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COOPERATIVE FABRICATION OF SPATIAL METAL STRUCTURES

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Machines have the ability to manipulate material cooperatively, enabling them to materialise structures that could not otherwise be realised individually. Operating with more than one (mechanical) arm allows for the exploitation of assembly processes by performing material manipulations on a shared fabrication task. The work presented here is an investigation of such cooperative robotic construction, wherein two industrial robots assemble a spatial metal structure consisting of discrete steel tubes. The developed construction method relies on the alternate positioning of building members into triangulated configurations, where one robot temporarily stabilises the assembly while the other places a tube and vice versa. The intricate geometric dependencies of this structural system, as well as the fact that the machines limit each other's operational range, led to the exploration of robotic simulation and path planning strategies as an integral part of the design process. The experimental results of realising a space frame structure at an architectural scale (Fig. 2) validate this approach.

Space frame structures have been traditionally constrained to regular systems using standardised elements and joints, or have required the development of complex prefabricated joints for the construction of differentiated structures (Chilton, 2000). The implementation of an industrial robot into the building process offers a new approach for the construction of non-regular spatial structures, since a 6-axis robotic arm can precisely move, position, orient and hold a building element in space, something a human cannot accomplish without a reference system and support structure (Gramazio et al., 2014).

In the work presented here, the digital fabrication of space frame structures is further explored with a cooperative robotic construction approach. Whereas multi-robotic material manipulation is well-established for repetitive pre-programmed tasks in assembly lines, its application in non-standard digital fabrication, derived from the inherent complexity of performing non-repetitive robotic movements in an altering building space, is still widely unexplored. Cooperating robots have been used in architectural research for filament winding (Parascho

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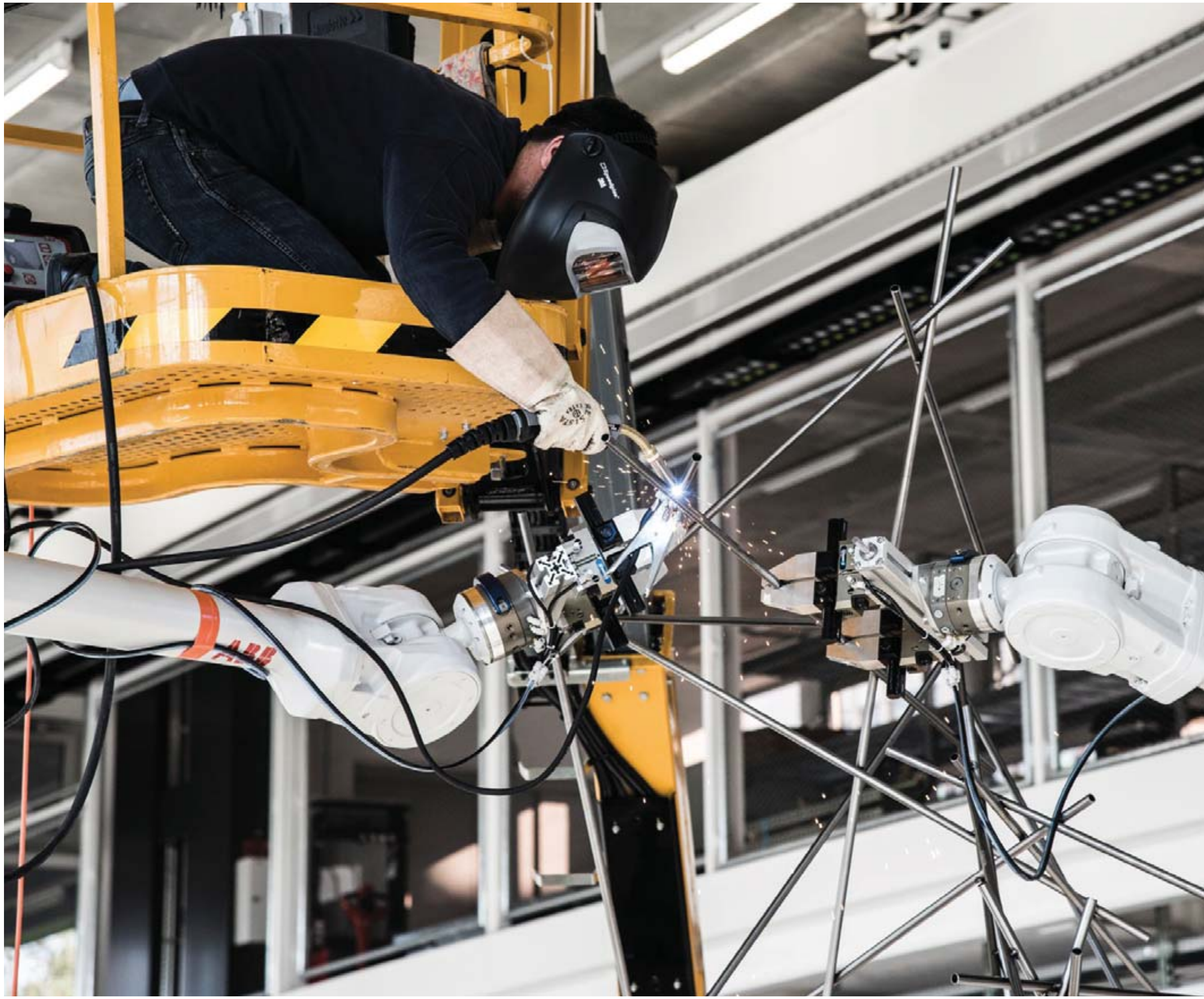

et al., 2015), hot wire cutting (Rust et al., 2016, Søndergaard et al., 2016) and metal folding (Saunders et al., 2016). While these applications hint towards the potential of using cooperating robots in architectural fabrication, they are usually manoeuvred at a safe distance from each other where the spatial configuration of the robotic arm is less of a concern than when operating at close proximity within the same fabrication space. Rather than merely focusing on the final pose of the robotic end effector when assembling an element, the research presented here considers the whole body of the robotic arm over time to guide building elements around material obstacles.

An investigation into possible assembly sequences for the realisation of space frame structures with multiple robots has shown that in principal only two cooperating manipulators are required to assemble stable, triangulated structures (Gramazio et al., 2014). This is based on the assumption that one robot can temporarily stabilise the structure while the other is picking and placing a new structural element. While one robot assembles a steel tube, the other briefly changes its function and acts as a structural support to balance the unstable assembly until it is triangulated and can be fixed. As a result, using digital design, robotic simulation and robotic fabrication in a negotiating manner, highly differentiated space frame structures can be erected without the need for additional support structures.

Computational design and fabrication simulation

Like other space frame structures, the system developed here is primarily characterised by the node. In order to allow for geometric flexibility in arranging the tubes at various angles, and to be able to later robotically fabricate them, the node is distinguished by the shifting of the tubes alongside each other around a shared centre point. As a result, two tubes connect at one point. While this shifted node offers a high degree of freedom in respect of possible spatial arrangement and robotic fabrication, it also presents structural challenges. In contrast to traditional space frame systems that join multiple structural members at a singular spherical point, the reciprocity of this expanded node induces flexural rigidity in the system, leading to a structure with a greater stiffness.

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1. Tubes are welded manually at their connection points after each assembly step.

2. Cooperative robotic assembly of a spatial metal structure.

3. Assembly of the structure.

4. Build-up sequence of the structure.

Images: Gramazio Kohler Research, ETH Zurich, 2016.

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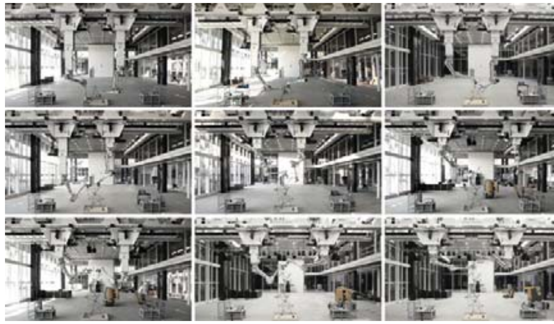

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Each newly added tube connects at each side to two neighbouring elements with the objective of assembling reciprocally closed nodes. These configurations are able to take bending forces, although every constructive joint between two tubes is hinged in a static sense. As a result, each tube, once assembled into a tetrahedral configuration, is comprised of at least four connections, making two reciprocal nodes with its neighbours. During the build, the number of connections to an individual tube increases over time, subsequent to the adding of neighbouring tubes requiring structural support points. This means that, in a final assembly, a tube can have up to eight connection points at each end, depending on the overall configuration. This novel construction system leads to geometric dependencies that require the use of computational design to explore possible spatial arrangements and to identify a fabrication sequence that considers the build-up of the structure into stable configurations accordingly.

The overall spatial organisation of the construction system is based on tetrahedra. A tetrahedron creates the minimum stable space frame structure. Combining a multitude of tetrahedra into larger, interconnected structures allows for the creation of complex load-bearing assemblies while assuring the structural integrity of the individual tetrahedron and, as such, the controlled assembly of tubular elements into spatial aggregations. When designing such an arrangement, the order of placing tubular elements has to be defined. This is directly related to the later construction of the structures. The fabrication space changes over time. Therefore it is crucial to define where and when to place the next building element and to which tubes it can connect, so that the computational design tool can find the appropriate geometrical solution for the tubular arrangements.

An important aspect of the design process, aside from the definition of the spatial arrangement, is the creation of the robotic movements that allow the integral verification of the fabrication feasibility. As described above, two cooperating robots are used to assemble the structures in a highly constrained three-dimensional space. A series of tests has shown that defining collision-free robotic movements is a challenging task that needs to be addressed at an early design stage. On one hand, this originates from the need to manoeuvre building elements into openings and gaps of already built parts to create the interlocking reciprocal joints, while avoiding collisions between the robot and the structure. On the other hand, the construction environment changes over time, as a result of the sequential and spatial build-up of the structure and of the continuously altering configurations of the robots, which limit each other's operational range.

Rather than only calculating the final pose of the tool centre point (TCP), the approach required designing the robotic configurations, translated into axis rotations, determining the entire spatial arrangement of the robot over time. For this reason, path planning strategies and robotic simulation tools that linked to the computational design were investigated. The proposed solution makes use of a robotic simulation platform (Coppelia Robotics, 2012) that uses the power of sampling-based path planning algorithms (Kavraki Lab, 2012) to generate collision-free trajectories. A software tool was created in a CAD environment (McNeel, 2013, McNeel, 2015) in order to integrate robotic simulation capabilities directly into the computational design process. The robotic trajectories can be generated by defining a start configuration of the robot and a desired end pose of the TCP, by outlining the robot's joint metrics (to set the joint constraints) and by setting a series of rapidly exploring random tree (RRT) algorithm-specific values, such as the sampling resolution. Following this method, a spatial configuration can be evaluated when designing it, which can be adapted if needed. For example, if no solution is found, the gripping pose can be shifted or the geometry of the structure can be altered.

Building a 4m-tall structure

To test the fabrication approach, a physical prototype was realised with two cooperating robot arms (Fig. 3). The structure is comprised of 72 steel tubes, creating 23 non-regular tetrahedra, concatenated into a spiral configuration growing from the ground to a height of 4.2m. The prototype is the first structure built in the Robotic Fabrication Laboratory (RFL), a test bed for large-scale robotic fabrication research at ETH Zurich. It consists of four 6-axis industrial robots mounted on a 3-axis gantry system that can cooperate on architectural fabrication tasks within a maximum building volume of 43 x 16 x 6m.

The structure was built from the ground up, pushing the vertical building envelope of the fabrication system (Fig. 4). Whereas from afar the construction process appeared as a surface-based assembly, the steel tubes were actually guided into the interlocking reciprocal node configurations in a truly spatial manner (Figs. 5 and 6). The non-intuitive robotic trajectories generated in the design environment were sent via a custom CAD-to-

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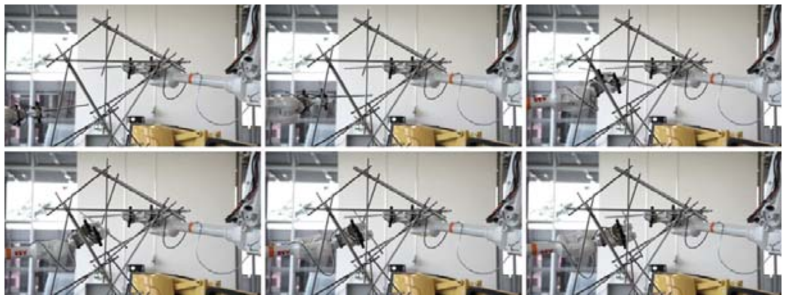
robotic-controller interface. In order to be able to create collision-free robotic movements, the model of the simulation had to match the actual physical set-up. While performing the first tests, collisions occurred – for example, because the kinematic model was not paired with the simulation or because the physical envelope of the IO box, mounted on the back of the robot, was ignored.

The 16mm diameter steel tubes were pre-cut at the required length and picked up by the robot from a pneumatically actuated pick-up station. The building elements were then guided through the building space, avoiding contact with physical obstacles, to their designated location within the structure. Once the element was in place, the robot changed its function from a tube manipulator to a tube holder. The element could then be joined to its neighbours by the manual welding of four spots around the connection (Fig. 1).



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5. Shifted node. The node consists of up to ten tubes and seven reciprocal connections.

6. Sequence of the placement of a tube. The geometrically complex connections require a specific spatial trajectory for the robots for each tube.

Images: Gramazio Kohler Research, ETH Zurich, 2016.

During the build, tolerances of up to approximately 5mm occurred at the joint between two building elements. The reason for this is that the robotic system, with its unprecedented large workspace, is still subject to initial adjustments and the large-scale metrology system of the RFL is not yet in operation; in addition, some of the tubes were slightly bent. However, since the welded joint can accommodate a few millimetres of tolerance and because each new structural element was placed according to the digital blueprint rather than based on what had already been built, the tolerances did not accumulate over time, which enabled a successful welding of the entire structure.

Successful cooperative fabrication

The work presented here successfully demonstrates the ability of cooperating robots to hold building elements in space, allowing for the building of non-regular spatial metal structures by integrating computational design, robotic simulation and digital fabrication. However, several aspects of the project require further development. Firstly, the settings of the simulation parameters still require several manual steps and knowledge from the designer about the functionality of the algorithm. Simplifying and further automating the integration of this process with the computational design environment would allow the user to interact more intuitively with the tool when designing robotic movements. Secondly, as described, the welding was manually performed, and further testing to transfer this joining to a robotic method is required. Finally, sensing the spatial arrangement of the structure while building on it would allow compensation for tolerances (for example, from bent tubes or errors that occur during the construction).

The realisation of the architectural scale physical prototype displays some of the potential of cooperatively building space frame structures with two robotic arms. Cooperative construction expands the capacity of digitally designed and robotically fabricated architecture. Here, multi-robotic cooperation is not merely used to distribute the workload between individual machines, but to perform building tasks a single robot (or a human) could not accomplish. The integration of path planning and robotic simulation capabilities within the computational design allowed for the generation and later physical realisation of intricate reciprocal space frame configurations. The project demonstrates the possibility of methods of computational design that take into account the full spatial movement of robots when materialising architecture and, as such, fosters a shift from layer- and surface-based assembly approaches towards truly spatial aggregations. As such, the construction system presented here is not limited to discrete metal tubes. Combining computational design with this increased three-dimensional autonomy of cooperative robotic construction potentially leads to novel architectural construction systems in general.

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