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Development and Testing of an Interface for Real-Time Visualization of Resin Flow in Composites

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Abstract

The manufacture of polymer composite materials has benefited greatly from the development of computer-based simulation tools and sensor-based instrumentation. The present research offers a unique and powerful interface for collecting, integrating, analyzing, and rendering critical data related to a dynamic composite manufacturing process. These operations are executed in real time over the internet, permitting unprecedented flexibility and speed in deploying and using the manufacturing "tools." These tools include, but are not limited to, resin flow sensors, a model-based resin-flow reconstruction procedure, and a user friendly display for remotely manipulating and monitoring composite process events. The interface developed herein is critical not only in improving the fundamental visualization of a process but also as a means of practically communicating process information between geographically distinct locations. Thus, manufacturing concerns with only modest computer infrastructure can remotely leverage these tools to improve the quality, performance, and cost of their products without the need for significant investment in high performance computing infrastructure.

Contents

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Acknowledgments

Building the system described in this report required both creativity and lots of hard work. It also demanded meticulous attention to detail. This difficult task was mitigated by the highly-skilled group of scientists working in the embedded sensors program. The authors wish to thank all of these team members. Particular gratitude is owed to William Ballata and Fred Goetz for providing the instrumentation and SMARTweave experimental suites and to Colin Freese for the dynamic mesh refinement technique.

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1 Introduction

Composite materials are increasingly being used in Army combat systems. They offer strength, are lightweight, and as such are faster to deploy. Composite parts provide excellent protection from projectiles due to their energy-dispersing characteristics. Thick composites, in which additional protective materials such as ceramic plates can be placed, provide even better protection. An interesting ability with composites is that "in-situ" sensors can be incorporated into a composite part during its manufacture. These types of sensors can be used to monitor manufacturing processes while having little or no effect on final mechanical and structural properties. Sensors can indicate or delineate different phases of a manufacturing process and determine when the process is complete. Sensors remaining in a composite part after manufacture can also be used for health monitoring of the part over its lifetime. There is also currently an emphasis on the creation of "intelligent" or "smart" composite structures. Sensors in smart structures would provide data to be applied for controlling the manufacturing process. The development of smart structures addresses the lack of consistency and uniformity in composite part manufacturing today.

Liquid composite molding (LCM) processes such as resin transfer molding (RTM) and structural reaction injection molding (SRIM) are high-potential manufacturing methods for fabricating high-strength, high-volume composite parts. In general, a fiber preform is placed inside a matched-die mold and a reactive liquid resin is injected into the mold cavity through a number of ports into porous areas of the preform. A number of vents are also put into the mold cavity to prevent excessive pressures and help guide the resin flow.

However, composite parts are still generally cured in autoclaves, ovens, or presses using empirically based "recipe" cures. The variability in batch-processed raw materials, degradation during shelf life and out time, and environmental factors such as temperature and humidity can rarely be accounted for with the use of recipe cures. As a result, recipe cures usually require a high degree of post fabrication inspection and frequently produce less than optimum parts. They also have the potential to yield very high levels of scrap, especially for complicated geometries. In order to offset this to some degree, recipe cures are conservatively designed to maximize polymerization. This results in an unnecessary increase in process cycle time, inefficient equipment utilization, shorter tool life, and inflated processing costs. Most previous attempts to solve the problems inherent in recipe cures have concentrated on reducing batch-to-batch variations in raw materials and preproduction "proof" processing to accommodate those variations. This approach has been only moderately successful and not optimally cost effective.

Certainly a more practical and elegant approach that would overcome these problems would be to create a monitoring and control methodology that would be capable of assessing and subsequently modifying the actual condition of the material in real time or near real time as it is being processed. This methodology must acquire data that are indicative of where the flowing resin is in relation to the ports and vents in the mold cavity. Optimally, the actual location of the flow front would be determinable from the data. Current studies of multiregional flow in LCM processes do not determine actual flow front location using real time sensor data during the process [1, 2, 3]. Another valuable flow state variable to know is flow front velocity, since location, speed, and direction would fully describe flow in the immediate future. Both the acquisition of data and reconstruction of the flow must be completed in a short time relative to the speed of the flow front. However, assuming that data acquisition and reconstruction of the flow is fast enough, the flow must still be quickly and accurately visualized. Furthermore, the location of the flow front must be easily interpretable from the visualization without requiring any detailed knowledge of the acquisition, reconstruction, and visualization methodology. This requires a robust combination of data acquisition, data analysis, and data visualization techniques to produce a fast and easily understood tool. Furthermore, to perform process control, the visualization tool must quickly respond to analysis results to modify flow parameters, e.g., port injection pressure, activation/shut off of injectors, etc.

In this report we describe the development of a visualization tool used to monitor and display the resin flow during fabrication of organic matrix composite laminates. The tool uses dynamic sensor data generated during part manufacture and was developed around a flexible and powerful scientific visualization framework. The successful integration of network-based data acquisition, fast finite element based reconstruction (smoothing) and contouring algorithms, and scientific visualization tools are described. The results of using the tool to visualize flow during fabrication of laminates, including flat panels and more complex parts, are discussed.

2 Developing a Visualization Tool

2.1 Data Acquisition

The U.S. Army Research Laboratory has developed a system known as SMARTweave (Sensors Mounted As Roving Threads) [4, 5, 6]. This is a novel approach of creating sensors by weaving flexible conductive fiber tows through composite preforms. Generally, a set of parallel tows is placed between two preform layers. A second set of parallel tows is placed at about 90° to the first set between different layers of preform material. Sets of tows are placed between different preform layers to prevent them from coming in contact with each other. These tows are then multiplexed with low-voltage electrical current being applied to one set of tows and sensing by voltage measurement being performed on the other set of tows. Basically, a sensor grid is formed in which sensor locations are where tows overlap one another. For example, a 7 × 7 grid would yield 49 sensor locations as shown in Figure 1.

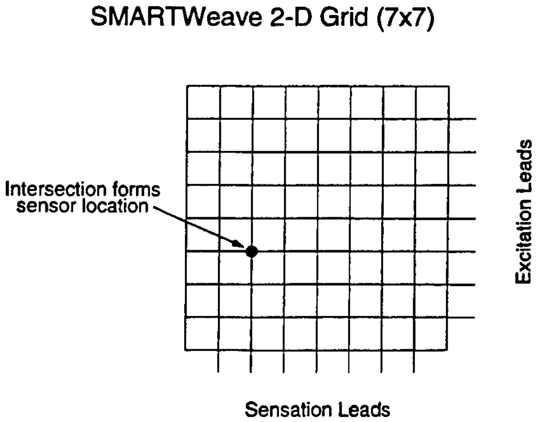


Figure 1: A SMARTweave 7 × 7 Sensor Grid.

This type of setup is easily applied to simple preform shapes, such as relatively thin, flat panels. However, any number of tows or sets of tows in any orientation relative to each other can be placed in a composite preform. This is limited by the size and geometry of the preform itself and not by the size or geometry of the sensor tows. This means sensor grids can be placed throughout a preform of any thickness. Therefore, sensor grids can be placed in any part of a preform, including curved sections and around corners from one plane of the part to another. This gives the SMARTweave system high flexibility and wide applicability.

The SMARTweave system has the potential to collect data from any position in a composite preform and thus determine the current location of the global flow front. Early developments in the SMARTweave system produced a simple yet effective monitoring system. The multiplexed data collected at the grid overlap points, or sensor locations, are interpreted by customized National Instruments LabVIEW software running on a personal computer (PC). Based on predetermined thresholds, voltages at the sensors were indicative of whether or not resin had filled the sensor. The user was presented a graphical, two-dimensional (2D) representation of the preform that was colored based on voltage readings from the sensors or whether or not voltage thresholds had been exceeded. However, this visualization tool was constrained in two ways. First, only 2D cases could be fully visualized, and second, the 2D representation was constructed using rectangles delimited by the grid tows. This always produced a flow front with 90° steps as shown in Figure 2. Of course, more tows could be added to decrease this effect, but a great advantage of the SMARTweave system is that flow can be determined where there are no sensors by analyzing sparse sensor data. Flow in these areas could not be accurately shown with the "blocky" output from the early, PC-based, visualization tool. Also, adding more tows becomes impractical at a certain point.

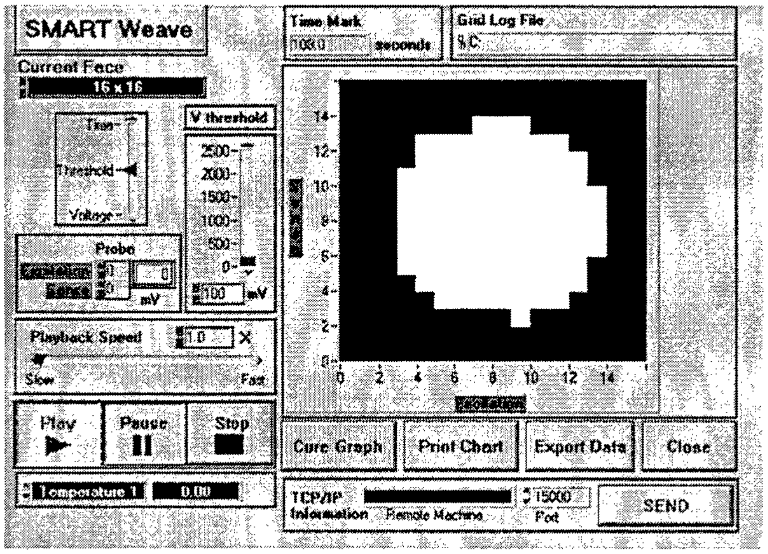


Figure 2: Early Visualization Interface.

The SMARTweave system is designed to be inexpensive and is taken "on the road" to perform analysis and gather data quickly. In order to visualize three-dimensional (3D) experiments, a method was developed to transfer the data from the monitoring computer to a Silicon Graphics Incorporated (SGI) workstation in near real time. The SGI computer system was chosen for several reasons. Most importantly, the SGI has graphics hardware and software that allows users to easily render and manipulate 3D objects. This is done using Open Inventor, which is an object-oriented 3D toolkit based on Open GL (Graphics Library)[7]. Open GL is the interface by which the graphics hardware is controlled. Secondly, the OSF/Motif (Open Software Foundation) programming toolkit, which is built on top of the X11 code used for the UNIX windows environment on the SGI, is used to implement user interface components, such as menus, scroll bars, message boxes, and buttons. Mechanisms exist that incorporate the Motif and X11 components with the Open Inventor components.

Remote acquisition of process or laboratory data in real time or near real time is a powerful application that Internet access provides [8]. Routines were written on the PC and on the SGI to allow communication between the two existing TCP/IP (Transmission Control Protocol/Internet Protocol) network channels. The LabVIEW software on the PC has routines specifically for TCP/IP network communication. These routines were used to allow the PC user to input the internet address of the SGI workstation and the port to which it should connect. The PC then collects data at user set intervals and sends bursts of data over the network to the SGI workstation. The SGI workstation could have been used as the data acquisition device. However, an effective and highly portable PC-based data monitoring system existed, allowing dedication of the SGI to data analysis and flow rendering. The PC was fitted with a network card. Code was written for the SGI that allows the user to specify a TCP/IP socket which will act as a listener. This is done in the SGI user interface for the SMARTweave monitoring system. Most workstations in the SGI family are network-ready. This system of data acquisition and transfer has two advantages. It does not require specialized connectors to interface the two computers, and it allows for distributed data collection and visualization.

2.2 Reconstructing the Flow Front

Any number of sensors can be created in the SMARTweave system. However, it is desirable to use as few sensors as possible to collect data without losing information necessary for correctly determining flow front location. Currently, the capability exists to visualize sensor activity in near real time. Sensor points are turned on when they are filled as resin flows through the preform. However, we also want to know where the flow front is between the sensor points. Off-line capability has been developed to quickly reconstruct the flow front based on sensor locations and sensor activation (on) times [9]. In the 2D case, the reconstruction (smoothing) algorithm uses a triangular, quadratic, and computationally efficient element possessing 9 degrees-of-freedom (DOF) to locate the flow front in time based on a finite element model. The response of this particular smoothing element (in finite element notation) is dictated by three separate components and can be summarized as

$$[K^e]\{u^e\} = ([K^e_\varepsilon] + [K^e_\alpha] + [K^e_\beta])\{u^e\} = \{f^e\}, \tag{1}$$

where K_ε, K_α, and K_β symbolically represent the contributions of least-square error, gradient control, and curvature constraint, respectively, and u^e represents the nodal DOF. The interpolation function U^e within an element is written

$$U^e = [N]\{u^e\}, \tag{2}$$

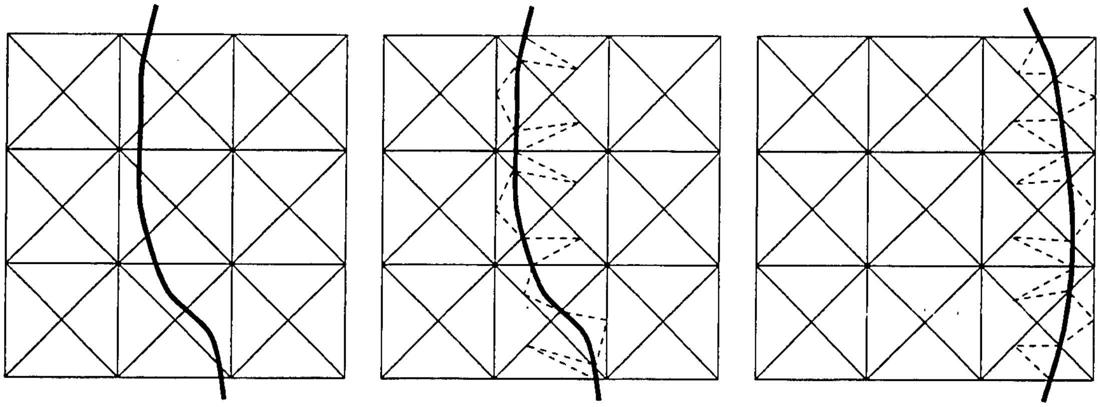
where $[N]$ are the element shape functions. The function U^e is related to the piecewise representation of the smooth function U(x, y), defined in region Ω, contained in Euclidean 2D space, by

$$\begin{aligned}\Phi(U) = \sum_{e=1}^{N_e} \Phi^e(U) = \sum_{e=1}^{N_e} \{ &\frac{1}{2N_d^e} \sum_{i=1}^{N_d^e} \omega_i [U^e(x_i, y_i) - u_i]^2 \\ &+ \frac{\alpha}{2} \int_{\Omega_e} [(\frac{\partial U^e}{\partial x} - \theta_x^e)^2 + (\frac{\partial U^e}{\partial y} - \theta_y^e)^2] d\Omega \\ &+ \frac{\beta}{2} \int_{\Omega_e} [(\frac{\partial U^e}{\partial^2 x})^2 + 2(\frac{\partial U^e}{\partial x \partial y})^2 + (\frac{\partial U^e}{\partial^2 y})^2] d\Omega \},\end{aligned} \tag{3}$$

where N_e is the number of finite elements, N_d^e is the number of data points falling within an element's space, $u_i = u(x_i, y_i)$ is an arbitrary representative data set, and U^e, θ_x^e, and θ_y^e are functions restricted to an element's domain. The data weighting constant, derivative, or gradient constraint constant, and the curvature constraint constant are represented by ω, α, and β, respectively. In this case, the data set u_i is time. An expression for K_ε, K_α, K_β, and f^e results from the minimization of functional equation (3) with respect to the nodal DOF, $\frac{\partial \Phi}{\partial u} = 0$, and combination with equation (2). Further description of the mathematical model is available [9].

The algorithm determines the time solution for every node in the finite element model given the times sensors are activated. Thus, sparse data from a small number of sensors are analyzed to get data over the entire finite element model, which gives the resin flow front at discrete time intervals. Some elements will have all their nodes in the filled (on) state, some will have all their nodes in the unfilled (off) state, and some will have only one or two nodes in the filled state. Any element that has only one or two nodes on is considered to be partially filled with resin. A linear first approximation contouring methodology was used to determine what areas of partially filled elements should be considered filled. Contouring is generally not necessary for a relatively fine finite element mesh. However, since contouring is only applied to partial (filled) elements, it is only applied along the flow front. Contouring a relatively small number of partial elements can take less time than smoothing a very fine mesh in order to avoid contouring, since solving for such a mesh can be computationally intensive.

Consider the meshes shown in Figure 3. Figure 3(a) is a 2D finite element mesh, or grid, with the flow front moving from left to right. Figure 3(b) is the same grid with four-element refinement applied to the partial elements along the flow front. Four-element refinement is the process of creating four new elements that collectively describe the same area in space as the partial element they temporarily replace such that the flow front is delineated, or



(a) Front moves left to right.

(b) Four element refinement applied.

(c) Front progression with refinement.

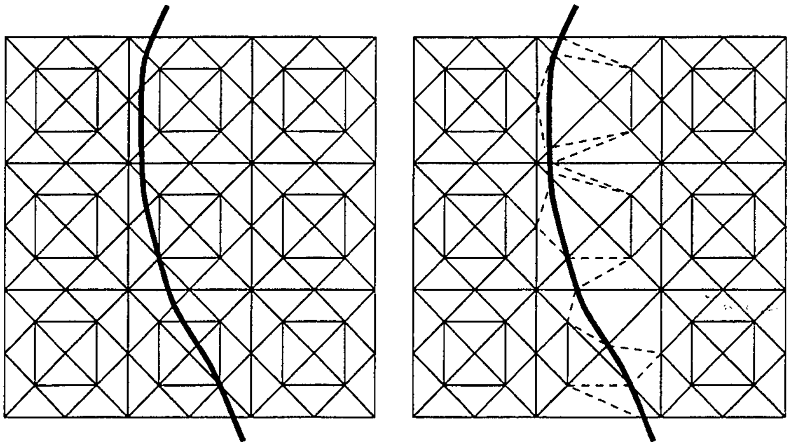
Figure 3: "Coarse" 2D Finite Element Mesh With Moving Flow Front.

contoured, in the area of the partial element. The flow front is contoured in the partial element because each temporary new element is either completely in the flow region or completely out of the flow region. Figure 3(c) shows four-element refinement applied to the flow front later in time. The 12 elements down the middle of the grid have been reset to their original size and their original position. These elements have gone from partial elements to filled elements, whereas the 12 elements to their right have gone from empty elements to partial elements. As the flow front moves through the grid, nodes and elements are added and removed from it as necessary to contour partial elements.

Figure 4 shows a "fine" finite element mesh. Figure 4(a) is a refined grid with the flow front moving from left to right. Figure 4(b) is the same grid with elements repositioned along the flow front, but no further refinement. Nine elements are dynamically replaced with 36 elements in Figures 3(b) and 3(c). An original finer mesh is used in Figures 4(a) and 4(b) with simple element repositioning by node relocation. In order to use as coarse a grid as possible and minimize processing time, Dynamic Mesh Refinement (DMR) as shown in Figures 3(b) and 3(c) was used for flow front contouring.

2.3 Developing the Visualization Interface

Visualization and modeling in various areas of industry and research (e.g., textile materials, satellite images, virtual environments, etc.) is becoming increasingly important [10, 11, 12]. Realistic and accurate representation of objects or images is often necessary to meet design or system requirements. Open Inventor is designed to create and display 3D objects. All of the information about an object, such as its size, position, color, etc. is stored in a data structure known as a scene database. This scene database is visually similar to a tree structure. When the scene database, or scene graph, is displayed or rendered, it is traversed



(a) Front moves left to right.

(b) Element repositioning by node relocation.

Figure 4: "Fine" Finite Element Mesh With Moving Flow Front.

top-down, left-to-right. For any object, the design is logical and can be easily understood by traversing the scene graph. Finite element mesh geometry of an object can be formatted into an Open Inventor scene graph. The flow visualization interface quickly reads and formats a NASTRAN (finite element) file into an Open Inventor scene graph, which renders the object described by the file. However, any data file specifying nodes and nodal connectivity can be used [13]. The NASTRAN file is generated from Parametric Technology Corporation Pro/ENGINEER computer-aided design (CAD) software. The same finite element mesh used for rendering the object is used for smoothing and contouring, and also for performing flow simulations. Thus, the mesh should not be made too fine or too coarse. If the mesh is too fine, it results in slow rendering and contouring, but very good simulations. If the mesh is too coarse, it results in bad simulations, but fast rendering and contouring.

The time to complete smoothing, contouring, and rendering tasks must be small relative to the speed of the flow front in order to accurately display the flow front when new sensor data are received. If the computation time required to complete these tasks is too large the displayed flow front will lag in time behind the actual flow front. The visualization interface allows the user to turn off smoothing and contouring in order to view the sensor state only. The interface can also apply only smoothing to sensor data. In this case, the time solution for each node in the mesh is compared to the current time and any node with time less than or equal to the current time is a filled node. The interface uses color shading around nodes to distinguish between filled and empty nodes. However, shading by node gives the flow front a step-like, unsharp edge. This method gave better results than the PC-based "blocky" display, but still did not clearly delineate the flow front. An example of this is shown in Figure 5.

As can be seen in the figure, active sensors are displayed in white and unactivated sensors

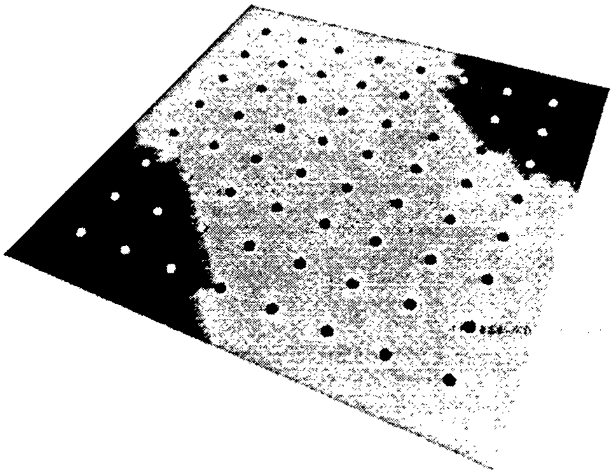


Figure 5: "Blocky" Effects From Coloring by Node.

are shown in black. Resin-filled areas are shown in dark gray and void areas are shown in a lighter gray. Notice that the flow front is "fuzzy." There is no clear defining line for the resin front. These results provided the impetus to develop element shading with DMR for contouring, which gives the flow front a well-defined edge without step-like contours between nodes. This approach shows the entire flow. An approach was also developed to show only the flow front, in which nodes on the front are marked by spheres and connected using straight-line segments. Results from these methods are shown in the following section.

3 Flow Visualization - Case Studies

3.1 Flat Panels

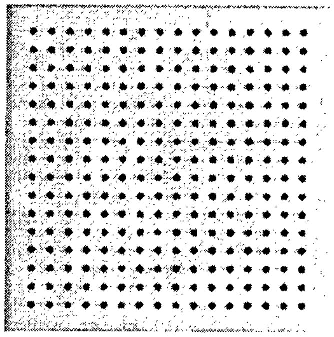
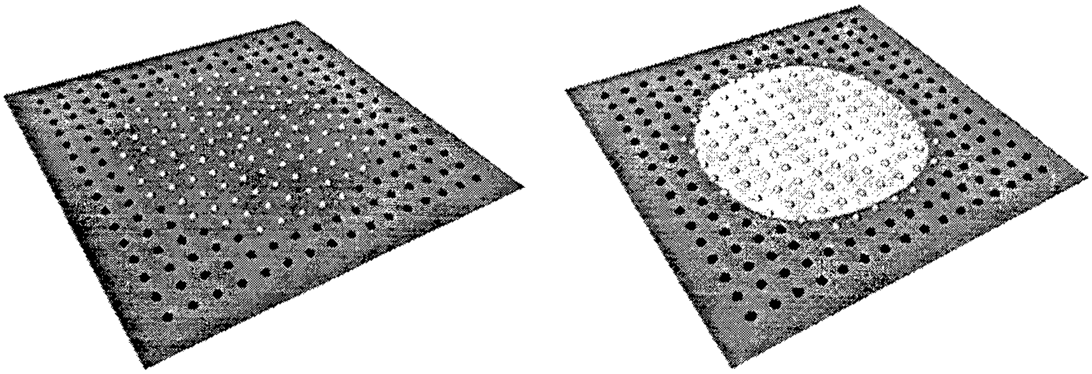


Figure 6: Experimental Flat Panel With 16 × 16 Sensor Grid.

The SGI visualization interface was first applied to monitoring flow in flat panels fabricated using the Seemann Composite Resin Infusion Molding Process (SCRIMP) [14]. SCRIMP uses a resin distribution system so that preforms with very large surface areas can be impregnated by vacuum force alone. This resin distribution system usually consists of a high-permeable medium placed between the fiber preform and the mold surface. It can also be augmented with grooves cut in the core or the mold. Using SCRIMP allowed testing of the visualization interface quickly and easily without requiring use of an autoclave. The process also allows the flow fronts to be visually tracked.

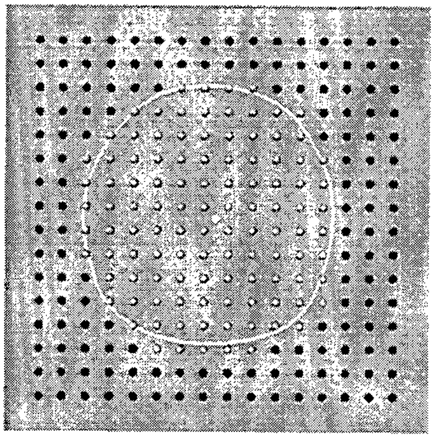
Figure 6 shows a flat panel with a 16 × 16 sensor grid. Sensor locations are delineated by the dark spheres coincident with the panel.

The panel was impregnated with resin (simulated with colored corn syrup) from the center. The center is marked by the small diamond-shaped hole. Figure 7 shows several rendering abilities of the scientific visualization system. Figure 7(a) shows the sensor data when the panel was about half filled with resin. Sensors that are on are colored white, and sensors that are off are colored black. Figure 7(b) shows the same sensor state with both reconstruction and contouring applied. The flow has been shaded by element (shown in white), and the flow front is well defined by using DMR. Figure 7(c) is the same flow showing only the flow front where DMR has been used.



(a) Sensor activation only.

(b) Sensor activation, reconstruction, and contouring.



(c) Sensor activation and flow front.

Figure 7: Flat Panel Experiments and Visualization.

Figure 8 is a video image snapshot of flow in the panel correlated in time with Figures 7(b) and 7(c). The flow in Figures 7(b), 7(c), and 8 is in very good agreement. It is very easy to apply reconstruction (for flow front rendering) only, reconstruction and contouring, or neither to sensor data in the visualization interface. Making the choice simply involves choosing a menu item from a list. This gives the user maximum flexibility in choosing how to visualize the flow and the flow front.

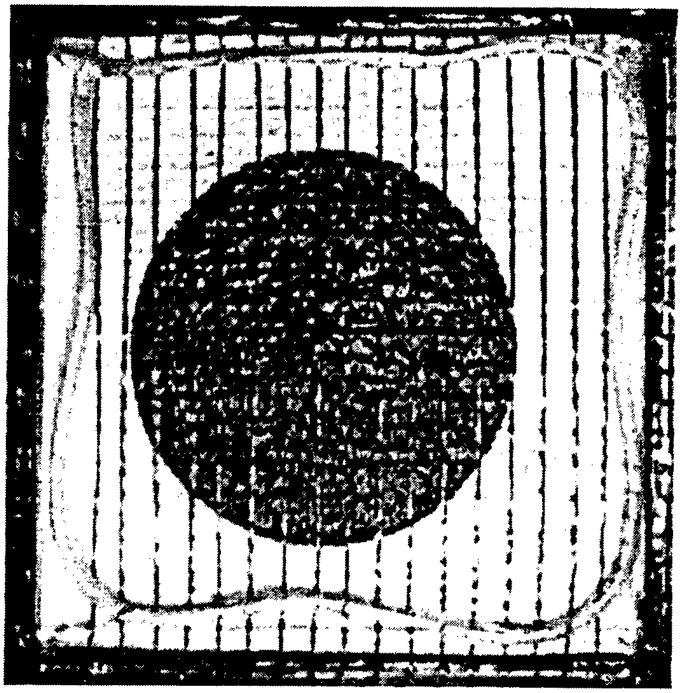


Figure 8: Video Image of Flat Panel Experiment.

3.2 Gun Mount Shield

The interface was also used to monitor flow in a much more complex composite part, the XM194 Gun Mount Shield, hereafter referred to as the ballistic shield. Again, SCRIMP was used to fabricate a thinner version of the full thickness ballistic shield. The actual ballistic shield part, in this case after some ballistic damage tests, is shown in Figure 9.

Tows were placed from front to back and from side to side across the top of the shield to form sensor grids. A total of six planar sensor grids were created, including one in the top, one in the back, one in each side, and two in the front. The PC visualization tool could only display one sensor grid at a time out of six possible grids. The SGI visualization tool continuously displays the entire ballistic shield, treating the shield as a single object with a set of properties to be rendered. Second, the SGI tool allows the user to move or spin the shield in space in order to view it from any angle.

The shield was impregnated with resin from the center of the back at the top. Figure 10(a) shows the sensor state after flow has proceeded through the top and into the front,

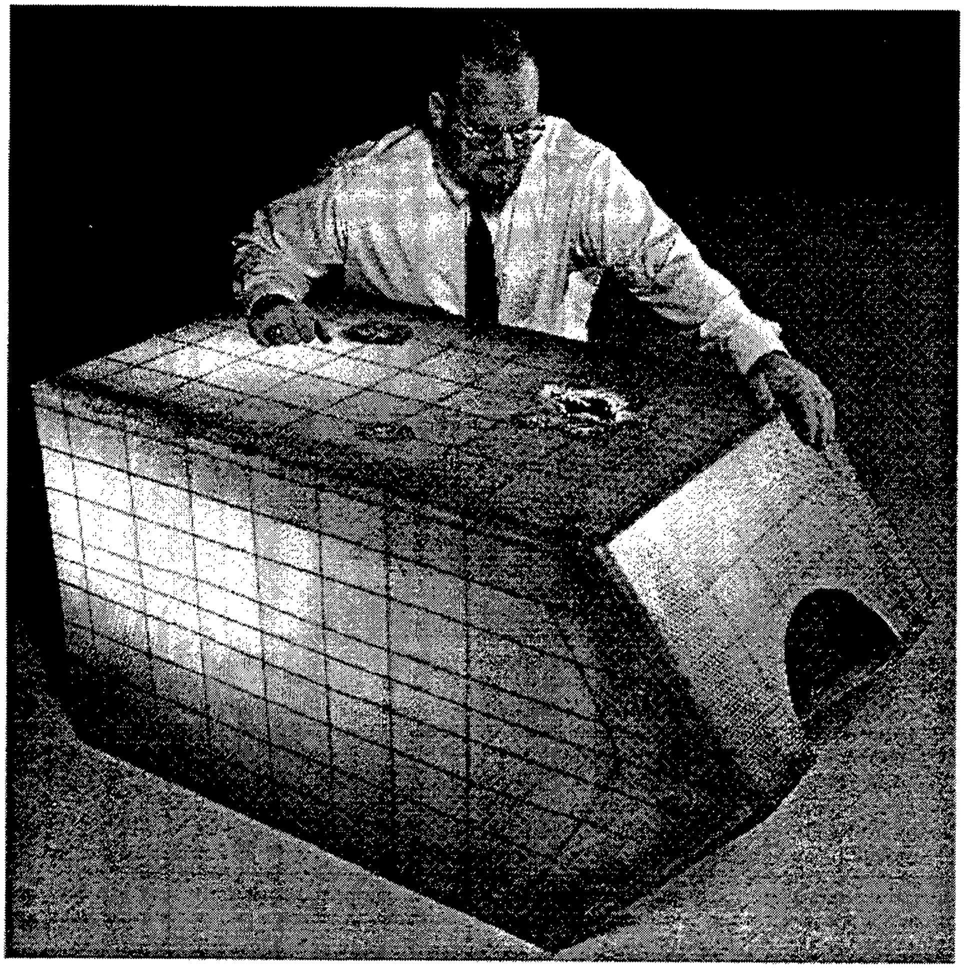


Figure 9: Ballistic Shield.

sides, and back of the shield. Sensors that are on are colored white, and sensors that are off are still colored black. Figure 10(b) shows the reconstructed and contoured flow for the sensor state, in which flow is shaded by element using DMR. Last, Figure 11 is a video image snapshot of flow in the shield correlated in time with Figures 10(a) and 10(b). Again, the flow in Figures 10(b) and 11 is in good agreement. This includes flow through edges and corners from one area of the shield to another. This is critical as effects like race tracking can occur along edges. The presence of race tracking often results in dry spot formation and other defects in molded composite parts [15].

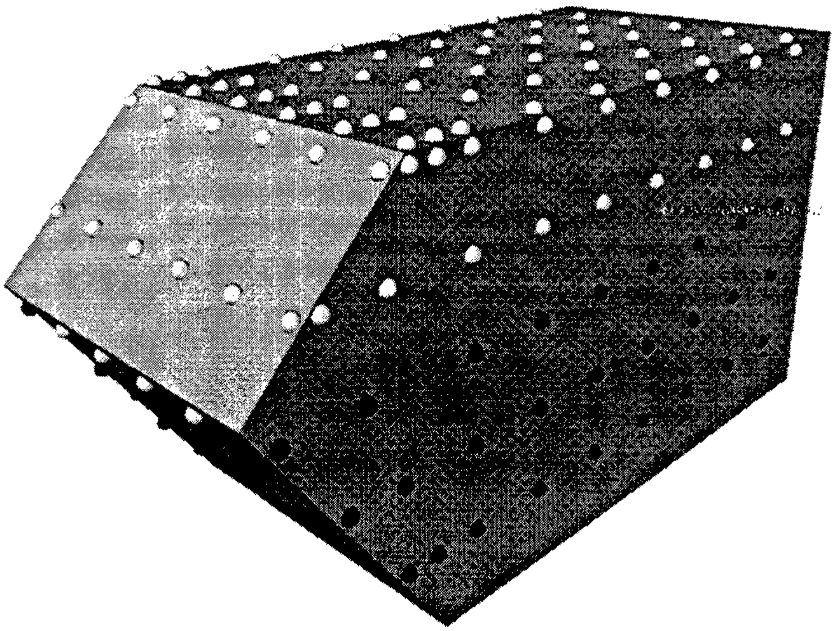
The SGI visualization interface successfully monitored resin flow in a simple panel and the significantly more complex ballistic shield. It produced accurate flow reconstruction results, which when shaded by element and contoured using dynamic mesh refinement resulted in well defined flow front boundaries.

4 Future Directions

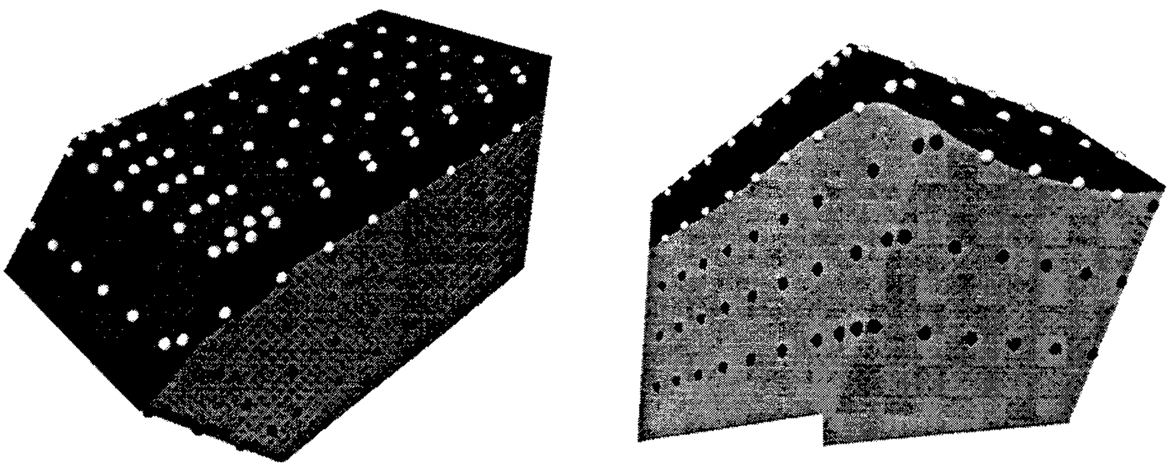
Resin flow in the flat panel and the ballistic shield was visualized in quasi-3D, in which flow is constrained in surfaces with no thickness. However, the 2D reconstruction algorithm is a simplification of the more general 3D case, which can reconstruct the flow front in full 3D. Visualization is significantly more difficult in full 3D, as individual faces of 3D elements with thickness will be shaded to produce an expanding "hollow solid" or shell representing the flow front, rather than filling of entire 3D elements. Of course, visualization in full 3D is necessary to show the flow front everywhere and not just near the surfaces, in thick composites. In the full 3D case, a tetrahedral finite element mesh and the 3D reconstruction algorithm would be used. The 3D algorithm would construct dynamic tetrahedral elements, which would be interrogated to determine what face(s) should be shaded for display.

Using the visualization interface to control the manufacturing processes for composites fabrication will be investigated in the near future as an appropriate control decision mechanism is added. The reconstruction algorithm solves for the time solution of every mesh node given the current sensor grid state. In addition, the algorithm can solve for the velocity at every mesh node. Knowledge of where the flow is (time) and where it is going (velocity) can be combined and utilized by some form of intelligent control. Control may be based on statistical methods, heuristic algorithms, neural networks or other artificial intelligence algorithms, or some other method.

Current work in RTM flow simulations has addressed designing and developing easy-to-use graphical interfaces for interactively changing simulation variables (e.g., number/location of ports and vents, open/close ports and vents, etc.) during the simulation [16]. The U.S. Army Research Laboratory, along with the Mechanical Engineering Department at the University of Minnesota, has developed a pure finite element methodology for RTM flow simulations [17, 18, 19]. It is based on the transient mass balance equation for the resin mass in conjunction with an implicit filling technique that provides solutions for both the pressure field as well as the resin front progression. Compared to the explicit Finite Element-Control Volume (FE-CV) methodologies used in other approaches, the new methodology developed



(a) Sensor activation only.



(b) Sensor activation, reconstruction, and contouring.

Figure 10: Ballistic Shield Experiments and Visualization.

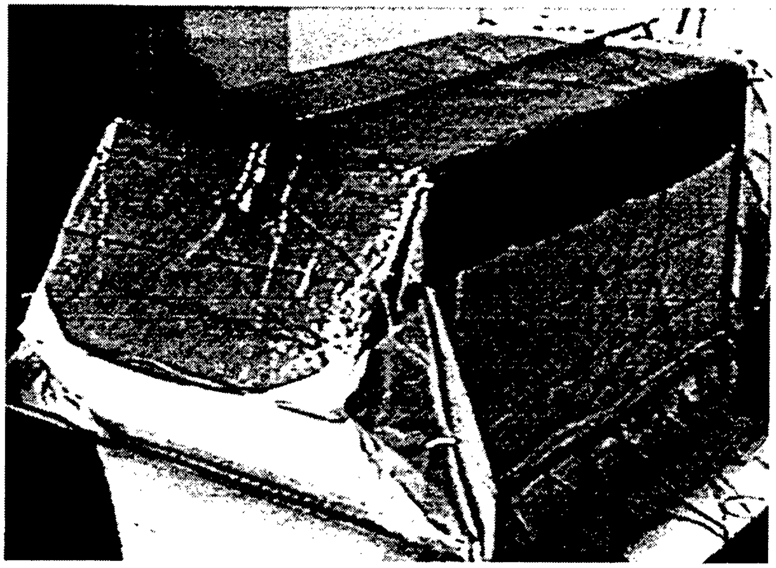


Figure 11: Photo of In-Process Ballistic Shield Manufacture.

is faster and is more physically accurate. By using the SGI computer system with custom-built interfaces from X11/Motif and Open Inventor, the simulation tool is quick and easy to interact with and provides robust 3D graphics rendering. The capability to graphically animate simulation results has also been developed. Currently, the flow front reconstruction methodology and the simulation methodology, including animation, exist as separate applications. Another area of future investigation is the combination of the two methodologies in the SGI visualization interface for monitoring and flow front reconstruction/contouring. An animated simulation could be shown side by side with contoured real-time data. The simulation would continue in time step with the acquisition and reconstruction of actual data, showing how, if at all, one differs from the other. Simulation results can also be incorporated with the dynamic contouring (DMR) routines to provide data in areas relatively far from the flow. This would allow a simulation to guide the flow reconstruction early in time when there is relatively little sensor data, but become less dominant as more sensor data is received until finally the simulation is dominated by the sensor data.

5 Conclusions

The U.S. Army Research Laboratory has developed an SGI-based graphical visualization tool for monitoring and displaying resin flow in near real time in composites fabrication. It receives data over the internet from a data acquisition PC via TCP/IP routines on the PC and a network listener on the SGI. The tool uses a fast 2D reconstruction algorithm to locate the flow front in time based on a finite element model. Second, the tool can apply a contouring algorithm with dynamic mesh refinement to the flow front. Writing the tool in Open Inventor resulted in an easy-to-use-and-understand 3D graphical interface in which an object described by a finite element mesh and the flow in the object are completely rendered.

Two different experiments were done to test the speed and accuracy of the visualization tool. In the first, resin flow in a flat panel was monitored and displayed (rendered) by the tool. There was good agreement between the actual flow front as recorded by video camera, the reconstructed flow front, and the reconstructed and contoured flow. In the second, resin flow in a thin version of the XM194 Gun Mount Shield was monitored and rendered by the tool. Again, there was good agreement between the actual flow front as recorded by video camera, the reconstructed flow front, and the reconstructed and contoured flow, including through edges from one plane of the shield to another.

Future work includes visualization of the flow front in full-3D, in which individual faces of 3D elements with thickness will be shaded to produce an expanding "hollow solid" or shell representing the flow front, rather than filling of entire 3D elements. Developing a control methodology based on the location (time) and the direction (velocity) of the flow front will also be investigated. Last, combining existing simulation methodology with the visualization tool will be investigated.

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13. ABSTRACT *(Maximum 200 words)*

The manufacture of polymer composite materials has benefited greatly from the development of computer-based simulation tools and sensor-based instrumentation. The present research offers a unique and powerful interface for collecting, integrating, analyzing, and rendering critical data related to a dynamic composite manufacturing process. These operations are executed in real time over the internet, permitting unprecedented flexibility and speed in deploying and using the manufacturing "tools." These tools include, but are not limited to, resin flow sensors, a model-based resin-flow reconstruction procedure, and a user friendly display for remotely manipulating and monitoring composite process events. The interface developed herein is critical not only in improving the fundamental visualization of a process but also as a means of practically communicating process information between geographically distinct locations. Thus, manufacturing concerns with only modest computer infrastructure can remotely leverage these tools to improve the quality, performance, and cost of their products without the need for significant investment in high performance computing infrastructure.

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