EMBEDDED SPACECRAFT THERMAL CONTROL
USING ULTRASONIC CONSOLIDATION

by

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Abstract

Embedded Spacecraft Thermal Control
Using Ultrasonic Consolidation

by

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Utah State University, 2009

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Research has been completed in order to rapidly manufacture spacecraft thermal control technologies embedded in spacecraft structural panels using ultrasonic consolidation. This rapid manufacturing process enables custom thermal control designs in the time frame necessary for responsive space. Successfully embedded components include temperature sensors, heaters, wire harnessing, pre-manufactured heat pipes, and custom integral heat pipes. High conductivity inserts and custom integral pulsating heat pipes were unsuccessfully attempted. This research shows the viability of rapid manufacturing of spacecraft structures with embedded thermal control using ultrasonic consolidation.

(78 pages)
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Jared Clements
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<td>AFRL/RV</td>
<td>Air Force Research Laboratory Space Vehicles Directorate</td>
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<td>CNC</td>
<td>Computer Numerically Controlled</td>
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<td>CPL</td>
<td>Capillary Pumped Loop</td>
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<tr>
<td>COTS</td>
<td>Commercial Off-The-Shelf</td>
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<tr>
<td>HVAC</td>
<td>Heating, Ventilation, and Air Conditioning</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<td>Low Earth Orbit</td>
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<td>Multi Layer Insulation</td>
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<td>Nippon Graphite Fiber Corporation</td>
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<td>PCM</td>
<td>Phase Change Material</td>
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<td>PnP Sat</td>
<td>Plug and Play Satellite</td>
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<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
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<td>UC</td>
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Chapter 1
Introduction

On 11 January 2007 China launched a missile at one of its own decommissioned weather satellites Feng Yun 1C. Feng Yun 1C shattered into more than 1600 pieces when it was impacted by the kinetic (nonexplosive) warhead at an altitude of 537 miles [1]. This successful test run of China’s anti-satellite system demonstrates the vulnerability of the United States military satellites in Low Earth Orbits (LEO). In the event of a conflict, many expensive and difficult to replace satellites could be destroyed in a short period of time, crippling US forces. In order to allow US forces to continue to have the military advantage LEO satellites offer, damaged and destroyed satellites would need to be replaced as soon as possible, which in today’s satellite industry would require a minimum of five years. In an effort to dramatically reduce the time needed to develop spacecraft as well as the cost of manufacturing the final product, many organizations within the space industry are funneling efforts into developing a responsive space program.

Responsive space, as a program, is being developed to allow the ever-changing needs of individuals and organizations on the ground to be met quickly and accurately in space. The design paradigm in today’s satellite industry can be described as an optimization paradigm. Every effort is expended to ensure top performance and each subsystem and component is finely tuned for minimum mass and maximum performance. Responsive space is a paradigm shift from this expensive and time consuming process. The ultimate goal of the responsive space community is a “six day spacecraft” or a spacecraft that can be ready to fly only six days after the realization of a need. In order to meet this time frame the processes used to design and manufacture satellites would need to undergo a variety of changes, as the development and use of highly optimized hardware is not feasible [2].
The responsive space community proposes designing a modular system of components that would be produced and kept in inventory until needed. When a need arises, components would be pulled from inventory and “mixed and matched” to produce a satellite based on the individual needs of a mission. While this “mix and match” approach allows the design and manufacture of satellites to be streamlined, it is not ideal or feasible for every subsystem required for a functional satellite.

Some subsystems are easily designed into modules because they have a minimum requirement or constraint that must be taken into consideration during the design process. For example, a communications link must be able to downlink at least a certain amount of data per day, and a structure must have at least a certain stiffness. Some level of extra capacity in the subsystem can be tolerated.

In contrast, the thermal control subsystem is doubly constrained. Excessive heat or cold are equally damaging to the spacecraft. Excess capacity, in both heat rejection or heat retention, will adversely affect the performance of the thermal control subsystem.

The wide range of temperatures a satellite can be exposed to when designing for any LEO orbit make it difficult to create an off the shelf modular thermal control subsystem. Different orbits vary widely in thermal environments. A thermal subsystem designed for one of the cooler environments (i.e. small radiator) would operate too hot for almost any common spacecraft components if placed in one of the warmer environments (where a large radiator would be required). The opposite is also true.

Another fundamental problem for a thermal control subsystem in a responsive space mission is the inherent “mix and match” nature of the spacecraft components. Low power components can be directly exchanged with high power components resulting in the need for both increased heat carrying capacity and increased heat rejection. Unfortunately, increasing the heat carrying and heat rejection capacity of the heat paths and radiator requires significant changes to the structural subsystem. Conductive heat paths always utilize structural hardware, and heat pipes are commonly embedded in structural panels in order to supplement the natural conduction. Radiators primarily utilize the exterior
surface of a structural panel as the heat rejecting element. The time required to modify
the structure in order to incorporate changes to the thermal subsystem breaks the six day
constraint for responsive space. The other feasible option, which is to build to inventory
all the likely permutations of a structural design which the possible thermal loads would
require, is prohibitively expensive.

A recently proposed solution to this thermal control problem is the use of rapid manu-
facturing methods to manufacture custom structural hardware with integrated thermal
control [3]. Ultrasonic consolidation (UC) is a rapid manufacturing process that has the
potential of producing fully custom hardware in hours. It also preserves the ability to embed
thermal control hardware within the structure.

Ultrasonic consolidation combines the ultrasonic welding of metal foils with com-
puter numerically controlled (CNC) machining. The UC process uses an aluminum sub-
strate/anvil, a cylindrical sonotrode and a roll of aluminum tape approximately one inch
wide and six thousandths thick to create a structure. The anvil is heated to 300° F and a
length of tape is placed on it. The cylindrical sonotrode is slowly rolled along the length of
the tape applying both a transverse ultrasonic vibration and a downward pressure. These
forces create differential motion at the interface between the anvil and the aluminum tape,
breaking up and dispersing surface oxide layers and causing plastic deformation and flow.
Metallurgical bonding then occurs across the atomically clean surfaces, bonding the tape
and anvil together. Multiple tapes are laid side by side to create a layer and new layers can
be deposited on top of the first [4–6]. The entire process is integrated into a CNC platform
with a milling spindle and head. Individual layers are trimmed to size and internal features
are machined prior to the deposition of the upper layers. Originally developed for the rapid
prototyping industry, UC enables direct manufacture of complex parts directly from CAD
models. Using this manufacturing method it is possible to manufacture integrated thermal
control hardware in a time frame that fits within the responsive space timeline: hours and
days, instead of months and years.

This thesis documents the attempt to design, manufacture, and test thermal control
components integrated into structural panels produced using ultrasonic consolidation. This proof-of-concept effort was designed to demonstrate that realistic spacecraft hardware can be manufactured using UC technology. Several thermal control technologies were attempted, including integral heat pipes, embedded temperature sensors, embedded heaters, embedded harnessing, integral high-conductivity thermal doublers, the embedding of commercial off the shelf (COTS) heat pipes, and the manufacture of integral pulsating heat pipes.
Chapter 2

Literature Survey

2.1 The Thermal Control Problem and Possible Solutions

The thermal control problem for responsive space has not yet been the focus of extensive research. The most thorough analysis of thermal control for responsive space to date was undertaken by Andrew Williams and Scott Palo and presented at the 2006 Small Satellite conference. This literature survey will review Williams and Palo and critique the solutions that have been proposed by the space industry to date. To the author’s knowledge, this effort, including the work documented in this thesis and the work performed by other students in the same research group, is the first attempt to apply ultrasonic consolidation to responsive space. To this end, a literature review has also been performed to review the state of the art in satellite thermal control techniques and the state of the art in the field of ultrasonic consolidation.

At the 2006 Small Satellite conference held at Utah State University, Andrew Williams of the Air Force Research Labs presented a paper outlining the thermal control problem for responsive space [7]. In their paper Williams and Palo describe the traditional thermal design method, discuss why this method will not work for producing spacecraft within the time frame designated for responsive space and then evaluate three simple thermal designs for suitability for responsive space.

The traditional method of thermal design begins after the orbit, orientation, and preliminary spacecraft configuration have been decided. At this point, a simplified thermal model is developed and a preliminary analysis is performed. Different design concepts are evaluated using this model and the optimum design is selected. This preliminary model is then improved upon as the detailed design of the spacecraft is refined by the design team.
When the design of the entire spacecraft is complete the final analysis and model are verified in the thermal balance test. This is an iterative and time intensive process, and is not suitable for a severely time constrained and responsive spacecraft.

Williams and Palo evaluate the performance of three different thermal design concepts which would likely meet the time limitations for a responsive spacecraft.

The first design concept is an isothermal structure. The structure incorporates high thermal conductivity inserts to rapidly spread heat throughout the spacecraft. Temperature control is achieved through tailoring the surface properties in order to balance the radiation exchange with the environment.

The second design is a modular approach. In this design the spacecraft is divided into thermally isolated modules, allowing the radiation exchange for each module to be balanced independent of the the rest of the spacecraft.

The third design concept proposes the use of a thermal switch between the satellite components and the structure. The switch would allow the structure to run cold and temperature sensitive components would be thermally connected only when they need to reject heat.

All three of the design concepts could be used to produce hardware which could then be built to inventory, thereby meeting the time constraint for responsive space. The design concepts appear to be ordered from simplest to most complex.

Each design was evaluated based on hot and cold cases that span the range of low earth orbits (LEO). They are therefore more extreme than can be found in any individual orbit.

The first design concept, the isothermal design, fared poorly. The surface characteristics were optimized so the satellite components consistently ran at the top of their operational temperature ranges during the hot case. Heaters were then used to supply the heat necessary to keep the spacecraft sufficiently warm during the cold case. Power usage of these survival heaters was significant, i.e. more than 50% of the power usage of the rest of the bus. Normal power margins reserved for a thermal system are usually around 5% [8]. Thermal power usage over 10% is considered excessive.
The performance of the second design was similar to the first, though with a 25% reduction in power usage of the survival heaters in the cold case. The reduction in power usage is significant, but insufficient to bring power usage down to an acceptable level.

Based on these results, both the isothermal and modular designs are incapable of adapting to the extreme environments that can be encountered by spacecraft in LEO orbits. Unless a more proactive approach is taken, i.e. rapid analysis and customization of the surface properties to the chosen orbit, passive designs are unsuitable for responsive space.

The third concept, the switch enabled design, is more promising for use in responsive spacecraft than either the isothermal or modular designs. The use of a thermal switch allows heater power usage to be reduced to almost nothing; however, a thermal switch with the required performance and cost is not currently available. Williams and Palo report that according to their analysis the needed conductance ratio of the switch would be on the order of 20:1 to 70:1 for robust operation. Preliminary work on a forced air convective thermal switch was performed by Williams and Palo [9]. Based on their preliminary work, they estimate that a conduction ratio of 69:1 should be obtainable with a forced air switch. Significant work remains to address reliability as failure of the fan or hermetically sealed enclosure would most likely mean failure of the entire subsystem in the enclosure.

In summary, Williams and Palo clearly define the thermal control problem for responsive space. They evaluate the potential of three simple design concepts for solving this problem: isothermal, modular, and active switching. The isothermal and modular designs were found to be too power hungry for responsive space applications. The thermal switch design provides the necessary performance, but suffers from the lack of an inexpensive and robust thermal switch. The possibility of rapid manufacturing is not reviewed or mentioned in the Williams and Palo article.

2.2 Responsive Space Development Programs

As of this writing, no spacecraft have yet flown that have been designed and built incorporating responsive space concepts. Several spacecraft have been designed as testbeds for proving responsive space technologies. These programs and efforts were not attempts
to build to inventory and actually provide a spacecraft in seven days, but to implement the other enabling technologies of responsive space, namely modular design, interface standards, and heavy use of COTS hardware. Most of these programs have been initiated by the already established players in the small satellite industry.

2.2.1 AeroAstro

AeroAstro is currently developing an architecture they have named the SMARTBus [10]. The SMARTBus’ structure is a stack of thin hexagonal modules. Each subsystem is contained in one hexagonal slice. Deployable solar arrays are housed in one, batteries and power conditioning occur in another, communications uses another module. All of the subsystems are connected by a standard bus that carries power and data. To produce a spacecraft for a responsive space mission AeroAstro would simply match the hexagonal modules to the mission specifications.

Thermal control for the SMARTBus is similar to the isolated module approach as analyzed by Williams and Palo with each module thermally isolated from the others. In addition to the shortcomings of this design approach shown by Williams and Palo, this particular implementation is limited in surface area for each slice. Any high power module would be severely limited in radiator area, making thermal control difficult if not impossible.

2.2.2 Lockheed Martin

Lockheed Martin is in development stages of HexPak, an architecture superficially similar to AeroAstro’s [11]. Like the SMARTBus, HexPak consists of a stack of thin hexagonal modules. Unlike the SMARTBus, the HexPak deploys after launch into a planar structure, each module unfolding outward on hinges. Data and power connections are on a standard bus.

In the deployed configuration the HexPak does not suffer from the lack of surface area endemic to the SMARTBus. Instead, the most likely concern with this thermal design is too much exposure to the environment. This would be in addition to the fundamental flaws of a passive modular system as pointed out by Williams and Palo. A modular passive design is
insufficient to handle the extreme environments that could be encountered in a responsive mission.

2.2.3 SpaceDev

SpaceDev’s efforts in designing a responsive space architecture center around their CHIPSat microsatellite. CHIPSat is a microsatellite launched in 2002 that made heavy use of COTS components in an effort to reduce costs. SpaceDev speaks mainly of a standard microsatellite bus as opposed to the mix and match approach favored by companies like AeroAstro. The concept being developed is to force the payload designers to work within the constraints imposed by a standard bus and the development costs would be amortized over multiple missions. There would be small, medium, and large sizes to accommodate different requirements [12–14].

The main disadvantage with standardizing the entire bus is that the bus eventually becomes obsolete and must be redesigned as new technologies are developed [7]. The costs of the redesign would then have to be amortized over the lifetime of the new spacecraft model. It soon becomes apparent that this approach is merely the traditional satellite design approach and significant cost savings cannot be realized, making the CHIPSat architecture too expensive for responsive space.

Thermal control on CHIPSat was achieved by tailoring the spacecraft thermal control system to the operational orbit. The solar arrays are all body mounted and appear to act as the primary radiators. The spacecraft is designed to run cold biased, meaning that its radiation properties are tailored to keep the spacecraft cool in the hot case, and the extra heat needed to keep the components within their operational range during the cold case is supplied by make up heaters [12]. The fact that the thermal control system was optimized for the operational orbit limits the use of the CHIPSat design to similar orbits, effectively excluding it from the responsive space market.

2.2.4 Surrey Satellite Technology Limited

Surrey is a well established player in the small satellite industry, with over 20 satellites
launched during the past 20 years. Their target is 80% of the functionality at 20% of the cost, [15] meaning their goal is to provide most of what can be provided with a large spacecraft at a fraction of the cost of the large spacecraft. Surrey has developed a family of small satellites based on common components and hardware. Surrey’s main advantage is, and always has been, low cost.

Though not optimized for the responsive space timeline, Surrey has developed a large assortment of self-compatible hardware [16–18]. Little modification would be required for a build-to-inventory approach for responsive space. However, Surrey’s custom hardware does not conform to interface standards. Rapid integration of non-Surrey sensors and hardware into the system would likely prove difficult. It also does not appear as though any modifications have been made to the spacecraft family that would easily allow the thermal control system to be rapidly customized for a responsive mission.

2.2.5 Department of Defense TacSat program

The Department of Defense is sponsoring the TacSat program as part of the Operationally Responsive Space Initiative [19, 20]. Originally sponsored by the Office of Force Transformation, much of the funding and work has been transferred to the new Operationally Responsive Space office [21]. This is characterized by what is termed "spiral development" where programs are initiated, approximately one per year, with steadily increasing requirements to incorporate enabling technologies and standards [22]. TacSats 1 through 5 have been selected and funded, while as of this writing only TacSats 2 and 3 have launched.

TacSat-1

TacSat-1 was given the objective to provide and launch an operationally relevant microsatellite in less than one year and for less than $15 million, including launch costs. The program was able to meet the cost and time constraints, however the launch was delayed due to technical problems with the launch vehicle. The Naval Research Lab was responsible for program management, integration, and system testing [23].

The payloads TacSat-1 has been designed to carry are COTS instruments currently in
use in unmanned aerial vehicles (UAVs). Little to no modifications were performed on the instruments. Instead the instruments have been enclosed in hermetically sealed containers in order to space harden them. The structural design incorporates near identical cylindrical decks for modularity.

Unlike most responsive missions, the TacSat program has the luxury of specifying the orbit for TacSat-1. Thermal control appears to be tailored to that specific orbit and not designed with the broader goals of responsive space in mind. It seems to have been designed using a rushed version of the traditional design approach to thermal control as detailed by Williams and Palo.

The TacSat-1 team states that the development of a standardized, modular, scalable satellite bus is beyond the scope of their program. Inspection of images of the hardware verifies this statement, revealing a lack of standardized interfaces in mechanical connections, harnessing, and general component design. The major accomplishment of this program has been the demonstration that a dedicated team can take a COTS payload and rapidly deploy a working solution to get it in space. One year is not one week, but TacSat-1 has shown how COTS payloads can be adapted for responsive space and what kind of payloads are likely to be flown on a responsive mission.

**TacSat-2**

The TacSat-2 program, aka Roadrunner, was completed by the Space Vehicles Directorate of the Air Force Research Labs (AFRL/RV), with the bus design by MicroSat Systems Incorporated. TacSat-2 carried 13 different payloads, many of them rolled in from a former AFRL/RV program TechSat21, some of them picked up from paying customers. TacSat-2 is somewhat unique in that an on-going satellite design effort was chosen as the TacSat-2 effort, thus the use of the Roadrunner moniker. The Roadrunner/TacSat-2 program started in late 2003, received TacSat funding approximately a year later, and launched 16 December 2006 [24].

The primary responsive space capabilities that Roadrunner demonstrated was the use of a high bandwidth, tactical Common Data Link for communications and one meter reso-
olution imaging payload, the imager being theoretically taskable by the warfighter through internet/web based means [25,26].

TacSat-2 did little to advance the six-day spacecraft, most of it’s contribution to the responsive space initiative being in the operational field. In particular the three year development cycle shows very little regard for the six day requirement. TacSat-2 appears to follow the traditional thermal design approach, and does not attempt to solve the thermal challenges presented by responsive space.

TacSat-3

The TacSat-3 mission has also been completed by AFRL/RV. Swales/ATK Space Systems is the contractor responsible for the bus design and fabrication. The primary instrument was provided by Raytheon. The TacSat-3 effort began in October 2004 and launched 19 May 2009 [22].

The primary payload is a hyperspectral imager, combined with direct theater tasking and immediate downlink to existing Army ground stations through the 274 Mbps Common Data Link [2].

The four and a half year development time for TacSat-3 speaks volumes as to its responsiveness. Like TacSat-2 before it, TacSat-3 appears to follow the traditional thermal design approach, and does not attempt to solve the thermal challenges inherent in compressed timelines, plug and play architectures, etc.

TacSat-4

The TacSat-4 program is being managed by the Naval Research Laboratory, with the bus design being completed by the Johns Hopkins University Applied Physics Laboratory. In contrast to the other TacSats, which have all been earth observing missions, TacSat-4 is intent on completing a communications mission, specifically to demonstrate the ability to rapidly augment or replace current communications capabilities [27].

The TacSat-4 team has decided to solve the thermal problem by conductively isolating the payload from the bus. This allows the bus thermal design to be mostly independent
from the effects of the payload, with the exception of the radiation exchange between the
two isolated modules. The thermal problem is then solved for each half independently,
apparently through the standard, traditional thermal design process [28].

**PnPSat/TacSat-5**

The Plug-and-Play Satellite (PnPSat) development effort has been underway at the
AFRL/RV for several years and the technology has been incorporated into the TacSat-5
effort [29]. The PnPSat specifications detail power, data, connector, and even software
interfaces, however the mechanical interface specifications are limited to a five centimeter
grid of 8-32 threaded holes. Thermal considerations are assumed to be controllable by simple
conduction [30]. Though many of the more difficult problems posed by the responsive space
paradigm are addressed by PnPSat and TacSat-5, the thermal problem is not one of them.

**2.2.6 Modular research**

The Space Dynamics Lab has recently undertaken an effort to further develop the mod-
ular thermal design concept. In this work Quinn Young adopts a more rigorous definition
of the term “modular” by the application of modular theory developed primarily in mass
production industries [31]. A modular design is broken into components that perform one
single function, this is in contrast to an integral design, where a component may perform
multiple functions. The primary advantage is that where an integral design may be more
cost effective/capable, in terms of money or mass etc, the modular design is easier to modify,
due to the inherent separation of function.

Young evaluates several types of modular thermal architectures, as well as a more
traditional thermal design. The best performing architecture incorporates an isothermal
bus and variable emissivity radiators. Each satellite component interfaces to the isothermal
bus, and variable emissivity radiators are used to control the temperature of the isothermal
bus. This design concept is implementable now, though with pumped fluid loops acting as
the isothermal bus and louvers acting as the variable radiators. This currently realizable
implementation is less than ideal, primarily due to the cost, limited performance, and
fragility of mechanical louvers. The reliability of pumped fluid loops may also be an issue, but is less important in the responsive space paradigm as long orbital lifetimes are not generally required.

Effective implementation in both the cost and performance aspects of this architecture requires advanced thermal control technologies such as multi-evaporator/multi-condenser loop heat pipes or electro-optical variable emissivity radiators. As these technologies are still a few years out the modular thermal design should be viewed as a road map to the future of thermal design, both for responsive space and general thermal design. If these advanced thermal technologies do not perform as hoped this concept becomes significantly less attractive [32–35].

2.2.7 Conclusion

As has been shown, there has yet to be a solution found to the thermal control problem in responsive space. Rapid manufacturing through ultrasonic consolidation provides a viable solution which may be implemented in the near future.

2.3 Ultrasonic Consolidation

Although ultrasonic welding has been in use since the late 1950s [36,37], it only emerged as a direct metal manufacturing technique and rapid prototyping technology in the late 1990s. In 1998 research by Johnson [38] at Tufts University found that ultrasonic welding could be used to make prototypes similar to other rapid prototyping machines with the added benefits of higher dimensional accuracy, low energy consumption, modest space requirements, no emission of fumes, and the ability to create a bond between dissimilar metals. In 1999 Gao [39], another researcher at Tufts University, used analytical modeling, finite element analysis, and experimental data acquisition to record the static and dynamic effects in the elastic and plastic flow regions during ultrasonic welding, producing the theory behind Johnson’s research. While Johnson and Gao’s research furthered ultrasonic welding as a manufacturing technique, ultrasonic welding’s rapid prototyping potential was not fully realized until 2000 when Dawn R. White founded the Solidica Corporation. White inte-
grated a tape feed mechanism, an ultrasonic welding sonotrode, and a milling machine into one computer controlled machining package, allowing direct metal manufactured prototypes to be produced in hours or days [4–6].

The material of choice for ultrasonic consolidation is aluminum alloy 3003. This alloy is ideal for creating UC bonds because it has a low yield strength, thin surface oxides, and minimal strain hardening. These qualities allow reliable consolidation to occur, when used with the proper combination of the process parameters, namely temperature, vertical force, vibrational amplitude, and rolling speed. Several studies have been performed to optimize these process parameters in order to consistently achieve nearly 100% weld density using Al 3003 [40–42]. To further improve the strength of UC products attempts have also been made to produce well-bonded samples using higher strength aluminum alloys, such as 6061. However, due to thicker surface oxides and higher strain hardening rates no one has yet published results showing 100% weld density in the bonding region [43].

Other efforts have been made to locate higher strength materials compatible with ultrasonic consolidation, mainly focused on multi-material composites using Al 3003 as one constituent. Tests have shown various bonding strengths and weld densities between the various materials which include Al 3003, Al 2024, Inconel 600, brass, and stainless 347 [44,45]. Fiber reinforced metal matrix composites have also been fabricated using Al 3003 as the matrix and fibers made of silicon carbide and stainless 304 [46–48]. Interestingly, the same techniques used for fiber reinforcement have also been used for embedding of optical and shape memory alloy fibers [41,49].

A theoretical understanding of the UC mechanism is progressing with the development of new models [48,50,51]. Though still a matter of some debate, many of the details in the welding process have recently become clearer.

Some design rules were established early on; of particular note is the maximum aspect ratio of a vertically built-up rib is limited to 1:1 [52].

A series of experimental projects specifically targeting embedding of functional objects and features using ultrasonic consolidation have also been undertaken at Utah State Univer-
sity. The goal of this research is to produce spaceflight hardware with multiple capabilities. One of these primary capabilities is rapid manufacturing for responsive space [3]. Rapid manufacturing of structural panels for responsive space enables customization of the panels, which is particularly necessary in doubly constrained systems like the thermal control system.

One prerequisite to building structural panels with embedded thermal control is the ability to build structural panels appropriate for satellite use, i.e. with high stiffness and low mass. Work by J. L. George showed that high performance lightweight stiff panels can be built using UC. His research showed that honeycomb core sandwich panels can be manufactured using UC and are able to give the desired performance [53–55].

Several other capabilities have also been demonstrated that are enabling for responsive space. One of these is machine layed up, embedded harnessing. This is accomplished by merging direct write and UC technologies. This has the capability of removing the time consuming touch labor currently required to fabricate harnessing, and embed the majority of the spacecraft harness inside the structure [56]. Another useful capability is the ability to embed sensors and even board level electronics assemblies. This has been shown to be feasible when the embedded components are potted into cavities in a UC fabricated part or panel [57].

2.4 Thermal Control Techniques

The range of technologies used for thermal control of satellites is broad. Some of the technologies are in wide use in ground-based thermal management, while others are unique to space. This section will review the primary technologies that are used in space. While some of these technologies may be incorporated in a panel fabricated using ultrasonic consolidation, some materials are too fragile or impossible to apply using UC technology.

2.4.1 Surface Finishes

In general, technologies that modify the optical properties of a spacecraft panel cannot be embedded within a panel. Due to the fragility of the current technologies even external
application using ultrasonic consolidation is unfeasible. These technologies include paints, chemical coatings (like anodize and chromates), quartz second surface mirrors, multi-layer insulation, and mechanical louvers. They are included for the sake of completeness in listing current thermal control technologies.

**Paints and Coatings**

Paints and chemical coatings are applied to the surface of a component or part to modify and control the optical properties of the surface [58]. Radiator panels are commonly coated with a white paint that reflects a high percentage of incident radiation at wavelengths corresponding to solar radiation. It also has a high emittance at infrared wavelengths, where a room temperature body, like a satellite, would radiate most of its thermal energy. Quartz second surface mirrors are also used as coatings on radiator panels, having both a higher reflectivity and a higher infrared emittance than white paints. Component boxes are commonly coated black, either through painting or anodizing. This practice enhances the emittance of the component, facilitating heat removal from the component box.

**Multi-layer Insulation**

Multi-layer insulation (MLI) has been used since the Apollo era as the primary thermal insulation for space vehicles. Multiple layers of high reflectivity/low emissivity aluminized Mylar or Kapton are layered one on top of each other, separated by a Dacron mesh. Layer counts can be as low as six or as high as twenty depending on the need of the spacecraft. Higher layer count insulation blankets can have an effective emittance as low as 0.015 [59–61].

**Louvers**

Louvers are a mechanical means of producing a surface with variable surface properties. A surface with high emittance is covered with a layer of low emissivity vanes. These vanes can be opened or closed, depending on the need to reject heat from the spacecraft. Originally, most louvers were designed like household window blinds, with an actuator on
each vane or some kind of linkage between vanes. Due to a desire to simplify the mechanism and increase reliability most louvers flown recently are of a pinwheel design, where a single moving part can alternately shield or expose the radiating surface [62–64].

Conclusion

Due to the fragility of the materials used to modify the optical properties of a spacecraft panel and the mechanisms used to control temperature it is unfeasible to apply them using ultrasonic consolidation.

2.4.2 Conduction Based Technologies

This section reviews the thermal control technologies that rely on conduction for heat transfer. In general, these are more amenable to embedding by UC. Each technology will be evaluated in turn.

Doublers

Doublers are commonly used to increase the heat path away from a component. They are comprised of an aluminum plate placed between a component and a structural panel, usually with two or three times the footprint of the component box. A doubler spreads the heat out until the panel can carry it away unassisted, thereby lowering the temperature of the component.

The same effect doublers create can be built into a UC panel by leaving a thicker skin under the component. The multi-material aspects of UC can also be utilized by placing a higher conductance material inside the panel to carry away the heat. Possible materials include copper and high conductance carbon fiber.

Heaters

Heaters in use in spacecraft today are either cartridge or patch electrical resistance heaters. They are commonly used during operational modes focused on survival, when components are turned off and still need to be kept warm to protect them from damage.
Cartridge heaters are generally about a quarter inch in diameter with varying lengths, consisting of coiled wire encased in a ceramic material. Patch heaters are thin and flexible, with a copper trace printed on a layer of flexible Kapton, and another Kapton layer bonded on top. Both types of heaters appear simple to embed. Due to their thin cross-section, patch type heaters may not even need a cavity [65].

**Heat Switches**

Heat switches are used for temporarily isolating components from conduction paths. This is useful when small heat leaks can cause failure, such as in cryogenic applications. One kind of heat switch is the gas filled, where two surfaces are kept separated by approximately one millimeter. The area between the two surfaces is evacuated, and a canister of activated carbon is attached. Nitrogen gas that has been absorbed by the activated carbon can be expelled by heating the carbon, it can also be re-absorbed by cooling the carbon. When the canister is heated the expelled gas floods the space between the two surfaces and conduction through the gas allows heat to flow. When the canister is cooled the gas is re-absorbed and the evacuated space insulates very effectively [66,67].

Other heat switches use the expansion and contraction of melting paraflin wax to actuate a bellows. The bellows expands and closes the insulating gap. When the paraflin cools the bellows contract and the contact is broken.

If a small flat plate switch was available embedding a switch would be feasible. As of today, the large size of the switches currently available precludes their embedding in panels.

**Phase Change Materials**

Phase change materials (PCM) are used to add heat capacity to a system. Paraflin wax is a common material used in this fashion, it being stable, non-corrosive, and it’s melting temperature can be finely tuned. PCMs absorb and reject heat at a constant temperature, the melting point of the material. A common usage of PCMs is for high power, low duty cycle components, such as a transmitter. A container of PCM is mounted between the heat producing component and the cooling path. The high heat load is absorbed by the PCM,
and rejected to the cooling path over time to re-solidify the PCM. Another usage would be during times of high environmental heat loads. The component could be isolated from the external heat for a time, the PCM would absorb the heat generated by the operating component, then when the external environment became more friendly the PCM can be cooled and returned to its solid form [68–70].

As PCMs can be packaged as desired, small flat compartments of PCM should be amenable to embedding in a UC fabricated panel.

### 2.4.3 Fluid Transport Devices

Fluid transport devices use the motion of a fluid to transfer heat. They can be single or dual phase. These are generally the highest performance heat transport devices available. The inclusion of fluid transport devices in a UC panel is dependent on the ability to seal any small holes that could cause leaks.

#### Mechanically Pumped Fluid Loops

Mechanically pumped fluid loops are fluid loops where a single phase fluid is mechanically pumped through a tubing loop to carry heat from hot locations to radiators. Pumped fluid loops have always found common usage in manned space vehicles [71, 72]. The comparatively low reliability of the mechanical pumps has precluded the usage of mechanically pumped fluid loops in long lifetime unmanned missions. The tubing portion of a pumped fluid loop is feasible to embed in a UC panel. Encapsulating the pump may be feasible as well but it appears more difficult [73].

#### Heat Pipes

A heat pipe is a two phase liquid-vapor thermodynamic system, where evaporation of the working fluid and capillary action drive the process. Figure 2.1 illustrates the structure and functions of a heat pipe. The vapor flows due to pressure gradients, pressure being formed where the vapor is evaporating and pressure dropping in areas where the vapor
is condensing. The liquid flows along the walls in the wick, drawn to the evaporator by capillary force. Heat pipes carry large amounts of heat at nearly isothermal conditions.

Directly embedding a small COTS heat pipe appears to be as feasible as embedding other components. Manufacturing an integral heat pipe, where the walls and wick are made of the deposited material, may also be feasible and add additional functionality. Curved heat pipes and even a network of heat pipes could be built in, which would allow a thermal engineer to tailor the thermal subsystem to a greater degree than is currently possible.

**Pulsating Heat Pipes**

Pulsating heat pipes carry heat through a pulsating motion. Like a heat pipe, it is a two phase system, where evaporation and condensation drive the fluid motion. Unlike a heat pipe, the heat is carried through sensible heat, i.e. the temperature of the liquid phase. Pulsating heat pipes are manufactured by bending multiple loops of small diameter piping back and forth between the heat source and the heat sink. As the working fluid evaporates at one of the bends in the heat source, it pushes the liquid phase near it down toward the heat sink. The warm liquid then rejects some of its heat to the sink. The traveling slug of warm liquid has pushed the cool liquid that was on the cool bend further down the tube, which means back up to the heat source at the next bend. As the cool liquid warms some of it evaporates, and this vapor pushes the slug of now-warm liquid back the way it came, pushing the now-cooled liquid slug back up to its original warm bend. The cycle then
repeats. In this way the working fluid pulsates back and forth and carries the heat from the source to the sink.

Lacking any wick structure, pulsating heat pipes are simpler to manufacture than standard heat pipes. It is expected that the process for embedding a pulsating heat pipe should be straightforward.

**Capillary Pumped Loops and Loop Heat Pipes**

Capillary pumped loops (CPL) and loop heat pipes (LHP) are two names for very similar designs. As the names suggest, they operate by capillary action, like heat pipes, and function in a loop. CPL/LHPs (hereafter referred to as LHPs only) are currently the state of the art in spacecraft thermal control and are capable of orders of magnitude higher heat carrying capacity than normal heat pipes. LHPs accomplish this increase in capacity by drawing the liquid phase through smooth walled pipes instead of through the tortuous flow paths of a lengthy wick.

Normal heat pipes are forced to operate in a compromise situation. A wick with more pores can produce a greater pressure head which will increase the mass flow rate and the performance of a heat pipe. However, the more pores there are, the smaller they need to be. The liquid phase of the working fluid must be drawn the full distance from the condenser to the evaporator through the wick. Smaller pores constrict the flow paths throughout the length of the wick, causing greater viscous pressure loss and lowering the overall performance.

LHPs sidestep this greater pressure head and loss quandary by separating the fluid carrying components, where the viscous pressure losses occur, from the wick, which creates the pressure head. In an LHP the wick is located at the evaporator only. Its only function is to form the meniscus and create the pressure head. It does not carry the liquid for any appreciable distance. This allows the use of a very small pore size in the wick, giving the LHP its high pressure head and high performance.

The fluid in an LHP flows through a piping loop, never reversing direction. This is significant only when compared to its predecessor, the standard heat pipe, in which the
fluid flows back and forth in the same tube. In the LHP the evaporated fluid leaving the evaporator travels down the tubing to the condenser. As it enters the cool condenser it begins to condense on the tubing walls. The droplets of condensate are drawn along by the bulk flow of the vapor. As the fluid flows through the length of the condenser it condenses more and more, until all the vapor is condensed to liquid. The liquid is drawn through the tubing back to the evaporator, where it flows through the wick and evaporates, thus completing the loop.

All LHPs currently in use are much too large to be embedded in a single UC panel. However, it may be possible to manufacture components of a LHP, like a condenser/radiator panel, using ultrasonic consolidation. Micro LHPs, which are currently in development, might be feasible to embed in a single panel, but are currently too immature to attempt at this time.

2.5 Conclusion

This chapter reviewed the state of the art in satellite thermal control technologies, ultrasonic consolidation, and the proposed solutions to the responsive space thermal control problem. As the only other credible effort that has been made to solve this problem is also dependent on other experimental technologies, it makes sense to pursue ultrasonic consolidation as a possible alternative. The review of current satellite thermal control technologies has identified which technologies would be good candidates for embedding. Embedded thermal control using ultrasonic consolidation shows promise as a possible solution to the responsive space thermal control problem.
Chapter 3
Ultrasonic Consolidation

3.1 The Solidica Formation

UC panels are built using a fully automated CNC milling system called the Solidica Formation, manufactured by Solidica Corporation. Panels are constructed using several different tools and features: an anvil, the substrate, a sonotrode, a transducer, a tape feed mechanism, the aluminum tape, a small milling head, an isopropanol coolant system for the milling head, and an air knife. All of these parts except the anvil and substrate are housed in a carriage.

3.1.1 Anvil

The anvil is an 18” x 18” x 1” square steel plate with embedded heaters. It is mounted to the base of the CNC enclosure, with a layer of chalk insulating it from the enclosure. The anvil is heated to 300°F Fahrenheit during the UC process.

3.1.2 Substrate

The substrate is a 14” x 14” x 1/2” aluminum plate bolted to the anvil. Lengths of aluminum tape are welded to the substrate during the UC process. Due to the bolt pattern affixing it to the anvil only an 11” x 11” area is available for ultrasonic consolidation.

3.1.3 Sonotrode

The sonotrode is a titanium alloy wheel that is approximately 10” in diameter and 1.5” thick, specially etched around the circumference in order to produce sufficient roughness to grip the tape without damaging it. The Formation process uses a rolling sonotrode to allow for semi-continuous usage. The sonotrode has three means of actuation; the first is simply
rotating or rolling, referred to as the feed rate; the second is the ultrasonic actuation, which is applied by the transducer; and the third is the application of vertical force by means of a ball screw. The vertical actuation is force limited through the use of a load cell.

3.1.4 Transducer

The transducer applies the ultrasonic vibration to the sonotrode through the use of stacked piezoelectric actuators. The piezoelectric actuators operate at a frequency of 20 kHz. The ultrasonic vibration is applied along the axis of the cylindrical sonotrode.

3.1.5 Tape Feed

The tape feed mechanism feeds the aluminum tape from the roll stored atop the carriage down to the sonotrode/substrate interface, positioning the tape to insure consistent placement and build accuracy.

3.1.6 Aluminum Tape

The aluminum tape is a roll of Al 3003 one inch wide and six thousandths of an inch thick. It is sometimes also called aluminum foil. In this document it will be called tape or aluminum tape. The aluminum tape is the material that is used to build up parts with UC.

3.1.7 Small Milling Head

A single axis mill head is used to trim the tapes after application. Internal features are also machined using this component. It is capable of light duty machining, as an 1/8” diameter bit is the maximum that can be used aggressively in this machine.

3.1.8 Isopropanol Coolant System

A stream of isopropanol is used as coolant for the mill bits during machining operations.

3.1.9 Air Knife

An air knife is used to blow the chips and excess tape from the work area.
3.1.10 Carriage

The sonotrode, transducer, tape feed, aluminum tape, mill head, coolant and air knife are all mounted on the CNC carriage, which gives three axes of movement to the whole assembly through the use of precision ball screws.

3.2 The UC Process

Panels are constructed on the 11” x 11” available surface on the substrate. Work begins by heating the anvil to 300°F, the temperature where optimum weld density occurs. The substrate is then machined flat by trimming several thousandths of an inch off the surface. The end of the roll of aluminum tape is then fed under the sonotrode and held in place by the tape feeder. The sonotrode is positioned into the desired location on the substrate, sandwiching the tape between the substrate and sonotrode. Ultrasonic consolidation then occurs by the simultaneous application of vertical force and ultrasonic actuation. The sonotrode is rolled down the length of the substrate, welding the tape to the substrate as it rolls.

The sonotrode is specially etched so it is able to grip the aluminum tape without slippage during the welding process. This ensures that the surface-to-surface differential motion occurs at the interface between the aluminum tape and the aluminum substrate. This vibratory scrubbing motion at the contact plane causes highly localized stresses which break up the surface oxide layer, causes plastic deformation and flow, and allows for clean metal-to-metal contact and fully metallic bonding between the tape and the substrate.

Multiple tapes are laid down side by side in order to build up a single layer of tape. The extra material that is not intended to become part of the final piece of hardware is trimmed away using the mill head. The air knife is then used to blow away the excess tape and chips produced by the machining process. A second layer is then placed on top of the first layer, care being taken to offset the second layer sufficiently to ensure that the seams between tapes in the lower layer do not line up with the seams in the new layer. Additional layers are added in this manner until the full height of the part is reached.

This build process makes it simple to add cavities or channels within a part. The layers
of tape can be machined using the mill head and the cavities or channels are then covered with subsequent layers. Care must be taken in the placement of the cavities and channels, as subsequent layers will not bond in the areas directly above the voids. Neither to the cavity (as expected) nor to each other, at least in the first few layers. Each subsequent layer adds stiffness until the stack becomes sufficiently stiff to support a complete bond. This gradual improvement is termed weld recovery and usually happens quickly. Small channels and cavities will see complete weld recovery in as few as three to five layers. Larger cavities may take as much as ten layers for full weld recovery.

Channel and cavity size is limited by the requirement that sonotrode be well supported. If a cavity is wide enough to allow the sonotrode to roll down into the void while laying tapes there will be slack or sag left in the tapes where they bridge the cavity. This slack provides no support for subsequent layers and inhibits weld recovery.

This limitation has interesting implications for channels and cavities. One of these is that channels running in the direction of the tapes can be as long as desired, but channels cannot run perpendicular to the tapes for more than the width of a single tape. Angled channels work well, the minimum angle depending on the width of the channel. For practical purposes a minimum of 25% of the contact area beneath the sonotrode must be supported. Larger cavities can be manufactured as well, but must be supported by other means. This is done by using an epoxy as filler material around an embedded component.

Support is also the primary concern when attempting to build thin wall or rib features, though for different reasons. As thin wall or rib features get taller their ability to resist lateral forces decreases. This reduction in stiffness is accompanied by an increase in deflection when forces are applied. Ultrasonic consolidation requires that the substrate be kept stationary during the application of the ultrasonic loads. When the substrate deflects with the vibrating tape it reduces the amplitude of the differential motion, reducing the scrubbing motion, and limiting the energy that can be put into forming the bond. When a rib or thin wall feature reaches an aspect ratio of approximately one-to-one the deflection has increased to the point where welding fails completely.
This is overcome in large part by not building thin wall structures additively, but subtractively. Large blocks of material are built up and thin wall structures are then machined out of the blocks. This provides full weld density the full height of the thin wall and allows aspect ratios significantly greater than simply one to one. Joshua L. George experimentally determined that a strong and lightweight sandwich panel can be designed using this principle and a honeycomb core. The honeycomb core design is laterally self-supporting and allows a skin to be bonded to the upper surface of the core [54].

3.3 Conclusion

The Solidica Formation has brought UC from experimentally intriguing to manufacturing reality. The manufacturing process described in this chapter includes preparation, deposition, and machining. By following a few simple design rules complex and intricate structures can be designed incorporating embedded objects and channels.
Chapter 4

Patch Heater

4.1 Three Attempts

Build one was undertaken to test the feasibility of embedding an electric resistance heater into a UC panel. It was decided that a patch heater commonly used in aerospace applications would provide the best test data. Accordingly, several one inch square heaters were purchased from Minco. The first attempt at embedding was made with a single heater being placed in a three inch square block of consolidated tapes. The original expectation, before the first attempt at embedding a heater, was that due to the thinness of the heater it would be feasible to simply slip it between two layers of the aluminum tape and proceed with normal consolidation. The Kapton heater has a thickness of 0.011”. Insertion of these heaters, which have a thickness of almost two layers of tape, is unlikely to work well. However, the possibility of a low complexity insertion technique indicated that it should be attempted.

Figure 4.1 shows the author’s step by step attempt to embed the Kapton heater. First, a channel and a cavity were made for the harnessing and connection points. The heater was placed appropriately so the harnessing could run through the channel. Second, a layer of tape was laid over top of the heater. During the tack it became clear that the heater would not bond to the aluminum, and was supporting the layer above it so that it could not touch or bond to the tape layer beneath. Third, the full layer was welded down. After the weld pass it can be seen that the aluminum tape in the same region as the heater is bubbled up and not well bonded with either the heater or the layer beneath.

A second build was made to embed a Kapton heater into a panel. This time a cavity slightly bigger than the Kapton heater was machined out of the build and the heater was dropped into it. Following the installation of the Kapton heater, several more layers of
Fig. 4.1: First attempt to embed a heater.
aluminum tape were welded above it. While machining a cavity into the panel for the heater allowed it to be embedded into the panel, several other unexpected problems arose. Initially, it was hoped that the heater would bond with the metal both underneath and above it, or failing that, to support the higher layers sufficiently to allow them to bond and bridge the cavity cleanly. Unfortunately, the heater lacked the stiffness needed to do either. It failed not only to bond with the aluminum tape but to produce sufficient support to allow for the recovery of subsequent layers. After four layers deposited no recovery had occurred. The upward bubbling of the tape made it so that it failed during a light machining pass normally used to reindex the machinery to a known height. See Figure 4.2.

The third attempt to embed a Kapton heater into a UC panel succeeded. The cavity was filled with an epoxy that contained a high percentage of aluminum oxide powder as a filler material. The heater was encased in this potting material. The excess epoxy from the application process was then machined flat and subsequent layers of tape were laid down above it. The layer directly above the heater did not bond to it but bonding did occur between the subsequent layers. It is thought that the high percentage of aluminum oxide in the filler material in the epoxy contributed significantly to the stiffness of the epoxy and the success of the build. See Figure 4.3.
4.2 Conclusion

Three attempts were made to embed a patch style electrical resistance heater. Direct insertion and dry embedding were not successful. The use of a high stiffness potting material led to success. Heaters provide the ability to add heat to important locations, providing protection from excessive cold.
Chapter 5
Integral Heat Pipe

5.1 Manufacture and Assembly

A heat pipe can be included in a UC panel in one of two ways; one, a COTS heat pipe can be dropped into a machined cavity and sealed by additional layers of aluminum tape or, two, a heat pipe can be machined directly into the panel itself. As the second option would allow for more flexibility in heat paths and placement it was determined that an integral heat pipe would be attempted. The objective of this effort is to evaluate if a heat pipe can be built using UC.

A heat pipe is a two-phase liquid-vapor thermodynamic system where evaporation of the working fluid and capillary action drive the process. Figure 5.1 illustrates the structure and functions of a heat pipe. The vapor flows due to pressure gradients, pressure being formed where the vapor is evaporating and pressure dropping in areas where the vapor is condensing. The liquid flows along the walls in the wick, drawn to the evaporator by capillary force.

The first challenge associated with building a heat pipe was the feasibility of building

![Fig. 5.1: Heat pipe operation.](image-url)
a wick using UC. Wicks are generally formed with grooves or screens. As this design was proof-of-concept, it was decided to only place the wicking structure on the bottom wall of the heat pipe. Adding wick structure to the side and top walls was deemed a secondary objective that could be completed in subsequent experiments. The wick was created by machining longitudinal grooves down the entire length of the bottom wall of the heat pipe. The author considered this configuration sufficient to show proper operation.

The panel was manufactured as shown in the series of pictures in Figure 5.2. First, the base of the part was laid down and then the grooves were machined into it. Extra material laid around the outside edge of the heat pipe so that the walls wouldn’t violate the one-to-one aspect ratio design rule. The part was then built up to the height of the vapor space and the vapor space was machined away. The vapor space was capped off with sufficient layers to create a quarter inch wall. It should be noted that weld recovery never occurred above the half inch wide vapor space. The heat pipe was then machined out of the supporting block. The substrate plate was removed from the CNC enclosure, and the anvil material was then machined away by the use of a mill. Holes for the fill and vacuum valves were drilled and tapped in the ends. Valves were installed into the tapped holes.

Ultrasonic consolidation does not produce air tight parts. Therefore, second challenge involves sealing the gaps left when two tapes are laid down side by side. The interface between the two tapes are not subject to the welding process and there is always some finite distance between the tapes. As the pressure inside a heat pipe at room temperature is generally lower than ambient pressure, gaps in the heat pipe wall allow air into the heat pipe. Air, a non-condensable gas at room temperature, blocks the flow of vapor down the center of a heat pipe, inhibiting the correct operation of the heat pipe.

Hernon Manufacturing HPS 1000 is a sealing compound that is generally used for sealing gaps and pores in cast metal parts. This compound was used to seal the gaps left by the UC process. The first attempt at following the sealant manufacturers instructions and soaking the part in the sealant under vacuum failed to force the sealant into the gaps. While this process is apparently enough to seal the porous surface of a cast metal part, it
Fig. 5.2: Heat pipe manufacturing process.
was insufficient to seal the minute gaps left between parallel tapes present in the heat pipe. A new process was developed, where the internal void was filled with sealant and the valves were closed on either end of the pipe. This allowed atmospheric pressure to be maintained inside the heat pipe. The heat pipe was then placed in a small vacuum chamber which was pumped down. The pressurized sealant trapped inside the heat pipe forced its way out through the gaps, filling them in the processes. The part was then removed, drained and flushed, and placed in boiling water to cure the sealant as per the manufacturer’s instructions.

Following the successful sealing of the gaps in the heat pipe, the heat pipe was filled with 2.5 ml of acetone. A vacuum pump was attached to one valve and a small graduated cylinder filled with acetone was attached to the other valve. The air was evacuated from the heat pipe and the valve closed to isolate the heat pipe from the vacuum pump. The valve separating the heat pipe from the acetone reservoir was opened slightly and 2.5 ml of acetone was drawn in. The valves were then both closed and the surface of the heat pipe was painted black in order to give a known emissivity to the surface for the thermal camera. The heat pipe was then ready for testing.

5.2 Testing

The functionality of the heat pipe was tested using a 20 W heat source and an impinging water jet as a heat sink. The impinging water jet was used to keep the condenser at a constant temperature, and the 20 W heater drove the evaporator. Thermocouples were mounted at both ends of the heat pipe, and thermal images were collected by a microbolometer infrared camera. The experimental setup can be seen in Figure 5.3.

Twenty watts of heat were applied to the heat pipe. When the heat pipe reached steady-state temperatures the data was recorded. This data is then compared with data taken with no working fluid loaded in the heat pipe. This gives the opportunity to view the contribution of the heat pipe to the temperature distribution, and compare it to the contribution due the conduction of the heat pipe walls.

The microbolometer images shown in Figure 5.4 were calibrated to the thermocouples
mounted to the heat pipe. Figure 5.4(a) shows the heat pipe running dry, and Figure 5.4(b) shows it operating successfully. Comparison of the two views shows not only that the source temperature was significantly lowered during the wet run, but that the center section of the heat pipe ran nearly isothermally. The microbolometer data was used to collect a temperature plot along the centerline of the heat pipe during both runs. Inspection of the data in Figure 5.5 verifies the visual impression. The data from the dry run is approximately linear as should be expected from conductive heat transfer governed by Fourier’s law. The data from the wet run also shows strong gradients, but only near the heat source and heat sink. The area in the center runs nearly isothermally. The clear dips that are seen at the left and right sides of the data are the signatures of the low-emissivity stainless steel brackets used to mount the heater and the water jet. The isothermal reading in the center shows successful heat pipe operation.
Fig. 5.4: Microbolometer images of the heat pipe in testing at steady-state temperatures.

(a) 0 ml acetone (dry).
(b) 2.5 ml acetone (optimum fill volume).

Fig. 5.5: Temperature data from both dry and optimum fill test runs.
5.3 Conclusion

The isothermal section of the heat pipe is a clear indication that the heat pipe was operating correctly. This shows that a heat pipe can be built using the UC process. It is expected that if some optimization was done to the heat pipe design, mostly in reducing the wall thickness, much of the end gradients could be reduced. Additional length, or a smaller diameter heat pipe, would also cause a reduction of these effects.
Chapter 6

Panel One

6.1 Introduction to Panels

With the preliminary testing of embedding a Kapton heater and creating a functioning heat pipe using UC completed, the focus of the research shifted to manufacturing structural panels with embedded thermal features. A strong and lightweight honeycomb structural panel was manufactured by Joshua L. George as part of his thesis work [54]. The author’s panels utilized J.L. George’s panel design to test the ability of UC to embed thermal control components into structural panels. Four panels were created using this honeycomb structure. The first panel was intended to act as a control panel for comparison with subsequent panels and only a Kapton heater and thermocouples were embedded. The second panel contained a high-conductivity carbon fiber insert and a Kapton heater and thermocouples. Instead of an integral heat pipe, a COTS heat pipe was embedded into the third panel. A pulsating heat pipe was embedded into the fourth panel.

Each panel was eleven inches long, five inches wide, and half an inch thick. Six tape layers were used as the skin on the top and the bottom, giving a skin thickness of 0.036”. Most of the material between the skins was machined away in the honeycomb structure as designed by George. Embedded components are placed directly above the bottom skin, when the honeycomb is machined away an encapsulating block of aluminum is left around the embedded component.

6.2 Manufacture and Assembly

Panel one was designed to test the feasibility of embedding a heater, thermocouples and harnessing into a honeycomb panel. Figure 6.1 illustrates the panel with different cutaway views. The heater was placed in the large square cavity, and the heater wiring and the
thermocouples occupied the long grooves and channels. The thermocouple placed closest to the heater was meant to capture the temperature there, the thermocouple farthest from the heater is located where the water jet impinges on the panel forming the heat sink.

The cavities and channels in panel one illustrate the methods used to avoid the concerns associated with the sonotrode dipping into voids. First, the heater is embedded using the thermal epoxy as in the preliminary experiments. Second, the channels for the heater harnessing and the hot thermocouple are run parallel to the tapes. Third, the channel for the cold thermocouple is angled sufficiently so as to support the sonotrode at all times.
Fourth, the curvature and radius used for the center thermocouple channel were specifically chosen such that the sonotrode would never be unsupported.

Throughout all of the panel designs all embedded components were embedded as close to the bottom of the panel as was feasible. Due to the order of operations which must occur in order to build a panel, all embedded components must have completely solid material beneath them. The mass penalty that would be imposed by embedding a component near the top of the panel is unacceptable for spaceflight hardware due to the large cost of payload mass to orbit. Therefore, in order to produce an acceptable panel all embedded hardware was placed near the bottom of the panel near the anvil (see Figure 6.1).

To create panel one, tapes were laid down and welded using the sonotrode. After the desired height was reached, cavities for the heater and the grooves for the thermocouples and harnessing were machined out. These cavities and grooves were then filled with the thermal epoxy identified in earlier experimentation and the heater, thermocouples and harnessing were pressed into the epoxy. The heater was then covered with the epoxy to enclose it. After the epoxy cured a machining pass was completed in order to clean off the excess epoxy on the heater and prepare it to support upper layers. This pass clearly showed that the thermocouples and harnessing wires were too close to the dimensions of the grooves, as significant sections were either shaved or removed completely (see Figure 6.2). Possible solutions to prevent this damage included machining larger grooves and cavities, using a smaller gauge thermocouple or trying to embed them dry. Embedding the thermocouples and harnessing dry was decided to be the preferred solution as it was the simplest. The heater was embedded using the thermal epoxy as this method had worked previously.

After some experimentation, it was found that embedding the components dry or without epoxy worked well as long as an occasional drop of super glue was used to anchor the components before the upper layers were applied. Though this worked significantly better than than the attempts with the epoxy, it is recommended that further experimentation with harnessing include channels that are healthily oversized. Figure 6.3 shows the setup and results of the dry embedding.
Fig. 6.2: Damaged thermocouples.

(a) Heater and thermocouple with epoxy.  
(b) Same location after single flat pass with mill.

Fig. 6.3: Dry embedding process.

(a) Thermocouples placed without epoxy.  
(b) First enclosing layer.
After the heater, thermocouples and harnessing were successfully embedded the honeycomb pattern was manufactured. The bulk material was built up over the heater and thermocouples until it reached a height of 0.464”. The honeycomb pattern was then machined into the block of material. In most of the panel the honeycomb was machined down to the back face sheet, which was left as a 0.036” thick face sheet. However, where the heater and thermocouples were placed an encapsulating structure was left to keep them embedded. In Figure 6.4(c) the encapsulating structure around a thermocouple can be seen inside the honeycomb structure.

Following the embedding of the components and the machining of the honeycomb structure a face sheet was applied to the panel using UC. The face sheet was applied according to the methods worked out by Joshua George. Detailed instructions for the application of this skin can be found within his thesis [54]. Six layers of aluminum tape were applied to the honeycomb structure providing it with a skin thickness of 0.036”. The substrate was then removed from the heated anvil and milled from the back side of the completed panel. Figure 6.5 shows the skin application and the completed panel.

6.3 Testing

Panel one was tested to show its thermal characteristics. These test results were used for comparison purposes for panels two through four. Panels two, three, and four were compared to panel one to show the improvements that can be realized by the insertion of heat carrying components.

Preparation for testing included painting the bottom side of the panel matte black so as to provide an emissivity close to one. This provides a good target for the thermal camera. The bottom side is the side closest to the embedded thermocouples. The panel was then mounted in an enclosure and imaged with the thermal camera while recording the thermocouple data. The testing setup can be seen in Figure 6.6.

The embedded heater was driven at 20 watts. An impinging water jet was again used as a heat sink. It impinged directly beneath the thermocouple furthest from the heater. The water was controlled to 30° C. Figure 6.7 shows the thermal camera image during
(a) Machining the honeycomb.  
(b) Completed honeycomb.  
(c) Enclosed thermocouple channel.

Fig. 6.4: Honeycomb.
(a) Skin application.  
(b) Completed panel.

Fig. 6.5: Panel one completion.

Fig. 6.6: Testing setup for all the panels.
the test. The temperature readings from the thermocouples are shown as well. The cold thermocouple read 36.5° C, the hot thermocouple read 76.9°, and the center thermocouple read 49.7° C. The temperature difference between the hot and cold thermocouples was 40.4° C. This corresponds with an effective thermal resistance of 2.0° C/W.

6.4 Conclusion

Panel one showed that thermocouples, heaters, and associated harnessing can be embedded using UC. The channels were carefully laid so as to enable further consolidation above them. The honeycomb design and skin application was successful. Testing was performed using a 20 W heat load. Measurements were taken with both thermocouples and a thermal imager. The temperature difference of 40.4° C was used to evaluate the improvements expected from the other embedded components in panels two through four.
Chapter 7

Panel Two

7.1 Manufacture and Assembly

The design of the second panel was much the same as panel one but included a high conductivity insert which the author hoped would act as a doubler. As described in Chapter 2, a doubler is usually an aluminum plate bolted or glued between a component box and the structure. The doubler acts to add thermal conductivity to the local area enabling the heat to be spread out over the structure more rapidly, thereby keeping the component cooler. An embedded doubler would use a high conductivity insert in the skin to add thermal conductivity and spread heat.

The figure of merit for a doubler intended for space flight is specific thermal conductivity, which is defined as the thermal conductivity divided by the density. The higher the specific thermal conductivity the better the performance per kilogram of mass. Table 7.1 shows the relative specific thermal conductivities of many of the materials commonly used for conductive thermal paths. Due to their high densities, gold, silver, and copper all have low specific thermal conductivities. Aluminum alloys perform 50% better than copper or silver, and elemental aluminum is twice as good as its alloys. The high modulus carbon fiber outperforms elemental aluminum by almost a factor of two, making it the most attractive engineering material for this application. A sample of Nippon Graphite Fiber (NGF) corporation ST-YS90A-125 plain weave was donated by YLA Incorporated.

As there had been some success at embedding a mesh of fibers directly between tape layers during previous attempts, notably a 400 count stainless steel mesh, it was expected that the carbon fiber mesh would easily embed as well. The images in Figure 7.1 show the attempt to embed the carbon fiber into panel two.
Fig. 7.1: Attempted embedding of ST-YS90A-125 carbon fiber.
Figure 7.1(a) shows the carbon fiber weave, a 0-90 orthogonal mesh, prior to the attempt to embed it. Figure 7.1(b) shows the surface of the aluminum tapes after both the tacking and welding processes have occurred. At this point it was already clear that something was not working as expected. After inspecting the build, it was determined that the aluminum tapes had not adhered to the sample either after the tacking procedure or the welding procedure. In addition to the lack of adhesion between tapes, large puffs of black powder were observed when the sonotrode attempted to weld the layers of tape above the carbon fiber. The final image, Figure 7.1(c) shows what had occurred; the mesh of carbon fiber had been shattered into a nest of fibers and there were very few continuous fibers still intact.

It was hypothesized that perhaps the overlapping nature of the weave was at fault and the fibers were cutting each other when pressure was applied from the sonotrode. To test this theory, several threads of carbon fiber were separated out of the mesh and laid parallel to each other on the build and an attempt was made to embed them. These fibers were turned to powder too. The sandwiching layers of aluminum did not bond with the fibers or the aluminum beneath it.

After some experimentation, it was found that small amounts of fiber could be embedded but they were severely fragmented. Unfortunately, the small mass fraction of fibers in the resulting composite material would make an insignificant change in the thermal conductivity of the panel. The root cause of this deviation from expectations was determined to

<table>
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<th>Material</th>
<th>Density (g/cc)</th>
<th>Thermal conductivity (W/m-K)</th>
<th>Specific conductivity (W-m²/kg-K)</th>
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<tr>
<td>Silver</td>
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</tr>
<tr>
<td>carbon fiber</td>
<td></td>
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</tr>
</tbody>
</table>
be the inherent brittleness of the pitch-based carbon fibers. The stainless steel mesh that had previously been embedded using UC was made of 304 stainless, and had significant toughness [74].

Perhaps significantly, success has been found in embedding silicon carbide fibers using ultrasonic consolidation [75]. Silicon carbide fibers have similar properties as the carbon fiber used in these experiments, both being brittle materials with similar tensile strengths. However there are two significant differences between the fibers. First, the modulus of elasticity of the silicon carbide is approximately 43% of that of the high modulus carbon fiber. This makes the silicon carbide somewhat tougher than the carbon fiber. The second difference is in the fiber diameter. The high modulus carbon fibers usually have a diameter less than 10 micrometers. The diameter is purposefully small in order to enhance the flexibility of the fibers. The silicon carbide fibers embedded were on the order of 100 micrometers [48]. This order of magnitude difference in diameter gives the silicon carbide fibers the ability to withstand proportionally higher forces before being damaged.

7.2 Testing

Due to the difficulty of producing panel two it was never tested.

7.3 Conclusion

Panel two was never completed. The brittleness of the high modulus carbon fiber precludes its use as an insert. It was decided that the loss in conductivity was too great to move to other materials.

Between the extremes of the high modulus carbon fiber and the silicon carbide fiber there exists a threshold where brittle materials can be used to manufacture composite materials like those attempted in this panel. The research that would be required in order to locate this threshold and model the interactions there would be an excellent location to begin further research. It is, however, beyond the scope of this effort.
Chapter 8
Panel Three

8.1 Manufacturing and Assembly

The third panel was designed to show that a COTS heat pipe can be embedded into a panel and used to isothermalize it. This is in comparison to the integral heat pipe that was detailed earlier in this thesis. This was done with the understanding that the ability to build an integral heat pipe had already been demonstrated and that a better use of limited time and resources would be to attempt other thermal control technologies. The heat pipes that were selected for use were 1/4” diameter copper/water heat pipes donated for this work by Thermacore, Inc. These heat pipes were selected based on availability (free) and size (10” long).

Panel three was manufactured in a process similar to panel one. A six layer skin was laid down first, followed by the material and machining necessary for the heater and the three thermocouples. The thermocouples and heater were then placed in the cavities. Aluminum tape was built up until it’s height was tall enough to incorporate the heat pipe. Grooves for three heat pipes were then machined running parallel between the heater and the heat sink. See Figure 8.1(a). The heat pipes were epoxied into place using the same thermal epoxy that had been used previously to embed the Kapton heaters. More aluminum tape was then deposited on top of the heat pipes until a height of 0.464” was reached. The honeycomb core was then machined out of the bulk material. As can be seen in Figure 8.1, after machining the honeycomb pattern the heat pipes were encased in an aluminum block. The six-layer top facesheet is then consolidated to the surface of the honeycomb to complete the half inch height panel.

While inspecting the completed part (see Figure 8.1(d)) it was noted that the skin did not consolidated above the heat pipes. A closer inspection (see Figure 8.1(c)) revealed that
(a) Heat pipes inserted.

(b) Embedded heat pipes and honeycomb prior to application of six layer skin.

(c) Close up view of embedded heat pipe.

(d) Completed panel.

Fig. 8.1: Panel three build process.
none of the layers deposited above the heat pipes had actually bonded. The explanation for this is the following: the heat pipes should not have been embedded so close together. The small ridges of material between the heat pipes were left largely unsupported in the lateral direction meaning that it was not stiff enough to support the bonding process. If only one heat pipe had been used in the panel it is expected that the bonding would have been significantly improved.

### 8.2 Testing

Panel three was tested for functionality in the same manner as panel one. The thermal image can be seen in Figure 8.2. Gradients can be seen near the heat source and sink, while the intervening regions are close to uniform. The overall temperature difference between the hot and cold thermocouples was 26.1°C. This corresponds to a thermal resistance of 1.3°C/W. This is a decrease in thermal resistance of 35%. These results show that the embedded heat pipes are augmenting the heat carrying capacity of the panel and functioning as designed.
8.3 Conclusion

Panel three successfully showed a 35% decrease in thermal resistance as compared to panel one. COTS heat pipes were shown to be easily incorporated into a panel. The poor bonding above the heat pipes has reiterated the need to avoid thin ribs in embedded structures.
Chapter 9

Panel Four

9.1 Manufacture and Assembly

Panel four was intended to demonstrate a relatively new technology: the pulsating heat pipe. A pulsating heat pipe would be simpler to manufacture using UC than a wicking heat pipe as smooth walled tubes may be used in lieu of the wick structures that are required for regular heat pipes. When panel four was designed it was hoped that simply embedding a series of tubes extending throughout the panel would be sufficient to distribute the heat, combining some of the simplicity of the doubler with some of the capability of the heat pipe.

In pursuit of the goal to combine the abilities of a doubler and a heat pipe, a panel with an embedded serpentine channel was manufactured. A heater and thermocouples were embedded in the same manner as panel one. Above that layer the channels intended for use in the pulsating heat pipe were laid. Figure 9.1 shows the design. The embedded channels did not significantly affect the mass of the panel as the channels shared the same walls as much of the honeycomb and the majority of the material between them could still be machined away as usual. Figure 9.2 shows a series of images during the build.

Unfortunately, this design pushed the limits of what size of gaps between parallel tapes can be reliably filled with sealant. The walls around the channels were only 0.062” thick, and some of the pores were not sufficiently long for the sealant compound to plug them, resulting in leaks. During the fourth or fifth attempt to seal it, the part was accidentally overheated, resulting in the delamination of the top skin. The damaged part can be seen in Figure 9.3. It was decided that a second attempt would be made to build the panel and changes would be made in the design to increase the wall thickness and hopefully improve the sealing characteristics of the part.
Fig. 9.1: Cutaway view of the serpentine channel in panel four.

(a) Serpentine channel.

(b) Honeycomb.

(c) Close up of honeycomb.

(d) Finished panel ready for sealant.

Fig. 9.2: Manufacturing process for panel four.
The design of panel 4a can be seen in Figure 9.4. If the serpentine channel design for panel four was kept, merely increasing the wall thickness would significantly impact our ability to remove material from the honeycomb and would leave the bottom half of the panel almost completely solid, not a desirable trait for a spacecraft due to the high cost of mass to orbit. It was decided to bring all the channels closer together and increase the wall thickness on the perimeter of the serpentine channel to 1/4”. This design would result in significant mass savings and hopefully allow the gaps between parallel tapes to be sealed. Constructing the channel following this design did succeed in solving the problem that was encountered in panel four and the pores were able to be sealed.
9.2 Testing

Like previous panels, panel 4a was tested by heating the embedded Kapton heater with 20 watts and placing an impinging jet of water in contact with the opposite corner of the panel (see Figure 17). Temperature measurements were taken from a thermocouple embedded near the heater and a second thermocouple embedded near the contact area for the jet of water. A thermal camera was also used to photograph the temperature differences across the panel. Success or failure was determined by the difference in the temperatures recorded during the testing of panel one and those recorded during the testing of panel 4a. Any significant drop in the temperature difference would be due to the contribution of the pulsating heat pipe to the total conductive capability of the panel. If there was little to no temperature difference between panel one and panel 4a then only the aluminum was conducting the heat and the pulsating heat pipe was not functioning.

The temperature difference between the hot and cold thermocouples was 41.0° C. This equates to a thermal resistance of 2.1° C/W. This is close enough to the results of panel one that it can safely be concluded that the pulsating heat pipe was not operating as planned. The slight increase can likely be attributed to external environmental effects, such as the ambient temperature in the laboratory or the effectiveness of the cardboard enclosure in minimizing convective currents from the laboratory HVAC system. The thermal image is shown in Figure 9.5.

It was determined that the failure of the pulsating heat pipe in panel 4a was not due to any flaws created using UC. The reason for this failure lies not in the UC process but in the author’s initial understanding of the concept of a pulsating heat pipe. A pulsating heat pipe transfers sensible heat, i.e. it heats and cools the liquid phase of the working fluid, physically moving that liquid back and forth between the heat source and the heat sink in order to heat and cool it. This is in contrast to regular heat pipes which transfer latent heat, meaning the working fluid carries heat through evaporation and condensation, working almost isothermally.

As the working fluid is heated by the heater part of it evaporates and expands, pushing
the liquid working fluid on each side of the bend near the heat source down toward the heat sink. As this fluid is pushed down the channel, the cool working fluid near the heat sink is pushed further along the channel, which brings that cool fluid up to the heat source. At this time, the cool liquid now at the heat source is warmed and the hot liquid now at the heat sink cools. The warming fluid will evaporate some of the liquid into vapor and the cooling fluid will condense some of the vapor into liquid. At this point the pressure differential reverses, and the new vapor will force the warmed liquid back down the channel to the heat sink, and the cooled liquid will be forced back up the other side to the hot bend again. The process then repeats \textit{ad infinitum}.

In panel 4a the traveling slugs of liquid are in close proximity to one another to the extent that significant heat transfer between them is possible. The effect of this is that the moving warm slugs cannot carry heat to the heat sink, as their heat is exchanged with the cool slug traveling in the opposite direction in the adjacent channel. This close proximity and heat transfer disrupts the driving force of the pulsating heat pipe, making it inoperable.
9.3 Conclusion

The fourth panel was intended to demonstrate that a functioning pulsating heat pipe could be produced and embedded into a panel using UC. Instead it was shown that pulsating heat pipes are not amenable to embedding in panels. The leaks that were easily sealed in a quarter inch wall for the integral heat pipe were not able to be sealed in the sixteenth of an inch wall used for the first pulsating heat pipe. Though the leakage concern was dealt with in panel 4a, conduction between adjacent channels sabotaged the driving force, making the pulsating heat pipe inoperable. Pulsating heat pipes were decided to be a poor match for panels built with ultrasonic consolidation.
Chapter 10

Conclusion

10.1 Results

This thesis documents the attempt to design, manufacture, and test thermal control components integrated into structural panels produced using ultrasonic consolidation. This proof-of-concept effort was designed to demonstrate that realistic spacecraft hardware can be manufactured using UC technology. Several thermal control technologies were attempted, including integral heat pipes, embedded temperature sensors, embedded heaters, embedded harnessing, integral high-conductivity thermal doublers, the embedding of commercial off-the-shelf (COTS) heat pipes, and the manufacture of integral pulsating heat pipes.

Those technologies that were the most successful were the ones that were embedded directly, such as the thermocouples, heaters, and COTS heat pipes. All three worked well, when due care was paid to the basic design rules of ultrasonic consolidation. The integral heat pipe was also a success, though much work needs to be done to make the design higher performance. The integral doubler and integral pulsating heat pipes were impressive failures. Lessons to be learned from the failures include the knowledge that brittle materials are particularly sensitive to ultrasonic loads and a thorough understanding of the design under test is required before building multiple structures incorporating that design.

10.2 Responsive Space Revisited

The rebuilds required for completion of panel four pushed the current state of the art to the limit. At the current state of the technology it takes one student working six to eight hours a day two weeks to produce a custom 5” x 11” panel with embedded thermal control hardware. Fully half of this time is spent in software generating CAD models and machining paths. This software work is necessary in order to work around certain limitations in the
software that produces the machine paths for the ultrasonic consolidation and machining operations.

With optimizations in software and machining paths, the author believes that this current generation of UC hardware could produce an integrated structure (with embedded thermal control) for one or possibly two 3U cubesats in a week’s time. This would require four panels that are 4” x 12” and two panels that are 4” square. This could be accomplished without any upgrades in hardware. The optimizations would include updating the software to handle this particular workflow, where large blocks of material are first built up and then machined away. Also included would be optimizations in the timings and machining paths followed by the CNC during the build and machining operations.

Larger hardware, for example Nanosat or ESPA class satellites between two foot and four foot dimensions would require significant upgrades in the hardware. Deposition rates would have to be increased, requiring a larger sonotrode and wider and thicker aluminum tape. Machining rates would also have to be improved by the incorporation of a larger mill head into the carriage assembly. Also needed would be a larger anvil and enclosure.

This thesis effort has shown the viability and limits of using Ultrasonic Consolidation for embedded spacecraft thermal control. Ultrasonic Consolidation provides new capabilities for system designers. Application of these new capabilities to spacecraft design has only just begun.
References


