competence in Research (NCCR) Digital Fabrication. The collaborating professorships enabling this case study were the Agile and Dexterous Robotics Lab (ADRL), led by Prof. Dr. Jonas Buchli, and Gramazio Kohler Research (GKR), led by Prof. Fabio Gramazio and Prof. Matthias Kohler. The PhD students and collaborators of the IF project within the NCCR—Markus Giftthaler and Timothy Sandy—developed the complementary robotic technologies in support of the architectural applications for the experiments. Specifically, the robot's track control and the remote control system for steering the robot's base was implemented by Markus Giftthaler; the sensing solution using the laser range finder was developed and implemented by Timothy Sandy. The experiment's accomplishment was further supported by Michael Lyrenmann, head of technicians of the Robotic Fabrication Laboratory (RFL) and Philippe Fleischmann (RFL technician), particularly in the development of the pick-and-place end effector. Finally, Keller Ziegeleien sponsored the building material.

B.3.2 Own contribution

The contributions by the author of this thesis for the realisation of this experiment consist of the following four points. First, a design tool for the fabrication of undulated brick walls using a mobile robot was implemented. This entailed the implementation of adaptive features that enabled the computational model of the brick wall being adaptable to the geometric sensor feedback of the robot in relation to building site tolerances. Second, it included implementing a high-level communication system for the sensor and actuator components of the IF robot. Third, an end effector was designed and integrated into the robotic control system. Finally, the overall build-up strategy and respective fabrication control loop was developed, implemented, and validated in the scope of the fabrication of the double-leaf brick wall.

B.4 Case study 3

B.4.1 Collaboration

The realisation of this experiment has been supported by the Swiss National Science Foundation through the National Centre of Competence in Research (NCCR) Digital Fabrication. The main collaborating professorships enabling the research for this case study were the Agile and Dexterous Robotics Lab (ADRL), led by Prof. Dr. Jonas Buchli, and Gramazio Kohler Research (GKR), led by Prof. Fabio Gramazio and Prof. Matthias Kohler. The extended list of collaborating professorships—directly connected to the development of the Mesh Mould construction system—included Prof. Dr. Robert Flatt from the Institute for Building Materials, Prof. Dr. Walter Kaufmann from the Institute for Structural Engineering, and Prof. Dr. Philippe Block from the Institute for Technology in Architecture. It was essentially the collaborative approach in between the research disciplines of Architecture, Robotics, Structural Engineering, and Material Science within the NCCR which enabled the successful implementation of the project within the given time frame.

The core team of Gramazio Kohler Research consisted of Norman Hack (project lead Mesh Mould), Alexander Walzer (research assistant), and the author of this thesis (project lead Robotic In situ Fabrication), with the support of Maximilian Seiferlein (intern) during the mesh fabrication phase. The developed sensing solution in support of the mesh fabrication using IF on the building site was developed by Timothy Sandy (PhD student ADRL), and implemented, tested, and validated by Manuel Lussi (research assistant ADRL). The mechatronic design of the end effector was conducted by Nitish Kumar (Postdoc ADRL), supported by Julio Lopez Alonso and Lukas Stadelmann (research assistants, ADRL). The end effector integration was supported by the RFL technicians Philippe Fleischmann and Michael Lyrenmann (head of technicians RFL). The underlying structural requirements informing the end effector design were provided by Jaime Mata Falcon (postdoc at the Chair of Concrete Structures and Bridge Design). The design evaluation through a preliminary FEM analysis was supported by Andrew Liew (Postdoc at Block Research Group). The development of concrete filling strategies for the Mesh Mould wall was supported by Lex Reiter, Tim Wrangler (PhD and postdoc at the chair of Physical Chemistry of Building Materials), and the concrete lab technicians Heinz Richner and Andreas Reusser. The team of project architects for the DFAB HOUSE and early adopters of the Mesh Mould design tool consisted of Konrad Graser and Marco Baur. The necessary construction deliveries in support of the robotic fabrication part (e.g., the transport of IF and the construction of the wall's foundation) were conducted by the team of ERNE AG (led by Pascal Breitenstein), the general contractor of the DFAB HOUSE. The team of Empa NEST—in particular Reto Largo, Reto Fischer, and Stephan Kälin—supported the project team and attended to a smooth operation on the DFAB HOUSE building site. The industry partners for the overall project realisation were Sika Technology AG, NOE Formwork, and Schlatter AG. The steel material was sponsored by Stahl Gerlafingen.

B.4.2 Own contribution

The contributions by the author of this thesis for the realisation of this experiment consist of the following points. First, the Mesh Mould construction system was customised for the in situ application for the DFAB HOUSE. This implied scaling up the construction system to improve the production speed but still complying with the structural requirements and concrete filling constraints of the wall building project. Furthermore, strategies for mobile fabrication (e.g., flipping the layer build-up direction by 90°) were developed and the robotic fabrication system's constraints were identified. Second, an integrated design and fabrication tool for undulated Mesh Mould walls was established. Third, the constructive details accompanying the robotic fabrication part on site were developed. Fourth, the previously developed communication system for both the sensor and actuator components of the IF robot was extended to integrate the sensor solution developed for this experiment. Finally, an adaptive fabrication control algorithm was developed, implemented, and validated by the mesh fabrication on NEST.

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Curriculum vitae

Kathrin Dörfler

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Education

2013–2018	Doctoral Studies at the Chair of Architecture and Digital Fabrication, Prof. Fabio Gramazio and Prof. Matthias Kohler, ETH Zurich, Switzerland
2005–2012	Study of Architecture, completion of Master's Degree with distinction, Supervisor: Prof. Christian Kern, Institute for Arts and Design, University of Technology Vienna, Austria
2008–2009	Study period abroad, Architecture, Universidade de Sao Paulo (USP), FAU, Brasil
2004–2008	Study of Digital Art, University for Applied Arts Vienna, Austria
2003–2004	Study of Architecture, University of Technology Graz, Austria

Professional experience

Apr 2018–	Postdoctoral researcher at the Chair of Architecture and Digital Fabrication, Prof. Fabio Gramazio and Prof. Matthias Kohler, ETH Zurich, Switzerland
Oct 2013–Mar 2018	PhD Researcher at the Chair of Architecture and Digital Fabrication, Prof. Fabio Gramazio and Prof. Matthias Kohler, ETH Zurich, Switzerland
Oct 2012–Sep 2013	Research and Teaching Assistant at the Institute for Arts and Design, Faculty of Architecture, University of Technology Vienna, Austria
2012	MVD, Office for Architecture and Graphic Design, Vienna, Austria
2011	Rüdiger Lainer + Partner Architects, Vienna, Austria
2010–2011	soma Architecture, Expo Pavilion in Yeosu, Vienna, Austria
2009–2012	Student Assistant at the Institute for Arts and Design, Model-Building Workshop, University of Technology Vienna, Austria
2009	Studio Vlay, competition Sonnwendviertel Wien, 1st prize, Vienna, Austria
2007–2009	Gaupenraub +/-, Office for Architecture, Vienna, Austria
2006–2007	MVD, Office for Architecture and Graphic Design, Vienna, Austria
2006	Internship at Azevedo Arquitetos Association, Rio de Janeiro, Brasil
2006–2012	Various self-employed activities in the field of architecture, design, graphic design and media art

Teaching experience

Sep–Dec 2016	Tutor in the Master of Advanced Studies (MAS) ETH in the Architecture and Digital Fabrication programme, ETH Zurich
June 2014	Summerschool 2014 – Remote Material Deposition, Sitterwerk St. Gallen, ETH Zurich
Jan 2014–Jun2014	Tutor in the elective course Remote Material Deposition, ETH Zurich
Oct 2012–Sep 2013	Teaching Assistant at the Institute for Arts and Design, Design Studio, University of Technology Vienna
Dec 2012	Workshop at the Rob|Arch Conference 2012

Awards

2018 *ICRA Best Automation Paper Award*, Winner, International Conference on Robotics and Automation (ICRA 2018), Brisbane, Australia

2018 *euRobotics TechTransfer Award*, Finalists, European Robotics Forum 2018 in Tampere, Finland

2017 *Concrete Innovation Award*, Concrete Innovation Conference (CIC 2017) in Tromsø, Norway

2016 *Swiss Technology Award*, category 'Inventors' at the 11th Swiss Innovation Forum in Basel, Switzerland

2013 *archdiploma'13*, Architecture Diploma Awards at University of Technology Vienna, special award

2012 *GAD Awards'12*, Architecture Diploma Awards at University of Technology Graz, second prize

Exhibitions

2017 *Reinforce Expose. The inner forms of tomorrow.*, exhibition, Gramazio Kohler Research at Istituto Svizzero, Milano Design Week, Italy

2014 *Quaero*, installation at Künstlerhaus Palais Thurn und Taxis, Bregenz, Austria

2013 *Zeichnen, Zeichnen*, installation at k/haus, Vienna, Austria

2013 *archdiploma'13*, exhibition, Vienna, Austria

2012 *GAD Awards'12*, exhibition, Graz, Austria

2009 *Object and Product Design Module*, exhibition, Zumtobel-Forum Vienna, Austria

2008 *(Mis)used Media*, installation at Sterngasse, Department for Digital Art, University for Applied Arts Vienna, Austria

2007 *Graduation Awards*, exhibition of the bachelor's programme, University of Technology Vienna, Austria

Talks

2016 "In situ robotic construction systems", Lecture at *IEEE/RSJ IROS 2016 conference: Workshop on Artistically Skilled Robots*, Daejeon, Korea

2016 "Robotic Fabrication Beyond Factory Settings", Lecture at *Game Set Match Symposium*, Delft University of Technology, Netherlands

2015 "Mobile Robotic Fabrication", Lecture at *ICD Expert Lecture*, Stuttgart University of Technology, Germany

2015 "Remote Material Deposition", Lecture at *InDeSem Recraft*, Delft University of Technology, Netherlands

Publications

2018 Jonas Buchli, Manuel Lussi, Markus Giftthaler, Kathrin Dörfler, Timothy Sandy, Norman Hack, and Nitish Kumar. “Digital in situ fabrication - Challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond”. In: *Cement and Concrete Research* (2018)

2018 Manuel Lussi, Timothy Sandy, Kathrin Dörfler, Norman Hack, Fabio Gramazio, Matthias Kohler, and Jonas Buchli. “Accurate and Adaptive In situ Fabrication of an Undulated Wall using an On-Board Visual Sensing System”. In: *Proceedings - IEEE International Conference on Robotics and Automation (ICRA 2018).* 2018

2017 Norman Hack, Timothy Wangler, Jaime Mata-Falcon, Kathrin Dörfler, Nitish Kumar, Alexander Nikolas Walzer, Konrad Graser, Lex Reiter, Heinz Richner, Jonas Buchli, Walter Kaufmann, Robert J Flatt, Fabio Gramazio, and Matthias Kohler. “Mesh Mould: An On Site, Robotically Fabricated, Functional Formwork”. In: *Proceedings of the Second Concrete Innovation Conference (2nd CIC).* 2017

2017 Nitish Kumar, Norman Hack, Kathrin Dörfler, Alexander Walzer, Gonzalo Rey, Fabio Gramazio, Matthias Kohler, and Jonas Buchli. “Design, Development and Experimental Assessment of a Robotic End-effector for Non-standard Concrete Applications”. In: *IEEE International Conference on Robotics and Automation (ICRA 2017).* IEEE International Conference on Robotics and Automation, 2017, pp. 1707–1713. ISBN: 9781509046324

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2016 Timothy Sandy, Markus Giftthaler, Kathrin Dörfler, Matthias Kohler, and Jonas Buchli. “Autonomous repositioning and localization of an in situ fabricator”. In: *Proceedings - IEEE International Conference on Robotics and Automation (ICRA 2016).* 2016, pp. 2852–2858. ISBN: 9781467380263. DOI: 10.1109/ICRA.2016.7487449

2016 Kathrin Dörfler, Timothy Sandy, Markus Giftthaler, Fabio Gramazio, Matthias Kohler, and Jonas Buchli. “Mobile Robotic Brickwork: Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot”. In: *Robotic Fabrication in Architecture, Art and Design 2016.* 2016, pp. 204–2017. ISBN: 978-3-319-04662-4. DOI: 10.1007/978-3-319-04663-1

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2014 Kathrin Dörfler, Sebastian Ernst, Luka Piskorec, Jan Willmann, Volker Helm, Fabio Gramazio, and Matthias Kohler. "Remote Material Deposition: Exploration of Reciprocal Digital and Material Computational Capacities". In: *What's the Matter: Materiality and Materialism at the Age of Computation*. 2014, pp. 361–377

2012 Kathrin Dörfler, Florian Rist, and Romana Rust. "Interlacing - An Experimental Approach of Integrating Digital and Physical Design Methods". In: *Rob|Arch 2012 - Robotic Fabrication in Architecture, Art and Design*. Ed. by S Brell-Çokcan and J Braumann. Vienna: Springer-Verlag Wien, 2012, pp. 82–91. ISBN: 978-3-7091-1465-0. DOI: 10.1007/978-3-7091-1465-0_7