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**FABRICATION OF CONFORMAL ULTRASOUND TRANSDUCER ARRAYS AND  
HORNS BASED ON MULTI-AXIS CNC ACCUMULATION**

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Ultrasound Transducer, CNC Accumulation.

**ABSTRACT**

Ultrasonic imaging is an important medical imaging technique. It uses ultrasound over 20K Hz to detect and visualize muscles, tendons, and many internal organs. Previous studies have shown that an improved acoustic performance can be achieved by conformal ultrasound transducer arrays and horns that can wrap conformably around curved surfaces. To address challenges in fabricating such curved ultrasound transducer arrays and horns, we investigate the possibility of using a newly developed additive manufacturing (AM) process named CNC accumulation. In such an AM process, an accumulation tool can have multi-axis motion, which is beneficial for building conformal ultrasound transducer arrays and horns on a curved surface. To address different resolution requirements, we illustrate the use of multiple accumulation tools that can have different curing sizes and power in the fabrication of a single component. The tool path planning methods for any given cylindrical and spherical surfaces have been discussed. Based on the developed prototype system,

various test cases have been performed. The experimental results have illustrated the capability of the process and its potential use in the fabrication of conformal ultrasound transducer arrays and horns. The current limitations and future development have also been discussed.

**1 INTRODUCTION**

Ultrasonic imaging is an important medical imaging technique. Since ultrasound poses no known risks to patients, the technology has become one of the most widely used diagnostic tools in modern medicine [1]. To send an ultrasound to detect and visualize muscles, tendons, and many internal organs, the ultrasound transducer array in the probe is generally made of a piezoelectric material such as lead zirconate titanate (PZT). The ultrasound transducer array can also have various shapes, such as 1-3 ceramic/polymer composites as shown in Figure 1.(c). In the design and manufacturing of ultrasound transducers, a matching layer is almost always used due to the large acoustic mismatch between the ceramic material and the tissues of the human body. The use of a matching layer could enhance the performance of the devices due to the better coupling between the two media. A novel design of impedance matching layers that consists of an array of micro-horns sandwiched between two solid plates is shown in Figure 1.(d)

[2]. Such micro-horn array can have a variety of cross sections. Hence, by tailoring the various features of the horn, a related transducer can have near perfect matching to a given acoustic load and the theoretical power transmission efficiencies can achieve 90% or greater with very large bandwidths.

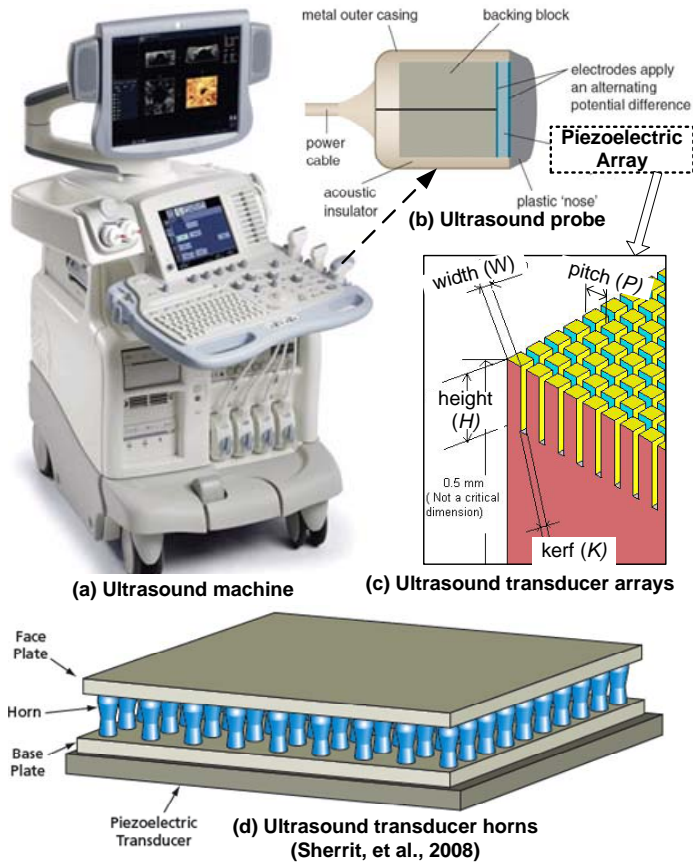


Figure 1: Ultrasound transducer arrays and horns.

### 1.1 Conformal Ultrasound Transducer Arrays and Horns

Recent developments on ultrasonic imaging have focused on improving its image resolution. There are many applications for such high-resolution imaging systems such as thickness measurements of the layers of skin tumors and eye tumor examination [1]. An effective way to obtain better lateral resolution is to use a higher frequency. The design and manufacturing of high frequency (over 20 MHz) ultrasound transducer array have been extensively studied. Another effective way to obtain better lateral resolution at a certain axial distance is to take advantage of acoustic focusing. That is, instead of based on a planar surface, focused dome-shaped-diaphragm transducers can be designed and manufactured with a readily adjustable focal distance to the aperture dimension (refer to Figure 2.b) [3, 4]. For other applications such as an endoscope or a catheter, the distal end is inserted into the body to get the transducer array close to the object. Hence, it is general desired to have a dispersed dome-shaped-diaphragm transducers to get a wider view of surrounding objects (refer to Figure 2.c). In addition to dome-shape, conformal ultrasound arrays have also been used in non-destructive testing and

thermal therapy to inspect irregular surfaces and complex geometries on components [5].

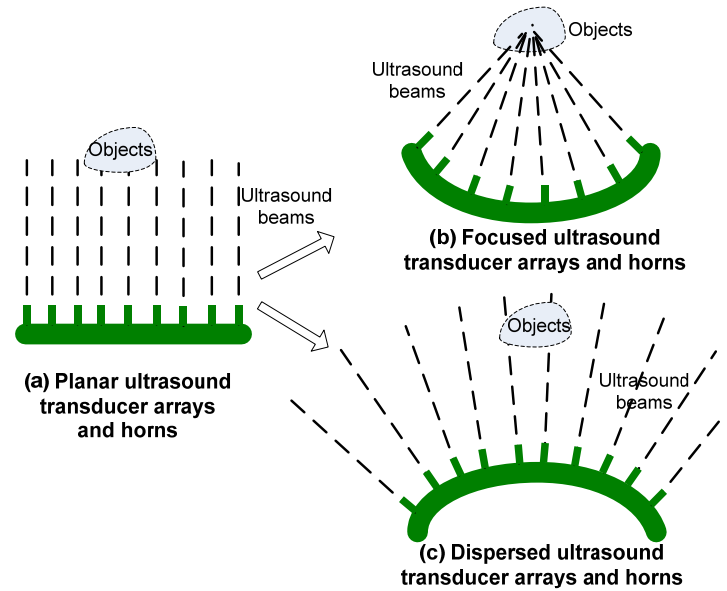


Figure 2: Conformal ultrasound transducer arrays and horns with curved surface.

Even though curving the arrays and horns is desirable in many situations for better scanning of ultrasound beams, the fabrication of such arrays and horns has been shown to be challenging. The established piezocomposites fabrication techniques such as dice-and-fill, laser dicing, and substrate spin coating are all developed based on a flat substrate. Even though fabrication techniques such as bending and compression have been developed before [4], it is generally difficult to achieve a wide range of curvature and also to control the fabricated arrays and horns to achieve consistent shape and material properties.

Therefore, the focus of the paper is to investigate the feasibility of using an additive manufacturing process for the fabrication of ultrasound transducer arrays and horns on a given curved surface. Such a manufacturing process will pave the way for further development of flexible conformable ultrasound transducers for a wide variety of applications such as the diagnosis of soft and hard tissue injuries.

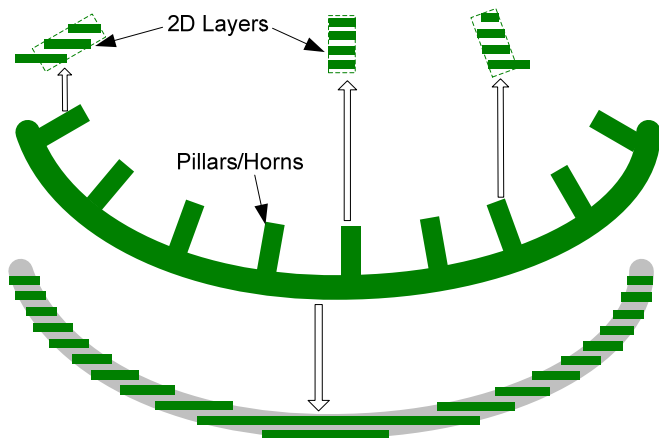
### 1.2 Layer-based Additive Manufacturing and Its Limitations

Layer-based additive manufacturing (AM) processes can fabricate parts directly from computer-aided design CAD models. During the last twenty-five years, many novel AM processes such as Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) have been successfully commercialized. Recent advances in material, process and machine development have enabled AM processes evolving from prototyping usage (Rapid Prototyping) to product manufacturing (Rapid Manufacturing) [6].

Several AM processes have been used before to make piezocomposites parts with intricate design. For example, Fused Deposition of Ceramics (FDC) can directly fabricate piezoceramics parts from CAD models [7]. Another AM

process that has been used in fabricating piezoceramics is *Stereolithography* [8, 9]. Complex ceramic objects can be built by using UV-curable suspensions of powder in acrylate monomers as the solution. To get a high-resolution structure, a highly focused laser beam is used to scan over the ceramic suspensions and induce a photo-polymerization process. Accordingly the rheological and photochemical properties of ceramic suspensions have been investigated.

Although the layer-based AM processes have been used in fabricating various complex shapes, such a layer-based approach could be problematic for the fabrication of ultrasound transducer arrays and horns on a curved surface. For example, as shown in Figure 3, several pillars or horns in various orientations are sliced into two-dimensional (2D) layers that are stacking together. Due to the small thickness that is usually required in ultrasound transducers ( $\ll 0.5\text{mm}$ ), the size and shape of the fabricated arrays and horns will be hard to control by using such an approach. Hence the achievable material property of the pillars and horns will be significantly affected by their building orientations. In addition, issues such as layer overcuring in Z axis and support requirement for extruding 2D layers will pose severe limitation on the surface curvature that can be built by the layer-based additive manufacturing processes.



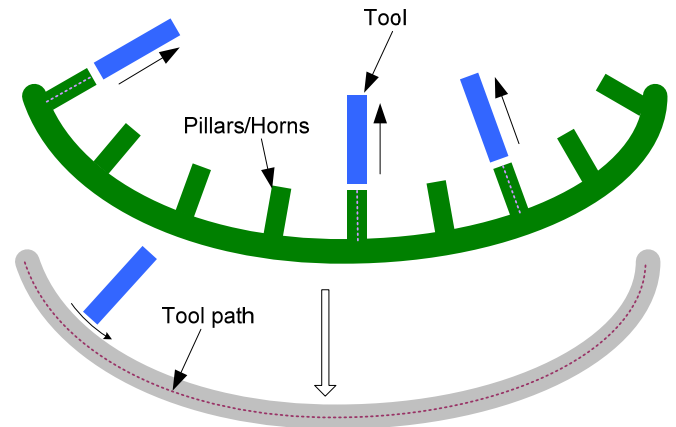
**Figure 3: Conformal ultrasound transducer arrays and horns with curved surface.**

To address such problems, we investigated the use of a non-layer-based additive manufacturing process named Computer Numerically Controlled (CNC) accumulation for the fabrication of ultrasound transducer arrays and horns on a curved surface. The remainder of the paper is organized as follows. The CNC accumulation process is first discussed in Section 2 with our previous work. The use of multiple accumulation tools for the fabrication of features with different resolution is then presented in Section 3. Based on them, the multi-axis tool path planning for cylindrical and spherical surfaces is discussed in section 4. The experimental test based on a conformal ultrasound transducer array design is presented in Section 5. We also discuss the material limitation in the section. Finally, Section 6 concludes the paper with a brief discussion on future work.

## 2 OVERVIEW OF MULTI-AXIS CNC ACCUMULATION

### 2.1 Process Description

As discussed in Section 1, the layer-based additive manufacturing processes have intrinsic limitations on fabricating conformal ultrasound transducer arrays or horns on a curved surface. Some identified limitations include (1) the inconsistent material properties among various building orientations; (2) the coarse surface quality and poor bonding for the inclined pillars/horns especially for those with big inclined angle; and (3) the low efficiency and high cost due to the requirement on building supports. Instead of the layer-based approach, a more ideal way of building the conformal ultrasound transducer arrays and horns is to move a suitable accumulation tool along the orientation of the related pillar/horn as shown in Figure 4.



**Figure 4: A non-layer based approach for building ultrasound transducer arrays and horns on a curved surface.**

A non-layer-based additive manufacturing process named CNC accumulation has been developed to achieve such motions [10]. Similar to the SLA process, the developed CNC accumulation process is based on ultraviolet (UV) curable resin. However, different from the SLA process, the curing tool in the CNC accumulation process is kept merging under the liquid resin. Hence the tool is capable of curing resin in various orientations.

A related problem by allowing the tool to directly contact liquid resin is that the newly cured resin may be attached to the curing tool instead of the base or the previously built part. We address the problem by studying the attaching forces related to the cured resin portion that are constrained between the curing tool and the base or the previously built part. It is found that the process can always be successful if: (1) certain type of coating (e.g. Teflon film) are added on the tip of the curing tool to reduce the attaching force between the cured resin and the tool; and (2) adequate over curing is ensured such that the attaching force between the cured resin and the base or the previously built part is sufficiently large. Hence the newly cured resin portion will always attach to the base or the previously built part to ensure the building process is successful.

Similar to the cutting tools used in the multi-axis CNC machining process, the accumulation tools used in the CNC

accumulation process can have multi-axis motions. Such multi-axis motions are critical to address the fabrication challenges that are posed by conformal ultrasound transducer arrays and horns. In comparison, 3D geometry is converted into 2D layers in the layer-based AM processes. Hence the allowable motions in most layer-based AM systems are translations in X, Y, and Z axes, which are more limited on addressing the fabrication challenges of conformal ultrasound transducer arrays and horns.

## 2.2 Process Principle and Our Previous Work

We studied the relations between the cured resin including its shape and sizes related to the light energy (i.e. exposure time and scanning speed) [10]. The experimental results showed that the curing depth  $C_d$  is proportional to the logarithm of the exposure energy, which conforms well to curing equation  $C_d = D_p \ln(E_{max} / E_c)$ . We also investigated the curing shape for line cross section, which follows the parabolic equation.

We also studied the attaching forces in the CNC accumulation process. Assume  $F_{Base}$  is the attaching force between the newly cured resin portion and the previously built part, and  $F_{Tool}$  is the attaching force between the newly cured resin portion and the curing tool. A proper gap needs to be maintained to ensure  $F_{Base} > F_{Tool}$ . The gap and the bonding force are highly related to the curing energy. Based on the curing equations and design of experiment, the attaching force related to the gap and the exposure energy was modeled. As shown in Figure 5, critical time-gap states are identified as a set of points on a curve such that the cured resin can be safely detached from the tool for the time-gap states that fall in the shaded region. We also studied the relation between the attaching force and different types of materials. Some results are shown in Figure 6 and Figure 7. Among them, the best detaching performance can be achieved based on a combination of resin base and Teflon film.

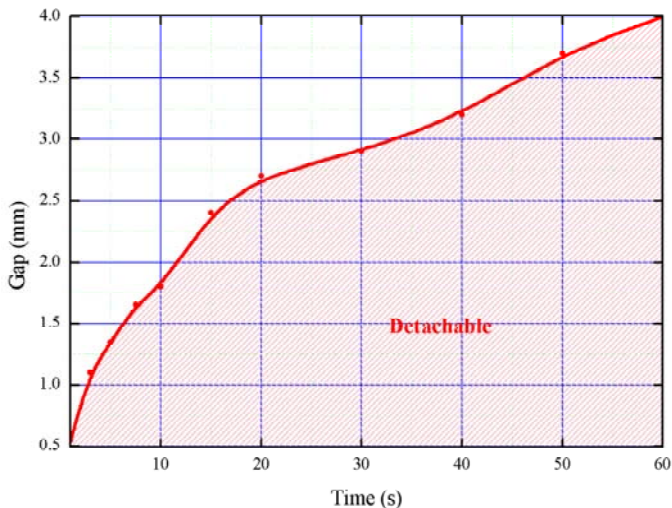


Figure 5: Detachable region with  $F_{Base} > F_{Tool}$ .

To illustrate the capability of the CNC accumulation process, a set of experiments on building various 2D/3D geometries have been performed. Figure 8 shows a 3D

geometry case, in which the characters “USC FIGHT ON” were added on the inner surface of a plastic bowl that was previously fabricated by an injection molding process.

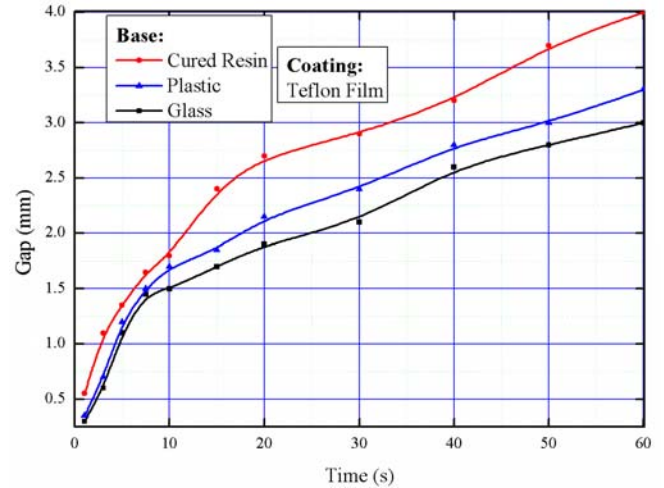


Figure 6: A comparison between different bases.

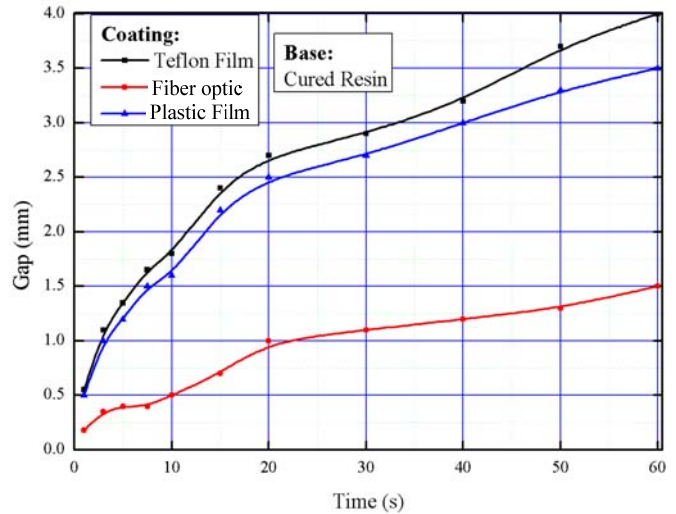


Figure 7: A comparison between different tool coatings.



Figure 8: Test of spatial characters [10].

We also illustrated some potential applications of the CNC accumulation process including part repairing and building around inserts [10]. Figure 9 shows a building around insert example, in which a metal spring is added between two laser-cut plastic pieces of a scissor. Notice three different types of materials are used in the fabricated scissor including steel, acrylic, and UV-curable resin.

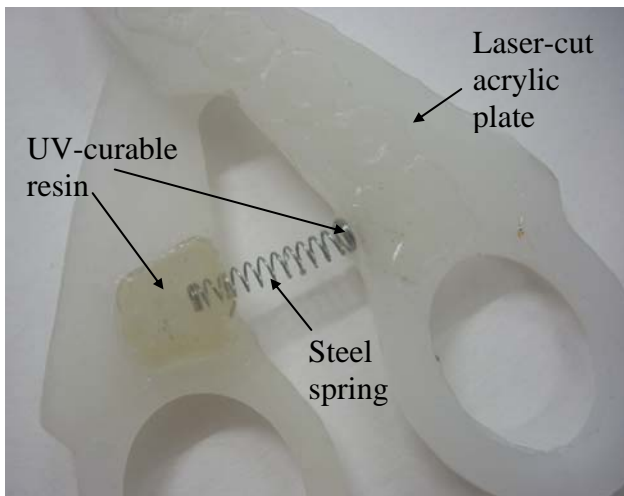


Figure 9: Test of building around insert [10].

### 3 MULTIPLE TOOLS IN CNC ACCUMULATION

#### 3.1 Tools with Different Sizes

In the CNC accumulation process, sufficient energy has to be provided to initiate the polymerization process. As extensively studied in the SLA process, a critical energy exposure threshold can be found for a given type of liquid resin. According to our previous study of the gap between the tool and the built part, a specific gap as well as the curing depth can be identified that are corresponding to the critical energy. For fixed curing depth and penetration depth, the curing width is proportional to the spot diameter. Thus, a highly focused UV spot can cure a feature with high resolution while a tool with a much larger UV spot size can cure a feature in a lower resolution with an increased building speed. Thus, similar to the CNC machining process, a wide variety of tools with different tool sizes can be used in the CNC accumulation process to achieve a good balance between the building resolution and speed. In our previous work [10], a single tool with a spot diameter around 2mm was used. In this study, we added a second tool with a spot diameter around 0.3mm (300  $\mu\text{m}$ ). In the paper we will call them *big tool* and *small tool* respectively. We demonstrate the use of multiple tools in building a single component.

A set of experiments have been conducted to model the curing behavior of the accumulation tools. Figure 10 shows the relation between curing depth and curing time for the point curing case (i.e. the curing tool is constantly moving in a direction that is aligned to the curing direction). As shown in the figure, the fitted curves are very close to the polymerization equation for both tools. However, for the same exposure time, the small tool will always cure deeper than the big tool. Results also indicate that the cured shape by using the small tool is thinner than the big tool.

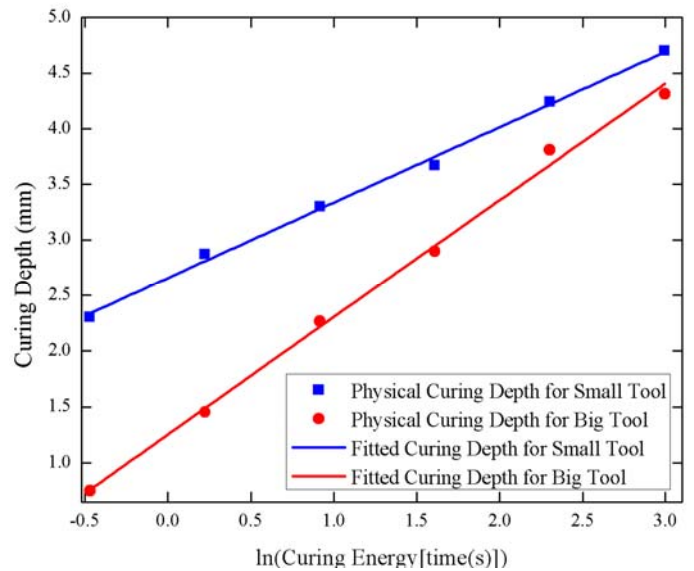


Figure 10: the relation between curing depth and exposure time by different tools for point curing.

Figure 11 shows the relation between the curing width and curing speed for the line curing case (i.e. the curing tool is constantly moving in a direction that is orthogonal to the curing direction). As shown in the figure, the big tool has much larger curing width than the small tool for the same motion speed. When the speed is fast enough, nothing will be cured by using the big tool while the small tool can still cure lines with a high resolution. Based on our experiments, the minimum line width (i.e. lateral resolution) that can be achieved by the small and big tools is around 0.2mm and 1.5mm respectively.

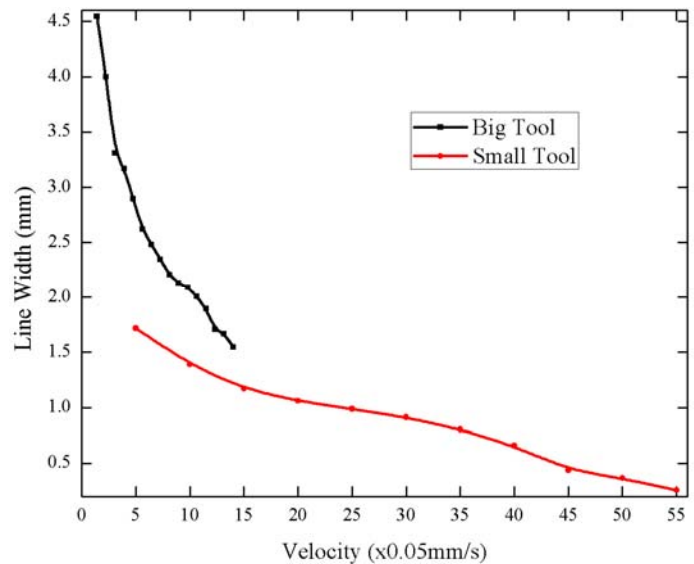
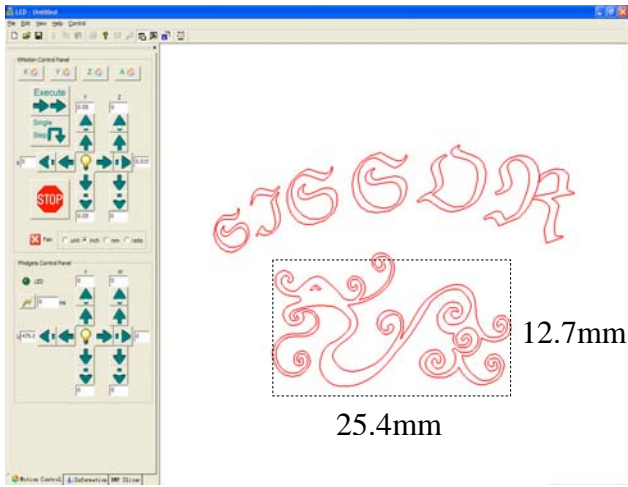


Figure 11: The relation between curing width and motion speed by different tools for line curing.

#### 3.2 Case Study

A test case based on a dragon pattern and several characters was performed to compare the building resolution of the two accumulation tools. The shape and related tool path of the dragon pattern and the characters are shown in Figure 12. The bounding box size of the dragon pattern is 25.4x12.7 mm.



**Figure 12: A test case on the dragon pattern and characters.**

The testing results are shown in **Figure 13**. A comparison of the cured dragon pattern between the big and small tools is shown in **Figure 13.(a)** and **Figure 13.(b)** respectively. A comparison of the cured characters between the big and small tools is shown in **Figure 13.(c)** and **Figure 13.(d)** respectively. The testing results illustrate that the small tool has a much higher building resolution, which is consistent to the developed models as shown in Figures 10 and 11.

#### 4 TOOL PATH PLANNING FOR FEATURES ON CYLINDRICAL AND SPHERICAL SURFACES

##### 4.1 Tool Motion and Building Process

To illustrate the good controllability of the CNC accumulation process in building features on curved surfaces, we will focus on cylindrical and spherical surfaces since they are two of the most common curved surfaces. The fabrication of dome-shaped diaphragm transducer arrays/horns on such surfaces will be studied. To achieve a particular  $f$ -number in the ultrasound transducer design, the cylindrical or spherical surfaces of a given dome-shaped diaphragm may have different curvatures and diameters. Hence the developed building process needs to be able to easily adjust its building parameters for the fabrication of the given surfaces.

As shown in 5-axis CNC machining, it is generally desired to plan the circular path by using pure rotation instead of the  $X$ - $Y$  interpolation in order to achieve a better lateral resolution and accuracy. Hence, for any given cylindrical and spherical surfaces, we can use 5-axis motions including three translations along  $X$ ,  $Y$ ,  $Z$  axis and two rotations  $A$  and  $B$  around  $Z$  and  $X$  axes respectively. The related 5-axis motion configuration is shown in Figure 14. In the configuration, rotation axis  $A$  is used for controlling the tools to scan around spherical or cylindrical surface. Rotation axis  $B$  is used to position the tool to the normal direction of the curved surface. Consequently, a good surface quality and material consistency can be achieved by using the process. To simplify the tool path planning, three constraints are added in the 5-axis motion configuration including: (1) the rotation centers  $O_1$  and  $O_2$  are aligned with the same height along  $Z$  axis; (2) the tool is coplanar with  $Z$  axis in  $X$ - $Z$  plane; and (3) the tool is pointing to the rotation center  $O_1$ .



(a) Dragon pattern built by the big tool



(b) Dragon pattern built by the small tool

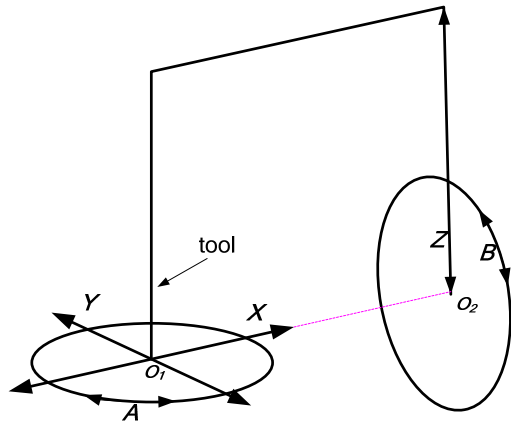


(c) Characters built by the big tool



(d) Characters built by the small tool

**Figure 13: Comparisons between the different tools for 2D dragon pattern and some characters.**



**Figure 14: A Schematic Illustration 5-axis Configuration.**

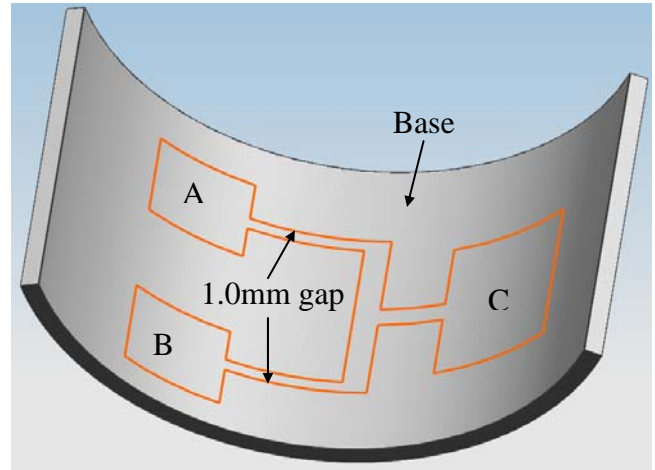
In an ultrasound transducer design, the pillars/horns usually require a higher building resolution while the base surface can be built with a much lower resolution. Consequently, accumulation tools with different sizes can be used in building them. In our study, we first use the big tool in building the base surface. After finishing the base surface, the small tool can then be used in building pillar/horn arrays on the surface. A detail description of the tool path planning for building pillar/horns on a spherical surface is given as follows.

1. Initialize the position of the big tool;
2. Rotate the tool (Rotation B) by  $\alpha$  to point the tool in the normal direction of the spherical surface;
3. Turn on the big tool;
4. Rotate the platform (Rotation A) by one full round;
5. Turn off the big tool;
6. Go to 2 if the based is not finished, otherwise go to 7;
7. Initialize the position of the small tool;
8. Rotate the tool (Rotation B) by  $\beta$  to point the tool in the normal direction of the spherical surface;
9. Rotate the platform (Rotation A) by  $\theta$  which decided by the distance between the adjacent pillars;
10. Turn on the small tool;
11. Move the small tool in a certain speed along the normal direction to the spherical surface (Y-Z translation);
12. Turn off the small tool if a certain height has been built for the pillar/horn;
13. Go to 10 if not all of the pillars/horns in the same Z level are finished; otherwise go to 9 if not all of the pillars/horns are finished.
14. Stop the building process when all the pillars/horns have been built.

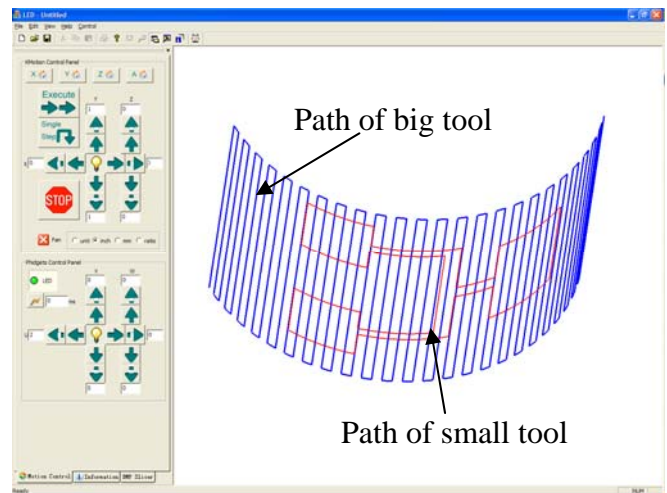
A similar process can be used in building pillars/horns on a cylindrical surface. Note the tool rotation B is independent with the Y-Z translations due to the three aforementioned constraints. Therefore no compensations are needed in Y-Z directions for a rotation B. Also the rotation A can achieve the desired motion on circular surface without any translational interpolation. Hence a higher resolution can be achieved by the building process.

## 4.2 Case Study

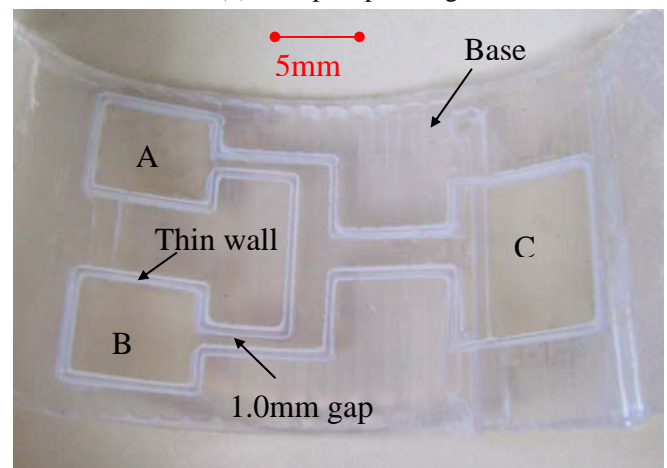
A test case of building fluidic channels on a cylindrical surface is performed to illustrate the discussed tool path planning based on the multi-axis CNC accumulation process. As shown in **Figure 15.a**, several fluidic chambers and channels are designed on a cylindrical surface. The main purpose of the design is to transport liquid from two chambers A and B into a mixing chamber C.



(a) CAD model



(b) Tool path planning



(c) Built physical model

**Figure 15: Fluid channels on a cylindrical surface.**

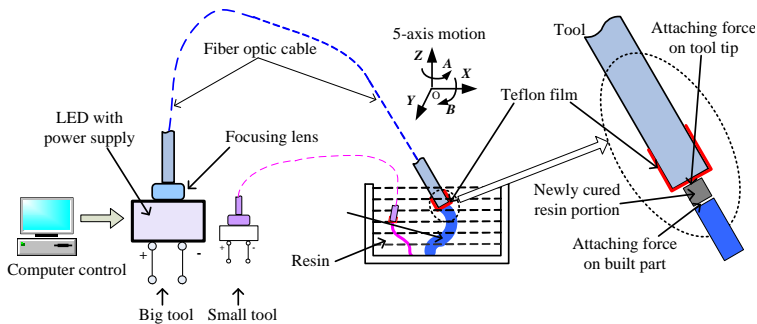
Since the cylindrical base is used for supporting the fluid channels, its uniform thickness is important while its lateral resolution is not. In comparison, the chambers and channels will define how liquid flows on the cylindrical surface. Consequently their resolution will determine the complexity of the fluidic system that can be achieved. In the test, we set the wall thickness at 0.5mm (or 500  $\mu\text{m}$ ) and the smallest gap of the channels at 1.0 mm. Accordingly the big tool is used in building the base surface while the small tool is used in building the fluidic chambers and channels. The planned tool paths are shown in **Figure 15.b**, in which the paths of the big and small tools are shown in blue and red colors respectively.

The building process on a cylindrical surface is very close to the one on a spherical surface as discussed in Section 4.1. The only difference is that the base surface and features are built by a combination of  $X$ - $Z$  translation,  $B$  rotation and  $Y$  translation. The built physical model is shown in **Figure 15.c**. The fine features of the walls and the coarse features of the base can be observed from the figure since they were built by the small and big tools respectively. All the fabricated features are conformed to the designed cylindrical surface.

## 5 EXPERIMENTS ON BUILDING PILLARS/HORNS ON A SPHERICAL SURFACE

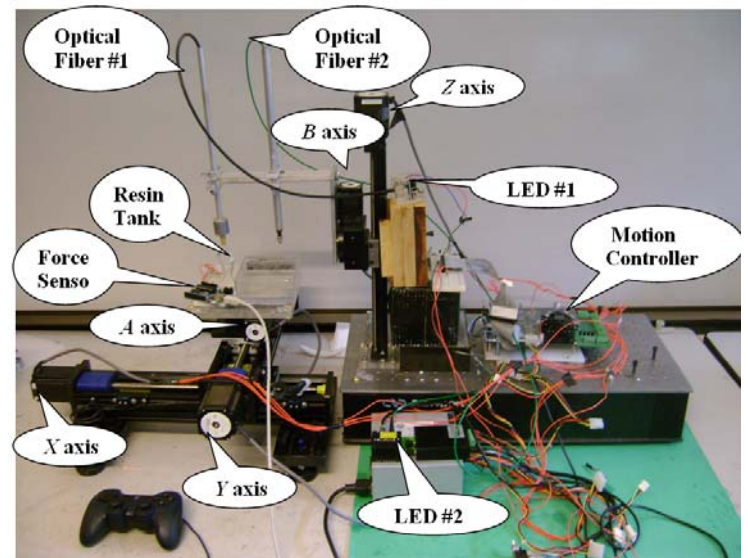
### 5.1 Experimental Setup

The multi-axis CNC accumulation is a layerless additive manufacturing process. A schematic illustration of the process is shown in **Figure 16**. Different from our previous work [10], two accumulation tools are used in this study to build features that have different resolutions.



**Figure 16: A schematic illustration of the CNC accumulation process based on multiple tools.**

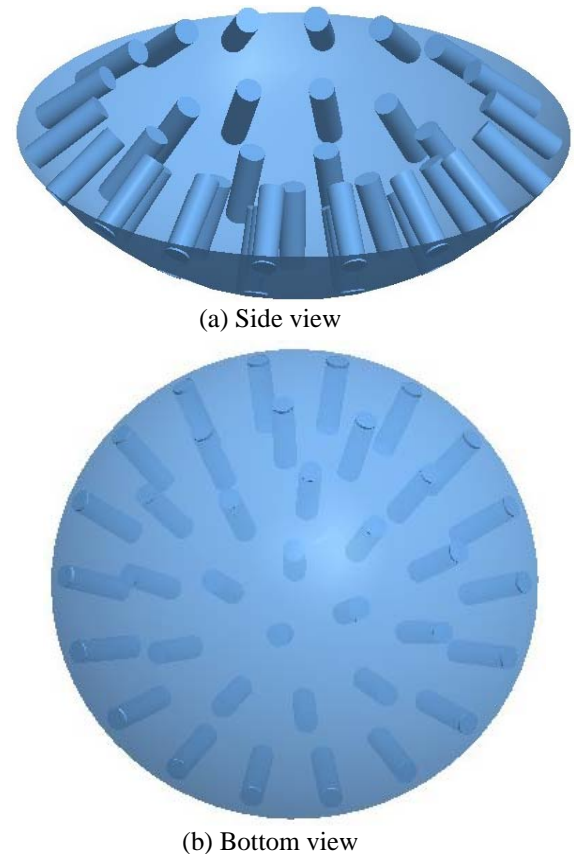
The hardware setup of our prototype system is shown in **Figure 17**. In the setup, the big tool is based on UV-LED #1 (NCSU033A from *Nichia*) and optical fiber #1 (NT38-954 from *Edmunds Optics*). A sapphire ball lenses (NT43-831 from *Edmunds Optics*) is used for focusing light on the optical fiber with a core size of 1.6 mm. The small tool is based on UV-LED #2 (FCS-0365-000 from *Mightex System*) and optical fiber #2 (FPC-0200-22-02SMA from *Mightex System*) with a core size of 0.2 mm. Based on our previous study, a Teflon film is applied on the tip of the tools as the coating media. A 5-axis motion system including  $X$ ,  $Y$ ,  $Z$  translations and  $A$ ,  $B$  rotations is designed to allow the light guides provide UV light in various directions. The system also includes other components such as force sensors for providing contact feedbacks.



**Figure 17: The prototype system of the multi-tool based CNC accumulation process.**

### 5.2 A Test Case Based on a Spherical Surface

A focused dome-shaped-diaphragm as shown in **Figure 18** was designed to demonstrate the feasibility and effectiveness of the multi-tool based CNC accumulation process in fabricating conformal ultrasound transducer pillars/horns.



**Figure 18: A focused dome-shaped-diaphragm transducer.**

Based on the given performance requirements, the parametric design of the dome-shaped-diaphragm can be easily changed by adjusting the following design parameters:

- $R$  : radius of the spherical base;
- $a$  : diameter of the pillar;
- $l$  : height of the pillar;
- $\theta$  : the angle between two neighboring pillars;
- $d$  : the distance between two neighboring pillars;
- $\theta_i$  : the angle between the bottom pillar with the pillars in the  $i^{\text{th}}$  round;
- $\beta_i$  : the angle that the plane should rotate to make each pillar in the  $i^{\text{th}}$  round;
- $N$  : the number of rounds.

Some design constraints may exist due to the hardware setup. For example, suppose  $D$  is the diameter of the tool head. As shown in Figure 19, the tool head may collide the neighboring pillars if  $\theta$  is too small. Hence the minimum value of  $\theta$  can be derived based on  $D$ ,  $a$ ,  $R$  and  $l$ . As another example, suppose  $\Psi$  is the maximum rotation angle that the tool head can achieve. Accordingly the maximum number of rounds ( $N$ ) will be limited by  $\Psi$ . A list of the constraints on the design parameters are given as follows.

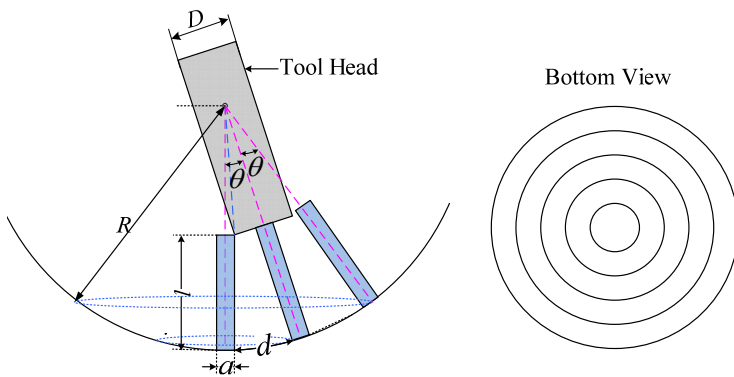
$$(1) \theta \geq \tan^{-1}\left(\frac{a}{2(R-l)}\right) + \sin^{-1}\left(\frac{2D}{\sqrt{a^2 + 4(R-l)^2}}\right)$$

$$(2) \theta_i = i * \theta = i * d / R$$

$$(3) n_i = \lfloor 2\pi R * \sin(\alpha_i) / d \rfloor$$

$$(4) \beta_i = 2\pi / n_i$$

$$(5) N \leq \lfloor \Psi / \theta \rfloor$$



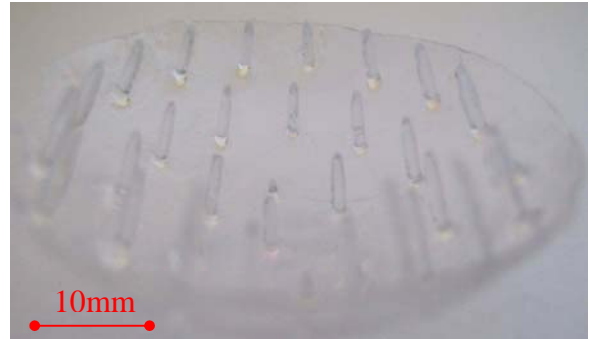
**Figure 19: Constraints on design parameters.**

As discussed in Section 4, tools with various spot size and light intensity can be used in building features that have different resolution requirements. In our test on building focused dome-shaped-diaphragm, the big tool is used in building the spherical base surface while the small tool is used

in building the pillar array. An illustration of related tool path is shown in **Figure 4**.

### 5.3 Testing Results

A fabricated physical model by using the developed prototype system is shown in **Figure 20**. The diameter of the fabricated pillars is around 1.2 mm. As shown in Section 3.1, the diameter of a pillar can be controlled by using different moving velocity of the tool. Hence non-uniform diameters along a pillar/horn can be achieved by dynamically adjusting the tool's moving velocity, which has also been demonstrated in the built model. Such non-uniform diameters of the built pillars may be important for some ultrasound transducer designs such as the one as shown in **Figure 1.d**.



(a) Side view



(b) Bottom view

**Figure 20: The built physical model of the focused dome-shaped-diaphragm transducer.**

## 6 DISCUSSIONS ON TECHNICAL CHALLENGES

### 6.1 Discussion on Material Extension

Our experimental results have demonstrated that a non-layer-based AM process is feasible and can be beneficial in fabricating conformal ultrasound transducer arrays and horns with consistent sizes on a cylindrical or spherical surface. However, our study only considers UV-curable photopolymer while the ultrasound transducer arrays are usually made by materials such as PZT ceramic.

There are numerous studies (e.g. [8, 9]) on using SLA process to fabricate ceramic components. The process is based on mixing the photopolymer with fine powders of ceramics into

paste material. We believe such an approach can be extended to the CNC accumulation process. That is, instead of using liquid resin, we can use a mixture of photopolymer and fine grain powders of desired materials including PZT ceramic. Accordingly the fabricated green parts (i.e. parts before heat treatment) will define the desired part geometry.

To achieve the required piezoelectric properties, an additional sintering process is required to burn out the polymer and decompose the organic compounds. During the sintering process, the PZT green-part will be converted into fully dense ceramics based on a series of processes including linear expansion of particles, solid-phase reaction, contraction of product, and grain growth. Such heat treatment procedure needs to be carefully designed to avoid cracking and lattice distortion, and maintain the required chemical ratio of PZT (i.e. the percent of Pb, Zr and Ti).

Another approach that can be used in transferring UV-curable photopolymer parts into PZT ceramic ones is rapid tooling. That is, the arrays and horns fabricated by the CNC accumulation process can be used as the tools or patterns for additional processes such as investment casting and injection molding. In rapid tooling, since the shape quality of the fabricated parts is defined by the fabricated tools or patterns, the CNC accumulation process is preferred which can fabricate arrays and horns on a curved surface with better surface finish and consistent dimension.

## 6.2 Discussion on Building Accuracy and Speed

Our experimental results have demonstrated that different tools can be used in fabricating features with different size and accuracy requirements. The feature sizes of ultrasound transducer arrays and horns are typically small (less than 250  $\mu\text{m}$ ). Hence the accumulation tool also needs to be small. This may affect the building speed. Similar to CNC machining, techniques such as using multiple tools can speed up the building speed. We are also investigating other technologies for alternative accumulation tools that can be dramatically faster.

## 7 CONCLUSION AND FUTURE WORK

Conformal ultrasound transducer arrays and horns that can wrap around curved surfaces are beneficial for the ultrasonic imaging technology. We presented an additive manufacturing process named CNC accumulation for the fabrication of such conformal arrays and horns. Accumulation tools in the CNC accumulation process can have multi-axis motion; hence it would enable the conformal arrays and horns to have accurate size and consistent material property. Similar to the CNC machining process, multiple accumulation tools with different curing sizes and power can be used in fabricating features with various resolution requirements. Based on the developed prototype system, we demonstrated the building processes for two common conformal shapes including cylindrical and spherical surfaces. The experimental results have illustrated the

capability of the CNC accumulation process and its potential use in fabricating conformal ultrasound transducer arrays and horns. Future technology challenges have also been discussed.

Considerable work remains to mature the developed process and the related prototype system. Some current work that we are investigating include: (1) performing experiments based on different paste materials; (2) developing accurate shape and size control; and (3) exploring new applications that are enabled by the CNC accumulation process.

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