Towards robotic fabrication in joining of steel

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Abstract –
Throughout history, waves of industrial revolutions have disrupted established manufacturing methodologies. Traditional construction processes have been transformed by new means of creating objects and computing information. The manufacturing of steel is no exception to this trend. Past methods for the creation of steel included hot forming (casting, extruding and welding), cold forming (subtractive milling, bending and rolling) and cold connected assemblies (bolts and rivets). All these methods create certain constraints to the application, form and function of steel elements. Developments within fabrication technologies bring a new dimension to the possibility of creating complex geometries in steel manufacturing. This article explores the use of new technologies including additive manufacturing as well as composite joints, and highlights the integration of new robotic programming paradigms for architectural production.

Typical 3D printing technologies create objects by incrementally adding layers of material in order to create a final part. Employing robotics does not only allow for fabrication on a larger architectural scale. The flexible configurations of the robotic arm, with its six degrees of freedom, allows for the additive manufacturing of elements on top of existing structures or surfaces.

Within this article we create an overview of fabrication technologies for joining steel, as well as their influence on architectural design. We explore how new technologies enable the creation of new design possibilities, through the increased flexibility of robotic fabrication.

Keywords –
Additive Manufacturing; Robotics; Fabrication; 3d Printing; Steel; Welding;

1 Introduction

Construction technology has a significant impact on the design and performance of architectural projects. The evolution of materials and methods of production has enabled the Architecture, Engineering and Construction (AEC) industry to design and build projects of increasing complexity, form and function. As new techniques develop, the industry integrates these innovations in order to push the boundaries of construction capabilities. This trend can be seen in the history of architecture as low rise buildings evolved into the skyscrapers that define modern skylines. The impact of manufacturing technology has a determinant role in shaping architecture. Many examples can be identified that attest to this connection whereby shifts in capabilities transform the AEC industry at large.

Advances in construction technology shape the design of architecture, from new digital information workflows to innovative fabrication processes. The current wave of fourth industrial revolution is now taking shape and architecture is again evolving. New levels of intelligent automation, and the increasing connectivity of information networks are creating more ambitious and efficient structures than ever before. The power of designers to computationally optimize designs is matched by new means of manufacturing complex components. This trend is amplified by new methods of collaboration, from algorithmic design to Building Information Models.

The development of new processes for using machines and materials is an important aspect of realizing innovative architectural ideas, from robotic fabrication to new methods of working in steel and composites. These advancing capabilities are combined with increasing ambitions for architecture that are cost competitive and efficient to assemble while still achieving high levels of performance, sustainability and geometric complexity. With this evolution in mind it is helpful to consider examples of architectural forms which encompass these transitions in process.

We can observe the evolution in architectural process by juxtaposing projects from the past with those from the present in order to see the impact of new means of construction. It is important to keep in mind that while technology may change there are many constants that remain. These constant conditions run throughout the course of architectural history to add a shared context to construction efforts. Each building for instance must negotiate a balance between form, function and structure in order to find a means of creating space which efficiently meets its design requirements and can be built within its constraints of technology, time and budget.

The Eiffel tower demonstrates this balance in a truly iconic way. By utilizing the height of the times existing technology and manufacturing methods this structure embodied the benefits of steel construction. From its structural definition of form to its rapid construction schedule, this tower became synonymous with the city of Paris and an age of advancing architecture. The form takes advantage of repetition as its symmetry allowed for the preparation of parts to have repeatability and structural integrity that could be calculated by hand.

In contrast to the Eiffel towers symmetry we can consider the ArcelorMittal Orbit, an observation tower designed for the London Olympic Games. This tower is a complex creation of non-symmetrical geometry in which each part is uniquely created according to a digital model. The asymmetric form was made possible through the utilization of computational design tools and advanced structural analysis software. The principles of structure, construction considerations, and the desire to create an iconic experience to represent a city are common to each project while the impact of digital design and fabrication processes can be seen to considerably increase the complexity of the built form.

A further example of the impact that advancements in technology has on architectural projects can be found in the evolution of thin shell structures. Engineers such as Richard Bradshaw were key figures in designing thin shell structures that utilized the strength of form to optimize structures. These designers required a deep understanding of structural analysis, hand calculations and the geometries required to create such impressive forms. New digital design tools, methods for iterative structural analysis and file to factory workflows that design for mass customization have empowered designers such as Marc Fornes to reimagine the shell structure as a highly complex geometry comprised of thin sheets of material that derive great structural integrity from the form of the construction.

Works produced by Marc Fornes, such as Minima | Maxima, create shell structures through continuous surfaces which draw their structural integrity from both the geometry of the construction and the aluminum laminate weave it is constructed from. This increase in design complexity continues the tradition of creating impressive structures that consider construction methods early in the conceptual process in order to integrate design and fabrication. These workflows seek to optimize a project and increase its ability to be constructed efficiently in light of bespoke geometry.

The integration between design and fabrication tools continues to grow. In the future of construction, digitalization will be the central interface in the supply chain. The integration of robots and automation technology can improve the competitiveness of the construction industry, which lags behind other industries in regards to increases in efficiency and productivity. The integration of digital processes has significantly advanced the tools of architecture in a short amount of time.

A concept for furthering this trend was commissioned by the BMVi in 2015. To guide the integration of modern digital processes and technologies in the planning, construction and operation of buildings envisages a step-by-step plan for the introduction of BIM [1] was developed. Building Information Modeling or Management (BIM) is ideally used to digitally create and manage information regarding the physical and functional properties of a building over the course of its entire lifecycle, from design, to construction, to occupancy and operation, to its eventual decommission. BIM serves as an information source and database for interdisciplinary collaboration between all parties involved. Currently, BIM is utilized mainly during the design stages of an architectural project and does not yet sufficiently integrate machine production. In many cases a BIM model must be rebuilt in a shop level tool or set of drawings before physical production of parts and assemblies can proceed.

These developments also affect the steel construction industries. New flexibilities within the digital tool chain of design to production also require new flexibilities in the fabrication processes. While casting of metal is a relatively cheap process especially for mass production, the fabrication constraints exclude a number of parts. Even though 3D printed sand molds already extended this process and allow for the creation of undercuts and can be created without draft, this is still a relatively time consuming process, which requires a high lot size to be efficient.

On the other hand, subtractive milling, generally limited to 3 axis of freedom, creates a high waste factor. Other limitations are inherent in this process including the creation of undercuts or parts that require tooling from all sides. While five axis CNC machines are able to create undercuts and CNC technology overall is distinguished by very high accuracies, they do not achieve the same flexibility as a robotic milling solutions both in workspace as well as reachability.

Within the field of forming through bending or pressing often times stencils need to be used. The high forces within the process require stiff machinery and therefore prevent the use of more flexible robotic solutions. However, the field of single point incremental forming has shown that robots are able to create a wider range of parts but only with materials up to a certain thickness.

Within this paper we take a closer look at direct additive manufacturing technologies such as welding for joinery, as well as incremental welding for part creation and hybrid processes which allow the use of composite materials for joining of steel parts. While flexibility can be achieved in every part, this often leads to higher fabrication times. We therefore focus on flexible joints for prefabricated parts.

2 Robotics in Steel Construction

Currently the construction industry utilizes automated production systems almost exclusively for prefabrication. Specialized systems for the production of standardized components are limited in flexibility and costly to obtain and operate. These systems often require specialists to program and are designed to repetitively execute movements without mass customization or variation. Feedback from these processes is generally not communicated to the design process. Sensors and intelligent dynamic adaptivity are also not the normal method for correcting errors in tool paths or part placement. While these methods are used in other industries, it is only recently that research aimed at bringing these processes into the architectural workflow. By considering these initiatives, we can observe a variety of further-reaching approaches that stand on the borderline between research and real-world use.

Over the last ten years, robotics has made its way into architecture schools all over the world. Conventional industrial robots serve as universally applicable machines. The possibility of combining abstract movements with various tools opens up a wide range of possibilities for individualized production.

Early projects incorporating robots into the architectural process explore the changing design to fabrication workflow and the exploration of possible tooling strategies [2]. Through cooperation with the construction industry, these efforts resulted in highly individualized objects as demonstrations of this new file to factory robotic strategy. Pioneering projects such as the exhibition hall of the Landesgartenschau of the University of Stuttgart [3], [4], the roof of the experimental hall for digital production at ETH Zurich [5] or the work of the Institute for Timber Construction of EPFL Lausanne [6] can be seen as demonstrator for the creation of complex high performance geometries particularly in timber construction.

Beyond digital prefabrication, there are various efforts to bring robotics to the construction site. Advances in drone and machine vision technology have fueled the use of these systems in stocktaking and inspection, as well as in construction documentation and analysis [7]. With these approaches, there are still far-reaching questions regarding the level of detail and sensible interfaces for rectifying deficiencies.

While manually controlled construction machines have long been at work on construction sites the future will find a greater integration of semi - autonomous or even fully autonomous machines involved in construction site logistics for civil engineering [8]. Lessons learned from other industries, such as agriculture, mining, automotive and aerospace will help to adapt technologically advanced manufacturing methods for use in the construction industry.

In the field of steel construction, semi-automated systems for welding were developed at an early stage, or systems for sheet metal forming were adapted from prefabrication to be used on construction sites [9]. Systems for in-situ production have different approaches to operation when compared to use of robotics in prefabrication. One example of the conversion of conventional construction machinery from prefabrication to on site application, is the Hadrian X brick building robot [10].

In research projects industrial robots are brought to the construction site as prototypical systems [11], [12]. However, such robots are not yet suitable for use beyond proof of concept development due to programming difficulties, safety issues, lack of contextual awareness and the low payload handling capabilities of robots used in research compared to those that may be used in production. For similar reasons, different directions of development are emerging for lightweight steel and metal construction. While the focus of robotic applications in steel construction will probably remain in the factory, development options for assembly will open up the field of robotics in lightweight metal construction.

Steel construction is one of the most common trades at work in the architectural enterprise. The steel industry is characterized by a high degree of prefabrication. This construction method has influenced the planning and execution process and led the industry towards an approach more traditionally seen in mass manufacturing as efficiencies of scale are utilized in order to bring down production time and costs while still increasing quality. To achieve this objective, the steel construction industry uses digital tools at every stage from design to production. This integrated, process-related planning already leads to BIM-based construction planning [13], which is highly demanded but rarely comprehensively implemented.

Automation has not only found its way into the planning process, but also into production. Not only serial or small series of steel components and modules are processed in specialized saw-drilling or welding systems, partly with industrial robots, but also individual productions. The robot has been used for a long time in industries where "exactly repeating" activities are characteristics of manufacturing. However, a robot-oriented further development of the steel construction production has to deal with facts such as very different component weights and sizes, a large number of primary materials, batch size 1 series and relatively large tolerances [14].

Despite the high level of automation, there are further potentials for the use of robotics in prefabrication. Where previously specialized stand-alone machines and associated software have been in use, more flexible systems and a higher-level view of the working structures can offer considerable advantages.

In construction steel production, the material flow, the recording of pre-material (tolerances), welding, cutting and drilling, the assembly sequence etc. are required for robot development and programming. Clearly, these things must be geared to the special requirements of steel construction and lightweight metal construction.

3 Prefabrication

In addition to subtractive manufacturing, assembly and joining, construction research also shows approaches to additive processes. The 3D printing of concrete is propagated by different companies for the printing of entire walls or even houses [15]. Others use 3D printing, partly with robots, to produce formwork and reinforcement [16]. The first experiments on the vertical application of mineral substances with robots are carried out at the RWTH [17]. In steel production, additive processes such as deposition welding or coating with robots could also gain in importance, since they enable complex geometries that are difficult or impossible to produce by subtraction [18].

Conventional prefabrication processes can be made more flexible, cheaper or even possible in the first place by using robots. For example, collaborating robots can bend a hot wire and guide it through polystyrene blocks to create moulds for free-formed concrete parts [19]. In cooperation with the Institute of Welding and Joining Technology, the Chair of Individualized Production in Architecture at the RWTH Aachen University is concerned in particular with further-reaching automation potentials and parametric factors of classical welding technology.

Arc welding processes are of particular interest for the production of large metallic structures [20], [21] due to their significantly higher melting capacity and comparatively lower plant and operating costs. As early as in the 1980s, generator shafts with a component mass of up to 225 tons were produced additive using the submerged powder (SAW) process. gas metal arc welding (GMAW) is much more mobile and flexible than the submerged arc welding process. In particular, the use of energy reduced short arc processes makes it possible to manufacture complex to highly complex metallic components in an additive manner. The LASIMM project relies on the collaboration of robots for fully automated additive and subtractive component production. In this case, the arc-based additive manufacturing is carried out by industrial robots in combination with machining, whereby a parallel kinematic structure is used here due to its increased stiffness [22].

Highly complex structures can be produced by incremental spot welding. A robot-guided GMAW torch places spot welds in any orientation on top of each other, thus creating structures of almost any size and complexity. Parametric models allow for the development of systematic approaches to design of robotic tool paths. In this way the robotic path, welding strategy: speed, angle, duration, weld height and resulting executable code can be programmatically updated to adapt to the mass customization of bespoke architectural elements. The parametric nature of the process empowers the robot with the ability to dynamically adapt to input provided by sensors. Figure 1 details experimentation in robotic wire arc additive manufacturing (WAAM) at the at the Welding and Joining Institute (ISF) of the RWTH Aachen. Figure 2 illustrates some of the results.

Figure 1 Robotic Incremental Point Welding

The development of additive manufacturing through the robotic fabrication of incremental point welding in steel can lead to advancements in construction technology and new ways of mass customization of bespoke geometries.

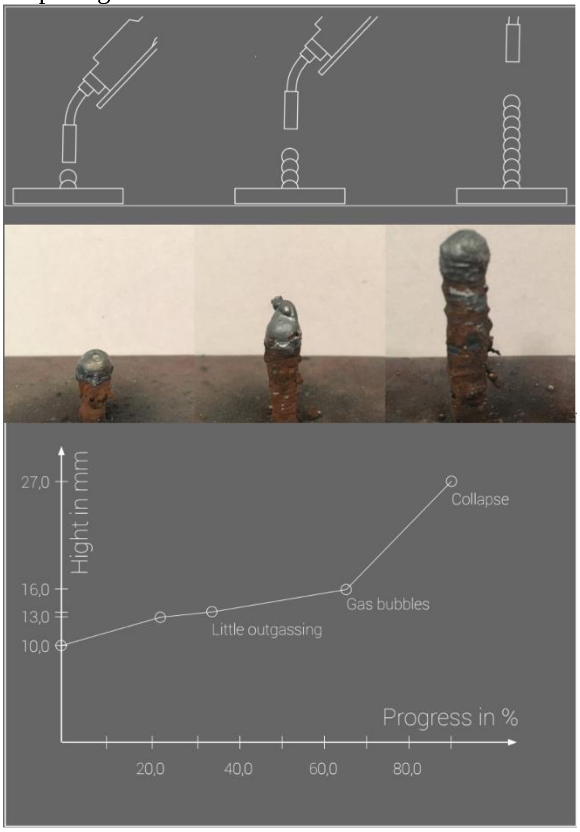

Figure 2: Incremental welding results

Another application area for flexible robot applications is the application of pin structures by means of CMT pin welding on complex shaped surfaces as illustrated in Figure 3. By a combination of targeted current conduction and the dynamic movement of the welding wire, it is possible to reproducibly create pin structures on metallic surfaces. This process opens up a multitude of possibilities for the production of composite components made of different materials.

Possible fields of application are metal-concrete composites for bridge construction or metal-CFRP composites for high-strength lightweight construction applications [23], [24].

The advantage of the high flexibility of GMAW welding can only be fully exploited if a suitable concept for implementing a complex adaptive path planning is available at the same time. In addition to a comprehensive analysis of the factors for an optimal development of the pin through the welding process, potential applications have been identified. A direct on-site production of composite materials is of particular interest, as this opens up new possibilities for the renovation of existing steel structures.

In order to provide the necessary flexibility, the process was transferred from a 3-axis positioning machine to an industrial robot with six degrees of freedom. A KUKA KR3 with a particularly high speed of movement was used. This makes it possible to flexibly design the distance of the pins in order to reduce the heat dissipation in between two weldments.

Figure 3: CMT pin welding with KUKA KR3

By increasing the degree of freedom, it is also possible to work on individually shaped metal surfaces. In order to enable the measurement and installation of the robot on site quickly and flexibly, a new robotics-based process for measuring surfaces was developed. Due to a direct communication between the planning tool and the robot controller, surface parameters at important points can be measured directly with the robot. Using these points, the surface description is used directly for the further path and process planning of the robot. In particular, the measurement can be carried out directly with the robot and reduced from a complete spatial positioning to an adaptation of individual parameters based on the working direction.

In the long term, innovative manufacturing processes will lead to a far reaching change in industrial prefabrication in the construction sector. This will not only lead to the development of new production facilities, but will also lead to a new planning and construction process. Due to the large dimensions of a building, modular components will continue to be in the foreground. Up to now, quite complex plant technology has been used which represents closed systems in terms of both hardware and software. The possible flexibility of the robot is limited here. As a universal tool carrier, it should be able to carry out various work steps, e. g. post-processing of the seams as required or combine more flexible process steps such as plasma cutting, notching and welding.

The demand for more flexible machine and software platforms will increase in the near future. The desire for individualized construction and increasing demands in terms of recyclability and reusability necessitate a rethinking of the concept of integral and differential construction. Prefabrication will have to be more agile. The aim of developing adaptive and flexible machines must extend the capabilities of people in the form of intelligent assistants. A transfer of experience from man to the digital machine is a sustainability strategy that allows companies to keep their manufacturing knowledge safe and free up resources for new developments.

4 In-Situ Fabrication

The main challenge for the work on the construction site is to support people in their work with machines. In addition to occupational safety, health protection and a shortage of skilled workers caused by various factors, the closing of the digital gap in the construction process is the driving force for innovation in this area. Since the construction site is currently dominated by machines without intelligence, there is great potential for improvement. However, this is also associated with high technical challenges.

Factory settings allow for a conclusive prior planning of fabrication. The construction site requires a new level of intelligence within the programming, that takes into account all possible and often unpredictable events and is therefore beyond the scope of current technologies. Simultaneously the construction environment does not constitute a completely unknown fabrication environment as is assumed in the field of service robotics. Over the course of multiple planning phases and experts integrate a high amount of basic information into digital tools. However, changing environmental influences and constant structural changes in the working area of the machines do not occur in the industrial factory environment.

This requires an intelligent use of planning knowledge in combination with easy configuration and adaptability on-site. Most sensors used in production are still not suitable or in most cases not as reliable in construction environments. Within the field of CMT Pin welding we implemented a new paradigm for in process surface measurements, which tries to combine the capabilities of robotics with human planning knowledge. Instead of measuring on a point by point basis a group of control parameters is combined with a parametric geometric surface model as illustrated in figure 4. Within a configuration program the robot movement approaches a number of sample positions.

Manually the distance and angle to these positions is adapted, which in turn inform a parametric surface model used for the welding process. Figure 5 shows the process in detail. After measurement of the surface within the planned constraints and parametric model the placement of each pin is then executed automatically. Depending on the complexity of the surface and therefore the used parametric model the configuration phase requires a much lower number of adaptation steps then an adaptation of each weld position.

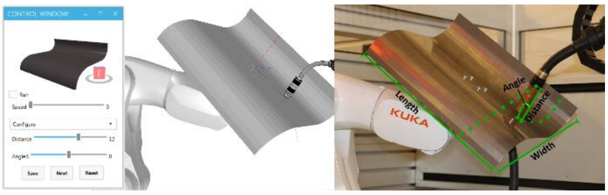

Figure 4 Link between parametric model & physical objects through robotics, with measurements through visual inspection

This allows the in-situ configuration based on parametric geometric models inside the parameter space instead of requiring and adaptation of the robot trajectory space. While in turn also informing the design and reducing sensor based adaptation to a local level.

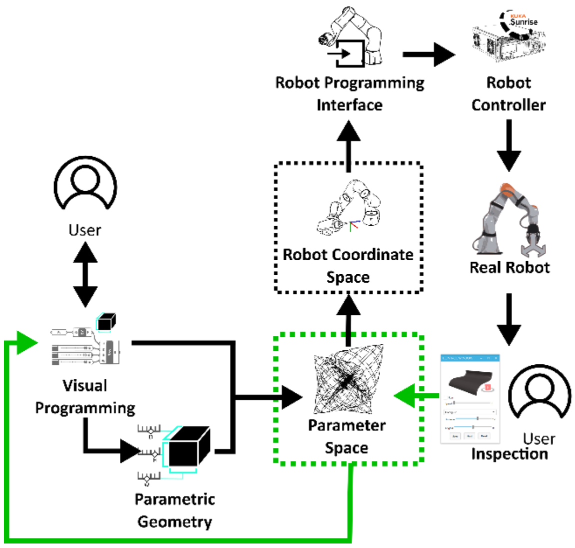

Figure 5 In-Situ parameter space adaptation in pin welding

While alternative approaches require a full scan of every part, the process can be optimized just by a distance measurement to ensure optimal fabrication while overall part position and dimensions are informed by interconnecting parameters within the robot coordinate space. Figure 6 shows the quality difference in aligned and unaligned pin welding.

Within other projects [25] for the assembly of timber structures the chair for individualized production in architecture used similar means of employing planning knowledge in combination with force torque sensors for localized measurements.

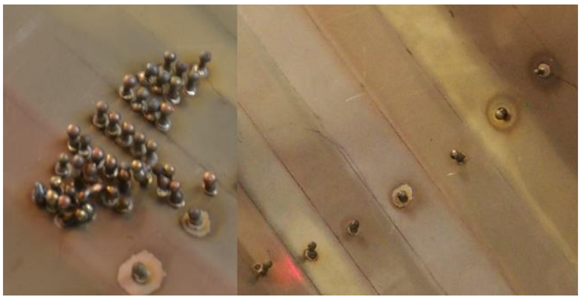

Figure 6 Pin welding with & without surface alignment

5 Approach for Planning and Scheduling

Due to the extensive changes both in prefabrication and in-situ production, it is necessary to adapt digital planning, working methods and organizational structures to changing circumstances. An important aspect here is the area of tension between the possibilities of industrial prefabrication of modular components in the factory for customized individualized application on the one hand and a targeted exploitation of site factors at the construction site, such as shortened transport routes, the use of local resources, assembly without devices and local production methods on the other hand.

This requires further development of agile planning methods and an uncertainty management for the building sector, which encompasses the entire construction process of a building from the beginning of the planning to the final acceptance of the finished building. Possible changes need to be evaluated at any time in a comprehensible way with regards to their effects (construction time, costs, etc.) according to the criteria of Lean Construction. Utilization can be increased due to the ever-increasing networking and the resulting improved possibilities of production planning and monitoring. In the event of planning or construction changes, both points provide the possibility of forecasting and initiating the costs and times of a necessary just-in-time production. The rigid structure of the production facilities in steel construction and the enormous specialization of workstations has so far prevented a high degree of individualization and the efficient production of small batch sizes and individual parts. However, the demand for this from architects and users of buildings is steadily increasing.

Here, the use of robots can achieve significant added value. If one understands the industrial robot as a machine for the assumption of stressful or highly precise motion sequences, a multitude of universal, adaptive tasks can be carried out with it, which only requires the development of adaptation to on-site factors and material- or product-specific process sequences. The same robot can take over a wide variety of sub-processes and minimize the organization and transport costs. The juxtaposition of bulky, locally tied special machines can be replaced by a flexible, multifunctional workspace. In order to further increase the degree of flexibility of such a highly adaptable workspace, mobile and stationary robots can be connected by means of intelligent, modular process flows. In addition, the wide range of movements of robots compared to conventional linear or gantry mounted machines enables simple and fast adaptation of standard mass production processes to the manufacture of highly individual components with complex geometries within the scope of mass customization. In addition to increasing the efficiency of the process and the cost-effectiveness and sustainability of buildings, further areas of application for steel construction are thus opened up and can lead to a general increase in production in the sector.

6 Usability and Adaptation

In order to guarantee a fast and continuously adapted development of new process sequences for individual, unique components, the handling of machines and machine programming must improve considerably with the help of adaptive software and intuitive operations. Up to now, the development of production processes and adapted machines has been in the hands of machine builders and computer scientists, leading to the accumulation of various special software. The adaptation of complete or individual process flows cannot usually be carried out by the steel constructors themselves, but only in consultation with specialists. This not only leads to unnecessarily long conversion and adjustment times for existing factories. It also prevents the seamless, direct integration of the existing material and process know-how of the steel constructors and other parties involved in planning into the production process. Uniform, intuitive software can lead to planners, employees and technicians of the steel construction companies being able to develop and map their production processes themselves in ever faster cycles. Stronger, interdisciplinary interaction between different disciplines for effective integral planning and BIM should be urgently implemented.

The software plug-in KUKA|prc (parametric robot control) [26] is a model for intuitive robot programming in the creative industry. The universally usable basic structure of the software enables a simple, geometry-dependent path planning of the robot as well as the smooth integration of further design and material parameters up to the optimization of the arrangement of work pieces in the working space of the robot to improve the production time. This is also what inspired the described process adaptation used within the described pin welding process.

The proliferation of such an open, intuitively operated system could, in turn, not only increase the efficiency of a single trade union, such as steelwork within the construction industry, but could also bring about the linking and simplified monitoring of the entire construction and planning process of a building. This offers advantages above all in the cross-facility production of highly complex, multifunctional components and building modules and saves the time-consuming assembly of individual parts on the construction site.

7 Conclusion

Even though theoretically there is already a high degree of automation in steel construction, high investment costs and extensive factories make it affordable only for large companies. Scalability of workspace through the flexible use of robots and intuitive, open software systems can be solutions here. The challenge for industrial scale applications will be to combine individualization, which is important for the construction industry, with process reliability. It is already becoming apparent that in the field of robot-assisted manufacturing, topics such as the standardization of interfaces can only be solved jointly and pre-competitively.

Innovative researchers such as MX3D [27] and the RAMLAB (Rotterdam Additive Manufacturing LAB [28] are developing the incremental welding of additive manufacturing. This approach lays down lines of welds to build up a three dimensional object. This method creates challenges for determination of structural integrity as the heating and cooling phases of each additive layer varies in terms of distance and durations. Fundamental research into the robotic fabrication of 3d printed steel is being undertaken. This research has the goal of analyzing the material characteristics and structural qualities of 3d printed metal deposition in order to optimize and speed up the process including the integration of adaptive methods informed by sensor data and predictive models.

The development of additive manufacturing through the robotic fabrication of 3d printing in steel can lead to advancements in construction technology and new ways of mass customizing bespoke geometries both on-site and in factory settings. This paper provided a first foundation for future architectural developments to build upon. Through a consideration of this technological innovation, both present and future potential applications, considerations, constraints and benefits of this new methodology were analyzed. This included a discussion on future challenges and opportunities, ranging from fundamental questions in need of analysis, as well as the possible applied opportunities that suit the unique capabilities inherent in the robotic 3d printing of steel.

The intersection of automation and material innovation can lead to new paradigms of architectural construction. Future industrial revolutions will continue to disrupt existing standards of practice. This paper brings to light the potential of steel's future in order to provide a milestone by which to measure our progress to date and plot a path into the future with respect to new methodologies for creating steel structures.

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