Collective Aerial Additive Manufacturing

Authors: Robert Stuart-Smith*[1 2], Durgesh Darekar [2], Patrick Danahy[1], Vijay Pawar*[2] & Mirko Kovac*[3]

* Corresponding authors
Affiliations: 1: University of Pennsylvania, 2: University College London, 3: Imperial College London

Collective Robotic Construction (CRC) enables a team of robots undertaking parallel building operations to construct a structure greater in size than the individual robot builders (K. H. Petersen et al., 2019), requiring scalability in both robot coordination and building design approaches. To date, CRC has primarily focused on the assembly of discrete volumetric elements (K. Petersen et al., 2011; Seo et al., 2013) and filament winding/weaving (Augugliaro et al., 2013; Duque Estrada et al., 2020; Stuart-Smith, 2016) with little research undertaken into CRC mission planning for additive manufacturing (AM) or its relation to digital twin building designs. AM CRC research has been demonstrated with mobile ground vehicles that remain on grade (Napp & Nagpal, 2014; Sustarevas et al., 2019; Zhang et al., 2018), or constrained to move on top of previously built material (Jokic et al., n.d.). In both cases, circulation is restricted by building operations that increase congestion. Aerial robots can circulate to and from building tasks without being constrained to sharing the congested space of the building site. To date, aerial robots have not been utilized for AM CRC, while assembly-based CRC (Augugliaro et al., 2014; Lindsey, Q., Mellinger, D., Kumar, 2011) has been demonstrated using pre-determined flight paths. Research challenges remain for securing a scalable, adaptive approach to AM aerial mission planning that is capable of responding to dynamic conditions such as impact from activities or air turbulence of individual robots, changing building, environmental and weather conditions, or in response to the state and robustness of individual robots.

Although AM allows for greater insitu adaptation of building compared to assembly-based modular designs, not all geometrical designs are viable for incremental manufacture. Inclined geometries can be unstable during the building process unless a scaffolding strategy is employed. However, scaffolding approaches scale poorly as increases in building surface area or structural span can require exponential increases in scaffolding volume. To support greater geometrical freedom, adaptive building and design approaches that can mitigate mid-build instability are needed.

An approach to Collective Aerial Additive Manufacturing (CAAM) is presented that involves real-time adaptive multi-agent flight, mission planning and task coordination, together with adaptive building design and construction sequencing. A series of experiments were undertaken to evaluate a real-time adaptive approach to aerial robot high-level flight control. Custom-built DJI F450 quadcopters with PX4 flight controllers, an onboard computer and custom ROS software stack were calibrated to fly continuously through small incremental vector-based steering behaviors in lieu of a sequence of predetermined waypoints. Proof of concept is achieved by a team of aerial robots producing a light-trace flight choreography of an AM geometry captured by time-lapse photography. Simulation modelling further explores the capacity of the method to support building design and robot behavior adjustments in relation to real-time anticipatory structural and geometric analysis of a 3D digital twin in-the-loop, monitoring both final and interim states of a building process. CAAM demonstrates an adaptive approach to the design and construction of structurally efficient freeform geometries, extending CRC into AM for scalable robot populations and variable geometrical conditions.

Augugliaro, F., Lupashin, S., Hamer, M., Male, C., Hehn, M., Mueller, M. W., Willmann, J. S., Gramazio, F., Kohler, M., & D'Andrea, R. (2014). The flight assembled architecture installation: Cooperative contruction with flying machines. *IEEE Control Systems*, *34*(4), 46–64. https://doi.org/10.1109/MCS.2014.2320359

Augugliaro, F., Mirjan, A., Gramazio, F., Kohler, M., & D'Andrea, R. (2013). Building tensile structures with flying machines. *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference On*, 3487–3492.

Duque Estrada, R., Kannenberg, F., Wagner, H. J., Yablonina, M., & Menges, A. (2020). Spatial winding: cooperative heterogeneous multi-robot system for fibrous structures. *Construction Robotics*, *4*(3–4). https://doi.org/10.1007/s41693-020-00036-7

Jokic, S., Novikov, P., Jin, S., Maggs, S., Nan, C., & Sadan, D. (n.d.). *Minibuilders*. IAAC. Retrieved April 14, 2022, from http://robots.iaac.net/

Lindsey, Q., Mellinger, D., Kumar, V. (2011). Construction of Cubic Structures with Quadrotor Teams. *Robotics: Science and Systems VII*. https://doi.org/10.15607/RSS.2011.VII.025

Napp, N., & Nagpal, R. (2014). Distributed amorphous ramp construction in unstructured environments. *Robotica*, *32*(02), 279–290.

Petersen, K. H., Napp, N., Stuart-Smith, R., Rus, D., & Kovac, M. (2019). A review of collective robotic construction. *Science Robotics*, *4*(28). https://doi.org/10.1126/scirobotics.aau8479

Petersen, K., Nagpal, R., & Werfel, J. (2011). TERMES: An autonomous robotic system for three-dimensional collective construction. *Robotics: Science and Systems Conference VII*.

Seo, J., Yim, M., & Kumar, V. (2013). *Assembly Planning for Planar Structures of a Brick Wall Pattern with Rectangular Modular Robots*. 1016–1021.

Stuart-Smith, R. (2016). Behavioural Production: Autonomous Swarm-Constructed Architecture. *Architectural Design*, *86*(2), 54–59. https://doi.org/https://doi.org/10.1002/ad.2024

Sustarevas, J., Benjamin Tan, K. X., Gerber, D., Stuart-Smith, R., & Pawar, V. M. (2019). YouWasps: Towards Autonomous Multi-Robot Mobile Deposition for Construction. *IEEE International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS40897.2019.8967766

Zhang, X., Li, M., Lim, J. H., Weng, Y., Tay, Y. W. D., Pham, H., & Pham, Q. C. (2018). Large-scale 3D printing by a team of mobile robots. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2018.08.004