Towards onsite, modular robotic carbon-fibre winding for an integrated ceiling structure

Dagmar Reinhardt¹ · Ninotschka Titchkosky² · Chris Bickerton² · Rodney Watt¹ · Dylan Wozniak-O'Connor¹ · Christhina Candido¹ · Densil Cabrera¹ · Mitchell Page² · Sascha Bohnenberger³

Received: 11 October 2018 / Accepted: 25 June 2019 / Published online: 12 September 2019
© The Author(s) 2019

Abstract

Among current adoptions of standard industrial robotic arms for automation and mass customisation in the building industry, robotic fabrication is of interest for bespoke manufacturing and advancing mobile and onsite construction processes. The use of robotic arms can be of significance particularly where access and site conditions limit further construction of building elements to be inserted in an existing architectural fabric. This paper introduces research and development of robotic carbon-fibre winding of an integrated ceiling structure to support open and flexible workspaces scenarios. The project Systems Reef 1.0 explores the potential and viability for an integrated infrastructure that expands standard office-ceiling grid systems to support flexible workspace scenario and the agency of networked, dynamic and self-organising teams. To this extent, multiple soffit-hung, rotational and retractable data booms provide fibre-optic data, electrical cabling and integrated lighting. Through geometrically complex, fibre-reinforced building elements that are robotically manufactured onsite, a new distribution system for data and light can be provided to support individual and multi-group collaborations in a contemporary open-plan office for maximum flexibility. In this paper, we discuss research into the development of robotic carbon-fibre threading sequences and physical demonstrators for an integrated ceiling structure that takes into account local ceiling constraints. Using a KUKA KR10 industrial robot and mobile platform, carbon-fibre threading prototypes were integrated with onsite conditions and synthesised in four physical demonstrators that support data provision for flexible desking in open-plan office environment where prefabrication of large-sized building modules is restricted due to access constraints. The paper discusses challenges in integrating robotic carbon-fibre threading, data-driven occupancy, structural performance and results for workspace flexibility, and concludes with an outlook towards future potentials.

Keywords Onsite construction robotics · Carbon-fibre winding · Flexible workspaces

✉ Dagmar Reinhardt
dagmar.reinhardt@sydney.edu.au

Ninotschka Titchkosky
ninotschka_titchkosky@bvn.com.au

Chris Bickerton
chris_bickerton@bvn.com.au

Rodney Watt
rodney.watt@sydney.edu.au

Dylan Wozniak-O'Connor
dylan.wozniak-oconnor@sydney.edu.au

Christhina Candido
christhina.candido@sydney.edu.au

Densil Cabrera
cabrera@sydney.edu.au

Mitchell Page
Mitch_page@bvn.au

Sascha Bohnenberger
sbohnberger@bollinger-grohmann.de

¹ Sydney School of Architecture, Design and Planning, The University of Sydney, Sydney, Australia

² BVN, Sydney, Australia

³ Faculty of Health, Arts and Design | Swinburne University of Technology, Melbourne, Australia

1 Introduction

Whereas industrial robotic arms have moved from a context of serialisation and automation in production to use for fabrication of customised modules or select building construction methods in architecture (Kohler and Gramazio 2014; Brell-Cokcan and Braumann 2012; Kohler et al. 2014), the utilisation of robotics for bespoke or customised fabrication coupled with mobile or onsite applications is of particular interest. In this context, robotic carbon-fibre-reinforced polymer (CFRP) can be of relevance due to an inherent potential for configurable material expressions, unique structural and fire-resistance capabilities. CFRP opens access to variations of density, patterning and overall shape. and thus allows for the creation of forms, with efficiencies and visual/tactile qualities that are unachievable in traditional materials and processes (Wit et al. 2017).

CFRP is a well-researched domain, with current research in fibre technologies, filament deposition and computer-controlled robotic manufacturing that investigate novel approaches to the geometric, material and structural use of fibres. These include CFRP composites formed as discrete material expressions (Menges 2016), in core-less fibre winding (Reichert et al. 2014; Menges 2014; Knippers et al. 2015; Prado et al. 2014), modular fibre winding (Wit et al. 2017; Wit and Kim 2016), fibre placements on pneumatic volumes (Vasey et al. 2015; Doerstelmann et al.

2015), onsite tensile expressions woven by semi-autonomous mini robots Yablonina and Menges 2018, or flying robotic deposition (Mirjan et al. 2016). It is significant that carbon-fibre applications commonly require curing and baking to achieve optimal structural stability, resulting in limited fabrication scales, modularity or prefabrication for adoption to architecture projects that require both tension and compression. Hence, applications in situ and for built environments are of interest, where robotic CFRP threading could be used as a lightweight, load-bearing element, embedded in existing and as bespoke response to preset constraints.

This paper reports on the cross-collaborative research and development of proof-of-concept demonstrators for an integrated and bespoke ceiling structure in an open and flexible work environment, developed between architecture practice BVN Sydney and the University of Sydney, Sydney School of Architecture, Design and Planning (Fig. 1). It discusses the robotic fabrication of suspended data booms for an office-ceiling system compliant with standard office requirements (such as building code, fire regulations and structural engineering). Embedded in the renovation and refurbishment of the company's spaces in a commercial office building, the project shares fabrication criteria of onsite construction work during full operation; and the objective for the design, production and operation of an infrastructural system geared towards continuous and differentiated spatial organisation of work teams, mobile desk-ing and data distribution. Beyond investigation for robotic

Fig. 1 Overhead and onsite robotic CFRP threading. Complex and bespoke material expression (left) and lightweight suspension element of an integrated ceiling system (right)

onsite applications, the research collaboration addressed more open-ended forms of material, organisational, spatial and temporal control. This included a multi-dimensional design approach for workspace scenarios at the intersection of work health and user satisfaction, acoustic performance, data and light infrastructure and building site management.

In the following, project dimensions and research objectives are introduced, with discussion of methods and processes for computational design, robotic control for carbon-fibre deposition, studies into structural performance of building components, initial prototype development, and onsite fabrication of demonstrators. Section 2 provides a background to multiple aspects that inform the project, including standard ceilings limits, flexible workspaces and acoustic performance in office environments, and the concept for data booms as novel distribution. Section 3 discusses the computational logic, threading syntax for shape variations, micro- and macro-geometries relative to obstacles and boundaries, and structural investigation. Section 4 reports on robotic workstation testing, lab- and onsite applications, and toolpath control for thread deposition. Section 5 discusses the transfer to an onsite context with construction phasing, 1:1 overhead robotic fabrication and resulting four demonstrators in operating office environment. Section 6 presents a criteria catalogue, and reports on challenges and results. Section 7 presents conclusions and gives an outline of future work.

2 Background: flexible workspaces, acoustics and data distribution for an integrated ceiling system

In this research project, workspace performance, acoustics and data distribution are combined to a system of differentiated elements that interrelate and constitute a new ‘work ecosystem’, termed Systems Reef 1.0. To derive a comprehensive approach, multiple criteria aspects were taken into account, as discussed in the following:

2.1 Conditions: flexible workspaces and building restrictions, surveys

Building stock Ceiling as intervention space for reconfiguration. Flexibility for open office spaces in highly collaborative organisations is a crucial point, as physical workplace conditions necessitate flexible and reconfigurable environments (Vischer 2006). Whereas solutions for secondary and after-construction build-ins such as walls, dividers and overflow or non-denominated areas provide some solutions, building services in ceiling systems have not substantially changed. Here, standard office-ceiling grid systems (1950, US Patent Bibbs) continue to provide building services but are limited

in enabling physical, and thus organisational changes for team formation and work processes. Post-occupancy adaptations depend on local building standards and fire codes. In this project context, construction was significantly restricted by accessibility of building sites through existing pathways, which consequently determines scale, weight and material aspects of future construction elements. Constraints posited by existing non-negotiable services such as columns, lights or air ducts needed to be considered for further ceiling works. Incremental variations in the ceiling due to settling of structural elements needed to be taken into account for onsite fabrication or construction (Fig. 2a).

Understanding flexible workspaces Workspace design has dramatically changed in the last decades towards integrating more open, flexible, mobile and programmable functions and elements. This marks a change in understanding how work environments can be improved to better provide for the daily, built, digital and social contexts within which people create, collaborate, share knowledge and solve problems (Groves and Marlow 2016). Beyond physical expressions of building modules, the operation of workspaces strongly influences organisational strategies, workforce attitudes and expectations (Brill 2001; Laing et al. 1998). For open office plans, alternating team constellations and desking arrangements can support communication and collaboration, yet still require novel solutions to exceed standard technological advancement, data provision and lighting integration. An initial occupancy survey using the BOSSA/Building Occupant Survey System (Candido et al. 2016) identified that capacity and performance of the existing workspaces were averaging below general performance, health and productivity levels (Fig. 2b). Consequently, flexibility for networked, dynamic and self-organising teams needed to be supported as a function of new post-built outfit that extends the standard ceiling fabric.

Data distribution Standard data distribution networks present a problem particularly in creative industries where high data loads exceed high WIFI transfers, and thus require a large volume of cabling. Fixed dropper location (umbilicals) force decisions on spatial functions and limit potential work zone layouts which restricts arrangement within a floor plate. Thus, the provision of data cabling to each desk needed to be reconsidered from significant barrier to creating a flexible workplace. Furthermore, spatial expressions of ceiling integrated services can also contribute to the aesthetic character in open-space work environments.

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 (Cox

Fig. 2 Ceiling system obstructions in existing workspace (a), occupant survey (b)

and D'Antonio 2009). 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 leads to a more relaxed vocal effort (Yadav et al. 2017). 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 [see (Hannouch et al. 2018) for discussion on retro-reflective ceiling treatment].

Based on the conditions and survey results, the project aims to establish a system that maintains existing general services and further enables a predictive but not prescriptive spatial mapping. Hence, the research focused on the bespoke robotic fabrication with carbon fibre as a strategy for lightweight, bespoke building modules with integrated fibre-optic data and lighting, to provide flexibility in collaborative workspaces.

2.2 Scope of research: data booms

Boom system as data distributor As design framework and to address previous aspects, the collaboration investigated a novel data distribution system. This focused on the fabrication of a suspension system to enable ceiling placement of four out of 38 soffit-hung data booms that each provide fibre-optic power, retractable data cable and ambient light for eight team desks. For placement of future robotic fabrication sites within the ceiling, an initial mapping system was developed for placement of a series data booms, based on an

initial photogrammetry survey [see (Reinhardt et al. 2018) for discussion of initial computational mapping strategies]. Here, a 3D spatial scan of existing ceiling restrictions (such as HVAC tracks, columns, walls) is referenced against a generic script for optimised shortest path distribution to data booms, while minimising cabling distances and accounting for existing obstacles, across the 1200 sqm office ceiling. Each data boom measures 1800 mm in diameter and consists of multiple elements, including a circular aluminium frame (Ronstan track rail), custom aluminium tripod distributor, embedded custom 3D-printed inset (ABS plastic) with 82 hooks and soffit circle segments with 8 hooks, data cable and retractor, inset LED lighting (Fig. 3a) and a carbon-fibre suspension structure.

Material system integrating structural performance Carbon-fibre threads are anisotropic (directionally dependent); thus, specific geometrical and structural characteristics can result in extraordinary mechanical properties that can be tailored depending on the placement of fibre (Wulforst et al. 2006). The directionality of anisotropic fibres can express different strength and so enables construction of complex, load-bearing surfaces that integrate loads and stresses (Steinmann and Saelhoff 2016). Furthermore, and significant in this research context, aesthetically differentiated material expressions can be produced through robotic CFPR winding that respond to access and onsite restrictions, and deliver for suspension of the booms that deploy directionality of fibres in tensile and compressive strength. This is particularly significant for this research to accommodate torsion on the system due to the travelling load when the network cable is re-distributed by manual adjustment, thus exerting an uneven and temporary

Fig. 3 Boom data system as prototype with principle hook inset and flexible tracking support (left, **a**); and data boom as suspension with initial requirements (right, **b**)

force load onto the CFRP suspension system (Fig. 3b). Here, CFRP characteristics directly inform the project through beneficial strength to weight ratio/lightness as the system exerts minimal weight for the existing ceiling structure.

Overcoming restrictions, regulations and limitations Beyond inherent structural and material characteristics, using CFRP responds to the rigorous project demands for access, fabrication, building site and operation. As negative criteria set, access was limited to standard lift dimensions on an inner city, level 11 office site. Fabrication had to be adaptable to continued operation in zones adjacent to the robotic fabrication which needed to be well contained. Size and resilience in transport of suspension modules did not allow prefabrication. While CFRP maintains some resistance in potential fire hazards (Hertzberg 2005), in case of high temperatures, it would suffer material decomposition (Saputo et al. 2018). Consequently, carbon fibre modules are assessed here not as building structure but as secondary ceiling element under the Building Code Australia (BCA; AS/NZ 3013:1995 fire ratings; AS/NZ 3000 wiring; AS/ACIF S009 Installation requirements for custom cabling).

3 Computational logic, fibre syntax and geometry sets

Different computational models and geometry sets were synchronised for fibre winding syntax, global geometry expressions, robotic workspace scenarios and local ceiling constraints:

3.1 Computational logic: tensioned, lofted surfaces as result of multiple winding

Whereas other methods of string deployment such as weaving traditionally use two sets of string or thread at right angles to each other and are interlaced, the topology for carbon-fibre-reinforced polymer (CFRP) winding used here belongs to a topological series of core-less fibre wound structures, and deposits multiple threads that respond to vertical, horizontal and lateral forces inherent in the system. The computational logic for the project first derived a shape catalogue for winding fibre in Grasshopper [GH, visual scripting (<http://www.grasshopper3d.com>)], as function of rule-based connections between a point matrix relative to boundary conditions, by generating a model based on number, relative distance, position and threading between the circular boom, and inside and outside soffit hooks. Then, an initial threading syntax for fibre deposition was developed focusing on the production of a doubly curved carbon-fibre surface, as a comparison study between computational logic for a shell surface, and doubly curved surfaces resulting from deposition of multiple strands (Fig. 4a–d). For vertical alignments, the sequence of fibres posits a crucial consideration since incremental fibre deposition, fibre length and multiple cross-overs of threads resulting from specific location produce variations in performance between theoretical shell surface (Fig. 4a, c) and effective threading (Fig. 4b, d). Further simulations in robot programming with KUKA|prc (<http://www.robotsinarchitecture.org/>) verified accessibility of points within 120° zones (Fig. 4e).

3.2 Micro-geometry: sequence of fibre deposition

Ceiling hooks and boom hooks form concave arcs relative to the robot position, with a surface ‘lofted’ between both

intersection, whilst minimising the total length of fibre and allowing for proportional reduction in deposition time.

As shown in Fig. 5, the threading sequence describes the deposition of fibres in a ‘fanning’ sequence between upper soffit hooks with 8 teeth, and the lower boom ring with min 12 access points (82 teeth for 360°, with 8 upper hooks relative to 12–32 lower hooks accessed for a zoning of 120°–140°). The robotic reach determines access to lower points, and threading is ordered by fibre length, starting with longest distance. Deposition follows an index (Fig. 5a), with index 1 starting with T1–T8 and deposition of 12 lower access points B1–12, then reversing the deposition order to returning to T1. Each fibre fan is connected in multiple step-overs of threads. Longest threads in a fan are laid first, with shorter fibres connecting in thread centre points and thus pulling deposited fibres in (Fig. 5b). The computational logic was further tested in manual, physically wound sequences on customised prototype sections in fibre, in robotic programming in KUKAlprc fabricated in builders’ rope, and in carbon fibre [see (Reinhardt et al. 2018) for a discussion of full-weave and circle segments in prototypes]. Intersections were, thus, further optimised to correct relative distances of threads within the ruled surface as loft between the two hook arches, applying a mid-point of curve to closest points and measuring distances of simulated winding for ruled surface, which resulted in an approximate 95% compression of multiple broad connection between fibre strands. This maximises the fusion between laid carbon-fibre threads, thus stabilising intersections and ensuring adhesion of resin required for achieving structural performance.

3.3 Macro-geometry: constraints and multiple robotic workspaces

To evaluate the fibre macro-geometry and winding sequence for robotic fabrication, a simulation in KUKAlprc with integration of site conditions and ceiling interruptions by HVAC and cabling was undertaken to consolidate the threading syntax, relative to criteria such as position, obstacles, number of soffit hooks, distances between hooks and boom, and taking into account toolpath and robot movement in relation to operable workspace (Fig. 6a).

Based on a relocatable platform with kinematic stability, the KUKA KR10 workspace extends to 1695-mm height from robot zero with an intersection zone of 1.65 m³ and thus accommodates reachability of the ceiling area. Expanding from constraints for a singular robot position and workspace (primary inside winding), multiple robot workspaces for consecutive two external threading per robot position with a maximum of 6 sequenced external configurations per robotic construction phase were addressed to evaluate potential geometry self-intersection of robotic toolpath and spatial constraints of accessible fabrication space. Figure 6b shows the macro-geometry of intersecting robotic workspaces, which indicate work envelopes between single robot position towards next robot steps and relation to other booms. This is also important to ensure human-based integration into the workflow required for potential correction in robotic fibre deposition, where robot, multiple humans, fibre configurations share the same work topography (Fig. 7).

3.4 Evaluating structural performance: comparative analysis

To investigate potential threshold, prototypes (with three inner and three plus six outer anchor points) were scripted

Fig. 6 Robot Access: winding protocol between data boom and soffit hooks with HVAC obstacle (a, left), potential robotic reach and intersecting work envelopes (b, right)

Fig. 7 Overhead, onsite robotic CFRP winding between with inside and outside ceiling hook positions that form a structural component in the integrated ceiling system

Fig. 8 Structural models testing performance across minimum (a) and optimised version (b) under impact of a 360° travelling point-load of cable towing. To mimic real-world operational conditions, we chose to assess the maximum structural deformation of the woven geometry under a 1kN vertical (-Z) point-load, applied to the circu-

lar Ronstan track at ~4° rotation intervals. The line-chart describing the indicative maximum deformation of both the maximum and minimum options against the rotational value of the point-load on the boom track (right)

(GH Grasshopper) and evaluated in karamba3D [(<https://www.karamba3d.com/>)], structural performance simulator], under a dynamic point-load of up to 1kN (exceeding an approximated 80 kg manual towing force). Forces were simulated for three key variables: the location of the point-load on the circular boomtrack, the number of

ceiling mounted hooking points, the location of these ceiling mounted hooking points, and the density of carbon-fibre woven into the geometry. In Fig. 8, two prototypes with a ‘maximal’ and ‘minimal’ structural arrangement are analysed, with max/min referring to length and density of carbon-fibre segments, and number of ceiling hooks. The

metric by which comparative structural performance of each option was evaluated is the maximum deformation value of the structure at equivalent point-load locations.

The maximal deformation analysis as shown in Fig. 8a provided an indication to the structural performance, whereby overall deformation is restrained (> 10 mm). The minimal option replaces the external ceiling mounted hooking points in favour of a rotationally symmetrical and widespread fibre distribution. It shows a highly predictable pattern of deformation, where the greater the angle between the point-load vector and the mean carbon-fibre strand vector, the greater the level of deformation. This is consistent with the well-known anisotropic material properties of carbon-fibre. Significantly, Fig. 8 chart indicates a lesser structural advantage of the maximal option to the minimal options. The comparison between 8a and 8b with increasing the number of ceiling hooking geometries and density of carbon fibre does significantly decrease the maximal deformation under a vertical (-Z) point-load. It increases the overall rigidity of the structure, hence localising deformation to a specific number of members. Thus, the minimal option, whilst a less rigid structure, can be considered comparably performant in resisting a 1kN vertical (-Z) point-load. This indicative structural analysis allowed us to confirm the onsite robotic

work, and to develop further structural options in parallel to inform the robotic fabrication.

4 Robot workstation in-lab, toolpath control

The robotic CFPR winding was further adopted for the onsite, on-ceiling industry-scale application, and tested in two initial robotic prototypes for configurable shapes, thread syntax and structural performance of CFRP [see (Reinhardt et al. 2018) for discussion of full circle prototypes vs partial winding]. For site adaptation, key objectives, thus, included a distinct material response, implementation of local constraints, development of a reconfigurable and robust work protocol responding to geometry affordances and local constraints, and a dynamic adaptability to allow robot and humans to inter-operate in an inhabitable environment where human flows and obstacles were unpredictable.

4.1 Lab-based and onsite conditions

As a proof-of-concept and feasibility study for the onsite robotic threading, a workcell was set up (17.5 m² plywood ceiling area with 1:1 exerts of HVAC tracks in Styrofoam) that physically simulates the onsite constraints, so that robot

Fig. 9 Lab test with simulated HVACs (Styrofoam), base frame with rigging acro-props testing reach-constraints of a KR-10 R900 robotic system on movable table-base (**a**, left). Incremental addition

of threads anchored with outer soffit hooks and relocation of robot to fit obstacles, illustrated example of ceiling-based and floor-based constraints within interior office environment (**b**, right)

and scaffold positions for winding sequences could be investigated (Fig. 9a, left). To minimise the scaffolding or temporary ceiling fixing of the data boom for stability whilst robotic winding, the data boom is first secured and fibre surfaces are fabricated based on the primary inside robot position which vertically stabilises the structure. Secondly, winding across outer soffit hooks progressively and laterally stabilises the structure and removes the need for continued scaffolding. In the onsite work zone integrated in the overall construction phasing, external weaves are each considered as an individual construction stage as the robot requires recalibration (Fig. 9b, right).

4.2 Robotic workstation

A customised three-part workstation setup enables temporary placement of the data boom and robotic winding, as shown in Fig. 10. Part one consists of an industrial KUKA KR 10 robotic arm, mounted on a customised platform to achieve reachability (+1500 mm from floorplate), containing the controller unit, and including a customised aluminium end effector with elastic band tensioner to pick up slack in the fibre thread during winding. Part two consists of the carbon-fibre feeder unit with resin bath, coupled with a commercially available, hacked X-winder and the accompanying resin station unit with cleaning zone, resin dispensing and storage. Part three consists of the three adjustable

acrow-props and clamping system that secure the lower hook and track assembly.

To test material applications under real-time conditions including discrete layering of multiple strands, a factory-wound bobbin of carbon-fibre tow (12 k, 2 kg standard industrial, T300) was used with a tensile strength 3530 MPa (Tensile Modulus/Gpa 230), and impregnated with resin (WEST 105) prior to robotic winding (Fig. 11). Using an ultraslow hardener, the curing process was further slowed down by adding only drops of hardener to the resin (approximately every 45 min), and continuously adding the resin mix to the resin bath (20 min periods). As the longest period for full deposition in adjoining fibre areas was under 60 min, impregnated treads maintained effective lamination and adhesion properties. The resin drying period terminated between 20 and 24 h at 22 °C, with a recommended 4–9 days finite curing time for maximum strength (though in reality, sufficient strength was achieved after 6 h). Though fluid spread was negligible, gloves/jackets for human and robot were used. As tested in the lab, fumes from resins/hardeners were minimal; so, safety concerns for work staff and robot fabricators could be sufficiently addressed.

4.3 Toolpath control

The robotic toolpath in a core segment is designed for the shortest access points, exact positions of hooks, repeat

Fig. 10 Robotic three-part, relocatable workstation with material preparation zone, boundary frames (circular boom track and exemplary soffit hook), and resin bath

Fig. 11 Industrial X-winder as a versatile system for impregnating the carbon-fiber tow with resin, and workstation

Fig. 12 Robotic threading between soffit and track hooks in lab environment (left), and control of robotic toolpath via a six-point access for each hook (right)

access for increased density, access angle of end effector reach towards hook heads, so as to wind the three hyperbolic inner surface segments required for structural viability. Robotic winding for each singular hook is set out according to a safe-frame approach to control the toolpath, which for each hook consists of several points (m1–7). As shown in Fig. 12, the end effector is moved between zero position (m1) to a ‘safe’ start (m2) with distance 5 mm as a transitional

point. The following four points (m3–m6) describe a circular motion that secures the thread around the hook, and then moving over to the safe frame for the next weave (m1/next sequence), so that that the robotic toolpath is not interfering with previously deposited layers. The robotic base script uses KUKAiprc to regulate fabrication in form of a data tree and is used for each of the three soffit hooks with eight access points that correspond with the varying number of

lower hooks on the boom track. This also ensures sufficient tensioning of the thread for further sequencing which is important since tension in fibre deposition must be continuous for passes between hooks ($8 \times 12\text{--}28$).

4.4 Adaptation and collision avoidance

Robotic control and path planning were reviewed for collision avoidance. Deposition order, number and degree of intersections and consecutive laying of fibres were revised with controlled angle of end effector so as to overcome obstacles (previously laid fibres or ducts), and not to exert abrasion to resin impregnated fibres that would diminish adhesion and curing between layers. This is significant as the mesh density, distance between intersections, and ‘lock-in’ of fibre nodes prevent buckling and thus contribute to resistance of torsion exerted on the system. Robotic script adaptation proceeds a ‘culling’, whereby a data list (GH) for 34 max bottom hooks is culled where robot motion would pass through intersecting lines between destination points and physical infrastructure. This also included extended amount of lower hook access for fibre spreading between two soffit elements, so that denser fibre deposition resulted in better compression between adjacent fibre layers between different hooks. Secondary scripts could vary, based on additional external robot positions, whereby increased distances of robot towards boom or soffit element would result in longer fibre deposition, expected fewer intersections and lower compression of fibres.

The primary robotic CFPR script sequence provided sufficient adaptability and inbuilt tolerance for dynamic adaptations onsite; so, further onsite production of four demonstrators as ‘fabrication-on-the-fly’ was deemed feasible.

5 Onsite implementation of robotic CPFR across sequenced work environment

The staged robotic fabrication onsite during ongoing business operation and simultaneous building works necessitated further evaluation and refinement of technical and material process knowledge, and data management and workflows from computational design input to robotic fabrication output. Significantly, this centred around mapping and adapting routines for onsite fabrication on one hand, sequencing robot–human interactions, and managing construction and business operation zones.

5.1 Top–down construction phasing and bottom–up robotic work sequences

As part of the overall office renovation, the robotic work submits to general top–down phasing for construction zones that accommodates continued work for collaborative teams during a three-month period. This included preset conditions for spatial planning of overall 32 data booms and predefined locations for data outlets within the office-ceiling grid (Fig. 13a), where zones for robotic fabrication were synchronised with general construction. The onsite adaptable

Fig. 13 General data outlets as top–down preset (left, a). Bottom–up approach for sequenced robotic workstations where robotic fabrication proceeds in direct vicinity to ongoing team collaborative work zones (right, b)

robotic work is sequenced as bottom–up, multi-position protocol that follows in four zones. In each, a distinct prototype was fabricated, resulting in a total of 16 robot positions (Fig. 13b), so that effectively the robotic workspace continuously shifted.

5.2 Robotic work: positioning, calibration and winding

For each nominated area sequenced with ongoing building works, the robot was positioned on a mobile platform for access (average 3175 mm ceiling height), calibrated by locating the project origin and referenced against a base 3D data scan and initial GH dataset. Soffit hooks and boom positions were fixed, physically measured as coordinates out of McNeel Rhino and checked against a KUKA! pre dry-run to confirm accuracy of robot movement or correct potential impediments of robot reach or tooling path. Similarly, acrow-prop clamps were checked against collision and accessibility with proximity of overlaid threads, density of pattern and order of deposition.

For each hook, positions were manually adjusted (embedded GH scripts take calibration points with base splines referencing ideal vs actual). The calibration process required robotic registration of 3 and 5 hooks entered into the script for interpolation of all hook positions. In practice, we

encountered acceptable errors of less than 3 mm for hook locations due to inaccuracies in of hook manufacture, the rolling Ronstan I-section and the manual assembly of the lower ring system. Robotic programming was confirmed for each winding sequence in builder's rope, and then fabricated in impregnated carbon-fibre (average of 2 h for primary sequence, with an approximate length of 180 m per hook position). The resulting integrated building component responds with 8–12 mm dislocation movement under manual, horizontal pressure, and thus proved structurally active. Then, up to six outer hooks per demonstrator were positioned (with distance to boundary frame measuring between 10 and 135 mm for outer hook positions), and hook calibration, testing and fabrication conducted. As part of the staged onsite fabrication, setup and production required a team of 2–3 staff (one expert competency, technically skilled member and several non-skilled members trained in process, Fig. 14). With completion of robotic work, the overall construction sequence in each sector was finalised, and work desking returned to occupy the area below the data boom.

5.3 Demonstrators onsite: four typologies

The onsite construction conditions provided a unique opportunity to extend serialisation of winding towards bespoke manufacturing of four distinct CFRP data booms.

Fig. 14 Onsite, overhead fabrication: set-out, calibration and fabrication in temporary restricted work-zones, and team members trained onsite for additional support

Fig. 15 Robotic Model as Prototype. Staging of prototypes and incremental variations: minimal/1 robot position (a); optimised/4 robot positions (b), maximum interrupted/5 (c), and maximum robot reach (d)

Table 1 Demonstrator types, implementation in BVN workspace/area of construction, robot position and anchor points

Demonstrator	BVN phase	Robot position Ri/internal, Ro/external	Anchor points (inside)	Anchor points (outside)	Robot reach access
DB 01	BVN 02	1 total, Ri1 (1 internal robot position)	3, A 1–3, symmetrical	None	Max 120°
DB 02	BVN 03	4 total, Ri1, Ro2–4 (1 internal, 3 external robot position)	3, A 1–3, symmetrical	B1, C1, D1 (three singular outside)	120°
DB 03	BVN 01	5 total, Ri1, Ro2–5 (1 internal, 4 external robot position)	3, A 1–3, asymmetrical (obstacle)	B1, C1, D1–2, E1–2 (two singular and two double outside)	Max 180°
DB 04	BVN 04	6 total, Ri1, Ro2–6 (1 internal, 5 external robot position)	2, A 1–2, asymmetrical (obstacle)	B1, C1, D1 (three singular, one double, two triple outside)	Max 180°

These demonstrators investigate individual sets of expanded criteria for robotic reach, fibre density, access points and structure (Fig. 15, Table 1):

- Data boom 1 (DB1) tested a singular robot position and three inner hooks in an uninterrupted ceiling area. This required minimal robot calibration and fabrication time (7 h), while providing sufficient structural rigidity.
- DB2 tested a symmetrical inner fibre distribution, and an additional three outer hooks with singular surfaces to boom area using four robot positions fit between two

obstacle zones. Thus, an optimised structural performance could be delivered (20 h).

- DB3 tested five robot positions that navigate a maximum of obstacles, whereby an HVAC canal intersects the fibre deposition. Consequently, fibre threading between two hooks in the same zone further stabilises the structure (18 h).
- DB4 tested six robot positions, and a maximum robot reach across the work envelope (180 degrees) and dual hook access, resulting in a maximal fibre and surface span (22 h).

The onsite robotic fabrication confirmed that the system was feasible for use as robust robotic work protocols that required minimal manual script changes, universal application to various constraints, allowed use of unskilled labour for fabrication, and enabled robot operations in unpredictable, human interrupted environments. However, while the demonstrators confirm acceptable proof-of-concept robotic work driven by primarily aesthetic aspects, and whereas materials costs for CFPR were low, the post-production cost analysis (in comparison for standard boom suspension) resulted in significant costs for 3D printed parts and manual labour for calibration. For a complete integration of a larger ceiling area (> 500 sm) or future work in a ‘stripped’ ceiling context, module parts for the boom would need to be revised.

6 Discussion

In the following, the paper discusses challenges, benefits and results, with a particular focus on derived criteria framework, limitations of robotic works, and achieved reconfigurability for the workspace environment.

6.1 Criteria framework

Standard industrial robot control uses largely pre-planned and -computed robotic motions, repetitive tasks, few sensing operations, and high-precision movement trajectories. In this context, standard programming techniques for industrial robots often lack key capabilities required to intelligently adapt to variable environments, as there is usually reliance on perfect task information, limited sensing capacities, and no interaction with humans (or human co-workers). Incorporation of uncertainty or variability then requires time- and cost-intensive re-programming or sensor feedback for continued data evaluation.

The applied onsite context allowed the research to proceed from prescriptive programming towards a declarative robotic protocol, based on a criteria framework that could potentially be further varied for future prototypes, relative to:

- (a) the boom itself with potential variables including track diameter, hook number, distance between individual hooks, overall distance to ceiling (global), reachability of track system;
- (b) the positioning of the boom with/out single or multiple interruptions impacting on robotic tooling path;
- (c) the ceiling hooks as variable in diameter, hook number, distance to centre, reachability of robot;
- (d) the packaging of threads based on ceiling hook number vs boom number

- e) the number of robot positions and definition of reach, and in- or outside positions relative to boom and max reach distance; and
- (f) the characteristics for carbon-fibre surface elements as variable in density of thread distribution and resulting factual intersections of fibres, number of passes and built-up of fibre surface, cross-overs.

The criteria framework in Table 2 scopes variability of the system for fabrication and material-specific opportunities and limitations, including those that would appear only during the process itself.

Based on this, robotic fabrication through modular components becomes intuitive and highly responsive; a catalyst technology for ad hoc design responses to aspects of accessibility, durability, performance, material, and innovation tool for a differentiated manufacturing process, under time constraints.

6.2 Adaptability and Limitations of Adopted Robotic protocols

The system adaptability and onsite implementation relied significantly on the robotic protocol to offer precision and flexibility as much as approximate limitations, and accommodate tolerances. Planned tolerances within the robotic motion protocol, for example, accommodated horizontal spacing between (48 and 68 mm), depending on hook orientation (internal or external) and location (upper soffit installed or lower track ring). For increased reachability, both in terms of robot reach and accessibility adjacent to obstacles such as ducting, wiring and sprinkler system, non-perpendicular approaches were utilised, greatly reducing the margin for error.

Whereas robotic programming is geared in this pilot study towards sufficient for enabling variability of threshold characteristics, the current limited degrees of mobility and freedom for the robotic workspace could be improved by implementing a mobile robotic platform, and adaptive robotic programming through live-data feedback or sensor-based calibration (Doerfler et al. 2016; Giftthaler et al. 2017), such as continued integration of 3D photogrammetry as basis for calibration of multiple hook sequences to improve data control for robotic fabrication and overcome time constraints in the setup process.

6.3 A networked and dynamic workspace environment

With finalisation of all robotic fabrication and construction works for Systems Reef 1.0, a preliminary survey yielded responses stating improved flexibility for desking and increased user agency, support of highly dynamic activities

Table 2 Multiple criteria catalogue for further implementation into workspace environment

Criteria	Level 1	Level 2	Level 3
Positioning of boom (global/office environment)	Boom positioned without obstacles	Boom positioned with singular obstacle (linear, or L-shaped)	Boom positioned with multiple obstacle impacting on robotic tooling path
Deposition hooks (soffit)	Deposition of hooks across diameter of boom (distances and equal numbers)	Hook number, width and distribution relative to diameter of corresponding parts (soffit vs boom)	Variation in ceiling hook diameter (standalone or as boom circle segment)
Robot position and reach (KUKA KR 10/1100), workspace envelope and resulting max trialling	Trialling maximum robot versatility, reach and thread deposition from centre (in 358° work field/blind spot)	Trialling maximum distance of robotic reach travelling from robot position (in 180° work field)	Trialling maximum intersections in hanging plane (in 90° work field) with boom and related circle segments in space
Carbon-fiber syntax	Density of deposition and resulting factual intersections of fibres (including curing)	Number of passes and built-up of fibre surface with maintained connectivity at cross-overs	Curvature and resulting depth of meshed surface (impacting structural performance)
Winding reference points (RP) relative to boom and ceiling hooks	RP1: winding access inside, centric to boom, between ceiling hooks and boom hooks	RP2: winding access outside boom, relative to global criteria, between ceiling hooks and boom hooks	RP3: winding access outside boom, relative to ceiling hooks and boom hooks (in-between)
Structural performance relative to robotic positions	Maximum fibre length between 9 designed robotic destination points as proof-of-concept	2 insides and 2 outsides as minimum robotic winding to maintain structural stability under relative force impact, regular distance	As before, but with longest distance to test structural performance in wider surface field

and self-organisation of team desking constellations in the new office environment. The system demonstrates sufficient operability as it is currently used for flexible desking of teams within 3–11-week periods, based on a networked distribution for all desk occupancy across available floor zones. Users noted a resonance between workplace experience and the data booms which provide as planned a flexible data distribution and light diffusion across the integrated ceiling system. Another post-construction survey is currently produced after the cooling-off period of 6 months, to evaluate long-term impacts for perception of workplace organisation and performance (Fig. 16).

7 Conclusion and future research

This paper presented a pilot study for robotic carbon-fibre threading as suspension for a novel data distribution as an integrated ceiling system for open and flexible workspaces scenarios. Four physical demonstrators were developed as differentiated robotic CFRP modules and proof-of-concept for onsite robotic fabrication during ongoing office occupation. A robust robotic protocol and manufacturing workflow resulted in differentiated prototypes that respond to contextual constraints and across sequenced construction zones. The system provides a viable alternative to standard ceiling service distribution in support of flexible desking and multi-group collaborations in a contemporary open-plan office.

Impact and significance of the research can be described across a number of dimensions. Through a versatile robotic fabrication, the system expresses novel material applications for adopting carbon fibre towards lightweight ceiling suspended structures with an inherent potential to change aesthetic appearance and operability of standard workspaces. A range for geometric morphologies supports creative decision-making processes for architects, designers and potential users from design to construction phases. The shift from in-lab prototypes to onsite demonstrators demonstrates potential for robotic fabrication to expand from small-scale studies towards a real-time application in high-resolution, design-engineering products.

Future research work could extend towards adaptive robotic protocols based on real-time sensor feedback or mobile robotic platforms. There also exists potential to consider investigation of structural dimensions for threading robotic carbon fibre as integrated ceiling component, producing an entire infrastructure system with robotic fabrication processes scaled up to supplement the entire ceiling topography. The discussed individualised solutions for construction robotics could be shifted in project scope, continuing into human–robot collaboration through augmented visualisations of construction components and phasing for

Fig. 16 Systems Reef 1.0 at BVN Sydney, with completed fibre suspension surfaces (data cabling to be implemented)

human co-workers (<https://fologram.com/>). Thus, advanced material applications and methods for industrial robotic arms could inform construction and building industries to transit from mass production to mass customisation and personalisation, and facilitate cost reduction, productivity, onsite flexibility in an increasingly demanding market.

Acknowledgements Systems Reef 1.0 is a research collaboration of the Robotics Lab, Sydney School of Architecture, Design and Planning, The University of Sydney, and industry partner BVN Sydney. The authors would like to acknowledge the contributions by collaborators and design team members of The University of Sydney with Lynn Masuda, Susana Alarcon Licona, and with research assistance by Eduardo Barata, Maryam Houda, Adam Hannouch, Matt Hunter. The BVN design team included Matthew Blair, Paul Wintour, Farbod Fathalipouri, Nazgol Asadi, Sam Sweeney, and Ross Seymour.

Funding This work was funded by an industry sponsorship (Grant IDG196262).

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

Brell-Cokcan S, Braumann J (2012) *RoblArch 2012: robotic fabrication in architecture, art, and design*. Springer, New York

- Brill M (2001) *Workplace design*. Kimball International, Jasper
- Candido C, Kim J, de Dear R, Thomas L (2016) BOSSA: a multi-dimensional post-occupancy evaluation tool. *Build Res Inform* 44(2):214–228
- Cox T, D’Antonio P (2009) *Acoustic absorbers and diffusers: theory, design and application*. Taylor & Francis, London
- Doerfler K, Sandy T, Gifftthaler M, Gramazio F, Kohler M, Buchli J (2016) Mobile robotic brickwork—automation of a discrete robotic fabrication process using an autonomous mobile robot. In: Reinhardt D, Burry J, Saunders R (eds) *Robotic fabrication in architecture, art and design*. Springer International Publishing, Switzerland, pp 205–217
- Doerstelmann M, Knippers J, Koslowski V, Menges A, Prado M, Schieber G, Vasey L (2015) *Fibre placement on a pneumatic body based on a water spider web*. Wiley, London
- Fologram, augmented reality tool for visualising. <https://fologram.com/>. Accessed 1 June 2019
- Gifftthaler M, Sandy T, Doerfler K, Brooks I, Buckingham M, Rey G, Kohler M, Gramazio F, Buchli J (2017) Mobile robotic fabrication at 1:1 scale: the in-situ fabricator System, Experiences and current developments. In *construction robotics*. Springer International Publishing, Switzerland
- Grasshopper, scripting environment and plug-in for McNeel Rhino. <http://www.grasshopper3d.com>. Accessed 1 June 2019
- Groves K, Marlow O (2016) *Spaces for innovation—the design and science of inspiring environments*. Frame Publishers, Amsterdam
- Hannouch A, Caldwell H, Cabrera D, Reinhardt D (2018) Non-standard production of retroreflective ceiling treatment—reducing speech distraction in an open work environment. In: Fukada T, Huang W, Janssen P, Crolla K, Alhadidi S (eds) *Learning, adapting and prototyping, proceedings of the 23rd international conference of the association for computer-aided architectural design research in asia (CAADRIA) 2018*, Hong Kong, pp 317–326
- Hertzberg Tommy (2005) Dangers relating to fires in carbon-fibre based composite material. *Fire Mater* 29:231–248. <https://doi.org/10.1002/fam.882>
- Karamba, structural simulation and plug-in for Grasshopper. <https://www.karamba3d.com/>. Accessed 1 June 2019
- Knippers J, La Magna R, Menges A, Reichert S, Schwinn T, Waimer F (2015) *Coreless filament winding based on the morphological principles of an arthropod exoskeleton*. Wiley, London

- Kohler M, Gramazio F (2014) *AD made by robots: challenging architecture at a larger scale*. Wiley, London
- Kohler M, Gramazio F, Willmann J (2014) *The robotic touch: how robots change architecture*. Park Books, Zurich
- KUKAL prc, robot simulation and plug-in for Grasshopper. <http://www.robotsinarchitecture.org/>. Accessed 1 June 2019
- Laing A, Duffy F, Jaunzens D, Willis S (1998) *New environments for working: the redesign of offices and the environmental systems for new ways of working*. Spon Press, London
- Menges A (2014) Core-less filament winding robotically fabricated fiber composite building components. In: McGee W, Ponce De Leon M (eds) *Robotic fabrication in architecture, art and design 2014*. Springer International Publishing, Switzerland
- Menges A (2016) *Material performance: fibrous tectonics & architectural morphology*. Harvard University Graduate School of Design, Harvard
- Mirjan A, Augugliaro F, D'Andrea R, Gramazio F, Kohler M (2016) Building a bridge with flying robots. In: Reinhardt D, Burry J, Saunders R (eds) *Robotic fabrication in architecture, art and design*. Springer, New York, pp 35–48
- Prado M, Dörstelmann M, Schwinn T, Menges A, Knippers J (2014) Core-less filament winding robotically fabricated fiber composite building components. In: McGee W, Ponce de Leon M (eds) *Robotic fabrication in architecture, art and design 2014*. Springer International Publishing, Switzerland
- Reichert S, Schwinn T, Magna R, Waimer F, Knippers J, Menges A (2014) *Fibrous structures: an integrative approach to design computation, simulation and fabrication for lightweight, glass and carbon fibre composite structures in architecture based on biomimetic design principles*. Elsevier. <https://doi.org/10.1016/j.cad.2014.02.005>. Accessed 3 Feb 2018
- Reinhardt D, Candido C, Cabrera D, Wozniak-O'Connor D, Watt R, Bickerton C, Titchkosky N, Houda M (2018) Onsite robotic fabrication for flexible workspaces- towards design and robotic fabrication of an integrated responsive ceiling system for a workspace environment. In: Fukada T, Huang W, Janssen P, Crolla K, Alhadidi S (eds) *Learning, adapting and prototyping, proceedings of the 23rd international conference of the association for computer-aided architectural design research in asia (CAADRIA) 2018*, Hong Kong, pp 59–68
- Saputo S et al (2018) Fire condition effects on the mechanical behaviour of composite structures. *Mater Sci Forum* 923:13–16
- Steinmann W, Saelhoff K (2016) Essential properties of fibres for composite applications. In: Figueiro R (ed) Rana S. *Fibrous and textile materials for composite applications*. Textile science and clothing technology. Springer, Singapore
- Vasey L, Baharlou E, Dörstelmann M, Koslowski V, Prado M, Schieber G, Menges A, Knippers J (2015) Behavioral design and adaptive robotic fabrication of a fiber composite compression shell with pneumatic formwork. In: Combs L, Perry C (eds) *Computational ecologies: design in the anthropocene*, Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), University of Cincinnati, Cincinnati, pp 297–309
- Vischer JC (2006) *Space meets status—designing workplace performance*. Routledge, London
- Wit A, Kim S (2016) Roly-poly: a hybrid prototype for digital techniques and analog craft in architecture. *eCAADe* 34:631–638
- Wit A, Ng R, Zhang C, Kim S (2017) *Composite systems for lightweight architectures*. Post-human Frontiers, Acadia
- Wulforth B, Gries T, Veit D (2006) *Textile technology*. Hanser, Munich
- Yablonina M, Menges A (2018) Towards the development of fabrication machine species for filament materials. In: Willmann J, Block P, Hutter M, Byrne K, Schork T (eds) *Robotic fabrication in architecture, art and design 2018*. ROBARCH 2018. Springer, Cham, pp 152–166
- Yadav Manuel, Kim Jon, Cabrera Densil, De Dear Richard (2017) Auditory distraction in open-plan office environments: the effect of multi-talker acoustics. *J Appl Acoust* 126:68–80

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.