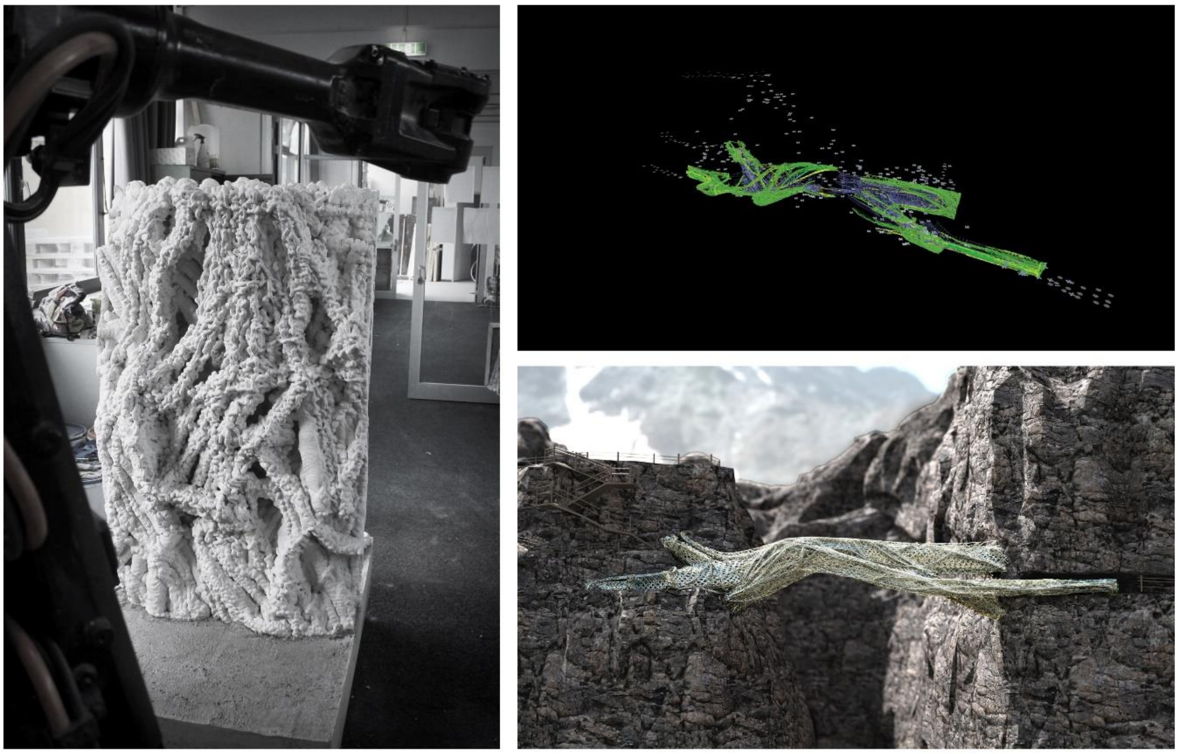
Towards Autonomous Architecture: The New Frontier at the Convergence of Digital Design, Robotics and the Built Environment.

<u>1 Line Abstract:</u>

The way we design, construct and inhabit buildings is changing -- moving towards greater integration of robotic and autonomous systems that challenge our preconceived notions of how buildings are made, what they are or what they should be.



Supporting new methods of architectural design and production using autonomous robotics, multi-agent control, construction simulation and environmental awareness. Left: Adaptive additive manufacturing in response to live scan data. Top-right: Aerial Additive Building Manufacturing (ABM) multi-agent construction simulation. Bottom-right: Aerial ABM bridge design

<u>Article Text (word count= 1199):</u>

The built environment of the future will be fundamentally different to today. Increasingly, the way we design, construct and inhabit buildings will incorporate greater use of robotics and autonomous systems (RAS) that challenges our perception of how buildings are made, what they are and their role in society. Progress in RAS, and more broadly Computer Science (CS) is unifying the activities of design and construction; by bringing the designer and maker closer together. As architecture embraces greater levels of autonomy to address industry needs for greater productivity, understanding the future role of design is becoming important, particularly in consideration of human activity and values.

Explorations in building design are intrinsically linked to the availability of the tools and materials utilised. As RAS becomes more pervasive, their enhancement of design and production capabilities is having an influential role; requiring architects to engage in deeper collaborations with engineering disciplines. Impact points include: flexible manufacturing platforms, advanced material deposition, robot manipulation, computational design, and machine learning. Importantly, research agendas that support the convergence of these disciplines are beginning to shape progress in construction and digital production; facilitating a step change in productivity, design flexibility, on-site safety and cost reductions. Architectural research departments are developing large-scale fabrication facilities to explore these potentials. Examples include: new robot fabrication facilities at the University of Michigan developed by Monica Pence de Leon; the Bartlett School of Architecture (University College London), whose industrial-scale robotic facilities are being leveraged within a new postgraduate programme in "Design for Manufacture"; the Robotic Fabrication Laboratory at ETHZ which offers a Masters in Architecture and Digital Fabrication, and includes Gramazio Kohler's Research Lab who designed and constructed the façades of Gantenbein Vineyard using an industrial robot to lay complex-patterned brickwork[1]. This initial research into "Design for Autonomous Production" is already helping manufacturers move past Ford-like production lines to implement scale-able methods for mass-customisation, whilst enabling new design possibilities.

Advances in materials science and additive manufacturing are also creating novel methods for construction. Coupled with flexible robotic technologies, they provide the ability to build with limitless geometric variety. Companies already operating include: Winsun Decoration Engineering Company (China), Apis Cor (Russia), and WASP (Italy). To gain market traction, these companies are now investing in CS development, creating tools for high-resolution design-engineering computational analysis and geometrical refinement. Self-adapting robotic technologies provide further opportunities when programmed to contribute to a design outcome in response to their environment. Achim Menges's Water Spider Pavilion demonstrated this capability by using an industrial robot to adaptively lay carbon fibre on the inside surface of an inflatable structure with the aid of pressure sensors [2]; producing a design result derived from the combination of the construction sequence, negotiation of material forces, and the protocols that govern the robot's motion.

The field of distributed robotics enables even greater scope for creativity. Resembling the process termites use to construct their mounds, a decentralised network of robots programmed to operate as a multi-agent system is capable of collectively building structures; in-directly designing through their individual construction actions that are locally reactive to the environment. In this capacity design becomes an emergent property of autonomous robotic construction. Harvard's TERMES project demonstrated such capabilities utilising bespoke robots and building blocks [3], whilst Vijay Kumar's group have shown a team of UAVs constructing a pre-designed space frame [4]. Similarly, Imperial College's 3d printing UAV [5] is being utilised within research into Aerial Additive Building Manufacturing that involves parallel developments in multi-agent programming, aerial robotics, 3d printing materials, human-robot collaboration, structural engineering and architectural design. It also explores the architect's role in the underlying programming logic, and how the nature of design changes; becoming a relationship between the robot and the collective protocols it operates under.

Embedding capabilities for multi-modal sensing, connectivity and self-reconfiguration within the fabric of buildings themselves offers radically different visions for the future. In this scenario, architects can consider the built environment as a network of autonomous systems that can evolve over time through self-determination; changing shape, collaborating and providing emergent solutions to human occupancy, operational and environmental concerns. Current initiatives that pursue these aims include Empa and Eawag's Nest Hilo building that incorporates an Adaptive Solar Facade [6] and Occupant-Centred Control System that utilises machine-learning during real-life operation [7]. While current design practices utilise software to optimise building performance prior to use, this data is not integrated within actual buildings. Incorporating this functionality within buildings, digital frameworks can improve environmental sustainability and the operational performance of a building and its relation to urban networks [8] through continuous design optimisation throughout its lifecycle. Nonetheless, as the use of robots becomes more integrated within the built environment this will impose additional design criteria and higher performance standards. DARPA's Robotics Challenge highlighted the ongoing need for further development in robot navigation, task proficiency and human-robot interaction. Seen from another perspective, it also indicated that buildings could do more to assist and communicate with RAS. The distinction between a building and its related RAS capabilities may decrease significantly, where other RAS entities contribute towards the function of a building; operating as a "RAS ecosystem". This will be most pronounced in buildings not well suited to human habitation, such as nuclear power stations and factories of the future where infrastructural systems of operation and control will become increasingly dependent on RAS.

To realise the path to greater autonomy within architecture, fundamental challenges in design and construction need to be overcome. This requires new software and hardware that bridge-the-gap between a diverse range of RAS and CS research fields. From the architect's perspective, new methods for digital manufacturing and automation that optimise the design process are needed. This includes: in-process monitoring and control, design and manufacturing in augmented and virtual realities, autonomous manufacturing, industrial internet of things, big data (and cybersecurity), in addition to the digitisation of and integration of supply chains. For safe implementation of RAS solutions in the built environment, continued progress in teleoperation, communication and design control is needed to achieve robust levels of performance that complement human interaction. RAS for out-door construction also requires substantial improvements to localisation, computer vision and sensor fusion capabilities compared with manufacturing sectors that operate within controlled environments. Not well suited to closed control-systems, these environments also necessitate greater levels of adaptive and collective control.

Whilst autonomous systems offer opportunities in design and production beyond human capabilities, they also require design intent to be embedded within protocols that govern manufacture, construction and building use. Integrating capabilities for sensing and machine learning provides a start, but mapping these circumstances is difficult to quantify. More research into intelligent robotics is of value, such as expanding Cynthia Breazeal's methods for embodied cognition and deduction of human intention [9]. Threats to production knowledge and diversity, such as the scarcity of skilled craft must be addressed, in addition to the need for buildings and their value chain to be energy efficient. Through research, we must ensure technological advances do not avertedly impose unintended constraints, but rather generate additional societal freedoms. Within the move towards autonomous architecture, RAS principles of shared knowledge, collective action and distributed thinking must develop meaningful exchanges between humanity and the built environment; which we not only construct, but are conditioned by.

References:

[1] F. Gramazio, M. Kohler, Facade Gantenbein Winery, Non-Standardised Brick Façade, Fläsch, (Switzerland, 2006); http://www.dfab.arch.ethz.ch/web/e/forschung/52.html

[2] M. Doerstelmann, J. Knippers, V. Koslowski, A. Menges, M. Prado, G. Schieber, L. Vasey. ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web, Architectural Design 85.5, 60-65 (2015)

[3] Werfel, J., K. Petersen, and R. Nagpal. "Designing Collective Behavior in a Termite-Inspired Robot Construction Team." Science 343.6172 (2014): 754-58.

[4] N. Michael, J. Fink, V. Kumar, Cooperative Manipulation and Transportation with Aerial Robots, Autonomous Robots, vol 30, no. 1, pp 73-86, (2011)

[5] G. Hunt, F. Mitzalis, T. Alhinai, P. A. Hooper and M. Kovac, "3D printing with flying robots," 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, 2014, pp. 4493-4499. doi: 10.1109/ICRA.2014.6907515

[6] Z. Nagy, M. Hazas, M. Frei, D. Rossi, A. Schlueter, Illuminating Adaptive Comfort: Dynamic Lighting for the Active Occupant, in Proc. 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, (London, UK, 2014)

[7] S. Bratislav, Z. Nagy, J. Hofer, D. Jacob, M. Begle, E. Chatzi, A. Schlueter, SoRo-Track: A two-axis soft robotic platform for solar tracking and building-integrated photovoltaic applications, IEEE International Conference on Robotics and Automation (ICRA), (2016)

[8] C-H. Peng, Y-L. Yang, F. Bao, D. Fink, D-M. Yan, P. Wonka, N.J. Mitra, Computational Network Design from Functional Specifications, ACM Transactions on Graphics (Proceedings of SIGGRAPH 2016), vol. 35, issue 4, (2016)

[9] C. Breazeal, J. Gray, M. Berlin, An Embodied Cognition Approach to Mindreading Skills for Socially Intelligent Robots, International Journal of Robotics Research, vol. 28, no. 5, pp.656-680 (2009)

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