Design Research between Academia and Practice:
Systems Reef – Developing A Robotic, Carbon-Fibre Wound, Integrated Ceiling Structure

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Abstract
Architectural practices are increasingly dealing with complex design and planning tasks, particularly for construction and advanced manufacturing industries where assembly and automated processes are prevalent in many sectors. The ability to consider and explore new pathways for design can be of economic significance, and investigating uses for industrial robots towards novel material, practical and large-scale applications provides a unique opportunity. Innovation within the Australian construction industry is relatively low compared with other developed countries globally. The construction industry in Australia has one of the highest % shares of GDP and employment but ranks third lowest in digitization of all sectors. In this context, design research conducted as collaboration between academia and practice can be used as a framework to actively and directly engage architectural firms in the accelerated developments in construction robotics and advanced manufacturing, and simultaneously enable academic researchers to develop prototypes and proofs-of-concept through applied case studies. Such applied research in and through design then allows practice and academia to rethink the way that architecture can operate.

In this paper, we present the project ‘Systems Reef’, an applied design research into the onsite, robotic carbon fibre threading of a bespoke ceiling system for a commercial building. The paper first introduces combinatory threads of research including workspace scenarios, data distribution, flexible team organisation and robotic applications, and discusses strategies for bridging knowledge dimensions and establishing joint learning essential to the research. In the second part, the paper reports on the consecutive phases of design research; from developing prototypes for robotic carbon fibre threading towards onsite building fabrication for a new infrastructure distribution system. We discuss criteria, benefits and results of the project, and conclude with an outlook towards future potentials of design research for ‘Systems Reef’.

1 Introduction

Advanced manufacturing has introduced significant changes to the production and construction industries in recent years, through automation, optimisation, precision and customisation of work processes, for manufacturing of building or industry components and products, and for optimising labour. In this context, robotic technologies show a wide-ranging potential for informing design approaches, material applications and building methods. Yet builders and fabricators, but more importantly architecture and design practices are often unfamiliar with robotic technology. Robotic fabrication requires in-depth technical knowledge for equipment and material processes, and an understanding of continuous workflows from design to production, such as handling a continuum of design data inputs and fabrication outputs feeding into each other. Systems and methods by which robotic processes can be developed, prototyped and then integrated within a construction site require an understanding for sequencing robot-human interactions, and how to measure and adapt different routines needed during the on-site fabrication of a project. These aspects present challenges but are also large areas for exploration through research and practice. Moreover, robotic applications can also foster novel design solutions, decision-making methods between designer and producer/manufacturer, new organisational structures. Hence, a critical step is the development of design research as an underlying technical foundation performed through interdisciplinary collaborations between industry, academia and government institutions.

All research constitutes ways for knowledge to be explored, captured and disseminated (Fraser, 2013, Archer 1995), but design research particularly extends research through different methods of enquiry. We consider design research as research through design, that is, as the development of knowledge through designing, prototyping, process development and material investigation for a design solution. Whereas research fundamentally frames questions and hypothesis for theoretical investigation and understanding, design is an embodied action and dynamic process. ‘Systems Reef’ presents here a specific use case that formed the basis of our research, whereby we indentified a real world problem with no known pre-existing solution. This enabled us to test the viability of potential options real time.
with users and create a feedback loop for the research. Design as a discipline integrates reflection and inquiry with tangible results (Friedman 1993, Schoen 1997), and combines a subjective process of search and research and a generalizable method that moves from prototype to practice (Fuller 1969). Design research can thus establish a foundation for design innovation and produce concrete results. We argue that design research offers a unique problem space, whereby design research acts as shared tool for practitioners and researchers to invest in critical enquiry, to develop systemic thinking, to access and combine ranges of experience and expertise for a knowledge economy from design to industry applications.

Figure 1. Robotic carbon-fibre winding of a new integrated ceiling system in simulated ceiling environment with obstacles.

Our approach towards design research as collaborative endeavour is illustrated in the following by ‘Systems Reef’, a project that explores the potential and viability of robotic onsite construction by investigating carbon fiber reinforced polymers (CFRP) for a bespoke ceiling infrastructure system for a flexible workspace scenario (Figure 1). This case study was developed over a 9-month period (2017-2018) by the Robotics Lab (DMAF, The Sydney School of Architecture, The University of Sydney) and architecture practice BVN (Sydney) and explored a design research framework that allowed both partners to develop research, designs and industrial solutions for construction robotics directly.

2 Research Project: Project Scope and Multi-Disciplinary Threads

The project scope for ‘Systems Reef’ spans multiple problem spaces and cross-collaborative threads; from workspace for flexible team organisation to acoustic performance integration, from prototype development for robotic CFRP applications to the navigation of onsite fabrication and constraints:

Workspace survey towards flexible scenarios: In highly collaborative organisations, workplace structures necessitate flexible and reconfigurable environments (Vischer 2005). Standard office-ceiling grid systems (1950, US Patent Bibbs) conceal building services and provide acoustic attenuation for spaces. However, these systems are monotonous and limit physical changes. Changing work and team constellations require a different organisational approach to general fit-out, table arrangements, data provision, and lighting integration (Brill 2001, Groves et al. 2016). The research conducted two surveys to understand the general capacity and performance of the existing open-plan workspace (BOSSA/Building Occupant Survey System) (Candido 2016). Providing flexibility for desking independent from services and physical infrastructure limitations enables user agency, increases self-organisation of teams and supports highly dynamic activities, factors that can be critical to the future success of contemporary business.
Acoustic performance in open-plan office: General noise levels produced by multiple talkers can be high specifically in open plan offices, and so speech distraction can be a significant cause of dissatisfaction and loss of productivity (Yadav 2017). Ceiling treatment in open-plan work environments can provide an essential way of ameliorating distraction from unattended speech, so that communication becomes more comfortable, and lead to a more relaxed vocal effort (Brunskog et al., 2009). The research conducted surveys to understand existing conditions. It then framed design strategies for reflecting sound back to the source, followed by ongoing research work into physical testing of prototypes towards site-specific deployment of acoustic reflective ceiling structures integrated into the project scope. An integrated workflow of computational design and digital fabrication technologies was created, allowing for the customised and programmable conditioning of spaces based on acoustic performance.

Development of robotic applications and configurable material practices: Recent advancements in CFRP technology and computer-controlled robotic manufacturing enable threading with consistent and reproducible material qualities. Substantial research includes carbon-fibre polymer composites formed over moulds or core-less fibre winding (Menges 2014, 2016), coreless and structure-focused winding (Prado et al, 2014, Reichert et al, 2017, Wit 2018), or semi-autonomous deposition by mini-robots (Yablonina 2016). Our research expanded a robotic filament deposition of fibre composites towards a context of on-site, on-ceiling industry-scale application, as a material response to flexible spatial programming, and with different structural performance implementing local constraints.

On-site, overhead and adaptable robotic fabrication: Recent projects have expanded the fabrication space from closed settings towards scenarios of onsite and versatile live robotic construction with mobile adaptive in-situ fabrication (Doerfler et al. 2016, Gifflhalter et al 2017a, 2017b) or aerial robots (Mirjan et al. 2016), including substantial research into onsite carbon-fiber threading as for example the V&A project (Menges et al., 2017). These systems build on live-data feedback with sensing and feedback control as part of robotic programming and fabrication. In contrast, this research prioritised developing a reconfigurable and robust work protocol for variable project constraints, allowing robot and humans to inter-operate in an inhabitable environment where human flows and obstacles were unpredictable.

3 Collaborating between Knowledge Dimensions

A key aspect for design research lies in new knowledge to be produced though the interaction of thinking, experience and action that ‘conjointly play a role in learning’ (Bunge, 1996). Collaborations between research and practice through design are particularly useful here; in bridging different dimensions that support problem solving, whereby (disciplinary) limitations can be overcome by working collaboratively and outside the ‘immediate constraints of practice’ (Friedmann 2000). Developing design research through inter-organisational arrangements between practice or industry
and academia extend to a variety of engagement levels, from contract research, use of equipment, to skill training and joint and equal research partnerships (Pecas et al. 2006). This potentially allows practices to rethink the way they operate (Hensel 2018), and academia to extend research limitations. Yet in order to do so successfully, designers and researchers must then fundamentally deal with learning methodologies that may differ between both groups. A systematic and organised enquiry into a defined problem with multiple feedback is essential for results and processes to become 'goal-oriented, knowledge-directed, and communicable' (Archer 1995), and this is irrespective of the organisational body that undertakes the enquiry (Bayazit 2007). Importantly, different resources and knowledge can be combined to support active decision-making processes (Alazmi and Zairi 2003, Cahill 2001). Pursuing a system enables mutual learning and synchronisation of known dimensions and disciplinary expertise, across a range of criteria (Friedmann 2000).

In ‘Systems Reef’, design research was characterised by a joint and ongoing development, undertaken by a large team with different skill sets, and thus design and prototyping required a concerted and continuous effort of mapping objectives and framework forward (Figure 3). From the outset, we developed a shared pathway through mapping out crucial questions with priority, high-level exchange of information, brainstorming to enable common areas of interest, and define research objectives.

Figure 3. Initial sketches and concept diagrams continued to final discussions onsite.

On a level of consultancy and sharing research foundations, this included connecting to ongoing design processes (workspace design) by providing surveys and analysing, and testing and evaluating existing work conditions (acoustics). On a level of shared technological and infrastructure equipment, this included research training phases for robotic technologies and continuous phases for robotic prototyping towards applied onsite robotic winding, thus shifting the robotic fabrication lab between institutions. As a consequence, academic and industry research partners were able to invest profoundly and across dimensions from design development, workspace, robotic fabrication, and organisational management (Figure 4). Hence, the multidisciplinary team moved across building a shared body of generalised knowledge towards the understanding of workspace conditions to develop problem-solving capacities for data distribution. Then, we developed insights, techniques and processes into new areas of 3D printing and robotic weaving, and evaluated these against design creation and cost effects driven by project management and production aspects. We bridged our first differences in objectives, from multiple computational design and simulation applications towards prototyping and onsite manufacturing), and developed tactics for meta-learning, as exchanges between design tools. Finally, we established strategies for learning on an individual and a collective level, across team members and institutions.
Figure 4. A taxonomy: dimensions of design knowledge, phases and prototypes (after Friedman 2000).

By adopting a multi-modal and multidisciplinary approach in this project, designers, researchers and professionals with different background knowledge and expertise worked directly together to integrate expert knowledge other than their own, develop synergies, and so push the boundaries of construction robotics. Key phases are introduced in the following to further discuss framework and systemic thinking across the fields of workspace, acoustics, and design for robotic fabrication and construction.

4 Research Project: Key Objective and Phasing

Robotic technology has introduced aspects of automation, optimisation and customisation to manufacturing and fabrication processes, and thus provides a considerable potential for construction industries (Gramazio et al., 2014a, 2014b). Human-robot collaborations for robotic-aided fabrication and onsite building sequencing are furthermore currently of substantial interest to robotics research. Consequently, design research for ‘Systems Real’ centred on the development of an integrated infrastructure to support the agency of networked, dynamic and self-organising teams. To this extend, multiple soffit-hung, rotational and retractable data booms were to be situated within an existing ceiling of a commercial building. Each boom holds a capacity to feed eight desks in direct vicinity and provides fibre-optic data, electrical cabling and integrated lighting.

For the data network to be adaptable to complex activities, the system had to be compliant with standard building requirements, and afford onsite and data-responsive advanced manufacturing. Hence, carbon fibre robotic threading was chosen to secure the data booms within existing ceiling services. We chose to use CFRP as a ‘non standard’ material to explore possibilities, and enable industry to consider new materials as a catalyst for innovation and rethinking current practices. The research developed knowledge for the complex, overhead and onsite robotic weaving across an existing ceiling condition that constitutes a three-dimensional structure. Distinct multiple robotic weaving deploys here intrinsic material properties and structural performance of a resulting fibre mesh to negotiate forces inherent in the system, and a travelling point load presented by temporary towing of the data cable. To do so, essential knowledge for geometry, weaving syntax, material constraints, structural performance and robotic feasibility, including evaluation of prototypes, had to be developed.

Phase 1: Developing Systemic Thinking and Design Capabilities
In the first phase, the team explored options for concepts, geometry, material studies through multi-scale models, scripts and robotic workspace in parallel to produce a knowledge base for the project:

**Conceptual brainstorming and definition of common denominator.** Precedents, concepts, diagrams, presentations and modelling workshops were conducted to arrive at a project approach and common design language. This allowed the team of researchers to visualise and discuss opportunities for shape, geometry, material applications and project scope (Figure 5).

**Global Geometry.** The team developed a range of possible shapes in Grasshopper (GH) as a function of rule-based connections between a point matrix relative to boundary conditions. The global geometry conceptually followed by generating a model based on a number, relative distance, position and weaving between the circular boom, and inside and outside soffit hooks. This approach provided a catalogue for testing the structural fitness of the shapes with tension-compression forces exerted to the system (Figure 6). The geometry displayed here requires four robot positions; one inside and three outside to produce resulting surfaces.

![Figure 5. Design languages and strategic development of communicable visuals.](image)

**Figure 5. Design languages and strategic development of communicable visuals.**

![Figure 6. Diagramming potential robotic prototypes (a-e), robotic workspace and reach (f), confirmation of primary weaving access (g), and robotic work volume intersections (h).](image)

**Figure 6.** Diagramming potential robotic prototypes (a-e), robotic workspace and reach (f), confirmation of primary weaving access (g), and robotic work volume intersections (h).
Situating data distributors. A generic script (kernel/circle packing, GH) was deployed to reference a data tree structure with organisational centres (booms) to minimise distances while accounting for existing obstacles (HVAC, columns). We applied a generative design for optimised shortest path distribution of power and data cabling, and one optimisation was chosen as macro-topography and referenced with a 3D scan. These initial 3D surveys provided an overall placement of data booms within the existing ceiling structure and indicated a preliminary installation of the future prototypes.

Developing material and fabrication process. Researchers explored many physical and scaled studies in builders’ rope and carbon fibre reinforced polymers (CFRP) on customised looms as a comprehensive description of morphogenetic weaving patterns, where the differentiated fibre layout weaving becomes a gradient variation of material properties and geometry (Steinmann 2018, Wulfhorst 2006). Customisation of the fibre threading process also included changes to the carbon fibre x-winder and development of a series of end-effectors for threading the fibre (Figure 7).

Weaving syntax. The robotic simulation in KUKA|prc follows the global geometry and consolidates the weaving syntax for the doubly curved carbon-fibre surface woven in multiple step-over for each ceiling hook. Priority is given to maximising fusion between laid carbon-fibre threads (Reinhardt et al, 2018). For internal weaving, ceiling hooks and ring hooks form concave arcs relative to the robot position, with a surface 'lofted' between both arches that are also concave relative to the robot. The script orchestrates weaving density, access angle of end effector reach towards hook heads, and exact position of fixings as a primary starting point of a weave (Figure 8). These preliminary studies enabled the research team to move forward into two research prototypes that confirmed the economic, aesthetic and structural feasibility.

Figure 7. Material computation models: Development of weaving models (analogue string weave, robotic string weave, robotic carbon-fibre).

Figure 8. Robotic weaving sequence applied to all prototypes (left), data boom with integrated carbon-fibre weaving (right).
Phase 2: Prototyping

The second phase centred on the development of the robotic threading for a series of prototypes from generic and full circle carbon-fibre deposition to prototyping in a simulated ceiling context.

Prototyping at 1:1 scale. As a proof of concept, robotic weaving was prototyped within two large-scale circle segments to test sequencing for weaving, test density patterns, overcome blind spots in robotic reach, and to achieve correct turnround at hook positions (Figure 9). The robot is placed centrally and weaves inside across 360 degrees. By transferring weaving patterns first into a sequence in a string (builders rope, first stepover), and then retracing in industrial carbon fibre strength and stiffness for the carbon fibre laminate could be evaluated. Results indicated that sufficient structural capacity results from material properties for a multi-directional layer with five stepovers. Further robotic studies replaced the closed upper circle with circle segments to increase reachability and navigation towards multiple ceiling hooks.

Figure 9. Simulated office ceiling, phase1 (ideal complete weave, a), multiple stepovers overcoming blind spot (b), and carbon fibre final (c).

Figure 10. Prototype 2 in simulated office ceiling, phase1 (inside three hooks, a) and onsite results carbon fibre threading inside and soft fabrication outside (b).

Prototyping in a simulated site context. The robotic workspace was further tested relative producible dimensions against four different site conditions for boom prototypes, given the current ceiling interruptions (HVAC). While the boom set-out is predetermined through the desking location, all
positions for hooks are adaptable but relative to the total number of required robot positions. The robot motion script is from the start constructed to privilege variability and allow a maximum of updates relative to criteria adaptations. At this stage, the script orchestrates weaving density, access angle of end effector reach towards hook heads, and exact position of fixings as the primary starting point of a weave. This enabled the research to move seamlessly into further development of the script for prototype 2, where the two complimentary rings and closed weaving was exchanged for multiple hooking points. Producible dimensions of one robot workspace take into account three initial, inside weaves and further consecutive 3-8 external weaves within the same ceiling context (Figure 10).

Phase 3: Developing Applied Design and Project Delivery

The third phase transferred updated scripts and workflow for integration with the added challenge of weaving inside a ceiling void, for testing the robustness of the robotic protocol and manufacturing four differentiated design solutions.

Developing adaptability and robustness. In-between standard obstacles and non-go zones set by different existing service elements including beams, HVAC, cabling, fire outlets, and core areas were embedded into the script, so suitable data solutions for manufacturing could be generated. Adaptability in the script provides an inbuilt tolerance that also caters for misplacements of soffit fixings due to human error, or previously unregistered site constraints. By re-referencing a fixing point once it is placed, the script maintains a capacity to semi-autonomously update robotic threading patterns, in response to system positioning, location, and available fixings points.

Choreographing robotic fabrication in a moving building site. The team conducted a standard procedure for set-up and calibration to respond dynamically to conditions of the building site. The robot was located on a platform and calibrated by determining the project origin through manual tracking. These actual data were referenced against the original 3D data scan and corrected through adaptability embedded in the script, simulated in Grasshopper and KUKA|prc to check sequence of robot positions and corresponding hook positions. Discrepancies in hook positions and robotic tooling path could thus be adjusted. Then, a robotic threading fabrication was deposited as a 'dry-run' in builders rope before fabricating in carbon-fibre. This process orchestrates 16 robot positions required for four weaving solutions, taking into account also the people and desk movements to enable continuous work across the office environment and its ongoing operation during construction.

Figure 11. Robotic Model as Prototype. Staging of prototypes and incremental variations: minimal/1 robot position (a); optimized/4 robot positions (b), maximum interrupted/ 5 (c), and maximum robot reach (d).
Developing diversity across four differentiated robotic weaving prototypes in situ. The complexities of onsite robotic weaving across existing ceiling conditions is expressed as unique three-dimensional structures that deploy specific material properties and exhibit particular structural characteristics. Each prototype is a discrete event within the overall process, fabricated in individual locations, whereby each geometry navigates the ceiling context of obstructive services (see Figure 11). Each started with weaving three inside hooks from the first primary position, with the constant weaving of 1-3 external ceiling hooks per following robot position. Criteria values were: a minimum robot calibration and weaving time with one robot position and three inner hooks only resulting in sufficient structural stiffness (11.a); an optimized version with three internal and three outer hooks across four robot positions (11.b); a maximum diversity weave due to prevalent interruptions with five robot positions (11.c); and maximum robot reach and surface span within robot work envelope (11.d).

Through robotic design tools (both relative to processes within the computational design and advanced manufacturing), the research could account for and expand limitations of precision and optimisation, dimensional tolerance and material resistance. By encouraging variation and differentiation instead of geometric simplification, standardisation and repetition, the robotic design model was advanced towards four differentiated prototypes of an integrated ceiling system that conditions flexible workspaces through data and light distribution.

5 Discussion

Common learning practices in research collaboration between practice and academia are a challenge, but more importantly offer an immense potential to go beyond immediate organisational constraints. Establishing a combined research agenda and systemic thinking across disciplinary fields proofed invaluable for the research team to combine different areas of expertise, and so be able to situate the research value in a field where sub-problems such as workspace, or CFC had been initially already explored but not been brought together. Developing pathways for a range of research activities jointly engaged researchers in phases from design, analysis, material and structural performance, whereas previously they would have been allocated only parts of this multi-dimensional problem space.

The research found that the objectives of the project could collaboratively be defined after a wide-ranging brainstorming regarding available expertise, research scope and general project requirements. As the project contained several complex and intricate problems, it was essential to decompose design aspects into several subprojects, but equally important to regularly interface objectives and methodologies across subgroups. A definition of project tasks and milestones was formulated at the outset, changes occurred, and so clear communication of developmental stages was important. The project contained strands of enquiry that differed between project partners, ranging from the application of universal design- and technical-based methods and tools towards optimising these for project production. To benefit both research investigators, continued and opened discussions in regards to strengths, limitations, and critical points were used to align these agendas. Finally, the parallel documenting of design methods in all phases allowed for updating team members regularly, and further served as an evaluation tool for all procedures.

Impacts and benefits of the research project, and particularly the move from basic research towards practical application, extended the design possibilities for both. This is demonstrated by the refinement of infinite geometric variety towards an ability to build high-resolution, design-engineering products. In adopting variable and adaptable methods towards customisation across four prototypes, the team derived solutions for advanced material deposition in carbon fibre that could be tested and evaluated under project criteria (material, structure, deposition, etc). The design research case study could thus invest in methods for robotic fabrication that specifically incorporate workflows for exploring construction sequence, negotiation of material forces, and robot motion protocols. While this particular study into onsite robotic weaving represents a defined and thus single design problem, this further indicates ways in which designers and researchers can facilitate productivity, design flexibility, on-site safety, and cost reduction for the construction industries.

6 Conclusion

Design research for ‘Systems Reef’ enabled us to establish strategies, project scope and bridging interdisciplinary knowledge and research strands between flexible workspace in open office
environments, acoustic performance criteria, novel robotic applications and material practices and onsite fabrication. Future research work could extend these individualised solutions for construction robotics by shifting the project scope and continuing into human-robot collaboration through construction visualisations for the human counterpart. This could also extend to semi-automating weaving processes through adaptive robotic protocols based on real-time sensor feedback or mobile robotic platforms, or further investigation of structural dimensions for threading robotic carbon fibre as integrated ceiling component. Between these options, the design research could proceed as basic research, such as industry mass customisation, or as a hybrid between both. Significantly, there exists the potential to consider producing the entire infrastructure system through its relationship with a flexible and self-organising workspace as initial setup, whereby robotic fabrication processes could be scaled up to supplement the entire ceiling topography.

The design research provided a methodology to synchronise and expand expertise and knowledge between research partners with different objectives – the method-oriented focus of basic research in academia, and the applied industry agenda of practice. Design research conducted jointly between practice and academia offers a potential to rethink the way that architecture practices operate, and at the same time allows academic researchers to develop proofs-of-concept through applied case studies. In a context of developing research for construction industries, particularly research into robotic fabrication processes for practical and large-scale applications can provide a platform and framework for architectural firms to pursue novel solutions for the constructions trades, and define new professional roles that reposition the architect again at the building site. Architects are then no longer limited to merely designing buildings but extend their work towards generating processes for human-robot collaborations, orchestrating constraints as much as sequences for environments that evolve through design research innovation.

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References


A Robotically Woven Ceiling Structure

Statement of Research Significance

The proposal showcases design research into prototyping a robotically woven ceiling system that allows to flexibly iterate, novel physical solutions for data distribution as a driver for work scenarios. Main drivers for workplaces can be identified as organisational strategies, workforce attitudes and expectations, and technological advancements for workplaces (Brill et al., 2001). To this extent, the research brings together different disciplinary domains; the development of workspace scenarios and conditions; ceiling services infrastructure and distribution; flexible team organisation; acoustic sound conditioning; and new robotic applications and material practices (more data can be displayed with accompanying materials/video).

As a collaboration between industry and practice, four of the prototypes have already been implemented in an onsite robotic fabrication while the architectural practice was ongoing. The proposed installation shows one, or a series of robotic prototypes that increase in complexity from a primary full figure weaving (a) to partial segments (b, c), and an expanded field (d), where shape and behavior of fibers are a function of the interaction of weave system and density, material properties and overall geometry. These extend previous research through:

Development of robotic applications and reconfigurable material practices. Recent advancements in carbon-fibre technology and computer-controlled robotic manufacturing now enable the delivery of threading with consistent and reproducible qualities. Research has been undertaken in recent years for carbon-fiber polymer composites formed over moulds or core-less fiber winding (Menges 2016, Doerstelmann 2016, 2017), or with semi-autonomous mini robots (Yablonina 2016). The research expanded a robotic filament deposition of fibre composites towards a context of on-site, on-ceiling weaving for industry-scale application, as a material response to flexible spatial programming, and with varied structural performance implementing local constraints.

On-site and mobile robotic fabrication. Recent projects have expanded the fabrication space from closed settings towards scenarios of onsite and adaptive live robotic construction with mobile adaptive in-situ fabrication (Doerfler 2016, Giffthaler et al 2017a, 2017b) or aerial robots (Mirjan 2016), including substantial research into onsite carbon-fiber threading as for example the V&A project (Menges, Doerstelmann 2017). Whereas these systems build on live-data feedback with sensing and
feedback control as part of robotic programming and fabrication, in contrast, this research priorities
developing robust work protocols that are universally applicable to a variety of project constraints in
the context of ceiling elements for workspaces, thus allowing robots to operate in inhabitable
environments where obstacles or human flows are unpredictable.

Prototypes and other physical scaled weaving studies in builders rope and carbon fiber on customised
looms can be displayed as a comprehensive description of morphogenetic weaving patterns, where
the differentiated fiber layout weaving becomes a gradient variation of material properties and
geometry. The prototypes show the directionality of anisotropic fibres, which express both tensile and
compressive strength and so enables construction of complex, load-bearing surfaces.

For the exhibition, three different types of carbon-fiber woven structures on a circular frame/frame
segment are presented, with maximum dimensions approx. 2150mm diameter wide, ca 700cm high.
Ceiling mounted, varying dimensions, patterns and densities possible (in setting up of approx.
3000x3000mm). The weaving structures are located at different heights, with potential real-time
robotic weaving as demonstration. The installation is accompanied with video footage of the research
process (design and manufacturing, June 2017-Feb 2018).
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<td><strong>Figure 11.</strong> Robotic Model as Prototype. Staging of prototypes and incremental variations: minimal/1 robot position (a); optimized/4 robot positions (b), maximum interrupted/ 5 (c), and maximum robot reach (d).</td>
<td>2018</td>
<td>Author(s)</td>
<td>author</td>
<td>RD</td>
<td>Aug 2018</td>
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