Compound Fabrication: A Multi-Functional Robotic Platform for Digital Design and Fabrication

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Abstract:

Supporting various applications of digital fabrication and manufacturing, the industrial robot is typically assigned repetitive tasks for specific pre-programmed and singular applications. We propose a novel approach for robotic fabrication and manufacturing entitled *Compound Fabrication*, supporting multi-functional and multi-material processes. This approach combines the major manufacturing technologies including additive, formative and subtractive fabrication, as well as their parallel integration. A 6-axis robotic arm, repurposed as an integrated 3D printing, milling and sculpting platform, enables shifting between fabrication modes and across scales using different end effectors. Promoting an integrated approach to robotic fabrication, novel combination processes are demonstrated including 3D printing and milling fabrication composites. In addition, novel robotic fabrication processes are developed and evaluated, such as multi-axis plastic 3D printing, direct recycling 3D printing, and embedded printing. The benefits and limitations of the *Compound Fabrication* approach and its experimental platform are reviewed and discussed. Finally, contemplation regarding the future of multi-functional robotic fabrication is offered, in the context of the experiments reviewed and demonstrated in this paper.

Keywords: Digital fabrication, compound fabrication, 3D printing, robotic milling, robotic arm, rapid prototyping

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1. Introduction

Since the advent of the industrial robot, the world has been captivated by the idea of an automatically controlled agent that could make anything [1]. Yet, in today's world, robotic arms are typically relegated to perform repetitive tasks, such as those seen in assembly lines [2]. Industrial robots excel at cyclic tasks because repetitive movements are relatively straightforward to program at start-up. However, given increased use of industrial robotic arms in new fields such as art and architecture, the role of the industrial arm is now transforming [3,4]. Coupled with the evolution in digital fabrication and manufacturing, industrial robots are being repurposed to accommodate for customized manufacturing roles. Digital fabrication techniques have become a widespread tool for rapid prototyping and customized fabrication of systems with complex geometry, multi-material elements, and internal features [5]. For instance, additive manufacturing techniques capable of 3D printing functional batteries, working mechanical clocks, and even full-scale housing have been developed [5,6,7]. Robotic arms are beginning to replace and advance now common digital fabrication technologies such as 3D printing processes, metal folding operations, multi-axis milling, hot-wire foam cutting systems, brick-laying, and more [4,8,9,10,11,12]. A notable setup relevant to this paper can be reviewed in the MultiFab project, which uses a robotic arm, combined with a conventional 5-axis milling machine, to create a machining cell capable of laser-based additive manufacturing and milling [13].

Despite their inherent advantages of workspace flexibility and adaptability over conventional gantry systems, industrial arms still are not fully utilized. In addition to their capabilities as positioning systems for single processes, robotic arms offers unparalleled possibilities through the use of end-effectors that can transform an arm into a fabricator, sensor, actuator, and manipulator. Typically, multiple discrete and dedicated gantry-style computer numerical control (CNC) machines are used for such purposes. But what if a single machine could do it all?

The concept of multi-functional machining has been previously studied, however the aforementioned CNC multi-functional machines are based on gantry milling setup with a tool changer, typically limiting their operations to subtractive processes [14].

In this paper, a multi-functional robotic arm platform capable of all three of the major fabrication categories (additive, formative, and subtractive) is demonstrated and explored in the context of a new approach to design fabrication coined by the authors *Compound Fabrication*. Combining new manufacturing processes, such as 3D printing and multi-axis milling, with the range of a robotic arm, offers a potential platform for integrated fabrication across spatial and temporal scales. By exploring compound processes within the same machine, the flexibility of robotic arms can be used in a multiple-operation technique with a single fixturing setup. Finally, the benefits, limitations, and the future of robotic arm platforms in fabrication are discussed.

2. Methodology and Materials

2.1 Overview

To investigate the idea of a multi-functional *Compound Fabrication* platform, an industrial robotic arm was utilized in the three conventional categories of fabrication: additive, formative, and subtractive. While numerous types of manufacturing exist within these three broad categories, a single representative fabrication process for each category was selected to explore and evaluate capabilities. In evaluating additive fabrication processes, 3D printing was selected as the fabrication technique. More specifically, extrusion-based 3D printing systems were used, where the deposited material solidifies due to thermal or chemical stimuli, implementing fused or cured deposition techniques respectively. In the formative category, sculpting was chosen. Sculpting operations that use pliable materials, like clay, can produce molds for cast parts. Lastly, for subtractive fabrication, milling was selected.

In addition to replicating conventional fabrication techniques, the flexibility of a 6-axis robotic arm offers new possibilities for manufacturing. With a minimal physical footprint, the workspace can accommodate parts larger than the arm itself and access interior regions that are not possible for a gantry-based machine. In addition, the added degrees of freedom over conventional 3-axis CNC machines can be utilized for multi-axis machining, assembly purposes, and novel processes like multi-axis 3D printing.

Multi-axis 3D printing utilizes four or more axes to print 3D structures with several benefits compared to the XYZ positioning systems of conventional 3D printers. First, complex 3D structures with sharp overhangs can be printed without support material by rotating the build platform in respect to a stationary extruder. This novel process reduces waste by eliminating the deposition of support material, and removes post-processing chemical steps. Furthermore, material can be deposited on complex 3D surfaces instead of solely on planar build platforms. This allows for objects to be placed into the printer and printed on top of, rather than printing parts as standalone processes starting from a blank build platform. While multi-axis additive processes have been previously demonstrated using laser-based systems [13], the authors believe this work is novel in its application to plastic deposition printers.

2.2 Robotic System Specification

The robotic arm employed in all reported experiments is a KUKA KR5 sixx R850. This industrial 6-axis robotic arm is lightweight (29 kg), fast (maximum speed of 7.6 m/s), and has a reach of 850 mm with a repeatability of +/- 0.03mm [15]. A KUKA KR C2 sr controller was used for communication with the robotic arm.

2.3 Software

The arm was programmed using KUKA Robot Language (KRL) and Python scripts written to generate the KRL files from coordinate tool paths. For the 3D printing control files that used a conventional XYZ extruder movement, the open-source ReplicatorG program was used to generate the tool paths from input 3D part files. For 3D printing utilizing 5 axes (with a fixed extruder and a moving build platform), the tool paths were written directly in KRL with the use of fixed tool frames to simplify the math. In this setup, the build platform is rotated about the fixed extruder to allow for complex structures without support material. For milling control files, HSMWorks was used to generate the KRL tool paths directly from within the CAD program SolidWorks through a custom post-processor script [16,17]. For sculpting, Python scripts were used to output the tool paths and KRL files directly. All KRL files were tested using KUKA SimPro to ensure no path singularities or work envelopes were exceeded.

2.4 End effectors

To enable the various functionalities, different end effectors were constructed. These effectors connect easily to the wrist faceplate of the robotic arm and can also be used in a fixed tool configuration. For the additive fabrication techniques, three special print heads were constructed for three distinctive 3D printing systems covering different scales and materials.

First, a print head that extrudes acrylonitrile butadiene styrene (ABS) plastic was built based on a MakerBot MK6 Extruder [18]. This extruder utilizes a stepper motor to feed an ABS filament through a heated 0.3 mm nozzle (Figure 1). The nozzle is heated with a nichrome element and a thermocouple to provide a feedback loop. The build platform is an electrically heated aluminum plate maintained at a temperature of 170°C in order to reduce thermal warping of the printed structures. The build platform is wrapped with tape (3M ScotchBlue Painter's Tape) to provide surface texture for the first printed layer to adhere to.

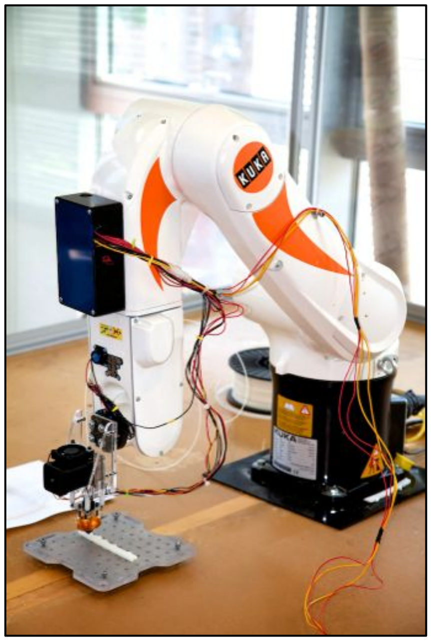

Figure 1. The KUKA robotic arm with the ABS 3D printing effector.

Secondly, a high-density polyethylene (HDPE) plastic print head was designed and assembled to explore the prospect of a direct recycling 3D printer (Figure 2). The extruder uses an auger to feed HDPE particles (shredded from used milk containers) into a heated 5 mm nozzle. Similarly to the ABS print head, a nichrome heating element is used with a thermocouple to maintain a desired melt temperature.

Figure 2. The HDPE 3D printing effector mounted to the robotic arm. Shredded HDPE plastic from recycled sources is fed into the hopper and extruded during printing.

Finally, in order to rapidly print larger structures, a third print head that deposits urethane foam was developed (Figure 3). A two-component urethane foam from Dow Chemical (FROTH-PAK Foam) was selected as the print material due to its quick cure time, high strength and low density [19]. A print head was constructed using a servo to control flow valves for each pressurized chemical component. Standard mix nozzles from Dow Chemical were used to provide uniform mixing and spray patterns.

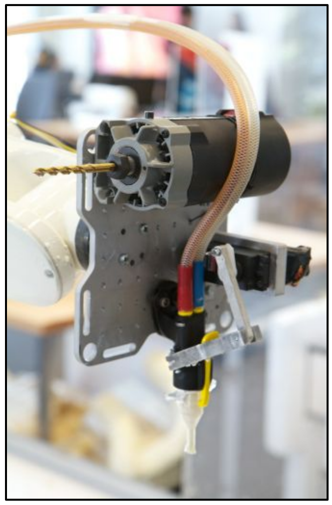

Figure 3. The spray urethane 3D printing and milling effector mounted to the robotic arm. The nozzle mixes the two-component foam and can be replaced for different spray patterns and print processes.

To explore formative fabrication techniques, a simple holder for a sculpting tool was created. Different sculpting tool heads can easily be altered with a screw tightening adjustment. Modeling clay (Plasticine) was used as the sculpting medium and objects cast using the sculpted clay molds were made with urethane plastic (Smooth-Cast 45D).

For subtractive fabrication, two different milling effectors were utilized. A rotary tool (Dremel 4000) with an adjustable chuck was used along with various milling bits to achieve fine detail. A larger router (Porter-Cable 7310) was used in as a milling effector for higher volume cuts and mounted alongside the urethane print head (Figure 3). Several materials were milled, including polyurethane foam, ABS, medium-density fiberboard, and modeling wax.

3. Results

3.1 Additive

The use of an industrial robot arm as a 3D printing platform was successful for the three different material systems: ABS, HDPE, and polyurethane. Using the ABS print head in a conventional XYZ extruder positioning system, the achieved layer resolution of 0.3 mm produced useable parts from a 3D input file (Figure 4a). Vibrations and rigidity did not restrict printing capabilities and the resolution was only limited by the nozzle extrusion size. Improvements were implemented by optimizing the path and extrusion speeds, applying approximate motion control to smooth the tool path, and by utilizing a heated print surface to reduce thermal stresses (Figure 4b). As support material was not used, parts were limited to geometries without large overhangs (over 45 degrees) or interior cavities. The printed parts demonstrated good layer adhesion and were of equal quality to a commercial MakerBot 3D printer [18]. The tolerances on the extruder positioning via the arm did not limit the printer; the printer was run at a speed of 0.05 m/s without any printing errors due to vibrations or instabilities. The use of an ABS filament feed was robust and allowed the machine to print for hours at a time without user interaction.

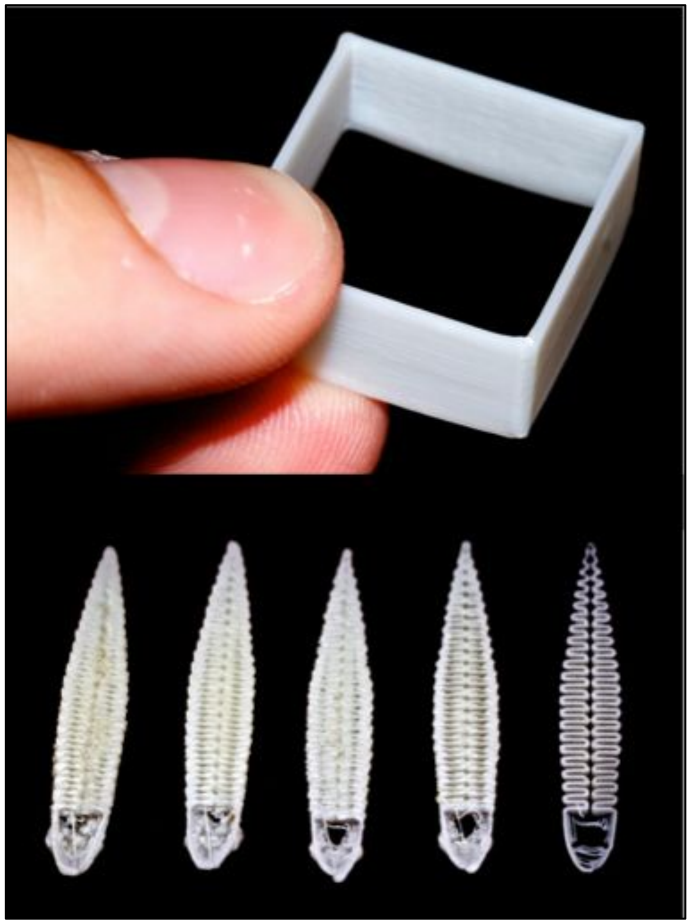

Figure 4. The 0.3 mm print resolution of the ABS 3D printer is seen at the top in a sample print (a) and the bottom image details iterative improvements in print quality from left to right due to implementing approximate motion control and a heated build platform (b), using a common test print file [20].

Utilizing the ABS print head in a novel multi-axis system was achieved by moving the build platform about the ABS extruder held in an external fixed tool position (Figure 5a). The robotic arm controlled the critical angle between the nozzle and the previous printed layer. By rotating the platform, the angle between the extruder and the previously printed layer of the structure was kept under 45 degrees, allowing for sharp overhangs to be printed without support material. This multi-axis configuration proved to be very flexible, allowing for complex structures made without support material. This opens the possibility of printing directly onto existing objects if their surface structure is known through either scanning or measurement. In addition, the lack of support material facilitates printing around objects and embedded printing. For instance, a 20 mm hollow cube was printed with a one-layer wall thickness of 0.3 mm and a loose screw was inserted into the center of the cube before printing the roof, leaving the captive screw within the closed structure (Figure 5b).

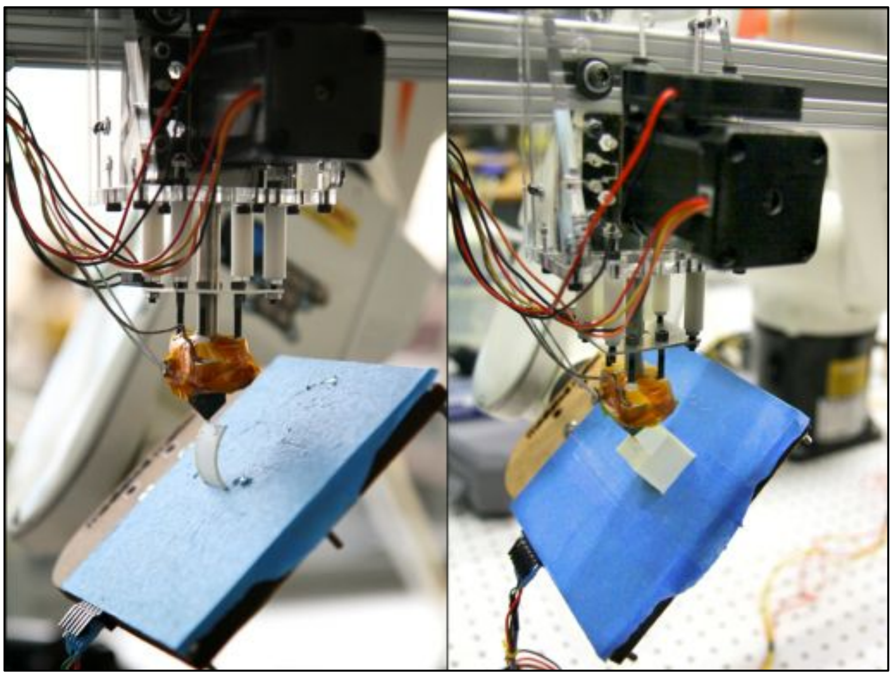

Figure 5. Multi-axis 3D printing of a curved part is seen on the left (a) and a hollow cube with a captive internal part is being printed on the right (b).

The HDPE print head successfully printed parts using ground milk containers as feedstock. Facilitating direct recycling, a user can grind a milk container using a standard paper shredder and place the shredded particles into the hopper of the extruder head. The shredded plastic scrap is then melted and extruded as a 3D printing medium (Figure 6). Due to the large nozzle size (5 mm), one of the main issues was thermal stresses and cooling rates. Warping of the initial printed layers was noticed in early iterations and was improved through the use of a heated print platform. Another issue noted was the extra vibrations incurred when the rotating auger sheared plastic grounds. This offset the extruder head slightly and reduced the accuracy of the printed part.

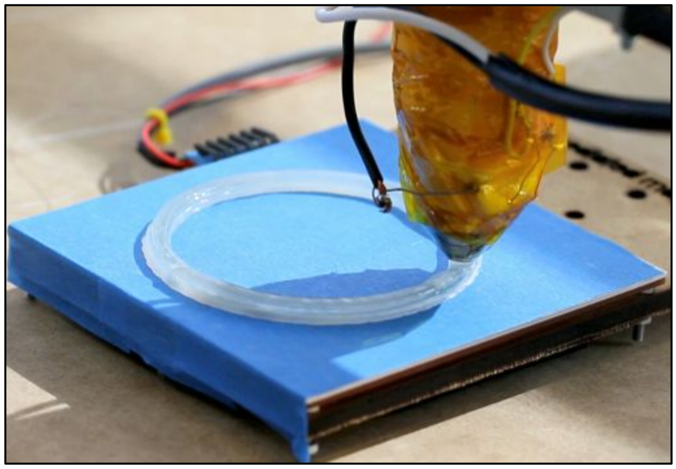

Figure 6. Recycled HDPE being extruded during the 3D printing process. The large nozzle diameter resulted in slow cooling times and issues with thermal warping. The heated build platform improved thermal warping issues significantly.

The urethane foam printing head functioned effectively, producing large structures rapidly (Figure 7). Due to the spray foam's low density and high adhesive properties, large overhangs were possible without support material by manipulating the angle of the extruder. Doubly curved surfaces without support material were achieved by offsetting the tool path and extruder angle, as seen in Figure 8a. The extruder head travel speed was 0.2 m/s. To allow for each layer to cure, a pause time between layers was utilized if the layer tool path was completed in less than 30 seconds (the cure time of the foam). To prevent the foam from curing inside the nozzle during this pause time, small bursts of foam were extruded every 10 seconds into a waste container. While the burst mode during pause time allow for one nozzle to be used per printed structure, using a replaceable nozzle system was very helpful for fast reset times between prints. The nozzle system also allowed for quick exchange of nozzle sizes, which controlled the path thickness. For most prints, a medium output cone nozzle was used, with a spray distance of 80 mm, resulting in a layer thickness of 40 mm. The resolution achieved was a function of nozzle size and spray distance. Due to the pressurized spray pattern, resolution was approximately 2 cm. For improved resolution, the milling effector proved effective on the printed foam (Figure 8b). The spray foam system proved to be a robust system with a fast build speed and low maintenance due to interchangeable nozzles. The spray urethane foam system allowed for embedding of objects within deposited layers, such as the plastic tie structures seen in the printed and finished wall mold structure in Figure 9.

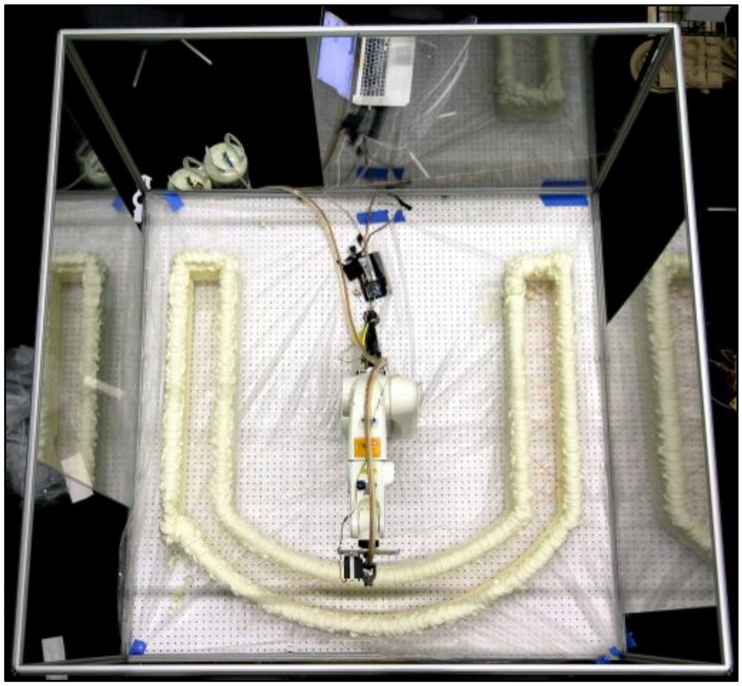

Figure 7. A top view of the robotic urethane 3D printer and a large printed foam structure for use as a curved wall mold.

Figure 8. The urethane 3D printing system can print doubly curved structures as seen on the left (a) and the milling effector can be used to subtractively finish the foam according to a digital design as seen on the right (b).

Figure 9. A 3D printed urethane foam wall mold with embedded plastic tie structures that has been milled and finished on the exterior with plaster and paint. This wall mold utilizes tie structures to support rebar during a concrete pour and the foam mold serves dual purpose as thermal insulation for the final wall. The wall structure is four feet tall and an American 25 cent coin is shown as a relative scale.

3.2 Formative

The formative clay sculpting utilized an indentation method where the depth of each indentation was informed by the thickness of the desired final object at any given point. This resulted in a 2.5D mold being formed in the clay (Figure 10a) that was used to cast the final object in urethane plastic (Figure 10b). The indentation method was simple, rapid, and effective, though the resolution was limited by the sculpting tool footprint, the step size, and the physical clay properties. The clay properties, especially its adhesion and viscosity, affected the sculpting tool and the desired material distribution. To limit the adhesion, a fast return stroke from each indentation was used to unstick the tool from the clay. Secondary passes and smoothing runs were investigated to further improve the sculpting resolution and showed significant improvements.

Figure 10. A Plasticine mold is sculpted by the robotic arm according to a design on the left (a) and a cast urethane part from the finished mold is seen on the right (b).

3.3 Subtractive

Milling was completed successfully on a range of soft material including foams, wood, and wax. For example, a urethane foam sign milled using a 3 mm end mill bit is shown in Figure 11 along with the tool path of the effector. In addition to 3-axis milling, multi-axis milling was explored to produce shapes with overhangs.

In the milling mode, the robotic arm was limited by its rigidity in comparison to conventional CNC milling machines. This reduced the material selection to softer materials and slower cutting speeds. Vibrations, causing chatter in the milled parts, was reduced by optimizing the position of the work piece. Based on visual observations and experimentation, it was found that moving the work piece towards the arm base reduced the system vibrations. This improvement can be attributed to reducing the moment arm and increasing the system stiffness.

Milling completed with the robotic arm platform was versatile due to the range of motion, ease of access to the work piece, and large working space. The milling setup was particularly simple to configure, due to a custom post-processing script integrated with a single CAD/CAM system (SolidWorks/HSMWorks). Using a base coordinate system referenced from the work piece surface allowed for quick calibration to each new stock material work piece.

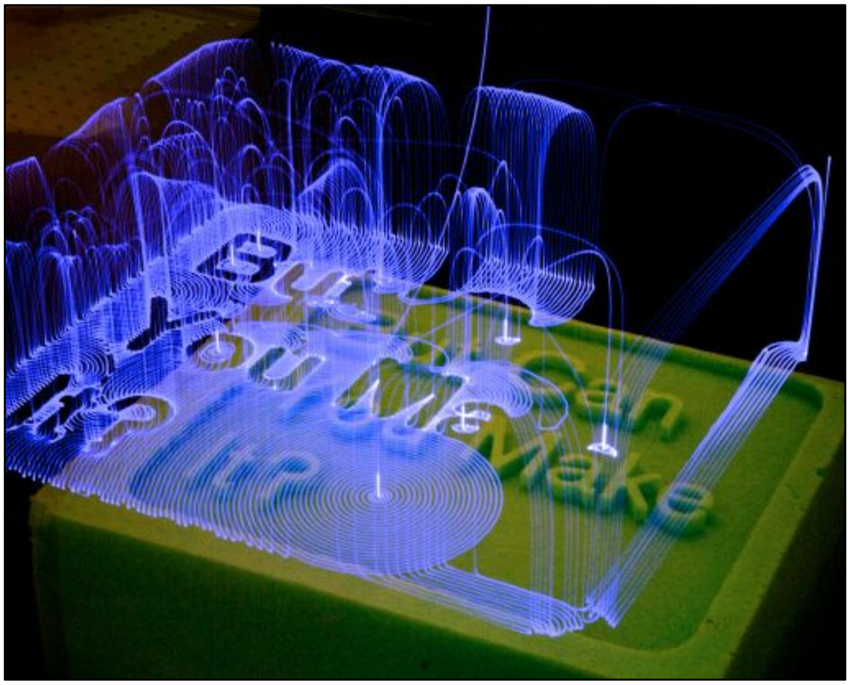

Figure 11. A milled urethane foam sign, along with some of the tool paths used to mill the sign. The tool paths were illuminated using a light mounted to the milling effector and a long-exposure photograph.

3.5 Combination

In order to explore the effectiveness in combining fabrication processes within a single platform, 3D printing and milling operations were automatically sequenced to generate an object and apply finishing cuts to obtain superior surface finishes and cutouts. Rather than switch end effectors on the arm, as was the case with the other experiments, fixed tool mounts in the workspace held the effectors and the arm manipulated the work piece (Figure 12). This configuration allowed seamless transitions between the processes and the work piece coordinates were maintained throughout the operations without recalibration or additional fixturing.

The ABS extruder was used to print a solid 2 cm cube that was then milled by a 3 mm end mill bit to improve the surface finish. The adhesion between the 3D printed ABS and the build platform provided sufficient fixturing of the cube for milling to proceed directly following the printing process. The heated build platform was turned off at the end of the printing process to facilitate cooling to provide a stronger fixture for milling.

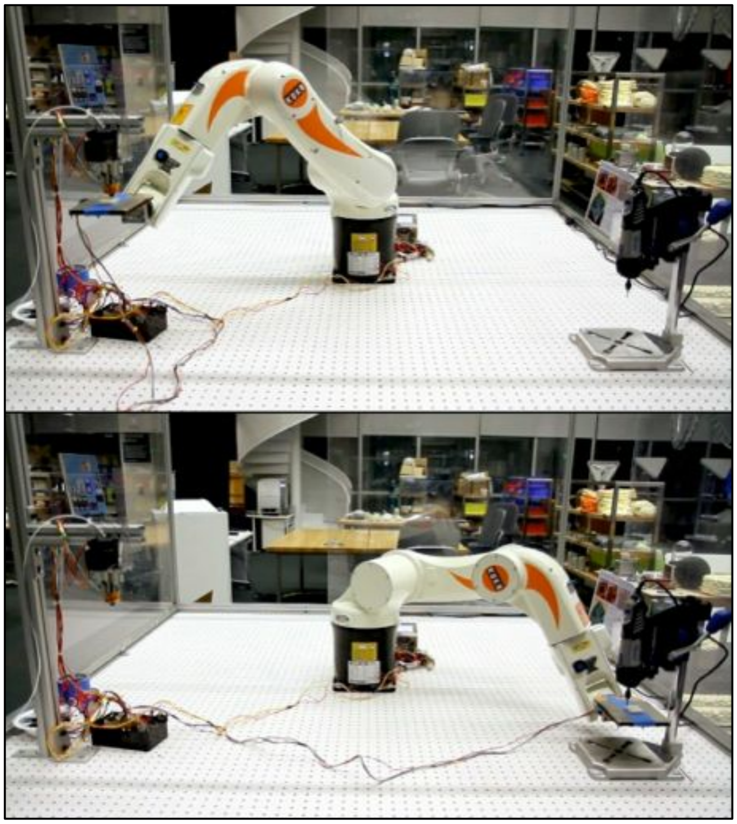

Figure 12. By configuring external effectors and moving the work piece, a single fixturing and calibration can serve many processes. The top image shows an ABS part being 3D printed and subsequently undergoing surface milling in the bottom image to achieve a better finish.

4. Discussion

4.1 Demonstrated techniques

4.1.1 Additive

The use of a robotic arm platform for additive manufacturing techniques is promising and offers several advantages compared to current technologies. First, the printable workspace area is significantly larger, especially considering the small footprint of the machine when compared to conventional printers. Secondly, robotic arms can easily be reconfigured for different print heads and systems (such as laser sintering, deposition-based systems, powder/binder systems), making them appealing for additive manufacturing research. For example, the described system was able to easily switch between an ABS printer, a direct recycling HDPE printer, and a urethane foam printer. Finally, the extra axes of robotic arms can be utilized for multi-axis 3D printing, enabling novel benefits as shown in these explorations.

While multi-axes milling has been used for decades [21], for all current methods of deposition-based 3D printing, only the XYZ positioning space is utilized. At first thought, there is no apparent use for multi-axis printing as the material nozzle is ideally a single spatial point without need of angular definition. However, the multi-axis 3D printing explored in these experiments offers a new realm of possibilities for additive manufacturing. While the single point argument stands, the angular control matters for deposition construction due to gravity. Multi-axis control allows for the rotation of the platform to use gravity as an advantage for printing structures with overhangs without support material. Support material is costly, significantly increases the printing time, and requires post-processing. In the experimental configuration, the part geometry and overhangs are only limited by the nozzle size and shape. To achieve sharper angles, the nozzle and extruder can also be angled to accommodate sharper angles than would be permitted by a solely vertical nozzle. The proof-of-concept parts printed with the multiple axes were generated with custom tool paths. An algorithmic approach to generating multi-axis tool paths can be developed by maintaining an angle under 45 degrees between the previous layer and the current nozzle position while avoiding a collision with previously printed features.

This concept of rotating the build platform to allow for printed overhangs without support material can be applied to standard gantry XYZ printers with the addition of a variable angle platform. This idea, which is useful for fused deposition printing without support material, could take the form of a tight tolerance pivot point, actuated by a small motor. An even simpler modification could be done with a manually-operated pivot joint, set to fixed angle intervals, which could be rotated at pre-programmed intervals calculated by the tool path generation to allow for structures with overhangs.

The direct recycling printing experiments provide for a strong visual demonstration emphasizing the potential and viability of recycling. A discarded object can be transformed into any arbitrary shape or design. The concept of direct recycling saves the step of transporting discarded objects to a centralized facility and the transport of the finished recycled good back to a consumer. From an energy and efficiency viewpoint, the concept is attractive. However, the present implementation of direct recycling as a single step process incurs several challenges that currently relegate the piece to a more artistic and representative proof-of-concept. As there are no filtering mechanisms, the printed material is an amalgamation of the input recycling stream that yields inferior and inconsistent properties. The outputted parts resulting from the milk jug recycling process contain bits of paper that can jam the nozzle and interfere with layer consistency. This filtering issue would also be useful to sort HDPE materials from other recyclable materials that cannot be directly printed. An additional noticeable issue was the relative difficulty encountered when controlling the extrusion rate, as one must accommodate for varying sizes of shredded input material passing through the auger feed at various rates. Both issues point to the idea of converting the recycled material into a filtered, uniform feedstock as an initial step before generating input into a 3D printer. This notion of a two-step method appears to offer additional process control and could be implemented in future iterations of the design.

The spray urethane 3D printing results demonstrated a feasible system for rapid large-scale additive manufacturing. The combination of a fast-curing material with the flexibility and range of a robotic arm opens the possibilities for additive manufacturing to new scales and opportunities. The benefit of compounding additive foam printing with subtractive milling is high resolution at a fast print speed. The larger layer height and fast cure time ensure a rapid printing process, while the surface milling enables significantly high resolution. The results suggest effective applications in construction, molding, composite manufacturing, and other large-scale fabrication processes. Future work on using polyurethane molds for 3D printed on-site castable wall structures is currently underway.

4.1.2 Formative

The robotic clay sculpting experiments demonstrate an environmentally-friendly method of manufacturing due to the lack of input material and relatively low energy input. Once a mold is sculpted and a part cast, clay media can be re-used to generate new molds. To reset the Plasticine clay, heat is applied and the clay is allowed to soften and re-form into a solid planar form. The lack of waste material allows for a cost-effective process where multiple mold designs can be tested and evaluated inexpensively.

Formative processes, such as clay sculpting, are well suited for robotic arm platforms due to the required degrees of freedom for material manipulation. Like a human sculptor, a robotic sculptor requires complex positioning abilities for the simultaneous positioning of multiple tools and for avoiding collision with the substrate material. However, while the robotic arms can mimic the mechanics of a human arm sufficiently for sculpting, emulating human feedback is still a challenge. In the experiment conducted, this was noticed in the form of the clay's variable physical behavior as it was sculpted. For instance, variability in the adhesion to the tool and the direction of the material flow during compression hindered the process. The human sculptor inherently controls their movements and pressure in response to dynamic behavior of the sculpted material; For a robotic system however, the physics must be explicitly modeled and evaluated in real-time. One way to avoid the complex behavior of non-Newtonian fluids (such as clay) is to use a granular material, though this substantially limits the geometrical range of produced designs (where the angle of repose controls the geometrical limits). This approach was recently implemented by a group using a robotic arm to form sand molds for custom cast concrete panels [22].

4.1.3 Subtractive

Of the various functionalities explored in this experiment (3D printing, sculpting, and milling), robotic arm milling appears to be most extensively explored in the literature [23,24]. While not yet a commonplace fixture in industry, robotic arm milling packages are gradually becoming commercially available and offer many benefits over CNC milling, such as a large workspace and flexible multi-axis options [25]. In robotic milling, material and precision limitations are acknowledged due to lack of system rigidity, though improvements could be made through optimizations in cutting parameters and work piece positioning [26].

4.2 Integrated performance

Using a single machine for multiple processes allows for integrated performance and novel combinations of manufacturing techniques. The main benefit is derived from the ability to process a single work piece using multiple effectors, without having to re-fixture, re-calibrate, or require human operation in a relatively small space. Conventional CNC mills regularly employ this benefit by switching milling heads for different operations. A multi-functional robotic arm platform takes the concept one step further with the ability to switch processes entirely. For instance, 3D printed parts can be immediately milled to achieve the desired tolerance and surface finish. By blending the two operations, the benefits of additive manufacturing (internal features, material usage) are combined with the benefits of subtractive manufacturing (higher precision, faster speeds, better surface finishes). A multitude of process combinations can yield hybrid advantages and offer a truly flexible manufacturing machine.

Multi-axis printing combined with assembly also facilitates the avenues of embedded printing and object printing. Current 3D printing technologies work from a blank canvas where the entire structure is printed and the outputted object is constrained to the limited materials available to 3D printing. The concept of embedded printing combines 3D printing with pick-and-place assembly techniques to merge 3D printed features with pre-fabricated objects like electronics, hardware, and fabrics. Utilizing a digital scanner, an object complex surface can be integrated into a design and 3D printed on or around. With the spatial flexibility of multi-axis printing, such complex surfaces can be operated upon and undercuts can be printed into them. Of all the 3D printing techniques, only lithographic methods based on curing photopolymers have allowed for 3D printed structures around physical inserts [27,28]. These lithographic techniques are limited to photopolymer materials and suffer from difficulties like laser shadowing from the inserted object [27]. The use of multi-axis 3D printing for embedded printing and assembly operations opens a realm of new possibilities for additive manufacturing.

Combining immaterial sensing and physical fabrication yields the notion of *Informed Manufacturing*, where environmental feedback contributes to the finished product. Using sensing equipment as an effector, the system can map out an environmental field or material property and use such information to control the fabrication process. For example, an x-ray imaging system can be used as a scanning sensor for crack detection on an aircraft part [29]. Extracting the information from the sensor effector, a welding effector can then be used to apply a repair weld to the precise area required. This method is made fast and efficient by combining operations, and it facilitates a secondary x-ray scan to evaluate the repaired weld seam. *Informed Fabrication* can be applied to any CNC manufacturing method, and is especially suited for robotic arm systems that have the required flexibility, internal space freedom, and dexterity.

One of the benefits of a robotic arm system for integrated performance is the open access to the workspace by the effector. Unlike a gantry system, a robotic arm can navigate around several fixed tools, offering an alternative approach to switching end effectors. Mounting the work piece on the arm, several fixed tools (print heads, milling stations, grinding stations, etc.) can be used without re-fixturing or swapping effectors. This efficient approach is successfully demonstrated with the combined 3D printing and milling.

4.3 Limitations

The avenues explored in these experiments are diverse and provide promising opportunities for the future development of multi-functional robotic fabrication systems. However, the limitations of robotic arm systems must be addressed in order to advance their use. These limitations include the programming environment, physical constraints, and economic considerations.

Software limitations are the primary reason for the lack of robotic arms in non-cyclic tasks. Generally speaking, the current hardware on industrial arms is more than capable for numerous fabrication tasks. While the issue is generally improving due to growth in programming languages and interest in digital fabrication, several issues still complicate the process.

First, the programming architectures of industrial robotic arms are not easily compatible with digital fabrication. Issues relating to singularity avoidance are not sufficiently solved in the programming architecture to enable the needed smooth, complex, and long tool paths required for digital fabrication. This problem arose many times during these experiments, where a tool path would be halted in-progress due to a singularity issue. To avoid this, all tool paths were digitally checked using a simulator (KUKA SimPro) and minor movements were added to bypass problem zones. Secondly, there is a lack of an easy interface supporting commonly used programming languages for industrial robotic arms. All major robotic arm manufacturers use proprietary programming languages that impede the use of third party software and open-source platforms. While the competitive nature of the industry dictates the evolution of the various proprietary industrial robotic control solutions, the introduction of easy interfaces to open-source control systems would allow for the rapid advancement in new growth areas, such as digital fabrication. Several groups around the world have made promising progress in this area, such as the open-source MATLAB KUKA Control Toolbox and the Parametric Robot Control plug-in for Grasshopper [30,31]. The industry is beginning to take notice as well, with KUKA's recent foray into arms specifically designed for research use, namely the Lightweight Robotic Arm and the YouBot [32,33]. These robotic systems have new control structures that facilitate open-source programming. The next few years will be an exciting time for industrial robotic arms due to a renewed interest in domestic manufacturing, open-source control, and digital fabrication.

Physical constraints of a robotic arm system for digital fabrication relate to the maximum accuracy, strength, and stiffness. Given the configuration of a conventional robotic arm, the system's accuracy, strength and stiffness are orders of magnitude lower than a similarly sized gantry system. As seen in the effects of system stiffness on milling, the lack of stiffness in a robotic arm limits the material choice to softer work pieces and slow cutting rates. This is also true for accuracy and strength. There are significant improvements that can be implemented to improve arm rigidity for milling operations, for instance in work piece position and in tool path optimization [26]. However, robotic arm milling operations will not be able to replicate the precision, material capabilities, and speed of gantry-style machines for processing requiring high forces (likely types of subtractive and formative fabrication).

Compared to conventional gantry platform, robotic arms are more expensive due to the additional complexity. For individual conventional fabrication processes, it will be challenging for robotic arm system to complete economically with gantry-style machines. However, the added capabilities and multi-functionality of a robotic arm platform justify the added cost. As shown by these experiments, a single platform can be quickly reconfigured to function in all of the major fabrication categories. Furthermore, the integration of multiple distinct machines into a single unit enticing possibilities of combining processes, such as 3D printing and milling as demonstrated. Such combinations could offer the benefits of both processes: allowing for complex internal structures reduced material usage, and precise surface finishes and tolerances. Assembly tasks can also be integrated directly into the digital fabrication workflow, for instance with pick-and-place functionality and embedded object 3D printing. With the flexibility of a multi-functional robotic arm fabrication platform, a truly integrated manufacturing machine may be achievable.

4.4 The future

The uses for robotic arm systems in digital fabrication are growing and will continue to grow due to their flexibility and size advantages over gantry-style positioning systems. While the inherent lack of rigidity and higher cost prevents direct replacement for many gantry-style CNC systems, new manufacturing avenues suitable for arms are appearing rapidly. As opposed to gantry systems that are typically heavy, and constrained to their internal workspace, robotic arms can be easily moved and tracks can be added for enormous workspace range. These benefits, combined with their potential multi-functionality as demonstrated in this paper, provide a strong argument for the future growth of robotic arm platform for digital fabrication.

When contemplating the future of composite fabrication, the authors envision mobile systems with robotic arms capable of 'swarm construction' techniques. Akin to termites building structures much larger than themselves, swarm construction robots could elevate digital fabrication to possibilities of on-site fabrication/repair and building-scale printed structures (Figure 13). Such capabilities would eliminate the dangers of human construction, reduce costs due to labor, and facilitate unique design options. Robotic arms are well suited to mobile fabrication due to their wide reach, robustness, and flexible reconfigurations.

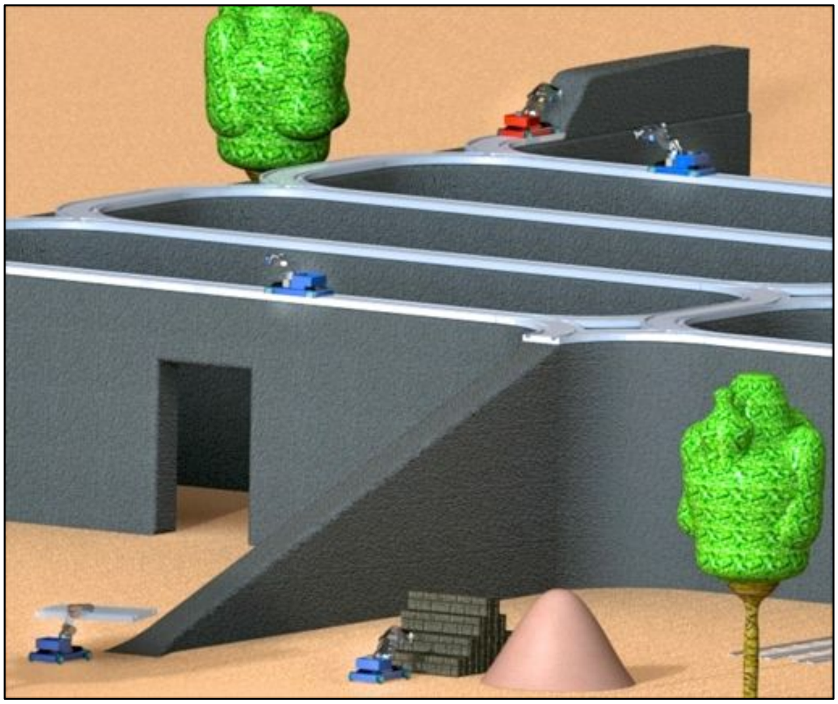

Figure 13. A computer rendering of a proposed swarm fabrication system. Small robotic agents equipped with robotic arms for on-site fabrication.

5. Conclusions

The true flexibility of industrial robotic arms appears to currently be underutilized due to their relegation to primarily cyclic tasks. As demonstrated in this paper, a single robotic arm system can serve as an additive, subtractive, and formative fabricator. By serving as a multi-functional fabrication platform, the robotic system can handle large and complex quantities of data in relatively short time and with a high degree of efficiency. By supporting the combination of several classes of fabrication processes (such as additive and subtractive) that are otherwise discrete and singular, the platform is able to act as a truly integrated design platform. Benefits range from integrated performance capabilities, large workspace performance, minimized physical footprint, and relatively low costs.

Beyond efficiency, the *Compound Fabrication* approach promotes new models of working and interacting with robotic fabrication systems at large. These models challenge traditional design processes and protocols by allowing the designer to utilize the robotic arm as a generative design platform not unlike a computational modeling environment. This multi-process, multi-parametric system offers on-the-fly flexibility in both process and product design.

In addition to conventional fabrication techniques, robotic arms are well suited for novel fabrication tasks that extend into sensing and design generation based on environmental data. While barriers still exists for robotic arm digital fabrication, such as the complexity of generating tool paths, the evolution of proprietary industrial control systems, and the issues of system rigidity, progress in all categories provides an optimistic outlook for robotic arms in digital fabrication, and for Composite Fabrication as a new paradigm for robotic manufacturing.

6. Acknowledgements

This work was supported in part by NSF EAGER grant award #1152550 "Bio-Beams: Functionally Graded Rapid Design & Fabrication". The authors wish to acknowledge Dr. David Wallace for his advice and guidance on the project and Jim Miller from KUKA Robotics for the robotic training. The authors also wish to acknowledge the Mediated Matter group and the undergraduate research assistants who have contributed to this work, including Ali AlShehab, Louis DeScioli, Keren Gu, Banks Hunter, Julian Merrick, Taylor Robertson, Nathan Spielberg, and Ann Warren.

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