Automating Sheet-Based Fabrication: The Conveyed-Adherent™ Process

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Abstract

A new automated fabrication technology is described which breaks the fabrication process into spatially separate layer-formation and layer-bonding stages. The technique uses sheet material on a substrate as feedstock and cuts cross-section contours into the material before conveying the material on the substrate to a stacking station. Advantages include (a) speed, (b) versatility in fabrication materials, and (c) ability to fabricate hollows, embed or cast secondary materials, and selectively enhance or degrade material properties on a regional basis.

A prototype fabricator has been built which automates all aspects of this process except weeding. Applications demonstrated using this machine include traditional rapid prototyping and visualization-model creation as well as functional machines taking advantage of embedding and cast-in-place techniques.

I. Introduction

The current commercial paradigm for automated fabrication (autofab) encompasses layered fabrication of plastic, paper, metal, or ceramic objects. The paradigm consists of decomposition of a 3-D object into 2-D cross sections and sequential construction of each cross section in a "form in place" strategy. In a form-in-place technique, successive layers are bonded to the previous layer as they are formed. Each of the devices available for doing this has unique advantages and disadvantages which allow several commercial systems to compete successfully with no single system dominating all applications.

This specialization is clearly demonstrated by comparing the Sanders thermoplastic droplet deposition process to the laser cut paper layering process of Helisys. The Sanders machine can produce layers as thin as 0.0004 inches which allows objects to be constructed with surfaces where the 3-D aliasing (or stair step effect) is greatly reduced. This process is excellent for producing small models of jewelry or similar items. The Helisys machine would have a difficult time producing these objects, and would require hand finishing to achieve a smooth surface finish. However, the Helisys machine is capable of producing models up to 32" by 22" by 20" in a single build. The Helisys device is capable of building a model significantly faster than the Sanders machine[1]. Since the Helisys device only needs to laser-cut the edges of each cross section to create each layer, the process is very efficient for large heavy-bodied objects, but not as useful for thin-walled structures.

To date, the prototyped objects are primarily considered models since their material properties and construction accuracy do not generally meet the capabilities of the intended production system[2,3]. In addition, while the construction speed varies from device to device, the current commercial systems typically cannot build at a rate much higher than 20 cubic inches per hour. The machine manufacturers recognize these limitations and are introducing solutions to the problems. Many of the commercial systems are introducing techniques for producing patterns for investment casting or direct production of tooling for injection molding. Achievable tolerances remain in the range of 5 to 10 thousandths, however, which limits the use of these models in fine tolerance applications. 3D Systems has recently introduced a thermoplastic droplet deposition device that is an attempt to address the build speed issue. Their Actua™ device is reported to be less accurate than their stereolithography machine, but faster.

In order to further address these problems, researchers are attempting to provide a larger variety of construction materials. They are attempting to work with metals and other traditional engineering materials[4,5,6]; they are attempting to work with multiple materials simultaneously[4,6]; and they are developing much faster processes aimed at production of large objects[7].

II. Form-then-Bond Fabrication

The work discussed in this paper is an attempt to improve the speed and flexibility of autofab processes by stepping outside the form-in-place paradigm to a "form-then-bond" technique. In this approach, layers of an object are first formed, and then registered and bonded together as separate operations. This change in paradigm produces devices that behave differently than the existing systems, with these differences resulting in both advantages and disadvantages. Physical realization of this process has been shown to be quite inexpensive.

An inexpensive manual system based on the form-then-bond approach has given an indication of it's potential. JP System 5 Desk Top Rapid Prototyping offered by Schroff Development Corp. of Mission, Kansas, employs an off-the-shelf cutting plotter along with custom modeling and slice generation software to create cross sections from sheet materials with a pressure-sensitive adhesive backing. The sheets are manually weeded of excess material and stacked after cutting. Although weeding and stacking each sheet can be tedious, construction of many objects can often proceed quite rapidly. A similar system was briefly offered several years ago by the Swedish company, Sparx AB. Case Western University and CAM-LEM Inc. have proposed an automated form-then-bond process with sheet handling performed by a robotic system.

Automating a form-then-bond process produces added potential for improved build speed. The form-in-place paradigm requires that each layer be bonded and formed sequentially, in close succession. In a form-then-bond technique this is not required. It is not even necessary to perform both operations on the same machine. One of the anticipated implementations of this device includes one or more cutters that produce sheets ready for stacking, and one or more stacking devices that are fed a collated stack of construction sheets and produce the registered and bonded object. Using this arrangement, the two processes don't have to wait on each other. If the stacker is faster than the cutter, one stacker could service several cutters, etc.

This potential for build speed increase can be investigated by expressing the build time for a fabrication process in a general equation:

$$T_{build} = T_{pre} + \sum_{i=1}^{n} T_{layer(i)} + T_{post}$$

where T_{pre} is preprocessing time, $T_{layer(i)}$ is the creation time for the ith layer, and T_{post} is the post-processing time. While the details of what goes on during the pre- and post-processing times vary from process to process, we will focus here on the variation in T_{layer}. The form this term of the equation takes depends on the specific technique used to create the layers of the object. We discuss here two overlapping classification schemes: 1) location of formation (form-in-place and form-then-bond) and 2) formation technique (volume building, periphery cutting, and 2-D mask). Only periphery cutting is today represented both in form-in-place devices, in which case it is called a "stack-first" process, or as a form-then-bond, "cut-first," process. For example stereolithography is a form-in-place volume-building technique that creates a cross section by sequential curing voxel by voxel; Laminated Object Manufacturing is a form-in-place periphery-cutting (stack-first) process; Cubital's Solid Ground Curing is a form-in-place 2-D mask process; and the JP5 (as well as the Conveyed-Adherent device discussed later in this paper) use a form-then-bond periphery-cutting (cut-first) process. Each layer creation scheme has a unique equation for calculating $T_{layer(i)}$, as shown in Table 1.

Location of Formation	Formation Technique	Examples	Layer-creation time
Form in place	Volume building	SLA, SLS, FDM	$T_{layer(i)} = T_r + \frac{A_i}{dv}$
	Stack first	LOM	$T_{layer(i)} = T_r + \frac{C_i}{v}$
	2D mask	Solider (Cubital)	$T_{layer} = T_r + T_c$
Form then bond	Cut first	JP5, Conveyed-Adherent	$T_{layer(i)} = \max\left\{\frac{C_i}{v}, T_r\right\}$

Table 1 Layer-creation time in various fabrication processes. In the equations, T_r represents the delay time between active geometry creation for each layer (e.g., recoating time for stereolithography or layer bonding time for LOM), A_i is the area of the ith cross section, C_i is the ith cut length, v is the cutting or laser-scanning velocity, d is the width of the line created by a volume-building process, and T_c is the cure time in a 2-D mask process. The second term on the right-hand side of each equation represents the time required for active geometry creation. Note that for a form-then-bond process the active geometry creation and the delay time (in this case layer registration and bonding) occur in parallel.

Using the equations in Table 1 with constants selected for convenience (not exactly corresponding to any real process), the qualitative behavior of the different process classes can be investigated. The build speed as a function of geometric complexity (e.g., thin walled vs. thick walled) is investigated in Fig. 1 using a simple cube that is hollowed into a rectangular tube. The geometry is varied by changing the wall thickness of the tube, and the complexity is varied by adding multiple copies to the build volume. For this geometry the area of each layer is $A = l_o^2 - l_i^2$, and the periphery length to be cut is $C = 4l_o + 4l_i$. Note that the build time increases for a volume-building process as the wall thickness increases, while the build time decreases for a periphery-cutting process (since the total

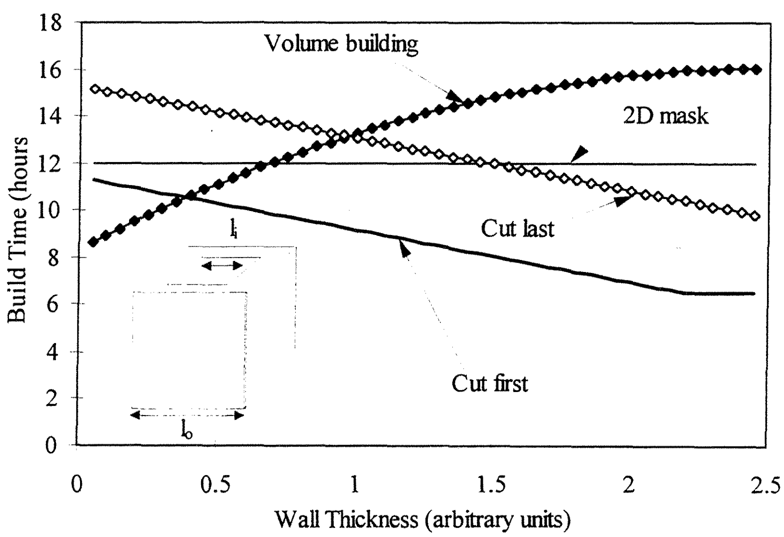

Fig. 1 An example of how build time for the several types of fabrication processes can vary with respect to the geometry being formed.

cut length decreases with increasing wall thickness in this example). The 2-D mask process is independent of the wall thickness. The build time for the cut-first (form-then-bond periphery cutting) process is shifted downward since the cutting and stacking processes run in parallel. Note that the build time becomes independent of wall thickness when the periphery cutting time drops below the register and stack time.

III. Automating Form-then-Bond Fabrication

Ennex Fabrication Technologies has automated form-then-bond fabrication with the development of the Conveyed-Adherent™ process. This jump to full automation solves the difficulties of sheet handling and stacking and potentially provides significantly improved speed and convenience. Automation is achieved by the use of a substrate to carry each formed layer in succession to be stacked and bonded to the previous layers. This technique has the potential to address many concerns in the fabricator market and to open up new markets previously not in reach because of price. A schematic of the process is shown in Fig. 2.

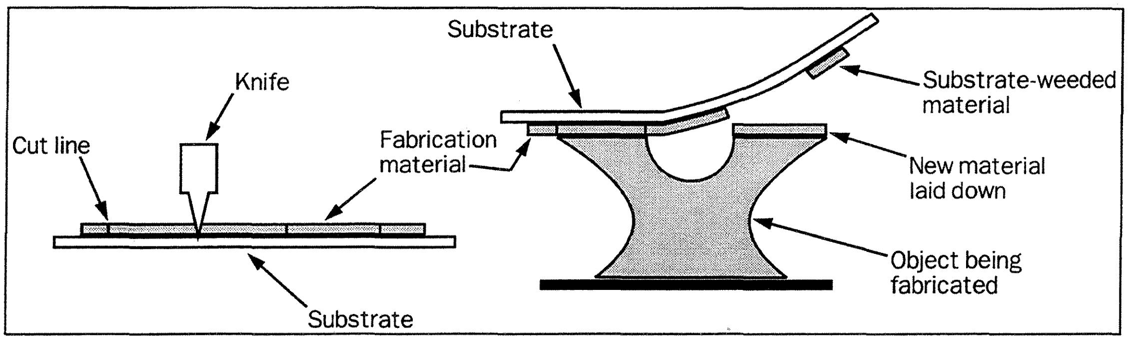

Fig. 2 The two stages of the Conveyed-Adherent™ process, layer formation on the left and layer bonding on the right.

Process Overview

The basic construction material required by the Conveyed-Adherent process is any sheet material which can be cut and bonded to itself, along with a release liner or backing paper referred to here as the substrate. A 2-D plotting device is used to cut the outlines of cross sections of the desired object into the sheet material without cutting through the substrate. In addition to the outline contours, the plotter can also cut parting lines and outlines for support structures. When required, the sheet is then "weeded" to remove some or all of the negative material. Finally the material is inverted so that the substrate is facing up and the material is brought into contact with the top of the growing object, and bonded to it. The substrate is then peeled off to reveal the new layer just added and a fresh surface ready to bond to the next layer. The process is started by applying an initial layer of adhesive on a stacking platform.

The Prototype Genie™ Fabricator

The Conveyed-Adherent process has been implemented in the laboratory of Ennex Fabrication Technologies in a working prototype called the Genie fabricator, named for the mythical creature in Arab literature which could grant its owner any object desired. A picture of the machine, with a model of an automobile it has built placed in its build area, is shown in Fig. 3.

The prototype Genie fabricator operates automatically, except for weeding, with processing monitored by a variety of sensors. Material jams and other machine faults are detected by sensors for limits of travel and arrival of material at each station.

The prototype Genie fabricator has built several objects, including various geometrical and automotive models in several colors. The models are attractive, although they suffer from problems due to registration errors and curl caused by internal stresses arising in the process. Research is underway to eliminate these problems and improve the quality of output of the fabricator. An example object made is shown in Fig. 4.

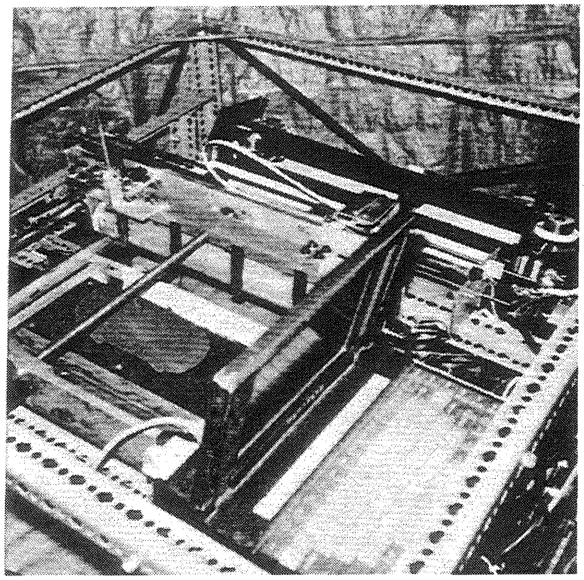

Fig. 3. The prototype Genie™ fabricator in the laboratory of Ennex Fabrication Technologies.

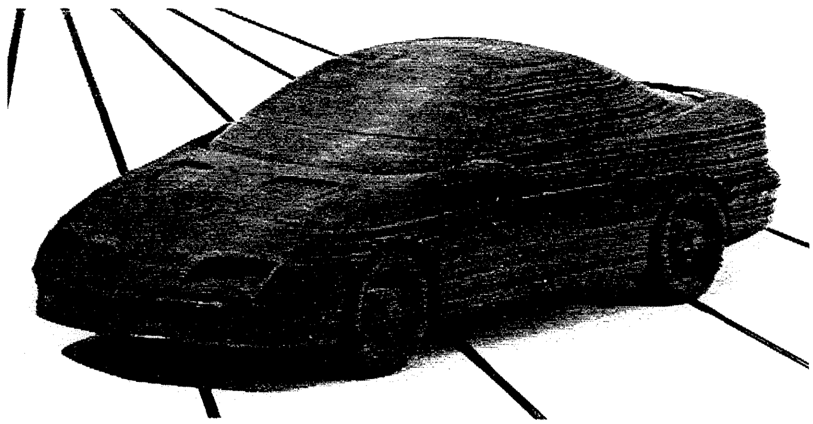

Fig. 4. Automobile model built on the prototype Genie fabricator at Ennex Fabrication Technologies. The car measures 9½ by 3¾ inches by 3 inches high. (Model data courtesy Viewpoint Datalabs International)

Materials

Many materials have been tested in the process, including label paper, adhesive-backed foam material, and sign maker's vinyl. Objects made from vinyl or paper are somewhat flexible due to the flowability of their pressure-sensitive adhesive. The paper material can be made more rigid by coating with epoxy or glue. The foam material is used to build patterns for investment casting, resulting in metal objects. Ceramic and metal tapes for the process are under development by Lone Peak Engineering. Potentially any material can be used that can be produced as a sheet, cut by a knife, and undergo some form of bonding from layer to layer.

Plotting

Layer cross sections are cut using a cutting plotter designed for the sign making industry. These plotters are capable of high dimensional accuracy with knife speeds up to 30 inches per second. Cutting plotters accept sheets of various widths up to over a meter wide and the vertical plotters, as opposed to bed plotters, have no limitation to length of sheet since the material is pulled back and forth through the machine. These machines can cut a wide variety of materials including the ceramic and metal tapes mentioned above, as well as very thin (less than a thousandth on an inch) and thick (up to .035 inch and more) materials. The knives for these plotters include high precision blades as well as cryogenically treated metal blades to increase knife lifetime. A plotter is available which has a knife along with a color ink-jet printer. This would allow color to be incorporated into the material by a process proposed by Kinsie [8]. In the prototype Genie fabricator, plotting is performed by a CAMM I cutting plotter made by Roland Digital Group.

Weeding

Weeding is the term used in the sign making industry for the process of removing the unwanted material around the letters and graphics coming from a sign plotter. To our knowledge there are no mechanical weeders available that can handle weeding of general complex shapes. These complex weeding operations are currently performed manually using tweezers and a good eye.

A mechanical weeder allows one to overcome some of the limitations of stack-first technology. The stack-first process, in its current realizations, has no means of removing negative material during a build and hence produces output of a solid block of material. This requires that the negative material complementary to the object be "diced" by a cross-hatched pattern of parting lines, which add considerably to the process time. After fabrication, the negative material is chiseled away to reveal the finished object. Thus, in the stack-first process, enclosed voids cannot be made, as well as embedded macro-composite structures and colored objects.

The engineering of a weeder, like the engineering of so many successful artificial intelligence programs, must use tricks and overt constraints to solve a less general problem. Some of the constraints are obvious, such as that the sheet is held down so as to remain a 2-D problem, and extra cuts can be provided to reduce difficult-to-weed shapes into smaller, simpler shapes. Some "tricks" that can be used to reduce the amount of mechanical weeding necessary are discussed below.

One trick to reduce the load on the weeder is to realize that most of the negative material can be dealt with using a few well-placed parting lines, so that the object can be easily broken out of its block-like enclosure by a simple turn of the wrist. The use of flexible materials makes this post-processing step particularly simple when compared to processes producing rigid final objects. A weeder is needed only in small regions of the object like enclosed voids or close approximations thereof. Therefore the weeder may be operating on only a fraction of the layers of an object and may be weeding only a small fraction of the negative space even on those layers.

Another trick, called substrate weeding, has the potential to drastically reduce the work load of the weeder. Each successive layer of material containing the cross section of the desired object as well as its negative material is pressed on top of the growing object. If there is a void space below a section of the negative space (i.e. the last layer was successfully weeded) this section will have nothing to adhere to. It will remain on the substrate and be tossed out with it. Thus, in principle, all that is needed to prevent growth of one of the problem negative regions is to weed its first layer. All subsequent sections will find no section below them to adhere to.

The actual practice of this powerful technique is not as simple as the above description may imply. There are several factors that limit the ease with which substrate weeding can be used. One factor is overlap of negative material onto positive material. If a negative region grows larger with the height of the object, the section of negative material on any given layer will find at least a small ledge below it on which to adhere. The degree to which this causes a problem depends on how large the ledge is and on the relative strength of adhesion to the fabrication material and to the substrate. Another factor is cross-boundary linking. Unlike a laser, a knife does not remove material when it makes a cut and the cut material has a tendency to self-heal. The linkage between already-cut sections within a layer is relatively weak, but can overpower lay-down adhesion for a small region whose cut periphery is large compared to its area.

The prototype Genie fabricator does not have a mechanical weeder. Layers that require weeding are handled by a special diverter that routes material to a station where it can be weeded manually. Due to substrate weeding, the number of layers on which this must be performed is small.

Lay-Down, and Peel-Off

The cut and weeded sheet is fed to a lay-down platen. The platen aligns the new sheet with the growing object and applies the pressure needed to bond the layers. Several designs are possible, including the simple roller used in the Genie fabricator, as well as arc-sections of rollers with much gentler slopes. A roller platen may approach the stack from the side or it may "land" on the stack from above. One problem that can occur is the formation of bubbles, trapped pockets of air, between the layers. Research at Ennex Fabrication has investigated the effect of various platen configurations on bubble formation and other relevant issues.

After the material is laid down, the substrate must then be peeled off. For substrate weeding to occur there are two competing forces which must be balanced against each other. As described in the weeding section, one force is the adherence of the material to the last layer, and the other force is the adherence of the material to the substrate. The process must ensure that no positive material is carried away by accident and that no negative material needing weeding is accidentally laid down. For instance, a small radius-of-curvature peel-off device will tend to favor leaving negative material.

The prototype Genie fabricator uses a simplified design in which a single roller performs lay-down and peel-off simultaneously. The roller lays down the material on its leading edge and peels off the substrate at its trailing edge. The substrate, along with any substrate-weeded sections of the layer, are automatically dropped at the far end of the roller's travel. The roller "lands" on the stack by the raising of the stack under the control of a vertical sensor. Proper registration has been one of the difficulties to be overcome in the design of the fabricator. Table 2 documents the improvement in layer registration that has been realized through several design iterations. Registration values reported are estimated values for registration error alone. They do not include error due to distortion, etc. The values in the first column are an estimate of typical registration error, ignoring the extreme values. Values in the second column represent the extreme values caused by machine jams, etc.

Design iteration	avg. error (in)	max. error (in)	frequency
1st iteration	0.015	0.035	50%
2nd iteration	0.005	0.035	<10%
3rd iteration	0.002	0.020	<1%

Table 2 Registration improvement in the prototype Genie fabricator. The average registration error of the prototype Genie fabricator, as well as magnitude and frequency of maximum registration error, has been reduced with each iteration of the design.

Data Formats

The Genie fabricator accepts a special layer-specification data format which includes the graphical instructions for each cross section and will include layer headers containing information about weeding, changing of feedstock material (such as color), and process pausing for manual embedding of components by the operator.

A special feature of the Genie fabricator is the ability to change the length of the build envelope for any layer in a build. This length is also specified in the data format.

IV. Demonstrated Applications

Several distinct advantages are realized in the form-then-bond paradigm. When using a cut-sheet process, it is possible to weed the negative areas of each construction layer before stacking, allowing the construction of hollow structures. These hollow structures can be filled during production producing cast in place internal structures. Objects may be inserted into these hollow spaces during construction producing a hybrid of fabricated and off-the-shelf components. Construction sheets of different materials can be used resulting in objects built of several different materials in a single build. By combining the ability to embed components in voids and cast plastic into voids along with cut patterns designed to weaken the material selectively, the material properties within an object can be selectively specified. One part of the object can be of rigid polyurethane, another bordering it can be of greater flexibility than even the original feed stock material. These techniques are demonstrated in the fabricated objects described below.

Embedded and Cast-in-Place Car Axles

The axles of two car models built in the Genie fabricator (e.g., see Fig. 4) serve as simple examples of cast-in-place and embedding techniques. If built in the same vinyl used for the bodies of the cars, the axles would have sagged under the weight of the cars. Instead, voids were designed into the car bodies, wheels, and support material to allow casting plastic in a shape which would look like an axle in the visible portions and function like anchors inside the vinyl wheels and body. For one car, the axles were formed of polyurethane resin cast into the voids at the last layer before the void closed during the build. For the other, steel axles were embedded in place with plastic extruded by a hot glue gun cast around them in the cavities. Both car models were in their complete form when the last layer was put down on the machine.

Robotic Manipulators

Fig. 5 shows a dual-link robotic manipulator (or robot finger) built in the Genie fabricator with cast-in-place rigid plastic stiffeners, use of two materials to provide a rigid manipulator frame with flexible joints, and control cables inserted during fabrication. The manipulator is designed to be functional at completion of fabrication.

The dual-link, four-degree-of-freedom manipulator demonstrates embedding of wire and tubing as well as casting-in-place of plastic. More importantly, the finger's design necessitated a new way of thinking about how a fabricator is used. Some of the shapes specified in the CAD file correspond to actual pieces of the build object made in the fabrication (vinyl sheet) material, while others correspond to voids and walls of molds to hold the casting resin, and still others must specify supports for embedded objects before the casting resin locks them in place. This is

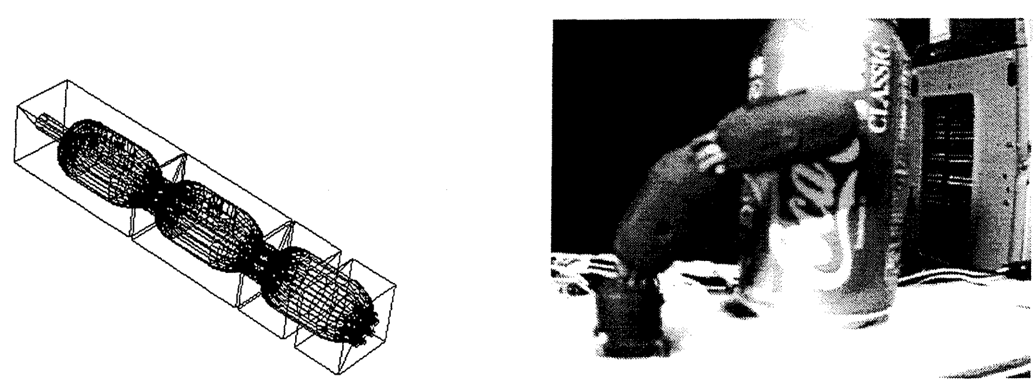

Fig. 5 Dual-link robotic manipulator made on the prototype Genie fabricator at Ennex Fabrication Technologies. Left: CAD design; right: photograph of fabricated manipulator.

very different from designing a monolithic prototype model for a fabricator to build where only support structures need be specified. This has some of the flavor of designing a skyscraper where initial framing and access ways for build materials and construction equipment are just as important as the final product specifications. This will become even more acute when more and more of the embedding and casting operation, here done by hand, are automated into the actual fabricator itself. Then the fabricator's ability to make arbitrarily complex monolithic shapes will provide problem constraints in the form of voids, supports, and fasteners to the very difficult problem of automated assembly itself.

A CAD design, shown on the left side of Fig. 5, was created in TriSpectives, which specified the vinyl outer body of the three manipulator segments. A hollow cavity was specified inside each segment for the cast plastic "bones". A cylinder of 6 mm diameter was specified to run down the long axis of the manipulator to hold a flexible plastic tube. This tube and two springs fitting tightly around it hold the segments together, provide flexible joints, and in the final product provide a tube for electrical wiring, etc. Eight smaller-diameter cylinders were placed radially around this central tube to hold metal pull cables and their housings. Holes were left in the tops of the segment cavities to allow pouring of the casting resin. The resin seeps into the voids left in each segment and forms the bones while at the same time locking the vinyl, tube, pull wires, and joint springs in place. The pull-wire housing provides a low friction surface for the wire to run in even while the housing itself is embedded in the solidified resin. The eight pull wire ends are terminated in the solidified resin locking them in place such that when one pulls the free end of the wire exiting the last segment of the finger the corresponding joint bends.

The right side of Fig. 5 shows the finished finger mounted on a platform and connected to four servo motors allowing computer control of its four degrees of freedom. Future directions include embedding the servo motors, along with rechargeable batteries, micro controller, pressure and strain sensors, and associated wiring in a quadruped robot with legs resembling the above manipulator. From our experience with the above manipulator we expect this robot to be very durable. It will be completely protected from the elements since its sensitive components are encased in a homogenous mass of solidified resin and its movable joints have no bearing surfaces. When you include the fabricator's ability to provide arbitrary complexity to the shape of the outer body skin we see that this is a different sort of robot from the ones built in most research labs today.

A single-link manipulator was built on the JP5 fabricator in a similar fashion. The frame for this manipulator was produced from multiple layers of paper; the hinge was constructed from four layers of vinyl. The dual-material build was realized by weeding an interior void from four interior layers of the paper and producing four vinyl construction sheets that contained only the hinge material. To construct a multiple-material layer, first a paper layer was applied, then the vinyl layer was laid down in the voids of the paper layer.

Motor-Driven Model Car

A model car was fabricated with interior voids for embedded devices. In this example the solid STL file was modified by adding interior voids before construction. An electric motor, cables, battery pack, and switch were installed as the layers were assembled. After the last layer was in place, the switch was activated and the model car drove across the room.

V. Conclusions

The Conveyed-Adherent process is an automated "form-then-bond" fabrication technique that has been demonstrated in the production of engineering prototypes and functioning machines. The new process shows potential to be many times faster than existing devices. It has demonstrated fabrication in multiple materials side-by-side. It also has demonstrated the potential to produce functioning machines through the use of embedded components and cast-in-place internal structures.

Notes and Acknowledgments

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