# Towards On-Demand Manufacturing: A Review of Technical Capabilities and Future Perspectives

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## Introduction

Manufacturing today relies on disparate, large machines spread across industrial facilities. These are further operated by domain experts to construct and assemble artefacts in sequential steps from large numbers of parts. This traditional, centralized mass manufacturing paradigm is characterized by large capital costs and inflexibility to changing needs, complex global supply chains hinged on economic and political stability, and waste and over-manufacturing of uniform artefacts that fail to meet the technical and personal needs of today's diverse individuals and use cases. However, technical advancements in digital fabrication and hardware miniaturization are now laying the groundwork for automated design and fabrication capabilities that permit the production of functional artefacts using inexpensive, distributed platforms by lay users. Nonetheless, technical advances on this front are distributed across communities spanning manufacturing, robotics, human-computer interaction and others. This compels a drive to consolidate the state of the art across these communities, in order to understand what the enablers are that may drive a paradigm shift to on-demand manufacturing, and what is yet to be done.

This paper reviews the state of the art and future perspectives for these on-demand manufacturing technologies. On-demand manufacturing is a notional manufacturing paradigm that is on-demand, local, and customizable. Often shorthanded as additive manufacturing (AM) or 3D printing, this has the promise of rapid manufacturing times, sustainable supply chains and mass customization to individual needs. However, AM is just one form of manufacturing by which personalized, distributed and on-demand manufacturing may be enabled. We introduce these complementary methods, including hybrid manufacturing, modular self-assembly, and programmable materials, and demonstrate their growing ability to enable in situ manufacturing in both domestic and remote environments, including space. This paper broadens the scope of additive manufacturing to all forms of vertically integrated manufacturing paradigms that may enable on-demand manufacturing, where users can be empowered to participate in the fabrication process

## Hybrid Manufacturing

Enabling users to fabricate a fully functional electromechanical device—a 3D structure with integrated electronics and actuators—requires three steps; (1) fabricating the device geometry, (2) creating conductive circuit traces, and (3) populating the structure with electronic components. Researchers have in recent decades developed numerous personal fabrication methods that democratize the creation of such functional devices. These methods typically focus on extending the abilities of existing fabrication machines designed to create geometry to also permit creating conductive traces, for example by generating hollow internal pipes for 3D prints that can be filled with conductive material, or using laser cutters to selectively ablate conductive films that can be populated with components. In recent work by the authors, we developed a system called LaserFactory, a vertically integrated machine capable of manufacturing fully-functioning robots and customized devices, including quadrotors and electronic health wearables, within minutes. The machine consists of a $150 add-on to a lasercutter which extends the laser's subtractive manufacturing capabilities with a conductive extruder, to deposit circuit traces, and a pick-and-place mechanism, to place components. In an accompanying software tool, users can drag-and-drop components and wires from a parts library onto a canvas to design a device, and then print it with a click. In 10 minutes, the machines manufactures a fully functional quadrotor that flies directly out of the platform; in 8 minutes, it prints a sensorized electronic health wristband tailored to the user's wrist, ready for use.

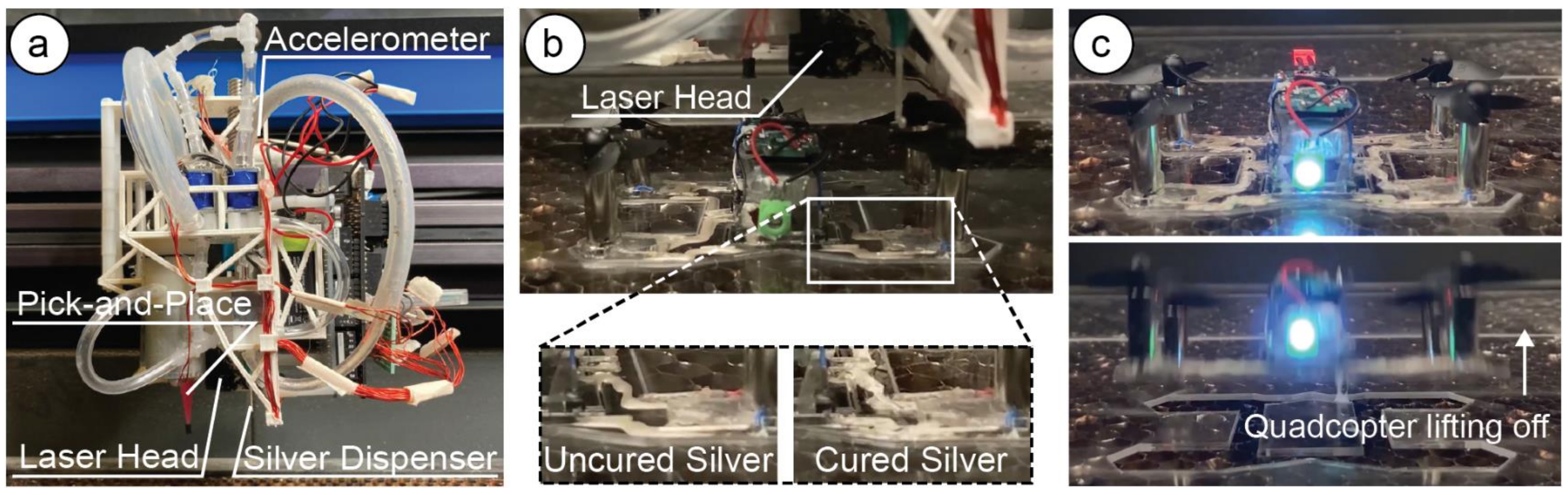

Figure 1. LaserFactory fabrication process. (a) Our hardware add-on to a laser cutter consists of a silver dispenser and pick-and-place mechanism, extending the machine's ability to create device geometries with the ability to deposit circuit traces and assemble electronic components. Our accelerometer-based motion classifier enables the add-on to interface with the laser cutter without the need to change the underlying firmware. (b) We developed a laser sintering method that leverages the defocused laser to cure and ridigze the traces, making them conductive. (c) After laser sintering, the fabricated device is fully functional.

## Modular Self-Assembly

As an alternative to the traditional, top-down method of assembling structures, roboticists have pursued a vision of modular self-assembly for both structures and robots for over 30 years. These systems discretize a target structure into functional blocks, and use self-reconfiguration to allow users to specify target shapes for the blocks to reconfigure into, without manual intervention. Exhibiting unique benefits in adaptability, scalability, and robustness, these systems promise to leverage mass manufacturing capabilities to manufacture modules, while affording end users customizability to assemble structures programmatically, without manufacturing expertise, with near-term application domains particularly emphasizing in-space assembly. In Electrovoxel, the authors introduced a cube-based modular system that utilizes an electromagnet-based actuation framework to reconfigure in three dimensions via pivoting. While a variety of actuation mechanisms for self-reconfigurable structures have been explored, they often suffer from cost, complexity, assembly and sizing requirements that prevent scaled production of such robots. To address this challenge, we use an actuation mechanism based on electromagnets embedded into the edges of each cube to interchangeably create identically or oppositely polarized electromagnet pairs, resulting in repulsive or attractive forces, respectively. By leveraging attraction for hinge formation, and repulsion to drive pivoting maneuvers, we can reconfigure the robot by voxelising it and actuating its constituent modules—termed Electrovoxels—via electromagnetically actuated pivoting. To demonstrate this, we developed fully untethered, three-dimensional self-reconfigurable robots and demonstrate 2D and 3D self-reconfiguration using pivot and traversal maneuvers on an air-table and in microgravity on a parabolic flight.

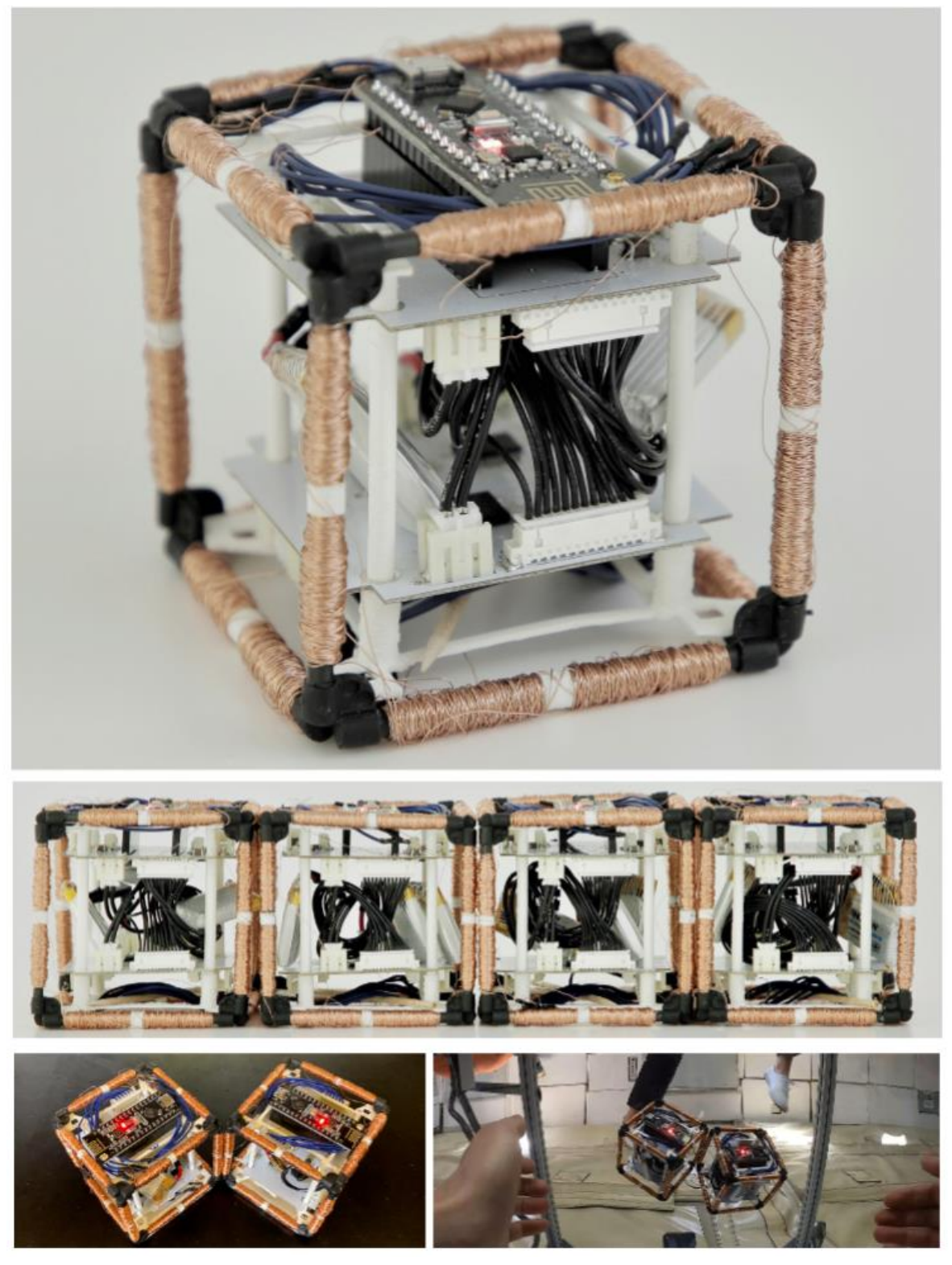

Figure 2. ElectroVoxels. (Above) A single module. (Middle) An array of four modules. (Bottom) 2D and 3D reconfiguration experiments on an air table and aboard a parabolic flight in microgravity.

## Programmable Materials

The assembly required to position and mate adjoining parts is a task requiring dexterous manipulation and path planning, in a process that today is commonly outsourced to expensive robotics. To unburden users from assembly tasks, while obviating the need for industrial robots to automate assembly, practitioners are developing methods to program materials and parts—similar to puzzle pieces—to enforce correct mating when parts contact their intended mate. These techniques are being used not just to enforce mating between parts, but to self-fold and self-assemble materials into target shapes in situ. Facilitated by programming specificity between pairs of mating faces, this has been achieved via minimization of free surface energy via topology, wettability, magnetic forces or electrostatic interaction. In work by the authors, we introduce a method to generate highly selective encodings that can be magnetically "programmed" onto physical modules to enable them to self-assemble in chosen configurations. We generate these encodings based on Hadamard matrices, and show how to design the faces of modules to be maximally attractive to their intended mate, while remaining maximally agnostic to other faces. Using cubic modules whose faces have been covered in soft magnetic material, we show how inexpensive, passive modules with planar faces can be used to selectively self-assemble into target shapes without control. We show that these modules can be easily re-programmed for new target shapes using a CNC-based magnetic plotter, and demonstrate self-assembly of 8 cubes in a water tank.

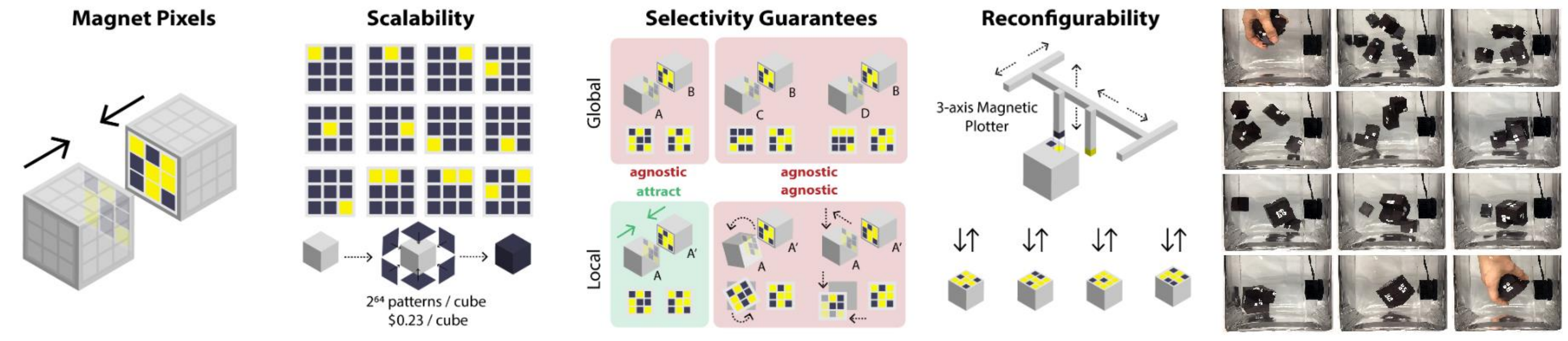

Figure 3. Magnetically programming structures for self-assembly. Cubic modules are programmed with matrices of magnetic pixels. Composed using Hadamard matrices, the pixel arrangements enforce selective mating between components, permitting modules to assemble into programmed target geometries. Our binary-valued 8x8 matrices can encode 264 module faces with unique permutations. Encodings are "programmed" as magnetic pixels using magnets installed on an inexpensive 3-axis CNC, and matrix encodings for new, custom structures can be generated by users in a web interface that automates the pixel design and plotting process. Once plotted, modules self-assemble in a water tank.

## Conclusion

Research across manufacturing, robotics, and human-interaction communities are developing new methods to program machines, modules and materials for on-demand assembly, enabling assembly in both new environments and by lay users. The examples here demonstrate automated fabrication and assembly of complex devices, like robots, in commercially available digital fabrication platforms, as well as in situ assembly of structures using programmable modules materials, including microgravity deployments for in-space assembly applications. These examples highlight the breadth of work across the academic and industrial communities that are empowering manufacturing and assembly processes to be done in inexpensive, consolidated platforms, by users without domain expertise. By consolidating this landscape of research, our work in this review highlights the state of the art of digital transformation in manufacturing, in order to understand what technology enablers are being developed that may drive a paradigm shift to on-demand manufacturing, and what is yet to be done.

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