Integration of Direct-Write (DW) and Ultrasonic Consolidation (UC) Technologies to Create Advanced Structures with Embedded Electrical Circuitry.

(Christopher J. Robinson, Brent Stucker: Utah State University, Amit J. Lopes, Ryan Wicker: University of Texas at El Paso, and Jeremy A. Palmer: Sandia National Laboratories)
Reviewed, accepted September 14, 2006

In many instances conductive traces are needed in small, compact and enclosed areas. However, with traditional manufacturing techniques, embedded electrical traces or antenna arrays have not been a possibility. By integrating Direct Write and Ultrasonic Consolidation technologies, electronic circuitry, antennas and other devices can be manufactured directly into a solid metal structure and subsequently completely enclosed. This can achieve a significant reduction in mass and volume of a complex electronic system without compromising performance.

Introduction

A common design driver for many industries and applications is the push to make products more compact and integrated. Additive manufacturing techniques are being used to create complex, compact integrated structures, thereby reducing cost, size, and mass. Ultrasonic Consolidation (UC) and Direct-Write (DW) are two types of additive fabrication techniques used to create integrated structures.

One application requiring small, integrated structures is small satellites. This paper overviews a recent study by the authors to, for the first time, integrate the technologies of UC and DW to create multifunctional panels that are relevant to the types of systems needed in a small satellite. Two panels were created to represent possible structural panel sections of a small satellite. One panel demonstrates the ability to embed electrical circuitry, connectors, switches, DW electrical traces, and other components. The second panel demonstrates the ability to use DW to apply a patch antenna on the surface of a UC panel with an embedded honeycomb core created using UC.

Ultrasonic Consolidation (UC)

Ultrasonic Consolidation is an additive manufacturing process which deposits metallic foils using ultrasonic energy, followed by a milling operation to create the desired cross-section. UC works by creating differential vibration between the substrate or previously deposited layers and a newly deposited layer using a sonotrode. This differential vibration results in plastic deformation and metallurgical bonding between clean metallic surfaces, which is discussed in more detail in a separate paper in these proceedings (Janaki Ram, 2006). UC is the only SFF technology which can create a solid metal part from engineering alloys at low temperatures, which enables the embedding of wiring, electronics, and other components without thermally destroying them. One important benefit of UC is that a build can be paused and left for essentially any amount of time and then restarted again with no adverse effects. In addition, the parts can be removed and set aside or used in another apparatus. This facilitates the combining of DW and UC without needing to integrate them into a single apparatus. However, for efficiency purposes, it would be possible to integrate a DW deposition head onto a UC apparatus for future work, which would eliminate the need to move the part between apparatuses.

The UC machine used for this work is a Solidica ***Formation***™ beta machine located at Utah State University (USU). This is the same technology used to make the Solidica Chorus sensor that won the Gold Award at the 2006 Sensors Expo. This sensor measures temperature, vibration, and three-dimensional acceleration, adds GPS/dead reckoning location data, and then transmits the data wirelessly to any ZigBee-compliant or 802.15.4 platform, while all electronics are embedded within a solid piece of aluminum (Solidica, 2006).

Direct-Write (DW)

Direct Write is the ability to write or print passive or active electronic components (conductors, insulators, batteries, capacitors, antennas, etc.) directly from a computer file without any tooling or masks. Many different direct write technologies have been developed over the recent years, following funding by the Defense Advanced Research Projects Agency (DARPA) (Church, 2000). These DARPA-funded projects included Matrix Assisted Pulsed Laser Evaporation (MAPLE), nScrypt 3De, Maskless Mesoscale Materials Deposition (M3D) and Direct Write Thermal Spraying. nScrypt and MicroPen are two examples of technologies which use liquid inks to create DW traces. In addition, these inks can also be extruded using simple extrusion devices. Ink is dispensed through a tip that is controlled by either a CNC head or other stage type controls; or it can also be dispensed by hand, depending on the apparatus. Many types of structures can be created using DW because traces can be drawn in three dimensions and vias can be created to step from one level to another in needed situations. Research in the area of new materials is ongoing, and as the number of useful materials increases so does the number of possibilities of this technology.

The DW apparatus used for this work is the 2405 Ultra Dispensing System (EFD Inc., East Providence, Rhode Island), shown in Figure 1, located at the University of Texas at El Paso (UTEP). The DW system consisted of an air pressure control console and a dispensing syringe and tip (with nozzle diameters down to 6 mils), which was connected to the console with a plastic hose. The console obtains an externally supplied inlet air pressure (up to 100 psi) and regulates the outlet pressure (from 0 – 5 psi), which was then supplied to the dispensing tip. The ink can be dispensed manually or controlled using LabVIEW® and stages integrated at UTEP to draw given circuit profiles. It may be adapted to dispense a variety of fluids including conductive inks and virtually any other fluid (Medina, 2005).

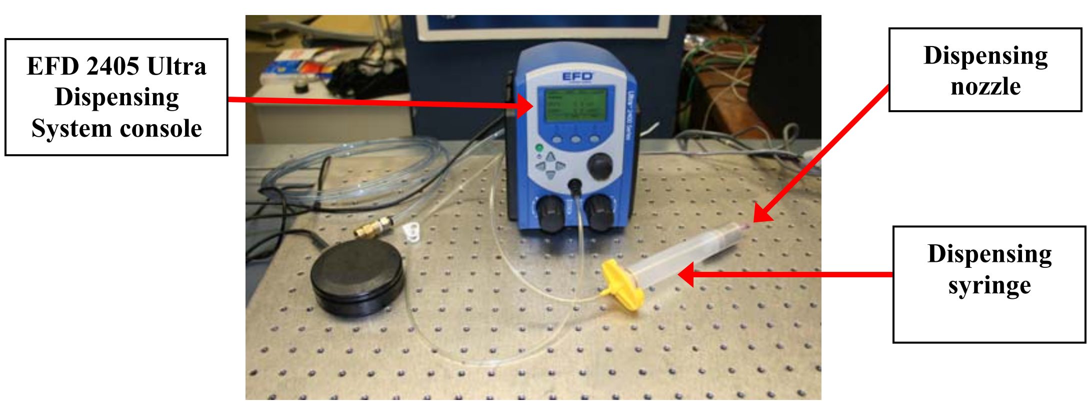

Figure 1: The DW 2405 Ultra Dispensing System, located at the University of Texas at El Paso

LED Panel Description

The first demonstration panel created using UC and DW is a 6” X 6” X ¾” honeycomb panel with solid aluminum outer walls and face sheets, and a solid network of aluminum to support embedded circuitry. Embedded in the structure is a common 9-pin space-rated connector, an LED and a mechanical on/off switch, all of which are connected with electrical traces drawn with conductive silver ink deposited using DW technology. A CAD model of this system is shown in Figure 2. While there are many different types of honeycomb structures and cores commercially available, a unique and custom honeycomb was created using UC, which has the added possibility of being able to embed components and circuitry directly into the honeycomb itself. As this demonstration panel had no specific structural constraints, the honeycomb was designed with an arbitrary wall thickness and height of 0.45 inches.

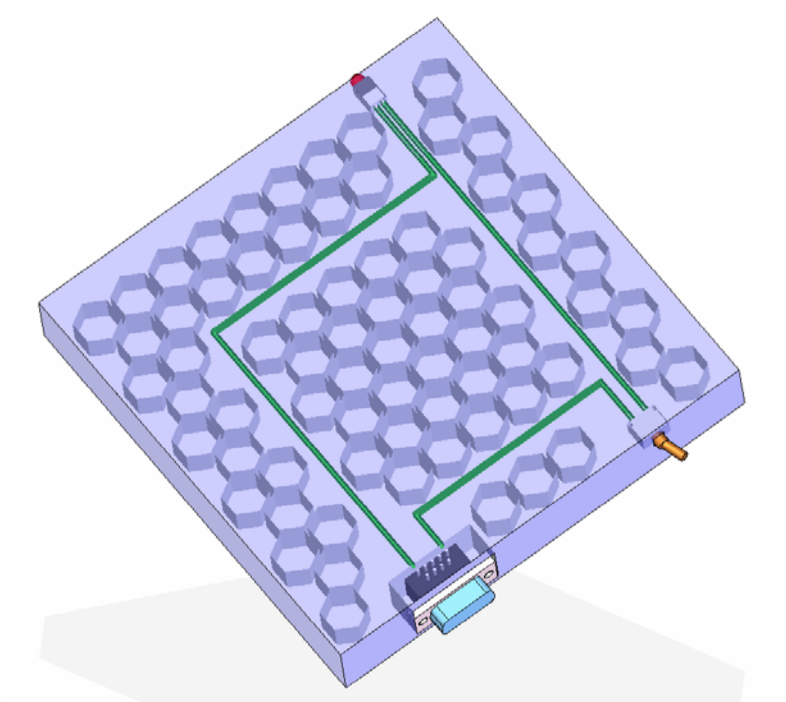

Figure 2: CAD model of an integrated structure built using UC and DW, shown with upper facesheet removed to illustrate the honeycomb network and embedded electrical traces.

Build Process for the LED Panel

Based on previous experience with embedding electronics in UC structures, the following process plan was used to create the LED demonstration panel. Al 3003 H18 tape was ultrasonically consolidated to a solid Al 3003 H18 substrate. The integrated CNC mill machined the geometry for the honeycomb, channels for the electrical traces, and pockets for embedding a space rated D-connector receptacle, a simple switch and an LED into the monolithic block that was formed from a combination of deposited Al and the Al substrate. The panel, attached to a larger substrate, after milling but prior to embedding of components is shown in Figure 3.

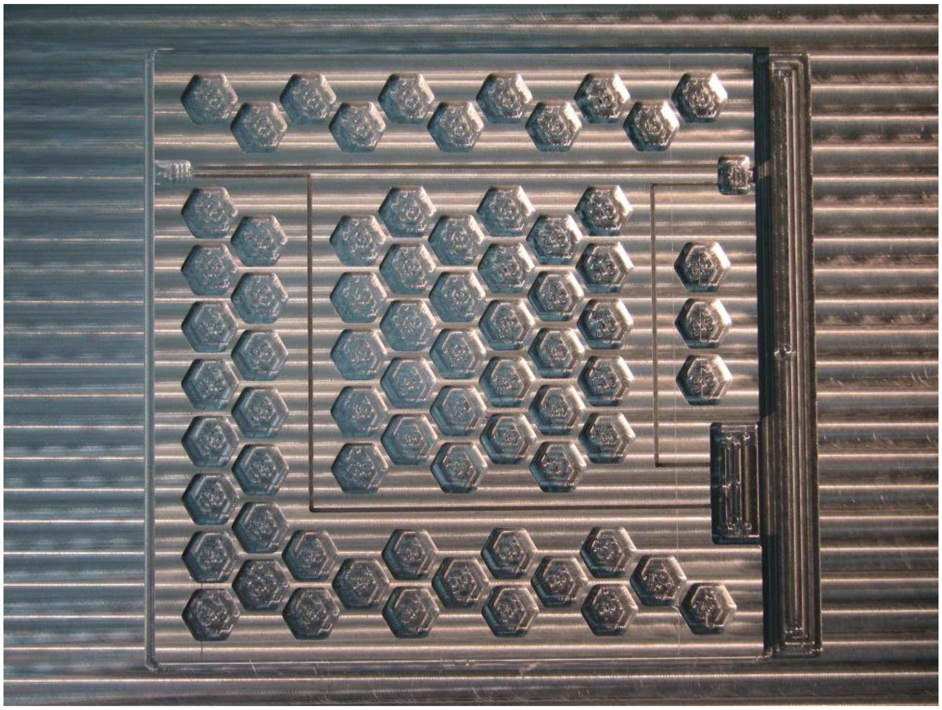

Figure 3: The LED panel after UC, but prior to component embedding, showing the honeycomb structure, pockets for electronic components, and channels for DW traces.

Following the creation of the basic panel structure, the various pre-manufactured components were potted into their respective pockets using Arctic Alumina thermal epoxy, which is both electrically non-conductive and non-capacitive. The demonstration panel and the connectors used were designed and selected so that all connections to pins and leads would be at the same height for easy accessibility for the DW tip. This was to minimize the number of times the panel had to be shipped between USU and UTEP. The channels for the conductive traces were then filled with the same epoxy. The channels were again milled with a smaller end mill so that a slot with insulator on three sides was created. At this point, the components were all checked to ensure operability and the panel was removed from the UC apparatus and taken to the DW apparatus.

At UTEP, DW traces were drawn to connect all parts of the system into one electrical circuit. The ink chosen for the traces was E1660-136 silver based ink. This ink was chosen for its properties of high conductivity, excellent wear resistance and very good flexibility.

In previous work at UTEP, an ink dispensing experiment was performed using several conductive inks on different substrates at a fixed dispensing pressure (4 psi), vertical gap (4 mils) and using a 6 mil dispensing tip. The parameters were chosen based on previous research done by Medina et al, and gave the most consistent interconnecting lines (Medina, 2005). Figure 4 summarizes the results of the ink dispensing experiments. The results indicate that the E 1660 silver conductive ink gave the lowest average resistivity after thermal cure on all the substrates as compared to the other inks. Thus the E 1660 ink was selected for making the electrical interconnects for this research. Future research will include experimentation with smaller dispensing tips to get the narrowest consistent DW interconnect line.

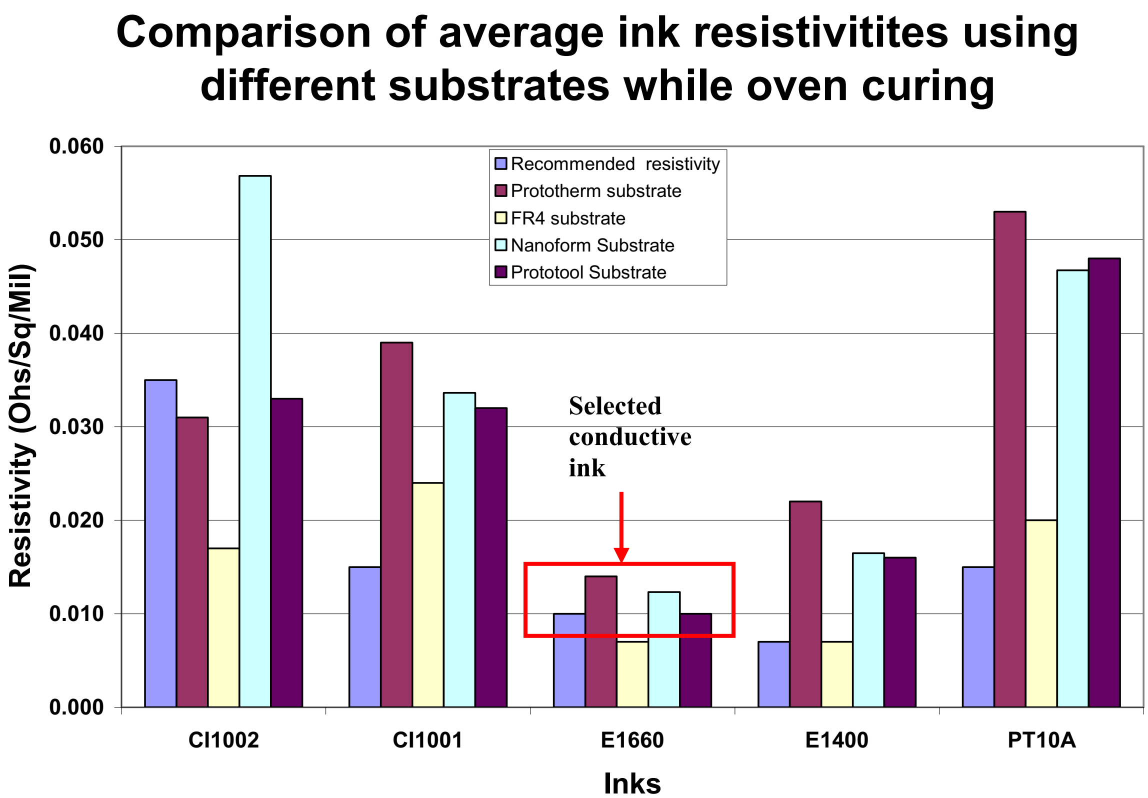

Figure 4: Resistivity comparison of different inks on a variety of substrates

The resulting circuit is powered through the connector by an external power source and controlled by the switch. A lit LED, when the switch is in the on position, indicates that the circuit is operating properly.

At USU, the DW traces were then covered with more insulator material. The panel was placed back in the UC apparatus and milled flat before the face sheet was deposited using UC, completely embedding the system into a panel that is solid aluminum on the outside with a connector, switch and LED protruding from around the edges, as seen in Figure 5. This panel, while low in mass, is relatively stiff because of the honeycomb structure embedded within.

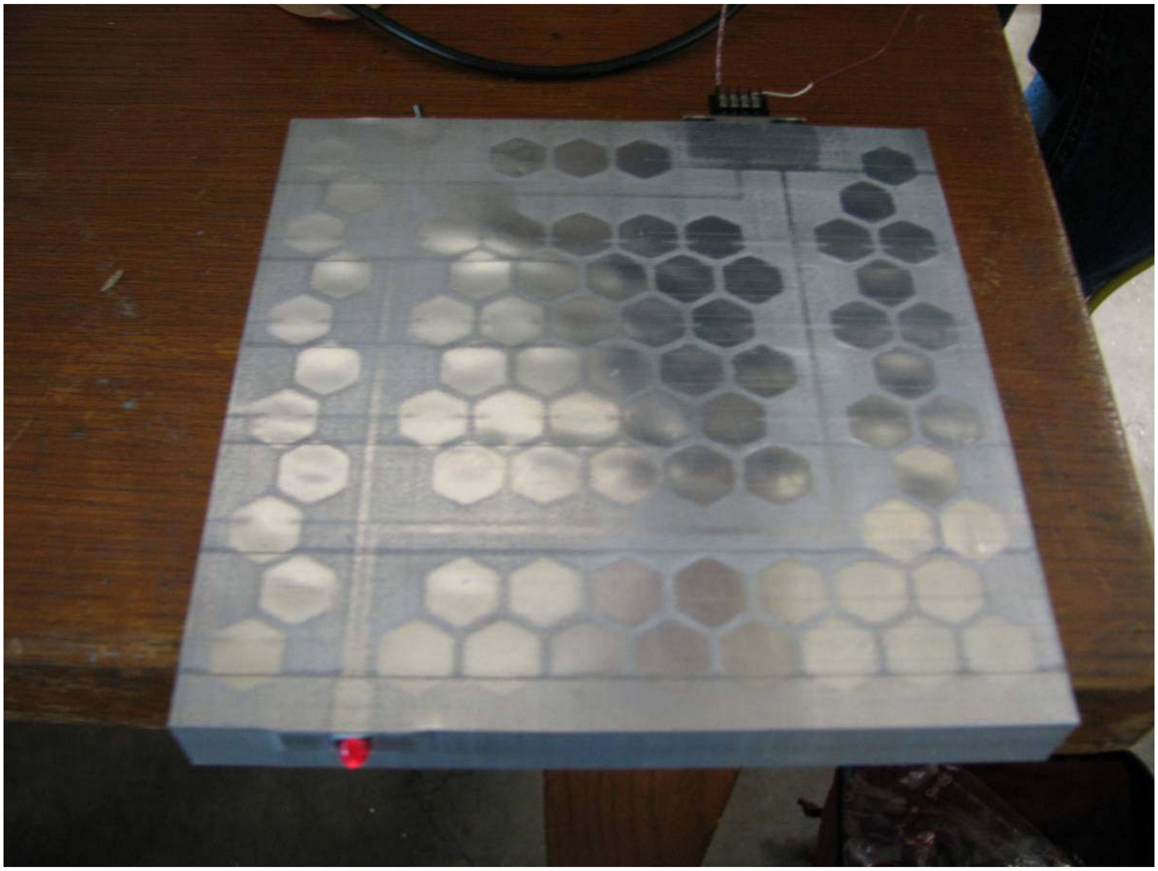

Figure 5: The LED panel after completion.

Testing of the DW Circuitry

Testing was performed throughout the entire LED panel build process. At every stage of the process, the LED responded properly, confirming that the circuit was functioning properly.

A parallel set of tests were performed on simple DW traces to ascertain the effects of the build process used on DW trace performance. For this test, there were no components for the traces to connect to; instead, simple DW pads were created external to a UC part so that electrical resistance could be checked, as shown in Figure 6. For this set of tests, the resistance of the traces was measured at different stages of the process and compared to see if there were any significant changes. Resistances of the straight and 90 degree bend DW traces prior to encapsulation by epoxy were 2.3Ω and 1.5Ω respectively. The resistance after epoxy encapsulation but prior to UC encapsulation was 2.8Ω and 1.9Ω, and the resistance after UC embedding was 2.3Ω and 1.6Ω. The decrease in resistance after UC embedding was likely due to additional curing of the ink traces and the epoxy from the elevated temperature (300º F) at which the UC deposition was performed; however, further studies would be necessary to ascertain whether ultrasonic vibration played any role in enhancing the conductance in addition to elevated temperature curing.

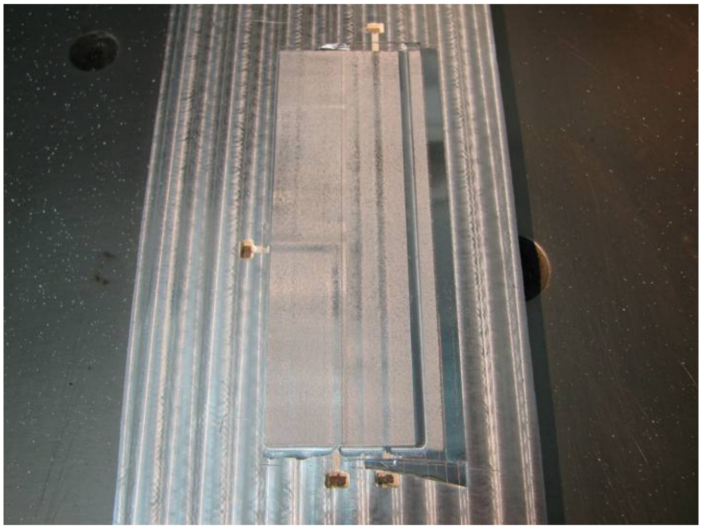
Figure 6: Various DW traces encapsulated in Al 3003 using UC to test for performance degradation.

Patch Antenna Panel Description

The panel design for the surface drawn patch antenna demonstration was a 6” x 6” panel that was approximately 0.65” thick, also made of Al 3003 H18 material. A CAD representation of the part is shown in Figure 7. This panel was built to demonstrate that a structural panel created using UC can have an antenna drawn directly onto the surface using DW technology. This antenna was designed to perform as a 10 GHz antenna, similar to one purchased from Labvolt. The antenna had critical dimensions in the width and length of the patch and microstrip as well as the trace thickness. The antenna also was attached to an SMA connector that was grounded to the backplane of the antenna, which in this case was the UC panel. A patch antenna works on the concept of capacitance so it was necessary to insert a dielectric material as the substrate for the antenna and to attach that to the backplane. The dielectric material chosen was 0.030” thick GML 1000. The ink chosen for the antenna was also E1660-136 silver based ink. A honeycomb structure with walls of 0.061” thickness was also used.

Build Process for the Patch Antenna

The process for building this panel was to start by directly using the CNC capabilities of the UC machine to create the honeycomb structure in the base substrate and then consolidating material on top of the substrate, thereby embedding the honeycomb. As aluminum face sheet material was added to the top, a lower area was created for attachment of the dielectric material using dielectric double-sided adhesive tape. Using this configuration, the antenna would not protrude above the surface of the overall aluminum structure, thus protecting it from damage. Slots for the SMA connector ground pins were cut into the panel and the connector was secured using arctic alumina epoxy. Care had to be taken to ensure that the ground pins of the connector were securely grounded to the panel. The antenna was then drawn onto the dielectric with the required dimensions starting from the end of the center connection pin of the SMA connector. Figure 8 shows the finished panel and antenna, with cylindrical testing attachment pins attached on two sides of the panel.

For future demonstrations, this panel could easily be integrated onto the surface of the LED panel, but for initial demonstration purposes these were built separately.

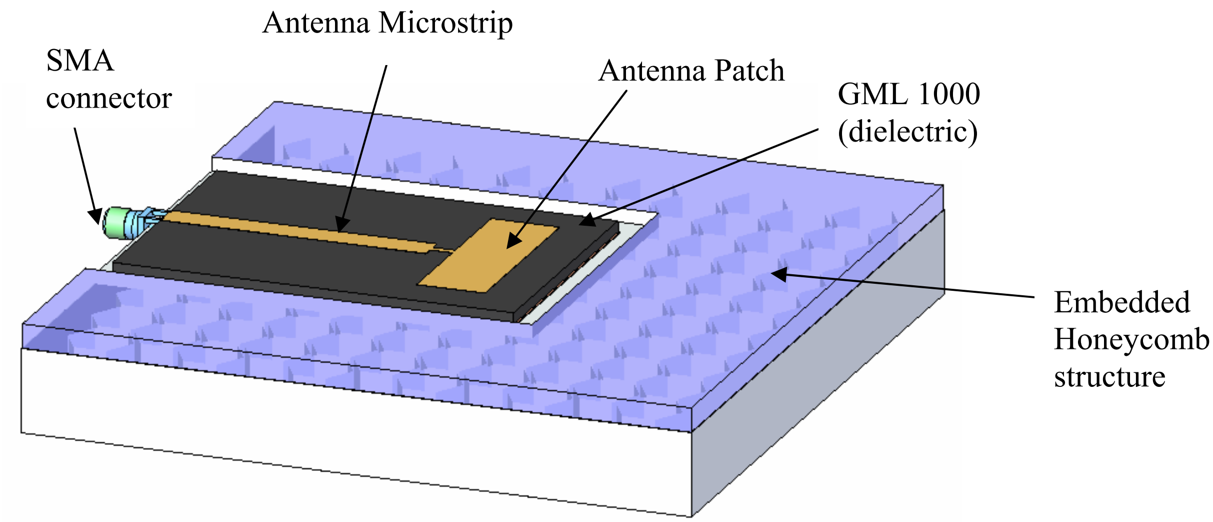

Figure 7: CAD model of Patch Antenna panel where antenna is drawn using DW technology.

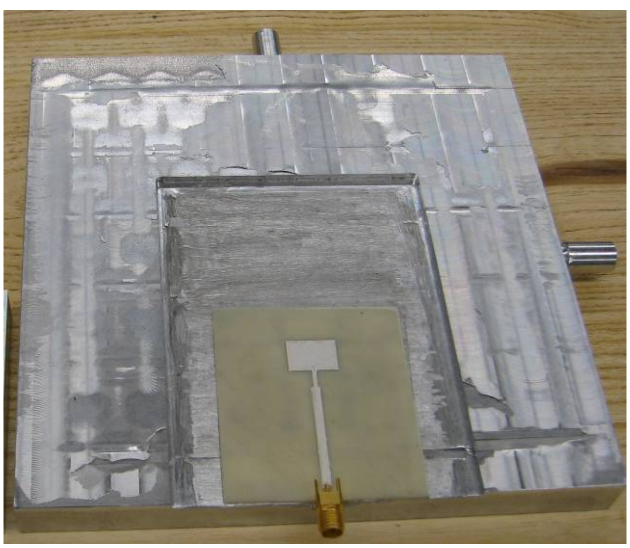

Figure 8: Finished panel with embedded honeycomb and external patch antenna

Testing of the Patch Antenna Panel

Because the antenna was designed to perform similarly to a Labvolt antenna, results were directly compared to the results from the commercial antenna. Testing was performed to measure the half power beam width. The first test performed was to expose the antenna to a signal at 10 GHz and record the output as the antenna was rotated 360 degrees. As can be seen in Figure 9, the pattern for the DW antenna is similar to the Labvolt antenna test results, but at a lower overall gain. The gain decrease is due to a number of factors, two of which are, that the dielectric substrates are not the same for the two antennas and the thickness of the patch was not accurately known. The half power beam width of the DW antenna was 62 degrees while the Labvolt was 74 degreees. The results of the test were promising and show that a working antenna can be directly written onto a structural UC panel.

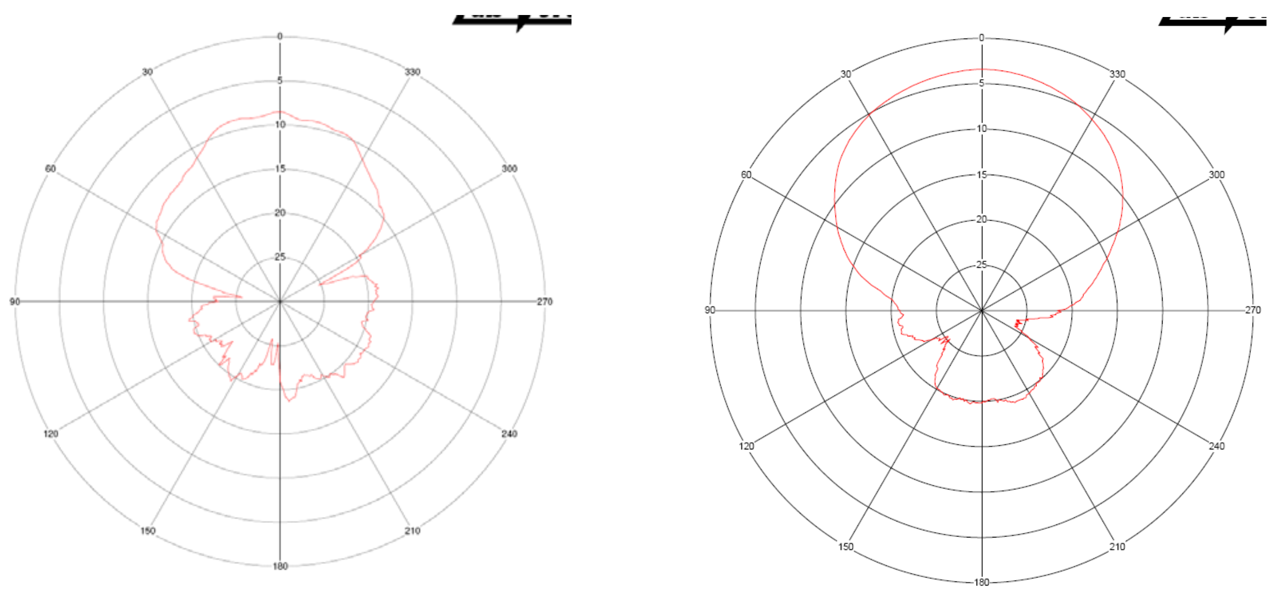

Figure 9: Results from testing of the DW antenna tested at 10 GHz (left) and results from similar Labvolt patch antenna (right).

Conclusions

Ultrasonic Consolidation and Direct-Write make the production of multifunctional satellite panels and other systems a possibility. By integrating these systems using simple process planning, it has been demonstrated that an integrated panel can have structural features, embedded circuitry and components, and serve as the backplane of an antenna that can easily be drawn on the surface using DW. The future integration of a DW apparatus onto the UC machine will make it simple to create multi-functional, integrated panels with embedded circuitry and components. For the case of small satellites, this should result in an overall decrease in the mass of the system, while increasing payload area and performance.

Acknowledgements

Support for this project was provided by the National Science Foundation by an STTR grant through MicroSat Systems, Inc. (OII 0512641) and by the State of Utah Centers of Excellence Program (Center for Advanced Satellite Manufacturing).

The DW work presented here was performed at UTEP in the W.M. Keck Border Biomedical Manufacturing and Engineering Laboratory using equipment purchased through Grant Number 11804 from the W.M. Keck Foundation. Development of the DW system was supported, in part, by the Texas Advanced Research (Advanced Technology/Technology Development and Transfer) Program under Grant Number 003661-0020-2003. Support was also provided through the Mr. and Mrs. MacIntosh Murchison Chair I in Engineering and through research contract 28643 from Sandia National Laboratories in the Laboratory Directed Research and Development (LDRD) program. Frank Medina, Keck Lab Manager, provided technical assistance during the development of the DW system and his efforts are appreciated. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

Church, K.H., Fore, C., and Feeley, T., "Commercial Applications and Review for Direct Write Technologies," *Materials Development for Direct Write Technologies,* San Francisco, CA, April 24-26, vol. 624, pp. 3-8, 2000.

F.R. Medina, A. Lopes, A. Inamdar, R. Hennessey, J. Palmer, B. Chavez, D. Davis, P. Gallegos, and R. Wicker (2005), "Hybrid Manufacturing: Integrating Direct Write and Stereolithography," *Solid Freeform Fabrication Symposium Proceedings*, Austin, TX, August, 2005.

G.D. Janaki Ram, Y. Yang, J. George, C. Robinson and B.E. Stucker (2006), "Improving Linear Weld Density in Ultrasonically Consolidated Parts," *Solid Freeform Fabrication Symposium Proceedings*, Austin, TX, August, 2006.

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