Microscale Freeform Integration by Directed Self Assembly (review)

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ABSTRACT **Reviewed, accepted August 21, 2007**

Most solid freeform fabrication (SFF) manufacturing processes assemble uniform components such as powder particles or polymer chains to produce desired geometries. Their capacity for producing highly functional parts (integrated actuation, sensing, and electronics) will dramatically increase when multiple materials and functional subcomponents can be automatically integrated. This paper addresses criteria for a system that integrates multiple materials and components through computer-controlled self-assembly. It builds complex systems from layers of self-assembled micro-components. The paper will address implementation methods, present a concept demonstration, and consider its application to micro-thermoelectric systems. This manufacturing process can be enhanced further through integration with mature additive processes.

INTRODUCTION

Solid Freeform Fabrication (SFF) describes a group of manufacturing processes that can produce parts directly from a computer model without need for part-specific tooling. These techniques are widely used in rapid production of appearance models and low volume manufacturing. SFF also permits the manufacture of some parts that are not feasible by other processes. [1, 2]

Most solid freeform fabrication (SFF) techniques create homogenous parts. Significant work has been done to incorporate multiple materials into SFF processes [3-5]. The incorporation of multiple materials increases the functionality of the final components to include components such as batteries and actuators. However, the performance of these structures is reduced by the geometry and materials limitations of the manufacturing methods. Alternatively, others have inserted components into SFF processes to increase functionality. [6, 7] Inserted components included motors, cables, sensors, and wiring. These techniques have been particularly useful in building small robotic components. Just as with traditional manufacturing methods, the value and functionality of the components increase exponentially when they are combined. However, this method requires intervention and is not easily applied in production quantities or to very small parts.

While macro- and meso-scale components are readily assembled to create highly functional devices, assembly at the microscale is challenging. At micro scale, there are many manufacturing and device technologies, but limited tools for integration. Morris [8] showed that assembly rates decrease at smaller sizes due to the increased difficulty of robotic approaches. Rather than integrate different components, many microsystems are built from a series of compatible processes. However, as complexity increases, it is more challenging to maintain acceptable yields. Self-assembly is a promising alternative method for integrating components at these size scales. In self-assembly, components are designed so that their combined energy is minimized when bonded together in the desired configuration. Since self-assembly is a highly parallel process and requires little support equipment, it can be an economical process. [8-10]

This paper explores the conditions necessary to extend the freedom of SFF processes to the integration of micro-components to create a self-assembly system for automatic micro-part assembly. This paper also considers one possible technical approach, and an application in which it would be useful. This capability will be termed Microscale Freeform Integration (MFI).

MICROSCALE FREEFORM INTEGRATION (MFI)

Microscale Freeform Integration (MFI) is the flexible, computer-controlled, integration of separate microscale components in order to integrate micro-technologies into microsystems. In the ideal case, MFI is solid freeform fabrication by automated assembly of functional components. These components might be blocks of homogenous material or they might be complex functional blocks containing sensors, actuators, and/or electronics. This system could be used to combine a limited number of components into infinitely many functional systems. This system would amount to a kit of Legos™ with a system for automatic assembly.

There are many requirements that must be addressed to create a complete MFI system. Process challenges include the design of the components to achieve desired functionality, methods to design the functional systems to be produced by MFI, and development of the MFI system to implement it. This paper addresses the challenge of physically integrating separate blocks under computer control. In particular, it addresses the use of self-assembly as a method for automatic integration.

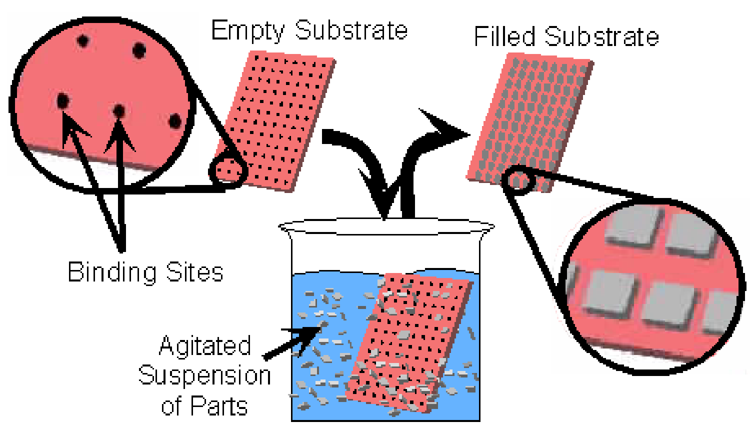

Figure 1 The basic fluidic self-assembly Process. One set of parts can generate only one assembly.

Figure 1 illustrates the basic self-assembly process as currently practiced in the literature. Current processes lack the control necessary to arbitrarily assembly components. Each set of components is carefully designed to create a particular assembly. [11] In contrast, an MFI system must permit substantial control over the assembly process to be able to assemble components at will. Some capabilities necessary to achieve this functionality include:

1. **One interface that can bond multiple different parts –** Full assembly flexibility requires that the process be able to assemble different components at the same location according to the process demands.
2. **Binding sites that can be selectively activated and/or deactivated –** This is the fundamental method of controlling the assembly outcome. This must be done under computer control to enable flexible integration under MFI.
3. **System that controls part orientation –** The functionality and geometry of many parts will be orientation specific. So the self-assembly process must be able to control component orientation. Most possible designs for part and binding sites contain multiple stable configurations due to local minima in the energy landscape. The assembly process must be able to eliminate the undesired configurations.
4. **Substrate that is reusable –** If multilayer components are to be constructed, the parts must be transferred from the assembly substrate or the control signals passed through the first layer of parts. Part transfer seems to be the more viable process.

These capabilities could be implemented in many different ways. However, a layer-based approach is perhaps easiest to conceptualize. **Figure 2** illustrates a possible implementation of this approach.

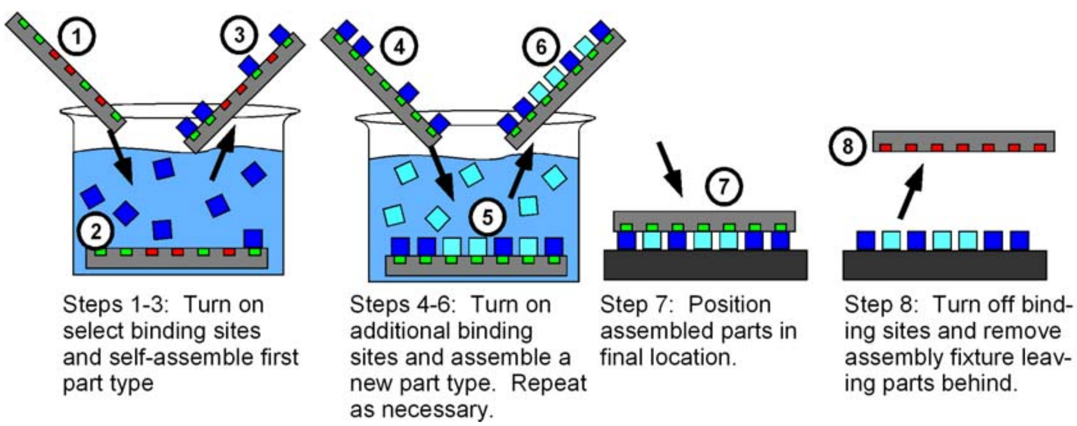

Figure 2 Basic process for implementing MFI. The process can be repeated for additional layers. Permanent bonds can be formed to the second substrate in Step 8 to finalize the assembly.

There are also part requirements that would need to be met. This would include some common geometrical features to enable integration. In the case of capillary self-assembly, this would include requirements on the surface properties. Parts might require temporary assembly coatings that were removed after assembly processing.

STATUS OF SELF ASSEMBLY PROCESSES

While self-assembly is an important natural and biological process, it has only recently been studied as a method for manufacture and assembly. It is therefore an immature process. To assess status, micro self-assembly is compared to the most developed assembly systems—macro scale.

Comparison of Micro and Macro Assemblies

This work proposes several criteria for comparing assemblies to see differences in assembly complexity. These criteria require only a bill of materials and knowledge of the connections between the parts. These connections can be captured using a "liaison diagram" as proposed by Whitney [12].

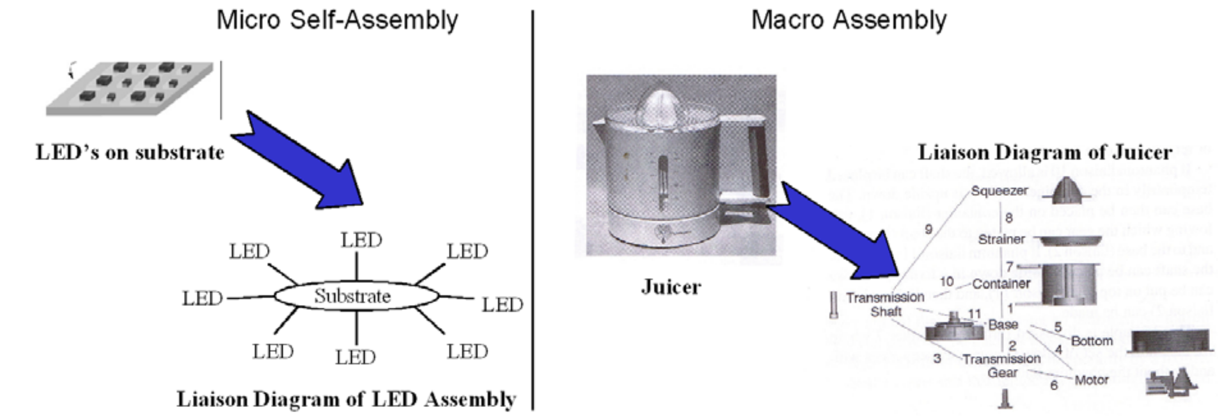

Figure 3 Example liaison diagrams of a microscale and macroscale assembly. [12]

Figure 3 shows an example assembly and it's liaison diagram. From these diagrams and the bill of materials, three criteria were considered. They are:

1. **Part Variety**- Defined as the ratio of unique parts to the total number of parts in the assembly.
2. **Liaison Index**- Defined as the ratio of number of liaisons per part divided by the minimum liaison per part. A liaison is defined a single line on the graph. Liaison per part is the total number of liaisons divided by the number of parts. The minimum number of liaisons per part for an assembly of *n* parts is given by

$$\frac{MinLiaisons}{Part} = \frac{n-1}{n}$$

For typical engineered products, the liaison index is near one (the theoretical minimum) and none exceeds two. Higher values of the Liaison index increase the potential for over constraint in the assembly.

3. **Max Liaison Chain Length**- Defined as the number of liaisons in the longest chain on the diagram.

Figure 4 compares the complexity of published reports of micro self-assembles and macro assemblies on these three criteria. There is clearly a significant difference between the two. The biggest difference is in the part variety where micro-assemblies had 1-3 different part types. There is also a substantial difference between micro and macro assemblies in the max chain length. This difference arises because most of the micro self-assemblies consist of parts connected to a substrate. The one exception is a case in which parts were connected together into a single chain—still a simple part structure. The difference in Liaison index was small, but this parameter is generally minimized for successful assemblies. It is interesting to note though that the macro assemblies did have higher values indicating a capability to create complex connections between multiple parts that does not appear to exist in micro self-assembly.

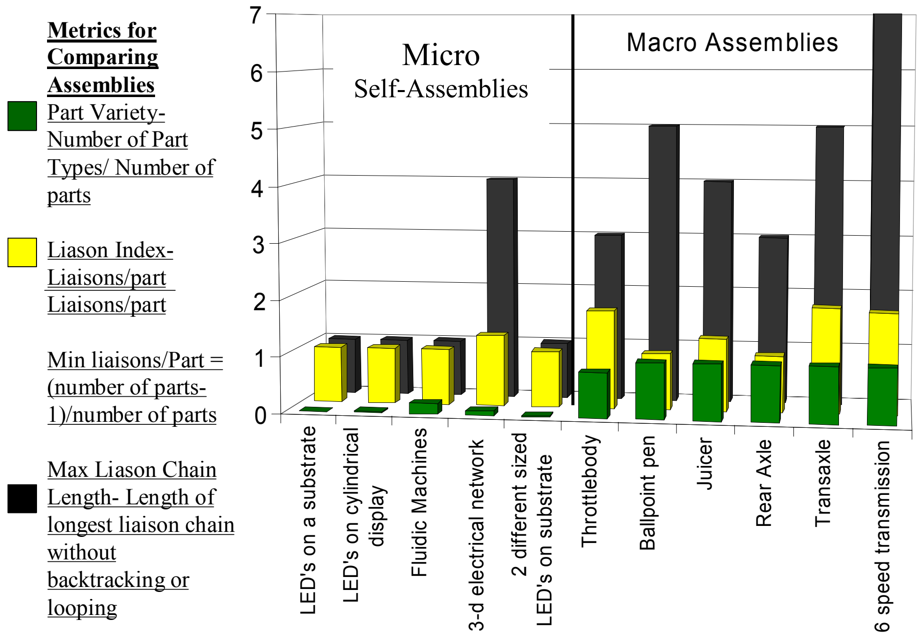

Figure 4 Comparison of micro self-assembly and macro assemblies. Macro-assemblies are more complex than micro-self-assemblies. [12-18]

Reasons for Differences

These indices do not prove capability or lack thereof. The difference could be due to a difference in design intent or component manufacturing capability rather than of assembly capability. However, there are clear fundamental differences in the capability to connect components by self-assembly. The key activity of assembly is the formation of connections between components that constrain one or more degrees of freedom. In examining the pattern of connection formation during assembly, the differences in capability can be related to the four requirements for MFI identified above:

1. **One interface that can bond multiple different parts** – Most component pairs published to date are custom manufactured. However, it is often a challenge to keep parts from assembling to the incorrect sites and bonding multiple part types is feasible. It must be coupled with the ability to selectively activate the bonds.
2. **Binding sites that can be selectively activated and/or deactivated** – Recent efforts have been made to permit bonding activation control. These techniques are generally cumbersome with very slow switching times (>1 hour) and/or increased part complexity. [19-21]
3. **System that controls part orientation** – Templating procedures have been employed to control assembly orientation. [18] Since these are not easily extended to the flexible assembly requirements of MFI, new approaches are necessary.
4. **Substrate that is reusable** – Some work has been done with transfer of self-assembled parts that showed encouraging results. [22]

Current man-made self assembly systems do not meet all the requirements simultaneously. However, progress has been made and the outlines of a potential solution are proposed below.

PROPOSED SELF-ASSEMBLY MFI SYSTEM

In this method, self-assembly is performed by capillary forces. Capillary or fluidic self-assembly is widely studied due to the relative strength of capillary forces at the micro-scale. Assembly is typically controlled by spatially varying the surface wetting properties of at least one part. Parts only bond to regions in which the bonding fluid wets as illustrated in **Figure 5**. The shape of the bonding region can be adjusted to provide a measure of control over the assembled orientation. Assembly is typically executed by submerging the parts in a liquid that is immiscible with the bonding liquid and agitating the solution. The agitation brings the parts together repeatedly until they form a successful bond.

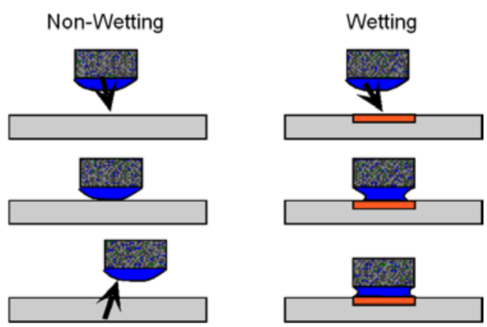

Figure 5 Parts contacting non-wetting regions are easily removed while those that impact a wetting region tend to stick.

Each of the basic characteristics of the MFI integration system are discussed below. Methods for achieving the basic functionality are discussed. The concepts are demonstrated using assembly of printed circuit board components (2-10 mm dimensions) bonded with a low melting point solder (mp = 47 C) agitated in a solution of dilute sulfuric acid with a Ph of 1.0 to prevent oxidation of the solder surfaces.

<u>Generic Interface</u>

In the initial work, the simplest of interfaces was selected—an array of circles. This approach makes the part orientation control more complex as discussed below.

<u>Binding Site Activation</u>

The key technical characteristic of a self-assembly MFI system is the means of controlling the bonding spatially and temporally. One method of controlling bond location is by controlling the distribution of the bonding liquid on a substrate. This could be done through inkjet printing to permit computer control. In this approach, inkjet printing is used to deliver the bonding liquid to the site where assembly is desired or an inhibition liquid to mask sites where assembly is not desired. Once the bonding liquid is printed, parts can be assembled in the desired locations shown in **Figure 6**. Bonding was also selectively inhibited by coloring the pads with a permanent marker. This effect can be removed by applying a solvent. The part's middle contact pad was covered with permanent marker. This allows the parts to only be assembled correctly and not have a part be assembled by the middle contact pad. Three binding sites were again covered with solder while the other three were masked. Masking is only necessary because the solder is being applied in bulk rather than through a printing process. **Figure 6** shows the process.

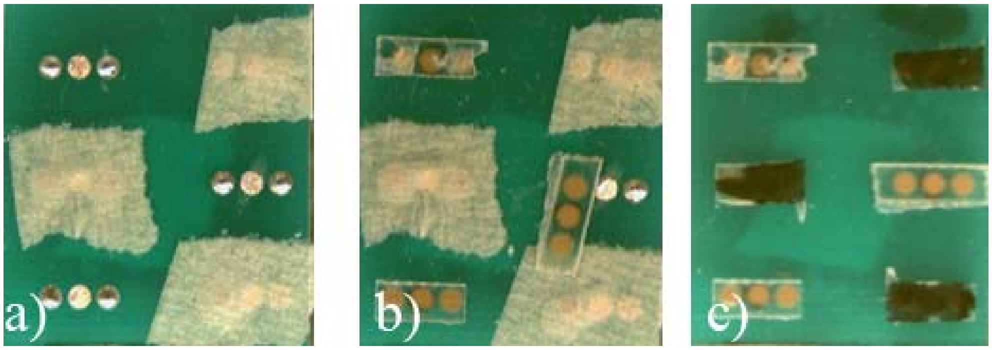

Figure 6 a) Initial substrate with solder applied, b) Assembly of bare parts. One part not completely assembled, c) Black parts assembled and final bare part assembled

Multiple part types can be assembled through a series of process steps. After the assembly is complete, it can be transferred to a second substrate and the process repeated to build more complex systems. This process is demonstrated in the section entitled "Experimental Demonstration".

<u>Part Orientation Control</u>

Using an array of circles as a bonding interface does not permit angular orientation of parts that only contact a single pad, but larger parts are orientated by their contact with multiple pads. The simple interface is also prone to many incorrect assembly configurations. **Figure 7** shows a test assembly in which parts have assembled incorrectly. While these incorrect assembly positions are stable, the bonds are not as strong as the correctly assembled components. Therefore, controlled vibration can remove the incorrectly assembled components while leaving the correctly assembled components in place.

The maximum force a bond can resist is dependent on the direction of the applied force as well as the assembled position. The direction of the vibrations can also be controlled to selectively remove or correct misassembled components.

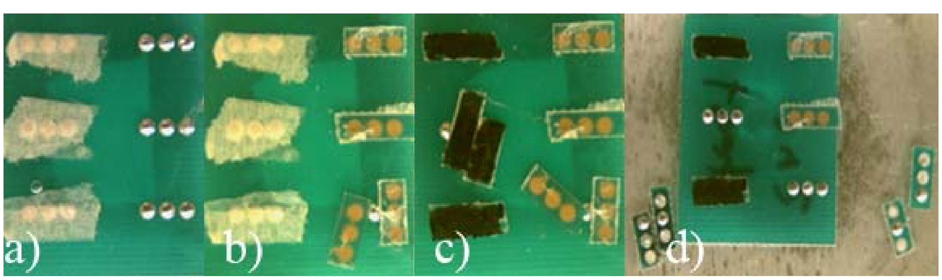

Figure 7 a) Initial substrate with solder, three binding sites masked, b) bare parts assembled with error, c) black parts assembled with error, d) after more intense agitation; incorrectly assembled parts are removed from substrate

A test was performed to show the incorrect assembly and removal of incorrect parts. The original sized parts (3mm by 8mm by 0.7mm) were assembled to a substrate with six binding sites with each of the binding sites having three contact pads as shown in **Figure 7**. As can be seen, some parts were assembled incorrectly. They were removed by striking the side of the substrate against the beaker. The resulting in-plane force dislodges the incorrectly assembled parts. Movement normal to the substrate plane was not sufficient to remove the parts due to the higher bond strength normal to the plane.

<u>Reusable Substrate</u>

The assembled components can be removed from the assembly tool by dissolving the liquid bond through submersion in an appropriate solvent. The part-tool bond may also be broken by formation of a stronger bond between the part and substrate as by bonding with a higher melting point material so that one bond is solid while the other is liquid. In the demonstrations, parts were removed from the assembly template by bonding to the final substrate with a cyanacrolate adhesive. The sample is then reheated to melt the solder. The solder bond is then easily broken while the adhesive bond remains intact. This technique is seen in the demonstration assembly below.

This approach integrates several mature technologies and can be readily implemented. In the following section, a demonstration is done of the concept using an alternative method of selectively applying the liquid.

APPLICATION: MICROTHERMOELECTRICS

Thermoelectric materials can pump heat when they carry electricity. This effect can be used to generate electricity from a temperature gradient or to actively cool without the complexity of a mechanical refrigeration system. They are widely used in compact coolers for consumers and advanced instrumentation. They are also used for power generation in space and increasingly on earth. One area of particular interest is in cooling local hot spots on electronics. However, the efficiency of current thin film methods is undermined by interface losses. [23]A self-assembled thermoelectric system could be used to locally cool electronic hot spots and be integrated into other products to provide localized cooling as necessary.

To form a thermoelectric system, n-type and p-type thermoelectric material must be arranged electrically in series but thermally in parallel. This typically requires four materials: n-type thermoelectric, p-type thermoelectric, electrical conductor, and thermally conductive electrical insulator. The integration of multiple materials and geometries required to form a thermoelectric generator makes this a challenging problem for self-assembly.

The basic process of assembling a thermoelectric cooler is illustrated below. Non-functional printed-circuit board components are used to self-assembly a multi-layer structure with the connectivity of a thermoelectric cooler. A typical thermoelectric side view is shown in **Figure 8**. Picture is shown with n-type thermoelectric, p-type thermoelectric, and metal interconnects. Not shown is the electrical insulation on the top and bottom.

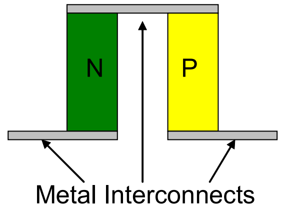

Figure 8 Side view of basic thermoelectric cell. Most thermoelectric applications require the formation of many thermoelectric cells. Most applications require an additional electrical insulator on the top and bottom to prevent electrical shorts. This insulator must have a large thermal conductivity to maximize performance.

EXPERIMENTAL DEMONSTRATION

Custom printed circuit boards (PCB) were manufactured by Pad2Pad and then cut using a CNC mill to create the parts and substrates for test assemblies. The parts were designed to have the dimensions of 3mm by 8mm by 0.7mm and have three contact pads on each part. The demonstration was done in a 40 ml beaker with a diameter of 42mm. The substrate was immersed in water made acidic (pH=1) by the addition of sulfuric acid. This prevents solder oxidation. The water with acid was kept at a temperature of 60°C to allow the low melting point solder (mp=47°C, Small Parts Catalog) remain molten.

The goal of the demonstration was to show that a multilayer assembly can be done using self assembly. This process will be used to assemble a functional thermoelectric module. The self-assembly substrate measures 8mm by 10mm by 0.7mm. The parts used measured 3mm by 3mm by 0.7mm and each had one contact pad. First the self-assembly substrate was immersed in the acidic water to apply the solder to the contact pads. The solder was applied to the contact pads using a pipette which allowed for a thin film of solder over each contact pad.

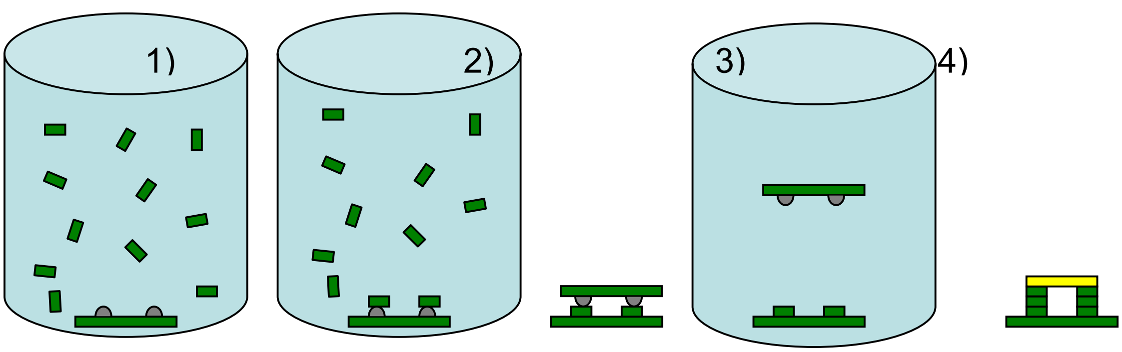

Figure 9 Assembly Process. 1) Solder is applied to self-assembly substrate and parts are put into beaker. 2) Manual stirring and agitation is then applied to assemble the parts onto the substrate. 3) Substrate is taken out of water and glued to final substrate. 4) Once glue is dry, assembled component is placed into beaker which allows the subassembly substrate to release the final substrate. 5) This process is repeated until the desired amount of layers is achieved.

After the solder has been applied to the self-assembly substrate, the parts were added to the beaker. Manual agitation and stirring was applied to assemble the parts to the self-assembly substrate. Once assembled, a part remains stable under continued agitation and when the substrate is turned upside down. The self-assembly substrate was then removed from the heated water and the solder allowed to solidify. After this, cyanacrolate adhesive was applied to the back of the four parts and then laid on top of the final substrate. Once the adhesive cured, the assembled pieces were put back into the heated water so the self-assembly substrate could be removed and the process was repeated to form the desired number of layers. **Figure 9** illustrates the process steps.

Three layers were assembled this way. A bridge across two of the stacked parts was shown to illustrate the connectivity typical of a thermoelectric cooler. To form the bridge, solder was applied to just 2 of the four self-assembly pads on the substrate. **Figure 10** shows the layers assembled. The orientation of the parts was not consistent because the parts only had one contact pad and no alignment mechanisms were present. Mechanisms are available for correcting this problem.

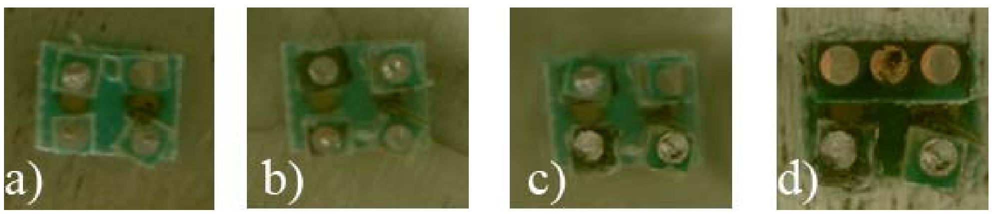

Figure 10 a) First layer, b) Second layer, c) Third layer, d) Final assembly with electrode across two of the parts.

The final assembly has similar structure as a thermoelectric cooler. **Figure 11** shows the side view of the initial substrate and the final substrate.

Figure 11 Self-assembly substrate and final substrate after completion of self-assembly process.

FUTURE WORK

In the broadest sense, SFF processes are flexible assembly processes. They assemble powder particles, monomers, and drops to form an infinite variety of products. The range of flexibility in these assembly processes is remarkable. However, they primarily assemble repeated identical units that are not sensitive to their geometric orientation. In contrast, mechanical assembly typically combines multiple parts of different materials and geometry. Generally, these components must be positioned in a specific orientation and often with significant limits on the acceptable assembly sequences. Thus, SFF processes are not directly applicable to flexible integration.

In the future, the geometric flexibility of SFF processes could be combined with a computer-controlled assembly process discussed here. Such a process would be uniquely capable of building functional components that could not be produced by traditional manufacturing methods. Such a system for the integration of thermoelectric materials is illustrated in **Figure 12**.

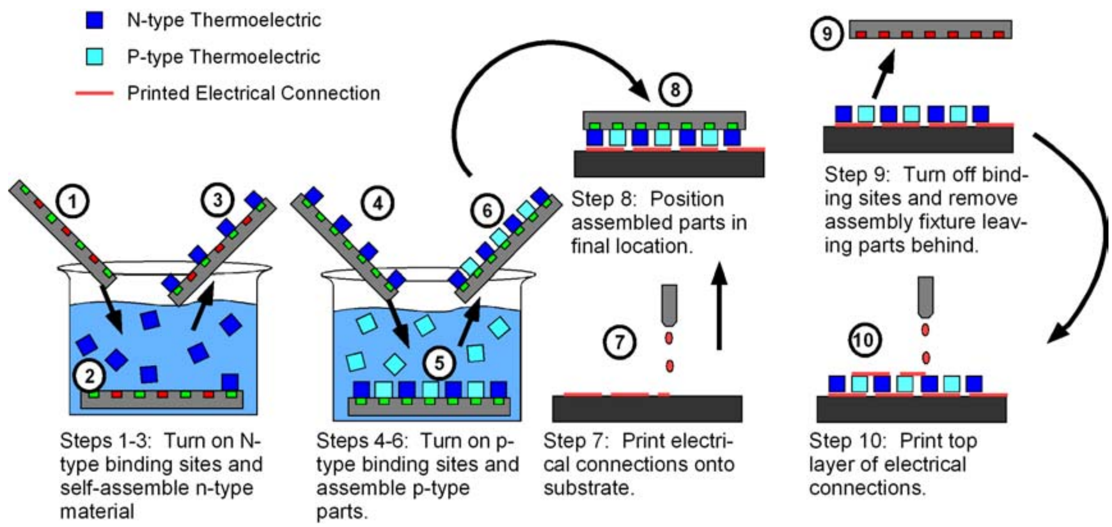

Figure 12 Illustration of MFI process integrated with 3D Printing to create a thermoelectric system.

This ability to automatically and flexibly integrate microscale components into SFF processes, would overcome many of the materials limitations of SFF. These integrated processes would be capable of creating unique products that would be impossible by traditional approaches.

CONCLUSIONS

Previous microscale system integration have been limited by the lack of effective methods for combining parts and materials produced by incompatible processes. This work addresses the concept of a flexible integration system that could integrate multiple part types under computer control to create a microscale freeform integration (MFI) system. Self-assembly is considered as a means of building the system. Analysis of current published self-assembly results shows that existing systems are not capable of these complex processes. However, a method is proposed which addresses one of the basic limitations—spatial and temporal assembly control. This method is demonstrated using simple printed circuit board components to replicate the basic assembly process of a thermoelectric cooler.

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