Shape Deposition Manufacturing of Wearable Computers

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Abstract

Shape Deposition Manufacturing (SDM) is a solid freefrom fabrication methodology which can fabricate heterogeneous structures, i.e., multi-material structures with embedded components. One application is to build-up electromechanical devices such as conformally shaped computer packages with embedded electronics. The goal is to be able to quickly design and manufacture, in small lots, personalized, rugged units for specialized applications. One example, which is described in this paper, is the manufacture of an underwater computer, the 'Frogman', which is built-up in layers of polyurethane.

Background

Current solid freeform fabrication (SFF) methodologies create 3D shapes by building up layers of material using material additive processes. One advantage of SFF is the capability to rapidly fabricate arbitrarily complex shapes. SFF processes which use selective material deposition techniques have additional advantages. They can be used to build up heterogeneous structures, *i.e.,* multi-material shapes with embedded structures[1,2,3]. The capability to fabricate heterogeneous structures is important because this capability enables novel designs which would not be practical to build with conventional manufacturing processes[4]. One class of heterogeneous structures is embedded electronic devices which are fabricated by building up nonconductive housing packages and simultaneously embedding and interconnecting electronic components within the housing. With this approach it is feasible to rapidly and economically fabricate compact, rugged, customized computer modules in small lot sizes. The military is particularly interested in the capability to manufacture mission-specific, conformal shaped 'smart' devices such as wearable computers tailored for an individual soldier or a small military unit. These computers might store maps, equipment descriptions, help to log data, or provide communication links. This paper describes the use of Shape Deposition Manufacturing (SDM), an SFF process which can build heterogeneous structures to fabricate a water-proof, wearable embedded computer called the 'Frogman.' SDM is reviewed in the next section.

Shape Deposition Manufacturing (SDM)

SDM integrates material addition processes with material removal processes (Figure 1). Individual layer segments are deposited as near-net shapes, then accurately machined to net-shape, with a CNC mill, before additional material is deposited[5]. Each layer is composed of primary material(s) and complementary shaped sacrificial supporting material which is removed when the part is completed. At selected layers, prefabricated components can be placed on the current upper surface before subsequent deposition takes place, thus permanently embedding the component.

Several alternative material deposition processes are available for SDM. Embedded electronic devices are built up with polyurethane, to form the housings, and sacrificial wax which is removed by melting. Polyurethanes are deposited as 2-part resin/activator mixtures, while the wax is deposited with a hot-glue gun. In the Carnegie Mellon and Stanford SDM testbeds, the parts are built on pallets which are transferred from station-to-station using robotic automation.

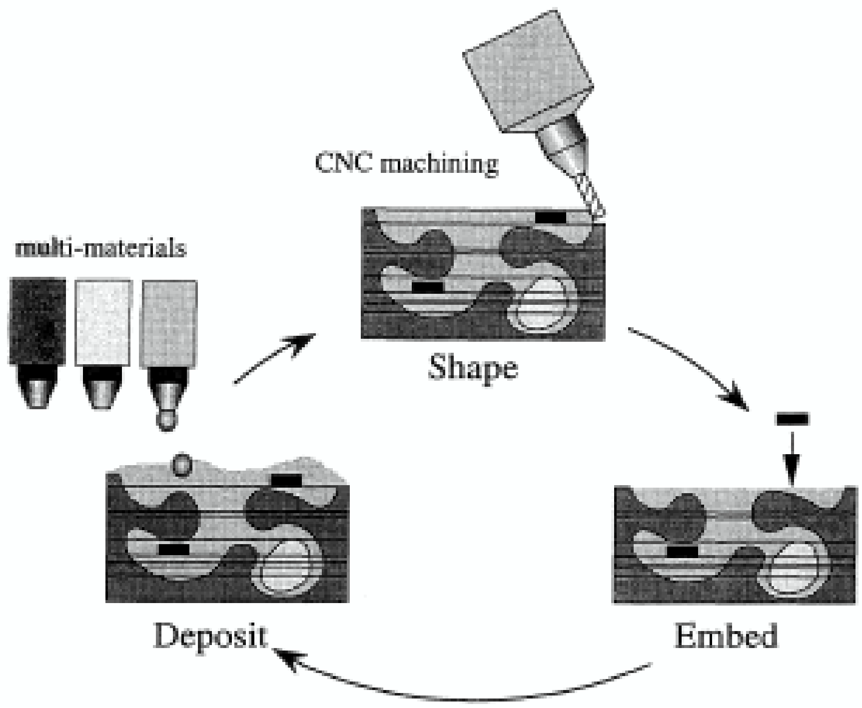


Figure 1. Shape Deposition Manufacturing

The basic SDM strategy is to slice the CAD model of the part into layers while maintaining the corresponding 3D geometry of the outer surfaces. The layer thicknesses vary depending on the local part geometry. Each layer is further decomposed into layer segments, or 'compacts', such that: undercut features need not be machined, but formed by previously shaped compacts, and each compact is composed of a single material. For example, Figure 2 shows the sequence for depositing and shaping the compacts and for embedding a component in a layer of a heterogeneous structure.

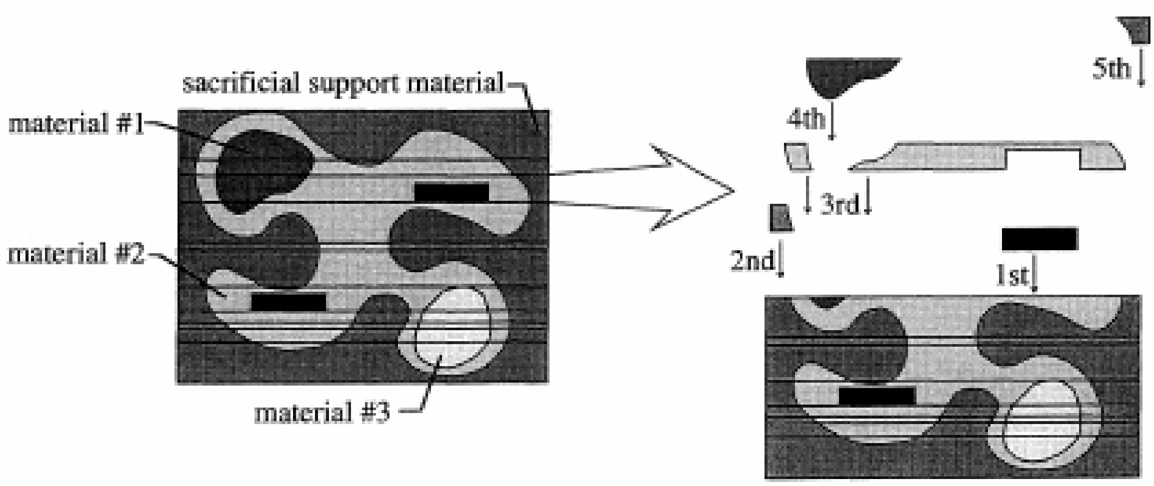
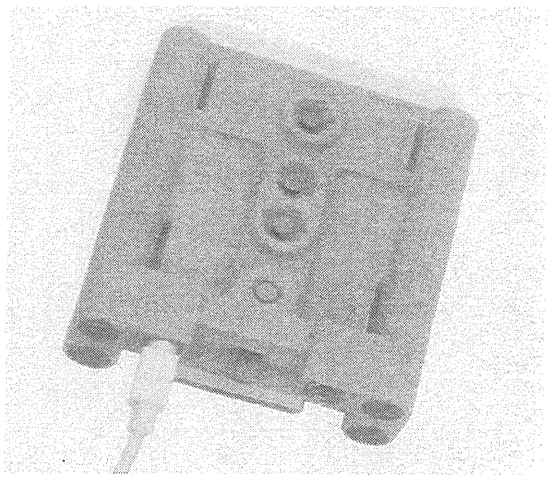


Figure 2. Deposition and shaping sequence.

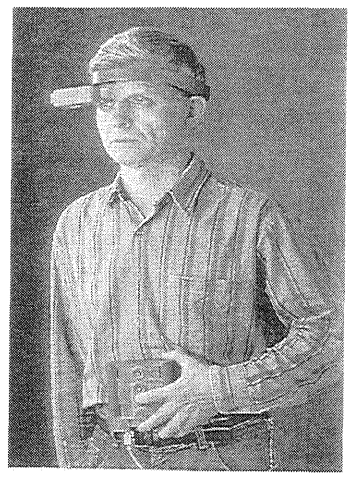
Wearable Computers Built With SDM

Several generations of wearable computers, such as the 'VuMan' series[6], have been designed and built at Carnegie Mellon using conventional packaging methods. Recently, the use of SDM been investigated as an alternative method to manufacture these devices. For example, the shape deposited VuMan shown in Figure 3a is a computer which can store maps for navigational aids, or detailed assembly drawings for service and maintenance applications. The graphical information is displayed on a commercially available heads-up display (Reflection Technology, Inc., 'Private Eye') as shown in Figure 3b. The graphical information is stored on PCMCIA cards.

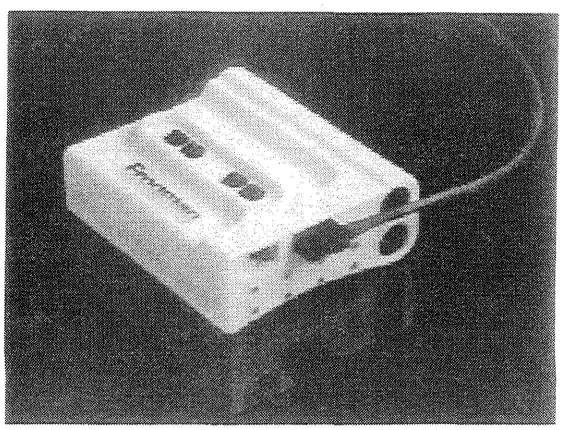
After completion of the VuMan-SDM, there was a request to repackage it, using the same set of PCBs, so that it would be waterproof to a depth of at least 100 feet. Several modifications had to be made, including using a different polyurethane formulation, incorporating waterproof switches, connectors and access covers, as well as using fewer batteries. A conformal shaped rear surface was also required so that the unit could be comfortably strapped to a diver's leg. A commercially available waterproof heads-up display would be interfaced to the unit. This waterproof Vuman, called the 'Frogman', is shown in Figure 3c. The important points are that re-tooling was not required to manufacture the Frogman and that embedding facilitates waterproofing. The construction of Frogman is described in the next section.



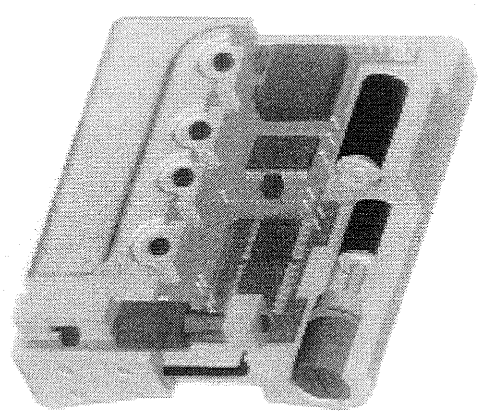
a. VuMan-SDM



b. Heads-up display.



c. Frogman



d. CAD rendering of Frogman

Figure 3. Wearable computers built with SDM.

Construction of Frogman

A cut-away, CAD rendering of Frogman is shown in Figure 3d. The unit is a four layer polyurethane structure. The polyurethane (Adtech Plastic Systems Corp., LUC-4180) is a two-part mixture which was deposited manually for this experiment. Each layer takes approximately 12 hours to gel before it is hard enough to be machined. The cured material has a tensile strength of 8 Kpsi with 15% elongation. A sacrificial wax support material (Kindt-Collins Company, MASTER Protowax) is deposited with a hot-glue gun. The Frogman contains two layers of printed circuit boards (PCBs); the first PCB is located on top of the first polyurethane layer, and the second PCB is located on top of the second PU layer. The two PCBs are electrically interconnected with vias made using pin receptacles (Mill-Max Mfg. Corp., pin recaptacle #0136) which are more commonly used to make conventional IC sockets. The steps for making an embedded interconnect are depicted in Figure 4. While the Frogman has only two layers of PCBs, the interconnect system is designed so that each via can be extended upward to an arbitrary number of layers.

In addition to embedding PCBs and vias, several other waterproof devices must be formed within the growing shape, including indicating lights, switches, accessible battery and PCMCIA card compartments, and an external connector. To form an indicating light (e.g., power off/on indicator), a translucent lucite pipe is first glued to the lens of a surface mounted LED (Figure 5a). The LED and pipe are then embedded in the next layer of polyurethane. Then both the plastic pipe and the polyurethane are machined to form a sealed, blended surface (Figure 5b). Switches are formed using magnetic reed switches (Figure 6a). After a reed switch is embedded in a layer of polyurethane, a receptacle is cut-out over it and a prefabricated, spring-loaded magnetic button is glued into the receptacle (figure 6b). In operation, the force required to activate the switch assembly is independent of the water depth since water will flow around the spring.

In order to connect to a heads-up display, a commercially available, vulcanized underwater female connector (Underwater Systems, Inc., Micro_Mini Square #MM8S) is used. Since polyuretane will not bond to rubber, a polyurethane clamp with an internal O-ring is first bonded around the cable connection from the connector to the PCB (Figure 7a). Tape is also placed on the connector face to protect it from subsequent deposition. The connector is then placed on a polyurethane layer and embedded in the next layer (Figure 7b). In operation, water, which penetrates between the rubber/polyurethane interface, is stopped at the embedded clamp.

The PCMCIA card is housed in a compartment which is sealed with a removable, gasketed cover. The compartment is formed by first cutting out a section into a layer of polyurethane for the PCMCIA receptacle as depicted in Figure 8a. Then, a prefabricated teflon cover, with attached metal anchors for the cover screws, is placed in guides cut into the compartment opening. The PCMCIA receptacle (which is affixed to the bottom of a PCB) is then placed into the compartment as depicted in Figure 8b. The next layer of polyurethane is deposited over that to form the entire compartment (Figure 8c). The teflon cover can be removed to access the PCMCIA receptacle, since the polyurethane does not stick to teflon (Figure 8d).

The battery compartment is formed with the aid of a teflon coated, aluminum mandrel which is removed when the entire computer is completed. First, a locating channel for the mandrel is cut into a layer of polyurethane, and the mandrel is placed in that channel adjacent to a PCB segment (Figure 9a). The mandrel contains a copper contact ring which will remain embedded in polyurethane once the mandrel is removed (Figure 9b). This ring, which is is soldered to the PCB, will form a battery contact and also act as an anchor for attaching the battery compartment cap (Figure 9c). The rear of the mandrel locates a second battery contact which is soldered to the PCB. After the mandrel is placed, the next layer of polyurethane is deposited over it. When the mandrel is removed, batteries are placed within the formed polyurethane tube, then a copper insert is locked into the retainer ring, a brass screw is screwed into the insert to contact the battery, a gasket is placed over the screw, and the prefabricated battery cap is screwed in place.

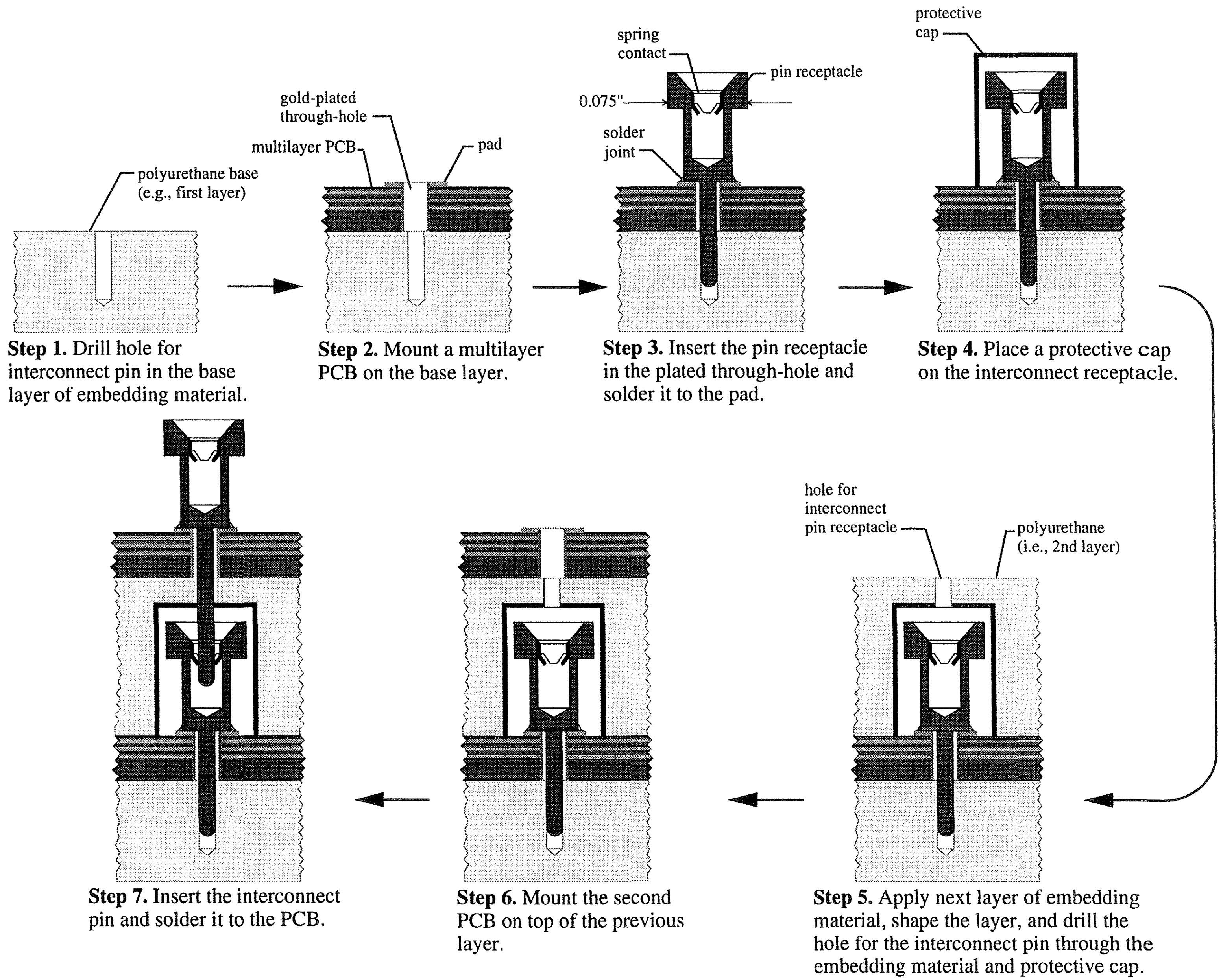


Figure 4. Sequence for installing vias.

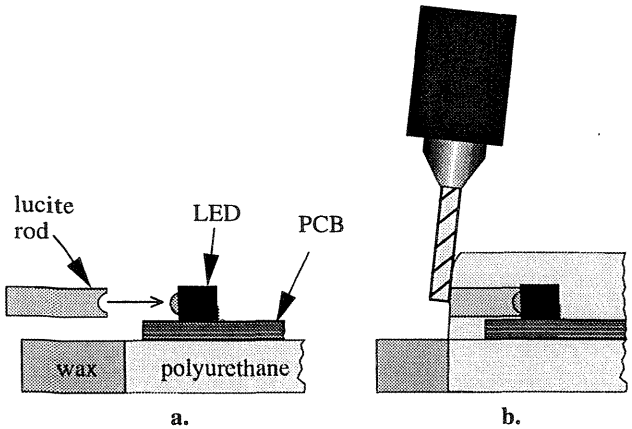


Figure 5. Embedding lights.

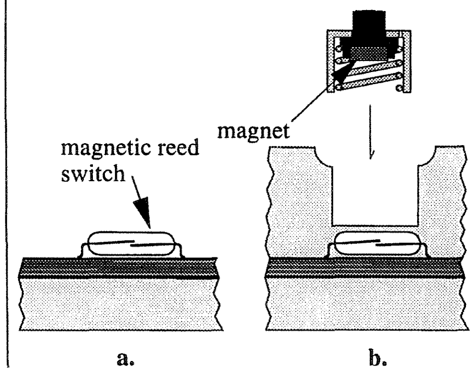


Figure 6. Embedding switches.

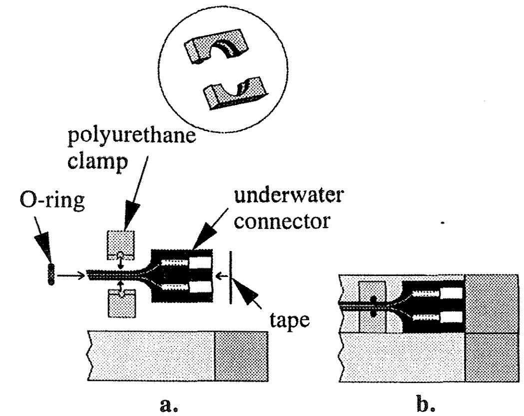


Figure 7. Embedding water-proof connector.

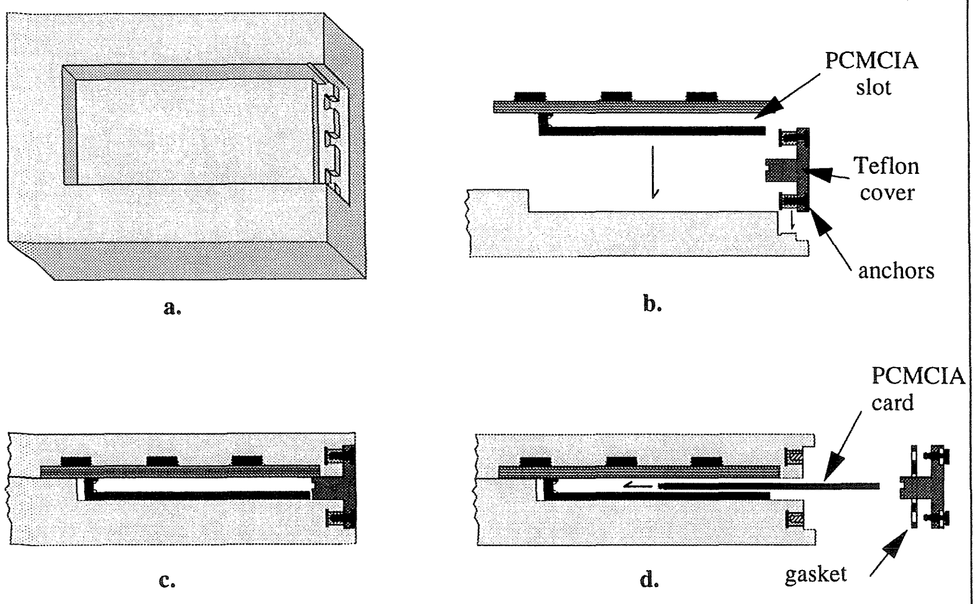


Figure 8. Embedding PCMCIA slot.

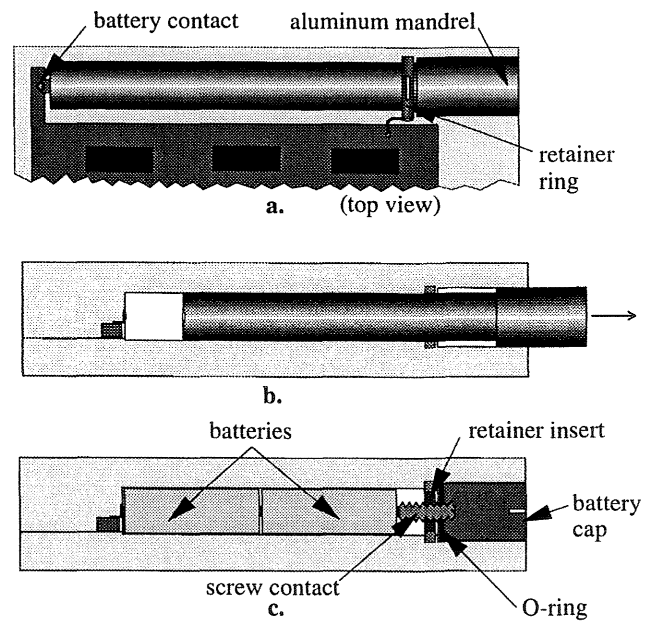


Figure 9. Embedding battery compartment.

Discussion

There are several issues which must still be addressed in order for freeform fabrication of embedded electronic structures to be a practical manufacturing approach. One key issue is that embedded devices are not easily repairable. While we have made repairs by drilling into completed units to expose and replace failed components, this takes considerable expertise. To minimize product failure, we test each layer of electronics as the units are built up. Assuming that embedded devices can be built up reliably, and that they fail predominantly in infant modes, then these products would be analogous to high-end processors, such as Pentiums, for which consumers are willing to pay a premium price even though they cannot be repaired.

It currently takes several days to build an embedded electronic structure with SDM due, in-part, to the relatively long time required for each layer of polyurethane to gel. With the current formulation, each layer of polyurethane takes approximately 12 hours to cure before it can be machined. While the Frogman was built in about 10 working days, which included the time it took to debug some new embedding strategies, it is estimated that one could be manufactured in ~60 hours by using more efficient machining plans and with full automation. To increase the net through-put, one option would be to build multiple devices, in parallel, using a palletizing system to both store and register the work pieces. Products would be queued so that as some layers are curing, others are being machined. The goal is to be able to manufacture 10 to 20 units per week (*i.e.*, a product with the complexity of the Frogman) using a single CNC machining center. Larger batch sizes could be built using additional machining centers.

An important quality measure of wearable computers is weight. The mechanical structure amounts to a significant portion (50% or more) of the total system weight. High bending stiffness and strength can be maintained by placing stiff and strong materials as close to the surface as possible. The rest of the inside structure can be filled with less dense material capable of preventing the transmission of vibratory and shock loads to the electronic components. The combination of high-strength, dense materials in the vicinity of outside surfaces, with lower density materials inside, allows minimizing weight while keeping bending and buckling strength at an acceptable level. While the Frogman was manufactured with a single material, SDM multi-material processing will enable designers to choose proper material combinations and create unique material distributions to build innovative and light computer devices which could not be fabricated with conventional methods such as injection molding.

Thermal and mechanical design specifications of wearable computers are highly interlinked and dependent upon each other. Three dimensional distribution of circuit components is controlled by device shape which, in turn, is determined by external specifications, as well as the arrangement of user-interface components (e.g., switches, connectors, displays). The current design methods used for Frogman required extensive and time consuming human interaction to link electronic and mechanical designs. For rapid production, automated links between electronic and mechanical design through proper CAD software are necessary.

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