TOPOLOGY DESIGN AND FREEFORM FABRICATION OF DEPLOYABLE STRUCTURES WITH LATTICE SKINS

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Abstract

Purpose: Solid freeform fabrication is particularly suitable for fabricating customized parts, but it has not been used for fabricating deployable structures that can be stored in a compact configuration and deployed quickly and easily in the field. In previous work, lattice structures have been established as a feasible means of deploying parts. Before fabricating the parts with a selective laser sintering (SLS) machine and Duraform® Flex material, lattice sub-skins are added strategically beneath the surface of the part. The lattice structure provides elastic energy for folding and deploying the structure and constrains expansion upon application of internal air pressure. In this paper, a procedure is presented for optimizing the lattice skin topology for improved overall performance of the structure, measured in terms of deviation from desired surface profile.

Design/methodology/approach: A ground structure-based topology optimization procedure is utilized, with a penalization scheme that encourages convergence to sets of thick lattice elements that are manufacturable and extremely thin lattice elements that are removed from the final structure.

Findings: A deployable wing is designed for a miniature unmanned aerial vehicle. A physical prototype of the optimal configuration is fabricated with SLS and compared with the virtual prototype. The proposed methodology results in a 78% improvement in deviations from the intended surface profile of the deployed part.

Originality/value: The results provide proof-of-concept for the use of lattice skins as a deployment mechanism. A topology optimization framework is also provided for designing these lattice skins. Potential applications include portable, camouflaged shelters and deployable aerial vehicles.

Key Words: deployable structures, topology optimization, lattice structures, solid freeform fabrication, selective laser sintering
1. Introduction

Deployable structures can be transformed from a compact configuration to a predetermined, expanded form for full functionality (Gantes, 2001; Pellegrino, 2001). Deployment mechanisms include pneumatic arches, membranes, pantographs, and tensegrity structures, as found in applications ranging from common umbrellas to temporary shelters to expandable satellite booms for solar arrays or antennas (Gantes, 2001; Pellegrino, 2001). Collectively, these deployment mechanisms often restrict the geometry of a deployed structure to symmetric, polygonal, or spherical shapes and make it difficult to rapidly customize the geometry and functionality of the device.

To overcome these limitations, lattice skins have been introduced as a deployment mechanism, along with an accompanying solid freeform fabrication approach for realizing them. The design and freeform fabrication process is illustrated in Figure 1. Beginning with a part of arbitrary surface profile and hollow interior, lattice sub-skins are added beneath the surface of the structure, as illustrated in Step 1. As illustrated in Figure 2, two types of lattice skins can be applied. Open lattice skins are truss-like structures that provide direct reinforcement of the surface of a part. Closed lattice structures connect the surface of a part to a concentric, inner skin. When air pressure is applied between the concentric skins, the closed lattice structures constrain expansion to maintain the desired surface profile of the part. In Step 2, the lattice structure is optimized with a topology optimization procedure described in detail in Section 2. If the part is larger than the build chamber, it is decomposed in Step 3 and fabricated as a collection of parts that are subsequently joined together. In Step 4, the part is fabricated using selective laser sintering (SLS) technology and a flexible, elastomer material called Duraform® FLEX. Processed parts are infiltrated with polyurethane to make the structures air-tight, and parts are assembled and joined in Step 5. The flexible structure can be folded in Step 6 for ease of storage and transport and then deployed in the field via a combination of elastic strain energy and pneumatics in Step 7. In this process, the lattice structure serves several functions. First, during the folding step, it stores strain energy that can be returned upon unfolding to help deploy the structure into its original configuration. Second, in its deployed form, the lattice structure supports the surface of the flexible part to prevent collapse and distortion of the desired surfaces.
Finally, if elastic energy is insufficient for deploying a large structure under its own weight, air pressure is applied inside the structure, and the lattice skin constrains the expansion of the structure to prevent balloon-like inflation and preserve desired surface profiles. If desired, thermoset polymers or other coatings can be applied to the deployed part to rigidize it in Step 8.

Lattice structure deployment mechanisms offer a number of advantages, relative to conventional deployment mechanisms. They provide shape control of relatively arbitrary, freeform geometries; occupy very little space in the build chamber; and do not require small-scale pivots or joints that can be difficult to fabricate and energy-intensive to deploy. They offer a combination of low relative density and high effective stiffness (a common characteristic of cellular or honeycomb materials (Gibson and Ashby, 1997)), providing high levels of rigidity for controlling deployment of a part without significantly impacting its relative density for collapsed storage and transport. The lattice skin can be used for multifunctional purposes, such as convective cooling when filled with air or blast protection when filled with earth, foam, or other materials. Finally, lattice skins are conducive to portable deployment, requiring only a portable air pump, rather than energy-intensive erection equipment or motors.

The use of lattice structures for deployment is unique to this research effort, with prior applications of lattice, cellular, or honeycomb materials focused primarily on lightweight strength and stiffness, energy absorption, and heat transfer (e.g., (Gibson and Ashby, 1997; Evans et al., 2001; Hayes et al., 2004; Seepersad et al., 2004; Wang et al., 2006)) or on solid freeform fabrication techniques for those applications (Zimbeck and Rice, 1999; Gervasi and Stahl, 2004; Oruganti et al., 2004; Stampfl et al., 2004; Brooks et al., 2005; Rosen, 2007; Williams and Rosen, 2007). In previous work by the authors, feasibility studies of lattice skin deployment have been conducted, and promising results have been reported (Maheshwaraa, 2007; Maheshwaraa et al., 2007). In this work, the focus is on topology design optimization of inflatable closed lattice skins for improved surface precision of deployed structures. A ground structure-based topology optimization approach is presented as a means of formalizing Steps 1 and 2 of the methodology.
in Figure 1. The approach is applied to the design of inflatable closed lattice structures for a UAV application.

2. Topology Optimization of Lattice Structures for Deployment

One of the most influential steps in the methodology for lattice skin deployment (Figure 1) is the design of the lattice structure (Step 2). Previous investigations have shown that the dimensions and arrangement of the lattice structure have a significant impact on the overall surface profile of the deployed part (Maheshwaraa et al., 2007). In fact, for a representative airfoil part, strategic adjustments of the thicknesses and configuration of the closed lattice structure resulted in a 70% reduction in deviations from the part’s intended surface profile (Maheshwaraa et al., 2007). Since the dimensions and configuration of the lattice structure have such a significant impact on the surface profile of the deployed part, a formal topology design procedure has been devised for systematically designing the lattice structure. The topology design procedure is illustrated in Figures 3 and 4.

2.1 Finite Element Analysis for Topology Design

As shown in Figure 3, the topology design procedure begins with a CAD file of the part. For a closed lattice configuration, a concentric skin is added beneath the surface of the part, as illustrated in the bottom left of Figure 3. The two skins are connected with a dense grid of lattice elements. From this CAD model, a finite element model is created in ANSYS (2006). The concentric skins are modeled with two-dimensional quadratic (8-node) elements (PLANE183) for the two-dimensional cross sections investigated in this paper. The lattice elements are modeled with beam elements (BEAM3), with nodes located at intersections of lattice elements and at interfaces between lattice elements and concentric skins. The density of the material is used to simulate the body weight of the structure in the finite element model, and internal (gauge) pressure is applied to simulate pneumatic inflation in the space between the concentric skins, as illustrated in Figure 4. Additional loading profiles and displacement constraints are
applied, as appropriate for specific applications. Large deformation analysis capabilities are activated in the ANSYS finite element model, and material properties for Duraform® FLEX are applied as follows: tensile modulus of 3.8 MPa, density of 486 kg/m³, and poisson ratio of 0.45. Preliminary work has verified the accuracy of this ANSYS-based finite element model for predicting the structural behavior of Duraform® FLEX in lattice skin applications (Maheshwaraa et al., 2007). Specifically, the model is useful for predicting the surface deviation of the deployed part, where surface deviation is measured as the displacement of any node on the predicted profile of the deployed part relative to its position in the intended profile of the deployed part.

The finite element model of the lattice structure is created using an APDL file, which is iteratively adjusted and re-executed during the optimization process. APDL is the ANSYS Parametric Design Language, a scripting language that allows the user to automate tasks and build a model in terms of parametric variables (2006). In the APDL file, a separate variable governs the in-plane thickness of each lattice element. The APDL file is interfaced with iSIGHT design exploration software (2005), which couples the analysis with an optimization algorithm. iSIGHT executes an optimization algorithm to iteratively adjust the dimensions of the lattice elements, as a means of minimizing the deviation of the outer surface of the part from its intended, deployed profile. Specifically, for each iteration of its optimization algorithm, iSIGHT adjusts the in-plane thickness of each lattice element by updating its associated variable in the APDL file, executing the APDL file in ANSYS, and then reading the ANSYS output file to assess the impact of the change on the surface deviation of the part. The optimization process in iSIGHT proceeds in two stages: a genetic algorithm to explore the nonlinear design space, followed by a gradient-based, sequential quadratic programming algorithm for further refining the best structure identified by the genetic algorithm.

1 The intersections of crossed lattice elements are accommodated by dividing each of the two intersecting elements into two BEAM3 elements with coupled in-plane thicknesses. The dimensions of the inner and outer concentric skins are not adjusted by the optimization algorithm.
2.2 Ground Structure-Based Topology Design with Penalty Functions

The goal of the design effort is to tailor not only the dimensions but also the topology of the lattice structure to achieve the intended deployed surface profile as closely as possible. Towards this goal, the topology of the lattice structure is represented and modified using a discrete topology design approach based on ground structures (cf. (Topping, 1984; Kirsch, 1989; Ohsaki and Swan, 2002) for relevant reviews and (Dorn et al., 1964) for an introduction). As shown on the right side of Figure 4, the lattice structure is modeled as a ground structure, consisting of a grid of regularly spaced nodes that are connected with beam finite elements in a predetermined pattern. The density of the ground structure is selected by the practitioner to provide a network of candidate lattice elements that is sufficiently dense to significantly improve the surface deviation of the part. In the ground structure, each finite element is assigned a constant length, \( l_i \), and a variable in-plane thickness, \( t_i \), as illustrated on the right side of Figure 4.\(^2\) The optimization algorithm adjusts the thickness of each element indirectly by varying the scaling factor, \( \rho_i \), of each element, which is related to its in-plane thickness, \( t_i \), and the maximum allowable in-plane thickness of a lattice element, \( t_{\text{max}} \), according to Equation (3) in Figure 4. In keeping with the ground structure approach, the lattice element scaling factors and corresponding thicknesses vary between large upper bounds (3 cm for \( t_{\text{max}} \), in this example) and extremely small lower bounds (0.0001\( t_{\text{max}} \), in this example) during the design process (cf. Equation (1) in Figure 4). The design variables are adjusted to minimize the maximum displacement, \( \delta \), of any node on the outer surface of the part relative to its intended position, thereby minimizing the surface deviation from the desired surface profile. A constraint is placed on volume fraction, \( v \), defined as the fraction of the maximum possible in-plane area, \( A_{\text{max}} \), occupied by lattice elements with uniformly maximum thickness (cf. Equations (2), (4) and (5) in Figure 4).\(^3\) Under the restriction of the volume fraction constraint, the optimization algorithm strategically allocates material to the elements with the greatest impact on the surface deviation of the part. After the optimization algorithm converges, the elements have different in-plane thicknesses. Elements with in-plane

\(^2\) All elements are assigned a unit depth in the out-of-plane direction. Therefore, the in-plane thickness, \( t_i \), of element \( i \) is equivalent to its cross-sectional area.

\(^3\) A stress constraint could also be added to the problem formulation. It was not included in the present work because maximum in-plane stresses in the lattice elements were observed to be at least an order of magnitude less than the tensile strength of the material for the example reported in Section 3.
thicknesses near the lower bound do not contribute significantly to the surface profile of the deployed part, since the lower bound is several orders of magnitude smaller than the upper bound and the dimensions of the surrounding structure. Therefore, elements with thicknesses near the lower bound are removed in a post-processing step, and they are not depicted in the final design. Each element removal constitutes a topology change in the lattice structure. Thick elements remain in the final lattice structure with their optimized thickness values. This type of ground structure-based topology design method is frequently applied to problems with truss-like structures (Ohsaki and Swan, 2002) because it offers reduced computational expense, relative to continuum-based approaches (cf. (Eschenauer and Olhoff, 2001) for a review), and straightforward translation into finalized truss designs. Ground structure methods have also been applied to problems such as compliant mechanisms (Saxena and Ananthasuresh, 2001) and crashworthy structures (Pedersen, 2003) that incorporate the large deformation analysis required for the present example.

One of the unique aspects of the topology optimization approach is the penalization scheme. The penalization scheme is implemented as a penalty factor, $p$, applied to the scaling factor, $\rho$, in the calculation of volume fraction, $\nu$, in Equation (4) in Figure 4. The penalty factor, $p$, penalizes intermediate thickness elements with an artificially high contribution to the volume fraction. This penalization scheme is designed to encourage convergence to either lower or upper bounds of element thickness and to discourage intermediate element thicknesses. The effectiveness of the penalty factor depends on its magnitude. A penalty factor value of 3 is used in this research. Parametric studies of penalty factor values for the present application indicate that smaller values are not effective for discouraging intermediate element thicknesses while larger values promote premature convergence of the search process, resulting in undesirably high objective function values (i.e., undesirably high deviations from the desired surface profile).

Manufacturability is the primary rationale for this penalization scheme. If the penalization scheme were removed from the topology optimization formulation (e.g., by setting the penalty factor, $p$, equal to one in Figure 4), the resulting topology would include elements with a broad variety of thicknesses, ranging from the lower bound to the upper bound on thickness. Elements with thicknesses near the lower bound contribute negligibly to structural properties, and they are
removed from the final topology. Elements with relatively large thicknesses (0.5 mm or larger) are manufacturable with the SLS process and remain in the final structure. Elements of intermediate thickness (e.g., 0.2 mm) are problematic because they are not manufacturable with the SLS process, but they can have a significant collective effect on structural properties. By penalizing the contribution of intermediate thickness elements to the volume fraction constraint, the penalization scheme seeks to replace intermediate thickness elements with thicker elements that provide greater stiffness with nearly equivalent contributions to the volume fraction. Accordingly, optimized topologies that are realized with the penalization scheme tend to exhibit element thicknesses that are clustered near their upper and lower bounds.

The penalization scheme builds on related work in ground structure-based topology optimization, but it is significantly different with respect to its purpose and means of implementation. For example, Sigmund (1995) devised a function for penalizing element length and/or location, to obtain structures with generally longer or shorter elements. The function penalizes deviation from a desired element length (or location in a ground structure). This type of approach does not address the issue of element in-plane thickness and manufacturability. Several authors impose manufacturability without penalty functions by specifying a discrete set of available element sizes for selection by a genetic algorithm (cf. (Kaveh and Kalatjari, 2003; Tang et al., 2005)). In contrast, the approach proposed in this paper preserves the continuous nature of the problem, which is exploited in the gradient-based phase of the optimization process and avoids unnecessarily assigning discrete element sizes. The proposed approach is most similar to the penalty functions in the SIMP (Solid Isotropic Material with Penalization) or artificial material approach to continuum topology optimization (Bendsoe, 1989; Sigmund, 2001). In the SIMP approach, intermediate stiffnesses are penalized to encourage convergence to solutions with predominantly solid (maximum density) and void (minimum density) regions. However, the approach proposed in this paper applies the penalty function to the volume fraction, rather than the stiffness, to avoid distortion of element thicknesses or stiffness matrices and to preserve the accuracy of the displacement and surface deviation calculations that determine the objective function values for the present application.
The proposed topology optimization approach also differs from similar efforts to design lattice, honeycomb, or cellular structures for additive manufacturing applications. Much of the foundational research in cellular and honeycomb materials focuses on developing analytical expressions for the properties of standard cell topologies such as hexagonal, square, or triangular cells (cf. (Gibson and Ashby, 1997; Evans et al., 1999; Evans et al., 2001; Hayes et al., 2004)), and several additive manufacturing researchers have investigated the challenges of fabricating these standard structures (Zimbeck and Rice, 1999; Gervasi and Stahl, 2004; Oruganti et al., 2004; Stampfl et al., 2004; Brooks et al., 2005; Wang, 2005). Other researchers have focused on developing ground structure-based or continuum topology optimization approaches for designing lattice or cellular structures (Sigmund, 1994; Sigmund, 1995; Hyun and Torquato, 2002; Seepersad et al., 2004; Seepersad et al., 2006; Seepersad et al., 2007), but they focus primarily on designing periodically repeating unit cells of material. In notable recent work, Rosen and coauthors demonstrated a topology design optimization technique for realizing functionally graded lattice structures (Wang, 2005; Wang et al., 2006; Rosen, 2007; Chu et al., 2008). The approach proposed in this paper accommodates not only functionally graded lattice structures but also the highly nonlinear material behavior associated with the elastomeric materials that comprise the lattice skins. The approach is demonstrated in the next section.

3. Deployable UAV Wing Example

The topology design approach is applied to design a deployable UAV wing that can be folded into a compact form and then deployed to its full size using an air pump. Several basic assumptions are applied to the UAV wing, as documented in Table 1 and Figure 5. A standard profile, NACA 4420, is chosen for the cross-section of the wing (Abbott and Von Doenhoff, 1959; Moran, 1984). The aerodynamic characteristics of the cross-section are analyzed with a linear vortex panel method (Katz and Plotkin, 2001) and a boundary layer growth method (Moran, 1984). One of the results is the coefficient of pressure ($C_p$) along the outer profile of the airfoil section. The coefficient of pressure can be used to calculate the pressure profile along the outer surface of the wing as follows:
\[ C_p = \frac{P - P_1}{\sigma \nu_1^2} \]  

where \( \sigma \) is the density of air, \( \nu_1 \) is the velocity of surrounding air at ambient pressure \( P_1 \), and \( P \) is the pressure profile. As a worst case scenario for this analysis, the wing section is assumed to be crushed by equivalent pressure acting on the top and bottom surface.

[INSERT FIGURE 5.]
[INSERT TABLE 1.]

### 3.1 UAV Wing Modeling and Topology Optimization Setup

For the purpose of topology design, a two-dimensional cross-section of the wing is modeled as shown in Figure 6. The outer profile of the wing follows the NACA 4420 profile and the dimensions documented in Table 1. The outer and inner skins are assigned a thickness of 1.5 mm, and the concentric distance between them is 10 mm. The material is assumed to be Duraform FLEX with a Young’s modulus of 3.8 MPa, a Poisson ratio of 0.45, and a density of 486 kg/m\(^3\), based on physical experiments performed in the laboratory. A dense network of lattice elements is added between the skins, as shown in Figure 6. The network is denser in regions of relatively high curvature. This strategy is based on the results of preliminary topology design exercises, which indicated that reducing the density of the lattice network leads to significant deterioration of the overall objective function while increasing the density provides insignificant improvements relative to the increased computational expense of the denser network.

[INSERT FIGURE 6.]

A finite element model of the cross-section is created in ANSYS finite element analysis software (2006). The inner skin and outer skin are modeled using PLANE183 two-dimensional elements, and the lattice elements are modeled using BEAM3 one-dimensional elements. The edge length for the two-dimensional mesh is set at 0.0005 mm. Vertical and horizontal displacements are constrained at the left-most point of the cross-section, and vertical displacement is constrained at the right-most point. The pressure profile from Equation (1) is applied to the outer surface of the
wing. Air pressure is applied between the inner skin and the outer skin at 700 Pa (gauge) to maintain the intended profile of the wing. Atmospheric pressure is applied to the inside surface of the inner skin. The self weight of the structure is simulated by setting a gravity load in ANSYS.

The next step is to optimize the topology of the lattice structure. The topology optimization problem is challenging. There are 76 lattice elements in the leading (left) and trailing (right) edges of the initial ground structure illustrated in Figure 6, and there are a total of 5700 finite elements in the entire structure. This nonlinear problem is expensive to solve iteratively with ANSYS. To reduce computational expense, the optimization problem is split into two phases. First, the UAV wing is optimized by varying the thickness of lattice elements in the left section of the UAV wing illustrated in Figure 6. After the left section is optimized, the lattice elements in the left section are fixed with their optimal thickness values. Then, the intermediate structure is optimized by varying the lattice elements in the right section of the UAV wing. The split is justified by the architecture of the part; the flat middle section of the wing separates the two sections and reduces variable interactions between sections.

Each phase of the topology optimization is governed by the problem formulation in Figure 4. The penalty factor, $p$, is assigned a value of three, and the maximum in-plane thickness of a lattice element, $t_{\text{max}}$, is limited to 3 mm. Other constraints are listed in Figure 4. At the beginning of the topology optimization process, the scaling factor, $\rho$, for each element ($i$) is assigned a random value within the bounds specified in Figure 4. For the initial lattice structure, the maximum surface deviation was 6.11 mm, and the volume fraction, $v_f$, was approximately 0.5. Each optimization (left section and right section) was performed by a genetic algorithm, followed by a sequential quadratic programming algorithm, which refined the best solution identified by the genetic algorithm. The algorithm parameters are documented in Table 2.

[INSERT TABLE 2.]

[INSERT TABLE 3.]
3.2 Results of Topology Optimization of UAV Wing

The results of the topology optimization of the left and right sections of the lattice structure are summarized in Table 3. As a result of the topology optimization process, the left lattice structure retained 14 of the 30 elements in its initial ground structure, as illustrated in Figure 7. An element was removed from the initial ground structure if its final, optimized thickness was near the lower bound (less than 0.1 mm in this example). The final values of the in-plane thickness of each element are listed in Table 4. As documented in Table 3, the in-plane area of the lattice structure was reduced to an in-plane area of 118 mm$^2$, which corresponds to a volume fraction of 0.24, relative to the maximum in-plane area of the elements, 491 mm$^2$ (calculated with all elements assuming a maximum thickness of 3 mm). The maximum surface deflection in the optimized UAV wing was 1.98 mm, which is 65% less than the pre-optimized deflection of 6.11 mm. The deflection value decreases because the optimized structure distributes material more effectively for maximum stiffness and reduced weight of the structure.

[INSERT FIGURE 7.]
[INSERT TABLE 4.]

The overall surface deviation was further minimized by optimizing the right section. During this process, the lattice elements in the left section were fixed with their optimal lattice element thickness values from the previous optimization. The topology optimization process reduced the number of lattice elements in the left ground structure from 46 to 25, as illustrated in Figure 8. The in-plane thickness of each retained element is listed in Table 5. The maximum surface deviation was reduced another 33%, from 1.98 mm (after optimization of the left section) to 1.30 mm.

[INSERT FIGURE 8.]
[INSERT TABLE 5.]

The final lattice element configuration with 39 retained lattice elements in the left and right sections of the UAV wing is shown in Figure 9. The maximum nodal deflection of the UAV
wing after optimization is improved by 78% from 6.11 mm to 1.30 mm for a structure with bounding dimensions of 27 cm by 40 cm. The surface deviations of the UAV wing before and after optimization are illustrated in Figure 10.

The results were validated by repeating the optimization procedure and by analyzing the convergence trends. Since the genetic algorithm is stochastic, different results are obtained for each trial. Three trials were conducted, and each resulted in a final surface deviation of less than 2 mm. Also, convergence plots were studied for gradual convergence to a final solution. As illustrated in Figure 11, each convergence plot showed a gradual (but somewhat stochastic) convergence from the genetic algorithm followed by a uniform convergence from the sequential quadratic programming algorithm. Validation also focused on the penalty function, which had a remarkable impact on the final topology. Without the penalty function, the final, optimized element thicknesses assumed a relatively uniform distribution of values between the lower bound and the upper bound, resulting in several elements with thicknesses that were neither negligible nor manufacturable (i.e., $0.1 \leq t \leq 0.5$ mm). After the penalty function was implemented, final, optimized element thicknesses bifurcated into two distinct sets. One set clustered near the upper bound, with element thicknesses between 0.7 and 3 mm. The other set of element thicknesses bunched near the lower bound, with values less than 0.1 mm. There were no element thicknesses in the non-negligible, non-manufacturable region (i.e., $0.1 \leq t \leq 0.5$ mm) for any of the optimization trials. Maximum stresses in the final part were approximately 80 kPa, relative to a reported tensile strength of 1.8 MPa for Duraform FLEX (www.3DSystems.com).

3.3 Final Model and Prototype

The results of the topology optimization procedure were used to design a prototype of the UAV wing. The optimal lattice topology was used to generate the cross section of the prototype
shown in Figure 12. As shown in the figure, the lattice cross-sections were repeated every 7 mm along the span of the wing to ensure that the wing could be folded. The span-wise depth of each lattice structure was fixed at 2 mm. One end of the UAV wing remained open for removing unsintered powder from the internal voids. Figure 13 displays the endcap that was used to seal the open end of the UAV wing.

[INSERT FIGURE 12.]
[INSERT FIGURE 13.]
[INSERT FIGURE 14.]
[INSERT FIGURE 15.]

The part was fabricated using Duraform® FLEX material in a selective laser sintering (SLS) machine and post-processed to remove unsintered powder. The UAV wing was then infiltrated using a mixture of ST-1040A and ST-1040B polyurethane (www.bjbenterprises.com/pdf/ST-3040.pdf) to make it air tight. The open end of the UAV wing was attached to its endcap with adhesives. The UAV wing was rolled along the span of the wing to condense it into a compact form as shown in Figure 14. The bounding dimensions of the folded UAV wing were 120 mm (length) x 70 mm (width) x 60 mm (height), whereas the bounding dimensions of the deployed UAV wing were 380 mm (length) x 100 mm (width) x 20 mm (height). The UAV wing was inflated successfully using an air pump at 1500 Pa (gauge pressure). The profile after inflation is shown in Figure 15.
4. **Closure**

A methodology has been presented for deploying flexible, freeform structures with lattice skins as the deployment mechanism. In this paper, the focus has been primarily on the methodology for generating lattice structures and optimizing them so that the deployable structure maintains its profile after deployment. A ground structure approach for topology optimization of the lattice structure has been presented and applied to a representative, deployable UAV wing. By adjusting the lattice structure density and configuration, the topology optimization procedure resulted in a 78% improvement in maximum surface deviation when compared with a non-optimized structure. The proposed ground structure approach penalizes lattice elements of non-manufacturable thicknesses, resulting in lattice structure topologies that meet manufacturability requirements while minimizing surface displacement as much as possible. A physical prototype of the structure was fabricated with SLS and Duraform® FLEX material. It was successfully folded into a package with a maximum dimension of 120 mm, relative to a maximum dimension of 380 mm for the deployed wing. When coupled with prior feasibility studies, these results provide additional proof of concept for the use of lattice skins as deployment mechanisms.

Opportunities for ongoing work include increasing the comprehensiveness of the topology optimization procedure and formalizing post-processing steps for infiltrating and rigidizing deployed parts. For the UAV airfoil, the topology optimization procedure is performed in two dimensions for cross-sections of the lattice skin and then periodically repeated in the span direction. In future work, the lattice skin needs to be designed in three dimensions with characteristics such as fold-ability taken into account. For large structures, it may be necessary to reduce computational complexity by continuing to design the lattice skin in spatial segments, but more systematic methods for decomposing the problem are needed. It would also be interesting to include shape optimization of the concentric skins and lattice structure, in addition to the topology design procedure. With respect to post-processing, repeated infiltration with polyurethane appears to provide adequate short-term air tightness for pneumatic inflation, but further work is needed to identify thermoset polymers or other spray-on materials for rigidization and long-term stability of the deployed structure. Finally, it would be interesting to explore the
possibility of virtually collapsing parts and fabricating them in their collapsed form, as a replacement for the current process of decomposing large parts into manufactureable pieces.

5. Acknowledgements

The authors gratefully acknowledge financial support from the University of Texas at Austin. The authors owe a special thanks to Dr. David Bourell for his valuable insights on SLS and motivation for the study of deployability, to Jennifer Torkelson for her help with the Duraform® FLEX material and infiltrant, and to the undergraduate students who participated in this project: Brian Nowotny, Trevor Page, Catherine Tradd and Brandon Walther.

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Figure 1. Design and solid freeform fabrication methodology for freeform deployable parts with lattice skins.
Figure 2. Open and closed lattice structures (Maheshwaraa et al., 2007).
Figure 3. Topology design process.
Minimize
\[ \delta, \text{ maximum displacement of any node on the outer surface relative to its intended position} \]

Find
\[ \rho_i, \text{ scaling factor for each lattice element, } i \]

Satisfy

Bounds
\[ 0.0001 \leq \rho_i \leq 1.0 \]  \hspace{1cm} (1)

Constraints
\[ v \leq 0.5 \]  \hspace{1cm} (2)

Given

Constants
\[ l_i, \text{ length of each lattice element, } i \]
\[ p, \text{ penalty factor (} p=3) \]
\[ t_i, \text{ in-plane thickness of lattice element } i \]
\[ t_{\text{max}}, \text{ maximum allowable in-plane thickness of a lattice element} \]
\[ v, \text{ volume fraction} \]

Calculations
\[ t_i = \rho_i t_{\text{max}} \]  \hspace{1cm} (3)
\[ v = \sum \frac{\rho_i^p l_i}{A_{\text{Max}}} \]  \hspace{1cm} (4)
\[ A_{\text{Max}} = \sum t_{\text{max}} \]  \hspace{1cm} (5)

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<tr>
<td>Maximum flight speed</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Altitude of flight</td>
<td>200 m</td>
</tr>
<tr>
<td>Pressure ($P_1$) at 200 m</td>
<td>$9.945 \times 10^4$ Pa</td>
</tr>
<tr>
<td>Density of air ($\sigma$) at 200 m</td>
<td>1.15 kg/m$^3$</td>
</tr>
<tr>
<td>Chord</td>
<td>10 cm</td>
</tr>
<tr>
<td>Span</td>
<td>40 cm</td>
</tr>
<tr>
<td>Required lift</td>
<td>9.81 N (1 kg per wing)</td>
</tr>
<tr>
<td>Maximum wing thickness</td>
<td>27 cm</td>
</tr>
</tbody>
</table>
Table 2. Optimization parameters for topology design.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic algorithm (Step 1)</td>
<td>Sub Population size</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Number of islands</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Number of generations</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Rate of Mutation</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Rate of Crossover</td>
<td>0.95</td>
</tr>
<tr>
<td>Sequential Quadratic Programming (Step 2)</td>
<td>Max. No of iterations</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Termination accuracy</td>
<td>0.000001</td>
</tr>
<tr>
<td></td>
<td>Gradient Step</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Table 3. Pre- and post-optimization characteristics of the lattice structure.

<table>
<thead>
<tr>
<th></th>
<th>Left section</th>
<th>Right section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of initial lattice elements</td>
<td>30</td>
<td>46</td>
</tr>
<tr>
<td>Number of retained lattice elements</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td>Maximum in-plane area of lattice</td>
<td>491.49 mm²</td>
<td>598.96 mm²</td>
</tr>
<tr>
<td>Initial volume fraction of lattice</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Final volume fraction of lattice</td>
<td>0.24</td>
<td>0.32</td>
</tr>
<tr>
<td>Initial surface deviation</td>
<td>6.11 mm</td>
<td></td>
</tr>
<tr>
<td>Final surface deviation</td>
<td>1.98 mm</td>
<td>1.30 mm</td>
</tr>
<tr>
<td>Total iterations for convergence</td>
<td>1467</td>
<td>1146</td>
</tr>
<tr>
<td>Time required for convergence⁴</td>
<td>33 hrs 24 mins</td>
<td>24 hrs 12 mins</td>
</tr>
</tbody>
</table>

⁴ x86 PC running Windows XP with a 3.0 GHz dual processor and 2 GB RAM
Table 4. Optimized in-plane thickness values (in mm) for retained elements in Figure 7.

<p>| | |</p>
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<thead>
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<tr>
<td>1</td>
<td>1.263</td>
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<tr>
<td>2</td>
<td>1.039</td>
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<tr>
<td>3</td>
<td>1.810</td>
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<tr>
<td>4</td>
<td>1.927</td>
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<tr>
<td>5</td>
<td>0.932</td>
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<tr>
<td>6</td>
<td>1.371</td>
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<td>7</td>
<td>1.743</td>
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<td>8</td>
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<tr>
<td>9</td>
<td>1.298</td>
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<td>10</td>
<td>0.860</td>
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<tr>
<td>11</td>
<td>2.259</td>
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<tr>
<td>12</td>
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<tr>
<td>13</td>
<td>1.179</td>
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<tr>
<td>14</td>
<td>2.752</td>
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</tbody>
</table>
Table 5. Optimized in-plane thickness values (in mm) for retained elements in Figure 8.

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
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<tr>
<td>2</td>
<td>2.033</td>
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<tr>
<td>3</td>
<td>1.687</td>
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<tr>
<td>4</td>
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<td>2.157</td>
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<td>1.557</td>
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<td>8</td>
<td>1.290</td>
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<tr>
<td>9</td>
<td>1.997</td>
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<td>10</td>
<td>1.132</td>
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<td>11</td>
<td>0.826</td>
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<tr>
<td>12</td>
<td>1.014</td>
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<td>2.497</td>
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<td>15</td>
<td>2.150</td>
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<td>16</td>
<td>1.928</td>
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<tr>
<td>17</td>
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<td>18</td>
<td>1.534</td>
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<td>22</td>
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<td>1.827</td>
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<tr>
<td>24</td>
<td>1.016</td>
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<tr>
<td>25</td>
<td>0.933</td>
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