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ON THE GEOMETRY OF LOW DEGREE-OF-FREEDOM DIGITAL CLAY HUMAN-COMPUTER INTERFACE DEVICES

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ABSTRACT

Digital clay represents a new type of 3-D human-computer interface device that enables tactile and haptic interactions. The digital clay surface is computer controlled and can be commanded to acquire a wide variety of desired shapes, or be deformed by the user in a manner similar to that of real clay. In this paper, we present the ideas underlying digital clay and an example design of a digital clay device meant for general-purpose modeling. We also introduce the concept of low degree-of-freedom digital clay devices, in which the clay surface can acquire a limited range of shapes, for example, to describe the shapes of automotive front-ends. Each degree of freedom moves a region of the clay surface through a range of predefined shapes. We investigate geometric modeling techniques for defining the ranges of shapes and relate the shapes to forward and inverse kinematics of the deformable structures that control surface shape. To illustrate the application of the digital clay concept, an example low degree-of-freedom clay device for modeling automotive front ends is presented and discussed.

1 DIGITAL CLAY CONCEPTS AND CONTEXT

Shape is a key element in successful communication, interpretation, and understanding of complex data in virtually every area of engineering, art, science, and medicine. In recent years, the communication of both form and complex data has been greatly enhanced by visualization technologies. However, these visualization technologies are based on planar images. With the advancement of computational power, it is now possible to consider real-time, tactile 3-D physical communication to overcome the inherent limitations of planar images. A novel type of human-computer interaction device called Digital Clay is being pursued by a team at the Georgia Institute of Technology. Digital clay will be a physical device capable of deforming into a desired shape via computer control (shape display), as well as being shaped by a user in a manner similar to real clay (shape editing). See Figure 1 for a schematic illustrating the use of a prototypical digital clay device for shape editing. In this paper, we describe the digital clay concept and its application to engineering design. We will then present the technical issues and approaches in developing digital clay and summarize its status.

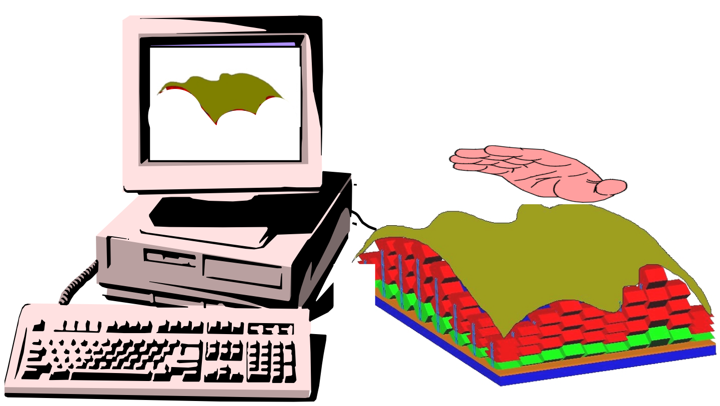


Figure 1 Schematic of Digital Clay in Use.

Digital clay is conceived as a haptic interface device for human-computer interaction, as well as collaboration. As a person manipulates the clay's surface, the shape change can be sensed and transmitted to the computer for conventional visual rendering and storage. Additionally, the shape change can be transmitted to other pieces of clay or devices at remote locations for collaborators to inspect or to modify.

Physical interaction between user and clay consists primarily of the forces applied by each to the other. In addition, the user can inspect the shape visually and by touching it without modifying it. Our approach is to investigate a single mode of interaction to explore capabilities and limitations of tactile interaction, with shape and force feedback through the device.

We believe that a wide variety of applications will be supported by successful digital clay devices, including mechanical computer-aided design, industrial design, distance collaboration for product development, medical diagnostics, bioengineering device design, reconfigurable displays, and possibly even aids for visually impaired persons. Some applications require the capability for direct shaping by the user, while others require shape display only. An intriguing possibility is to support shape and stiffness "display," enabling certain classes of medical diagnostics, for example, that requires the digital clay to "feel" like an organ or a type of tissue.

The "clay" metaphor for human-computer interfaces is a powerful one, one that has been explored by other researchers. Some implementations have focused on reshaping of non-physical volumes of 'virtual clay' using glove-like or haptic manipulator interfaces that interact with digital models of the 'clay.' Applications such as surgical training [1] require that the physical volumes behave in a physically based manner. Some sculpting systems have also relied upon physically based behavior [2, 3, 4], utilizing multiscale techniques or precomputed material properties to achieve real-time performance.

Other approaches have taken liberties with the clay metaphor for interfaces, or were based on a different interaction metaphor. Physically based behaviors are often computationally expensive and may lead to unnecessary interaction difficulties. For example, the volume preservation behavior of physical clay is an unwanted and unneeded behavior for our work. Other work in freeform deformation implemented some physically based behaviors [5, 6] and has utilized a variety of deformation tools [7].

The advent of commercial haptic interface devices, such as the PHANTOM [8] has spawned a wide variety of applications. In the area of mechanical product development, investigations of assembly and disassembly tasks have been undertaken with the PHANTOM [9]. Other types of haptic interface devices have also been developed and tested for product development applications [10]. However, devices like the PHANTOM stimulate the kinesthetic channel (sensory receptors in muscles), but do little to stimulate the cutaneous channel in the skin, which senses pressure information. This is necessary for sensing textures and finer shape details. Some research systems are exploring the cutaneous channel for human-computer interaction. For example, a tactile display that stretches the skin was recently reported [11]. Digital clay devices are also capable of stimulating the cutaneous channel since the user can touch the device's physical surface. However, providing meaningful tactile information requires high resolution that will be challenging to achieve in digital clay devices.

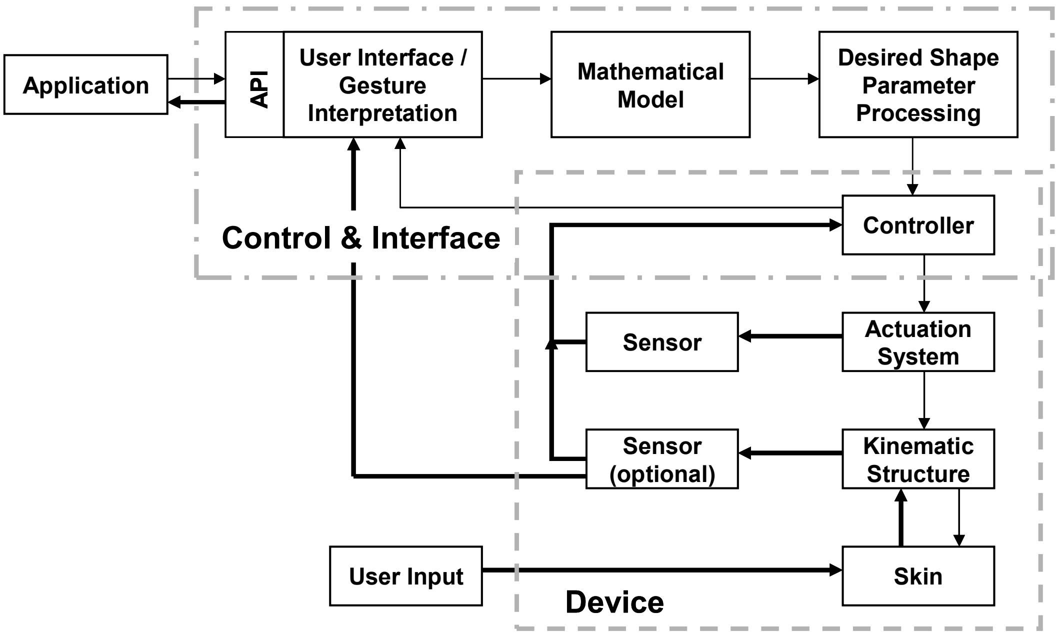
Research is underway on the development of physical devices that have considerable similarity with our digital clay designs. The FEELEX system [12] consists of a device with an array of pins that can translate vertically to form a wide variety of surface shapes (essentially a "bed of nails" device). However, since these pins are linearly actuated using electric motors, the device is complex and its resolution is limited.

Despite the considerable research in the virtual environment, haptic interaction, and human-computer interface areas, the usefulness of tactile and haptic user interface devices is very limited for many engineering applications. The need exists for better 3-D shape display, creation, and communication systems that take advantage of more than one sensory channel. In an attempt to meet this need, we are investigating a variety of potential solutions that involve physical devices that support visual, tactile, and haptic interactions in the digital clay project.

This paper is primarily a concept paper that reports research directions and some early results. The remainder of the paper is organized as follows. In Section 2 we present the general architecture of our digital clay devices. Section 3 contains a more detailed presentation of the device's subsystems. Emphasis is on general digital clay devices that, when developed, will be composed of scalable technologies with hundreds or thousands of degrees of freedom and very fine resolution. In Section 4, we present the concept of a low degree-of-freedom clay device, discuss the geometric modeling aspects of its deformable surface, and present some aspects of its kinematic behavior. Then, an example low degree-of-freedom clay device is presented that models the shapes of automotive front ends. In the final section, we discuss what has been accomplished to date and present directions for future work.

2 DIGITAL CLAY ARCHITECTURE

Technically, digital clay will be an instrumented, actuated, computer-interfaced physical volume bounded by an actuatable surface that acts as the haptic interface. The surface is displaced by an array of controllable, interconnected fluidic-driven actuators, which together act to convey the surface topography of a 3-D object manipulating a scaffold internal to the volume of the clay. Each actuator comprises a discrete fluidically inflatable cell that is connected to two common pressurized reservoirs (within a base) through a dedicated two-way miniature valve. An array or valves and pressure sensors will be micromachined into a base that controls fluid flow to



3 DIGITAL CLAY SUBSYSTEMS

Each of the major digital clay subsystems will be discussed. Emphasis is placed on both the planned physical embodiment of the subsystem and how that subsystem contributes to the overall behavior of the clay.

3.1 Skin and Kinematic Structure

The skin and kinematic structure of the digital clay form the "volume" of the clay device with which the user interacts. In some initial designs, the skin and structure are separate, while in newer designs, we have combined these two elements into a common component. The kinematic structure is intended to enable the clay to maintain its shape and to give it some stiffness. The inflatable cells will be attached to the structure to control its shape or to sense user pressures. The skin is simply meant to form the barrier that the user touches. As shown in Figure 1, one initial clay design utilizes arrays of hexagonal elements as the kinematic structure. Inflatable cells fill each of these elements, while a flexible skin is stretched over the array.

It is also possible to integrate the structure and skin. We call such designs "formable crust" or simply "crust" designs. Kinematically, formable crusts consist of arrays of spherical joints that are connected by rigid links, hinged links, or links that include prismatic joints (so they can essentially stretch). Recent research has led to some novel kinematic structures and measures of their degrees-of-freedom [13]. In Figure 3, some sketches of crusts are given.

The challenge with crust designs is their manufactability. The construction of spherical, revolute, or other kinematic joints at small size scales is difficult. Instead, we have pursued the design and fabrication of compliant joints. To duplicate the behavior of spherical joints, we can use a collection of links and revolute joints, where the joint axes have a common intersection point [14]. Then, each revolute joint is replaced with a compliant joint. Figure 4a shows the resulting design that has the behavior of four concentric spherical joints connected to four links. These compliant spherical joints can be connected into arrays that can deform as shown in Figure 4b, which uses the array type shown in Figure 3a (rigid links). Our designs are fabricated in stereolithography machines, but other rapid prototyping technologies could be used. To give a sense of scale for the model in Figure 4b, the spacing between spherical joints is 12.7 mm and the compliant joints have radii

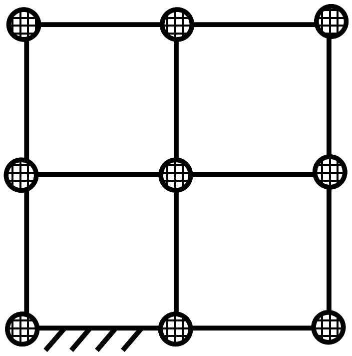
and from the inflatable cells. Optionally, an additional array of sensors may be incorporated into the scaffold to measure deformations and/or displacements of the scaffold. The digital clay device architecture described above is shown schematically within the dashed (bottom) box in Figure 2.

The control and interface subsystems are shown within the dot-dashed (top) box in Figure 2. The operation of the digital clay depends upon the mode in which the clay is being used. In display mode, the Application, through an API (application programming interface) translates a digital representation of the desired shape into commands and parameter values that can be sent to a lower-level control unit. The lower level control unit regulates fluid flow until the digital clay has taken the desired shape. This information flow is shown using thin arrows.

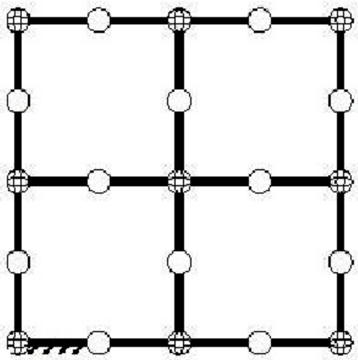
In shape editing mode, the user will press and deform the digital clay through haptic interactions. The user can produce a shape by pressing on the skin, causing the pressure within the inflatable cells to rise above a threshold value, which forces fluid out of the cells. Or, the user can apply certain gestures to indicate that the control unit should inflate the cells. In either case, the top level of control will first interpret the user's gestures to determine his/her intent. A mathematical model of the clay's behavior will be used to compute commands and parameter values that can drive the clay according to the user's actions. These values are then sent to the lower level clay controller for communication to the actuators. The additional information flow for this mode is shown in bold arrows. Further discussion of the clay architecture and subsystems is given in the next section.

of 0.8 mm and wall thicknesses of 0.4 mm. The model was fabricated on a SLA-3500 machine in SOMOS 8120 resin, which has an elastic modulus that approximates polyethylene.

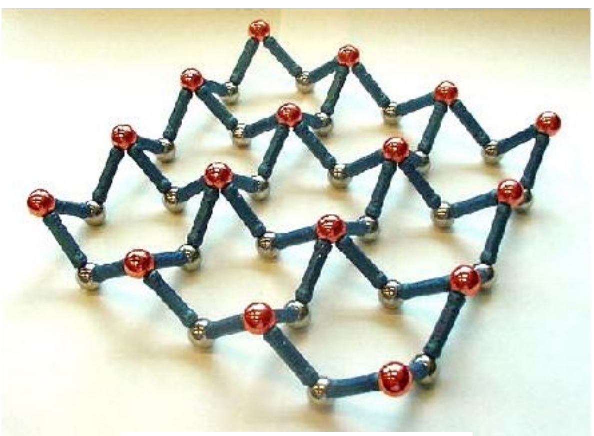
To sense user pressure or to actuate the crust, inflatable cells can be mounted in some of the compliant joints. Cells must be connected with the MEMS backplane, to be discussed next, and must be controlled by the control system (Section 3.3).



a) schematic of 3x3 array with rigid links.



b) 3x3 array with hinged links.



c) model of 4x4 array.

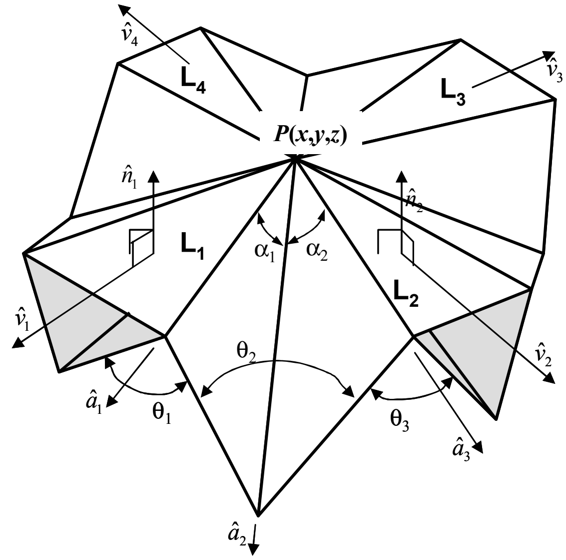
Figure 3 Crust designs consisting of arrays of spherical joints.

3.2 MEMS Backplane

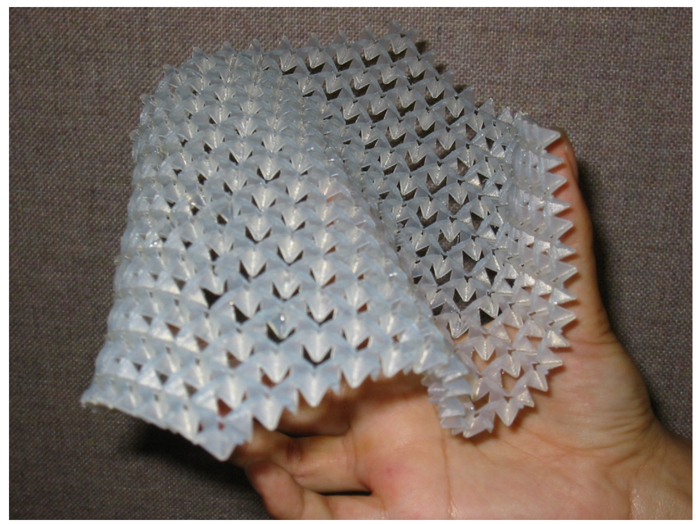
The inflatable cells in the crust, or internal clay structure, must be connected to fluid reservoirs and be controllable. Tubes from each inflatable cell are connected to a backplane that contains pressure sensors and valves, which are connected electronically to the low level controller. From the valves, fluid flows to the low pressure reservoir; or, fluid flows from the high pressure reservoir through the valves and into the cells.

We envision the backplane to be a MEMS device. The unique MEMS technology planned for this project allows the parallel, batch fabrication of multiple cells together with any required fluidic interconnect, and interfaces this resultant ‘clay’ and its array of fluidic orifices with valve, sensing, and electronics capabilities. Unlike typical micromachining approaches, which tend to be silicon-based, our group has developed a number of large-area, non-silicon MEMS technologies, including lamination-based polymeric approaches. In these approaches, analogous to lamination-based electronic packaging approaches, individual sheets of material are lithographically patterned to form the required chambers and fluidic interconnects, and then are laminated together to form the final backplane structure.

In our current embodiment, the backplane consists of a rigid base bearing a dense array of individual modular elements, wherein each module possesses means for a fluidic connection to the actuator cells in the volume of the clay. At a minimum, each module comprises three components: a pressure sensor, a passive or active hysteretic valve, and control logic / electrical interconnect.



a) compliant spherical joint.



b) array of joints.

Figure 4 Manufacturable crust design.

Hysteretic valves are valves that do not conduct fluid in either direction until a threshold pressure drop, significantly greater than zero, is exceeded. A hysteretic valve can be turned 'on' in one of two ways: either the threshold pressure in either direction is exceeded (passive operation), or the hysteresis pressure is lowered to zero by some external, active control means (active operation). Passive operation would be primarily used when the user is 'sculpting' a shape out of the digital clay (shape editing mode). Active operation would primarily be used when, under computer control, the digital clay is being programmed to assume a specific shape.

3.3 Controls

The controls subsystem is organized into three levels [15]. At the top level, the Application Programming Interface (API) software kernel receives commands or queries from an application and generates commands for the surface control level, the second level. The surface controller commands actuation of the cell control level. The lowest level, cell control, incorporates sensor feedback to drive individual valves in response to commands and sensed pressure.

In Figure 2, the API is shown as the layer that interfaces with the application and User Interface / Gesture Interpretation. Surface control consists of the three top boxes, while the lowest level, cell control, is represented by the box labeled Controller.

In display mode, the API will translate a digital representation of a 3-D shape into commands for the surface controller, which will generate parameter values that can be read by the cell controller. The low level cell controller then regulates the fluid flow until the digital clay has taken the desired shape.

In shape editing mode, the user interacts with the clay surface to cause it to change shape. If the user is actively deforming the clay, then the increased pressure within cells is sensed by the cell controller which opens the low pressure valve to let fluid flow out of the cell. The surface level controller monitors the pressure changes and updates its geometric model of the clay surface. Periodically, the application is updated with shape changes through the API. If the user is issuing gestures to cause other types of shape changes (e.g., gesturing for the surface to rise), the surface controller will recognize the gesture and propagate commands to the cell controller, as appropriate.

Considerable research remains to better define controller properties and behaviors. Furthermore, it is likely that controller behavior will be application specific.

3.4 Human-Clay Interaction

We intend for human-clay interactions to be touch-based, without other modes of interaction, such as voice, keyboard, mouse, etc. As indicated in the Controls subsection, there are numerous types of human-clay interactions that we envision supporting. In display mode, the clay is passive, allowing the user to touch, push, or otherwise interact with the clay surface without causing changes in the surface.

In shape editing mode, several issues arise:

- How does the clay know when to switch from display to shape mode?
- How does the clay know where it is being touched/deformed?
- While deforming the clay, how does the clay know how much surface to include in the deformation, how deep the deformation should be, and what shape the transition from undeformed to deformed regions should be?
- How does the user indicate for the surface to rise?

One method to indicate the transition from display to shape editing mode would be by the user pressing on the clay with a force above a threshold value. Other methods are possible; this is a minor issue.

The second issue is more challenging. Our initial clay device will only have pressure sensors connected to the inflatable cells. By knowing which cells experience increased pressure, the clay device can determine where on the surface the user is pressing. However, this is a superficial answer that does not address possible coupling among cells and coupling caused by surface designs and shapes. The formable crust surface designs have stiff links and compliant joints that will act to distribute forces throughout a much larger area than the user is likely to be acting upon. Hence, it will be necessary to interpret pressure measurements in the context of surface shapes and formable crust designs to properly deduce the regions where the user intends for surface changes to occur.

When deforming the clay, the controller needs to determine which regions of the surface to modify and how much deformation should occur. The third issue is complex and many possible resolutions exist. Geometric and dynamic behavior models of the clay will be developed that enable the surface controller to interpret user inputs.

In our current approach, the user can indicate for the clay surface to rise through a specific gesture: s/he should quickly press into the clay above the force threshold, then release his/her hand. This will indicate that the clay should rise until the user's hand again exerts a pressure on the clay surface. We envision fine-tuning interactions of this type to enable the user to raise bumps and ridges, emboss surfaces, and describe undulating terrains.

We have implemented a "finger sculpting" testbed for experiments on shape control gestures [16]. The testbed utilizes a Phantom haptic interface device, a simulation environment, and a graphics display. A simple behavioral model of the clay surface has been implemented that enables real-time response to shape manipulation inputs with the Phantom. Using this testbed, we have demonstrated various types of user inputs, including raising bumps, digging holes, embossing various shapes, and extruding regions. Gestures have been developed for indicating shape deformation regions. Although this human-clay interaction work to date has been limited to single finger actions, we believe that the concepts can be generalized to work with a single hand and with two hands that are manipulating a digital clay device.

4 LOW DOF DIGITAL CLAY

Much of our research to date has focused on the design of general purpose digital clay devices. The design of these devices should be scalable to thousands of degrees of freedom and to resolutions of less than 3 mm. However, the digital clay concept can also be applied to product-specific applications where narrow ranges of shapes are to be explored. One intriguing idea is to construct style-specific clay designs. For example, a kitchen appliance clay design could embody the Braun style such that, when manipulated, the clay surface always takes on shapes that are representative of the Braun style.

In this section, we explore the idea of product-specific clay designs that have a small number of ***input*** degrees of freedom. Each degree of freedom will control some aspect of the product and style's shape. The overall range of motion of the clay surface will be fairly narrow. Furthermore, we will limit ourselves to clay designs that operate in the display mode only.

4.1 Forward and Inverse Kinematics

Before describing how clay surface shapes will be controlled, it is necessary to describe the behavior of the formable crust designs from Section 3.1. Conventionally, mechanism behavior is described by kinematics models that describe mechanism positions as a function of mechanism input values and link lengths. In forward kinematics, mechanism inputs are given and the mechanism positions are computed. For example, the specification of joint angles in a typical serial robot will determine the position and orientation of the end-effector. In inverse kinematics, the mechanism positions are given, and joint angles are computed. In the robot example, the end effector position and orientation would be given and the joint angles are determined.

For the crust designs, the inverse kinematics problem is trivial in some cases and straightforward in others. For example, the inverse kinematics of the rectangular grid shown in Figure 3 is straightforward to determine. The positions of each shaded spherical joint (Figure 3a) would be given. From these positions, it is easy to determine link positions, orientations, and joint angles. However, the forward kinematics of these grids is more difficult. In mathematical notation, the forward and inverse kinematics problems are given as:

$$\text{Forward: } C(x,y,z) = k\,(\Psi) \tag{1}$$

$$\text{Inverse: } \Psi = k^{-1}\,(C(x,y,z)) \tag{2}$$

where the $C(x,y,z)$ represents the crust shape (spherical joint positions and link positions), Ψ = set of inputs, and k () describes the relationships between inputs and crust shape. For the general digital clay designs presented earlier, the inputs, Ψ, could be considered as the pressure of the fluid flowing into and out of the inflatable cells or the joint angles that these cells actuate. For the low degree-of-freedom clay designs, however, the inputs will be translations of certain points on the crust surface. These points will be controlled by linear actuators, such as hydraulic cylinders, or by linkages that are actuated by those linear actuators.

Our current formable crust design is shown in Figure 4. The compliant spherical joint shown in Figure 4a can be arranged in a variety of patterns, one of which is shown in Figure 4b. For the inverse kinematics problem, the position of the spherical joint center, $P(x,y,z)$ and the orientations of links L_1, L_2, L_3, and L_4 are given, while the angles between links are to be computed. Mathematically, the inverse kinematics problem can be stated as:

$$\theta_1,\theta_2,\theta_3 = f^{-1}\left(\hat{v}_1,\hat{v}_2,\hat{n}_1,\hat{n}_2,\alpha_1,\alpha_2,\beta_1,\beta_2\right) \tag{3}$$

It is straightforward (but tedious) to derive the relationships represented by $f^{-1}()$. We have not worked out the forward kinematics as of yet.

4.2 Surface Modeling Approach

In this subsection, we present two approaches to modeling the shape of digital clay surfaces, the "formable crusts." Given a clay design, there are two questions that should be asked of its capability for shape display:

1. Given a desired surface shape, how well can the crust represent that desired shape?
2. Given a set of inputs to the clay device, what shape will the crust acquire?

Question 1 involves the application of inverse kinematics, while question 2 involves forward kinematics. Our approach to answering these questions relies on the application of geometric modeling techniques.

4.2.1 Array of Points

In the first approach to modeling clay surface shapes, the surface will be controlled by controlling the positions of an array of points. Inputs Ψ will control the positions of certain points, t_i, on the crust surface. Hence,

$$t_i = f\,(\Psi) \tag{4}$$

where the t_i are (x,y,z) coordinates. Furthermore, assume that each point is attached to the crust at certain u, w coordinates embedded in the crust. Thus,

$$c_i(u,w) \leftrightarrow t_i \qquad 1 \le i \le n \tag{5}$$

If the $c_i(u,w)$ are spaced evenly in u,w parametric space, then a b-spline surface can be fit to these points to obtain a mathematical description of the crust's assumed shape. Standard techniques can be used to derive the equation of a b-spline surface that interpolates a set of points [17]. The b-spline surface will be denoted $B(u,w)$.

$$B(u,w) = g\,(c_i(u,w)) \tag{6}$$

Given the set of points $c_i(u,w)$, it is possible to compute joint angles and link positions of the crust by using the inverse kinematics solution. Joint angles can be compared with rotational limits of crust designs to determine where problems may arise, that is, where the crust may have difficulties in achieving desired surface shapes.

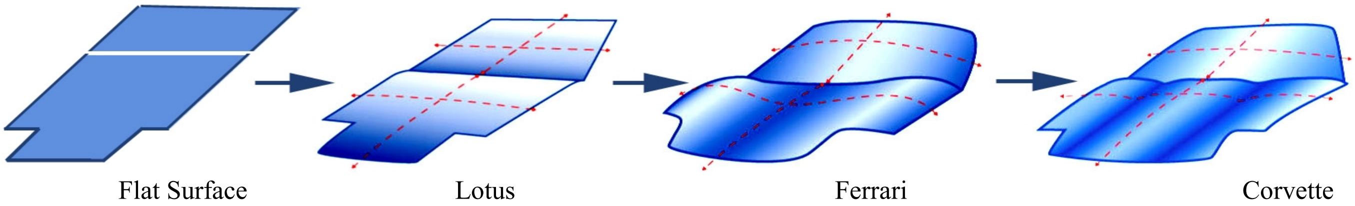


Figure 5 Renderings of Car Front Ends

This approach is sensible if the compliant joints of the crust behave in a manner similar to revolute joints. If the compliant joints have significant stiffness, however, the crust will not acquire the kinematically derived shape. In this case, the crust shape will be a function of input positions t_i and the stiffness of compliant joints. To handle this problem without resorting to models of material behaviors, we can assume a class of shapes that crusts will acquire. We assume that crusts will behave like bending beams or plates and assume cubic polynomial behaviors.

To answer the first question above, we assume that we are given a desired surface, $B(u,w)$, a cubic b-spline surface. The $c_i(u,w)$ points on the surface can be computed. From these, the joint angles within the crust can be computed, completing the inverse kinematics computations. The computed joint angles should be compared with the maximum allowable joint angle, θ_{max}, to determine the feasibility of the crust acquiring the desired shape. If some joint angles are not feasible, it remains to determine the resulting crust shape.

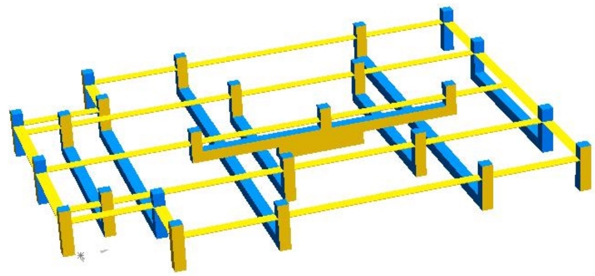
One approach would be to fix joint angles at θ_{max} for those joints whose computed angle is larger than θ_{max}, then compute the crust shape. A better approach would be to iteratively fit crust shapes to the desired $B(u,w)$ shape until a best fit is achieved. This approach will be pursued in the future.

To answer the second question, the procedure outlined above would be reversed. Given the $t_i = c_i(u,w)$ inputs, the joint angles and link positions can be computed using the forward kinematics model, which describes the crust shape. If desired, a b-spline surface could be fit to the $c_i(u,w)$ and compared with the computed crust shape.

4.2.2 Net of Curves

As an alternative approach, the crust could be made to interpolate a set of curves forming a net, rather than individual points. In this manner, beams could be fastened to the underside of a crust and, when a clay device's actuators modify beam shapes, the shape of the crust will also be modified. The idea is that using beams to control crust shape will constrain crust shapes more than using points.

With this alternative approach, lofted or interpolation surface models can be used to model crust shapes. For example, if the four bounding curves of a surface patch are given, then a bilinear Coons patch could be used to model the surface. Alternative formulations of surface models are possible if other sets of curves are to be interpolated.



a) frame with columns and beams.

b) top view.

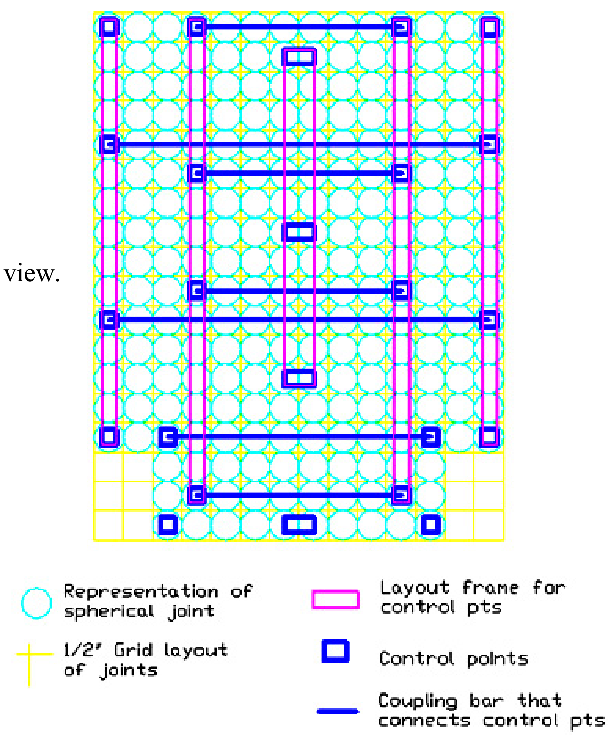


Figure 6 Automotive Front End Model.

4.3 Automotive Front End Model

To illustrate the construction of a low DOF digital clay device, we present a model of an automotive front end, where the designer can manipulate 15 independent inputs to control various aspects of the front end's shape. A formable crust design is used to model the hood. The user will control the hood shape by manipulating the positions of points on the hood,

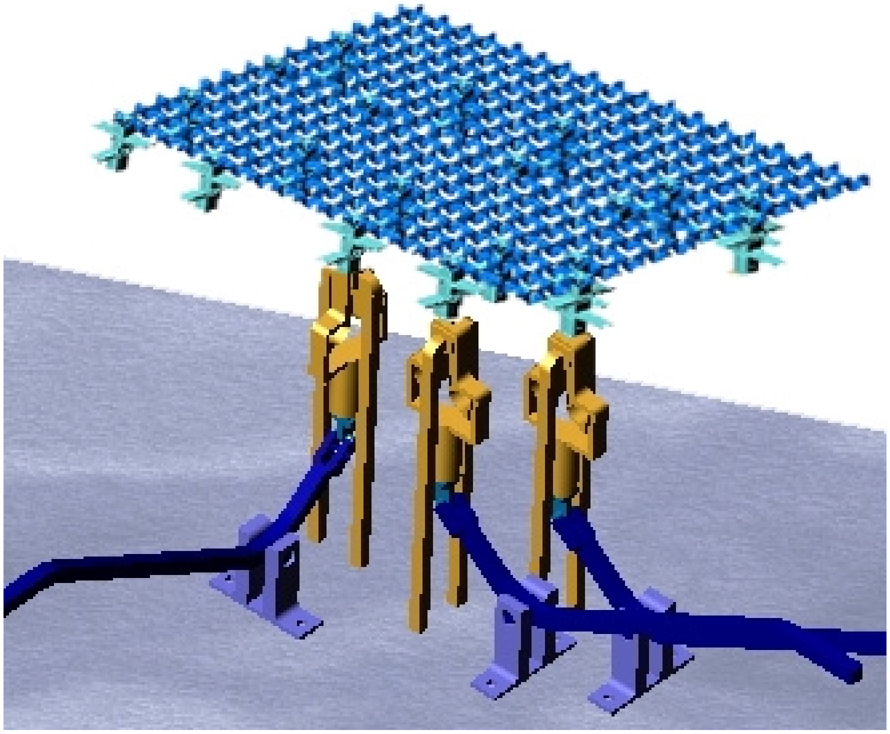


Figure 7 CAD Image of Low DOF Automotive Front End Model.

with the 'array of points' approach to modeling surface shape. The motions of many of these points will be coupled.

We desire the crust to start as a flat surface that morphs into various hood designs of high end sports cars, such as the Lotus, Ferrari, and Corvette, sketches of which are shown in Figure 5. The construction of a formable hood model will be described. To connect the inputs to the crust, a set of compliant mechanisms will be integrated with beams that are connected to the crust. The arrangement of columns and beams to control positions of points on the crust is shown in Figure 6a. The two front corner columns will be fixed, while the other columns can be vertically displaced and flexed laterally when necessary to produce smooth surfaces. The beams ensure longitudinal symmetry of the hood, which can be seen in Figure 6b. Each beam will be driven vertically by one compliant mechanism. The two columns at the top of the hood (hood-windshield joint) will be coupled by another beam (not shown). The crust will consist of a 14x18 array of spherical joints (Figure 4a) that are spaced 12.7 mm apart to give an overall size of about 177.8 X 228.6 mm (7 X 9 inches).

One partial implementation of the hood part of the model is shown in Figure 7. Inputs will be manually actuated using levers that connect to 1 DOF compliant mechanisms for displacement amplification which are connected to the beams that were shown in Figure 6. Not all levers and compliant mechanisms are shown for clarity. A formable crust is attached to the beam and column tops. Covering the crust will be a flexible skin. The actuators and columns will be rigidly attached to a base. In the future we will add a windshield and fenders (non-formable) to complete the model. The completed hood model with 12 user input levers is shown in Figure 8. This model was fabricated using stereolithography. In the near future, a colored skin will be added to the formable crust and a windshield (non-formable) will be added so the model looks more like an automotive front-end.

5 DISCUSSION AND FUTURE WORK

In this paper, we have presented the purpose of digital clay devices, summarized the concepts and approaches for their realization, and proposed designs for formable crust surfaces and low degree-of-freedom clay devices. Digital clay devices are intended to be human-computer interface devices that support touch and force-based (tactile and haptic) interactions. Both shape display and shape editing operations will be supported. The ultimate, general clay devices will have thousands of degrees of freedom and resolutions of 3 mm or less. A scalable, manufacturable design is needed for all elements of these devices. In this paper, we focused primarily on the interaction surface of the clay.

In contrast to general purpose clay devices, we presented low degree-of-freedom clay designs that are meant to model a class of shapes that are limited in their variety. For these low DOF clays, their surfaces must be capable of acquiring any shape in the class through a limited number of inputs (10 to 20). Scalable designs of the surfaces are needed with high resolution.

We presented the general approach to modeling clay surface shape as a function of inputs for the low DOF designs. Both forward and inverse kinematics were discussed, although specific mathematics models were not developed. The principles of predicting surface shape from the inputs was presented and issues were raised. In particular, the use of compliant joints for the formable crust clay surfaces complicates the kinematic analysis due to the non-negligible stiffness of compliant joints. However, this type of joint simplifies manufacturing of the surfaces. An example low DOF clay device was introduced for modeling automotive front ends. It was approximately 18x23 cm in size and had 15 independent inputs, each of which will be capable of translating at least 2 cm under direct control of the user (manual actuation).

The design of the formable crust surface for the low DOF clay design is scalable to much higher resolutions. Scaling the size down from 1.3 cm spacing between spherical joints to 2 mm spacing requires higher resolution manufacturing processes than are currently available. It should be possible to incorporate inflatable cell actuators in the compliant joints of the crust. It is not yet known if the backplane, with the

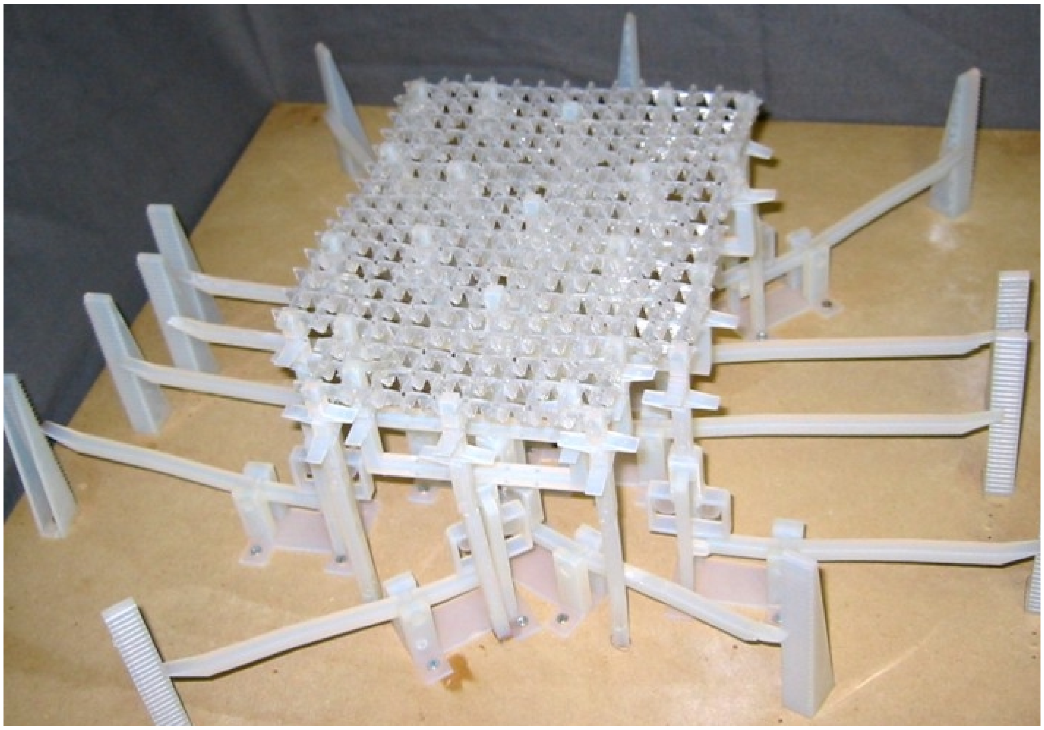


Figure 8 Automotive Hood Digital Clay Device Fabricated using Stereolithography.

microfluidic components can be designed and fabricated at appropriate scales.

Future work will proceed in several directions. First, the automotive front end clay device will be constructed and tested to verify its shape representation capabilities. Other researchers on this project are developing actuator and control subsystems with 5 – 25 actuators. Second, we will construct an automated low DOF clay device in the near future with both shape display and editing capabilities under computer control. Third, research proceeds on developing and evaluating user interaction methods that can be applied to clay devices. To us, the digital clay concept is very compelling. However, it remains to be tested whether or not these devices are effective and efficient at communicating shape between users and computers. This will be tested.

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