Proceedings of 2004 IMECE
2004 International Mechanical Engineering Congress and RD & D Expo
November 21, CA

IMECE2004-59743

Practical Structure Design and Control for Digital Clay

Haihong Zhu
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta GA 30332-0405 USA
gtg680c@mail.gatech.edu

Wayne J. Book
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta GA 30332-0405 USA
wayne.book@me.gatech.edu

ABSTRACT

Digital Clay is a proposed novel three-dimensional computer input and output device for surface shape and haptic effects. The device consists of an array of fluidic actuators under the control of valves connected to two pressure reservoirs in a manner ultimately suitable to an implementation in MEMS technology. The challenges to build this device lie in both the kinematical structure design and the control architecture. Though it is proposed to ultimately build the actuators and control valves using MEMS technology, conventional methods are used at the current prototype stage. In this paper, several designs of the practical kinematical structure will be discussed and the proposed control architecture for the Digital Clay will be introduced.

Keywords: Haptics, Shape Display, Shape Input, Digital Clay, Large Scale System Control, Bed of nails

1. INTRODUCTION

Human-machine communication is still dominated by the keyboard, mouse, monitor and speaker. These traditional methods stimulate two senses: sight and hearing. To make the human-machine communication more effective, research is being carried out on enhancements of human-computer interfaces by providing comparable modalities between input, display and task. Shape is a key element in successful communication, interpretation, and understanding of complex data in virtually every area of engineering, art, science, and medicine. Touch, as another important sense, has been introduced to the human-machine interface for quite some time. Applications for which touch may be the preferred modality include: design of shape, feel, resistance (mechanical impedance), texture, spatial relationship; exploration of models and experimental data for understanding; training of both rare and common skills, retraining/rehabilitation, conditioning; enhancement of motion capabilities in surgery, manufacturing, construction in normal and hazardous environments; and entertainment and communication of emotion.

Digital Clay is proposed as a novel computer based haptic 3D interface device whose surface can be shaped by a human user and immediately acquired by a computer or shaped by the computer for the human to examine. It is called Digital Clay because, like ordinary clay, digital clay will allow an area of moderate size to be touched, reshaped with pressure, and inspected by the user in a three-dimensional form as illustrated in Figure 1-1; unlike ordinary clay, Digital Clay also provides parameters to the computer that will represent the shape to the computer for further analysis, storage, replication, communication and/or modification. Digital Clay will also allow the computer to prescribe its shape as portrayed in Figure 1-1. Note that though the concept shown in figure 1-1 is more likely a 2.5D device, the ultimate device could be a true 3D device depending on the actuators' structure.

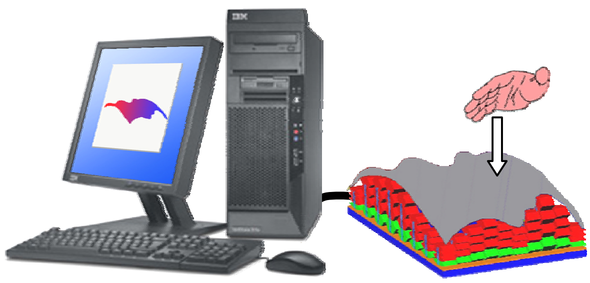


Figure 1-1 Digital Clay Concept

This paper focuses on the conceptual design of the practical kinematical structure and the control of Digital Clay.

There is some significant research in the area of shape and force display. To display small shapes, arrays of stimulators are necessary. To achieve both kinesthetic and tactile sensations simultaneously, the combination of a haptic manipulator and a tactile array is currently required. For example, a tactile array is a device typically constructed by a planar arrangement of linear actuators and sensors acting perpendicular to that plane. In some aspects, Digital Clay is similar to tactile sensors plus tactile stimulators [1][2]. Current interest is greater in the combination of sensor and display (stimulator) to be used in teleoperation, with a particular interest in telesurgery [3]. Electromagnetic [4], pneumatic [5] and shape memory alloy [6] actuators have been tried use in the tactile arrays. The sizes of these arrays are small, about the size of the pad of a finger. The recent device by Kammermeier [4], for example, covers 16x16 mm with 36 sensors in an attempt to follow Fearing's target specifications for an ideal stimulator. However, the displacement of these tactile devices is too small for shape display.

Figure 1-2 Prototype of FEELEX [7]

In 1998, Hiroo Iwata reported project FEELEX [7]. It develops a new technology that combines the haptic sensation with computer graphics. As shown in figure 1-2, the prototype comprises an array of electrical motors working as the actuators. The size of the motor will ultimately limit the resolution of the displayed surface. Digital Clay comprises an instrumented, actuated, computer-interfaced physical volume bounded by an actuatable surface that acts as the haptic interface. This surface is displaced by arrays of controllable interconnected fluidic actuators, which act together to convey the surface topography of 3D objects by means of manipulation of 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 two dedicated miniature valves. As proposed, the distance between the centers of the cells of the Digital Clay is less than 3 mm, one dimensional extension is larger than 50 mm, and cell array size is larger than 100x100. Ultimately each valve will be integrated with a pressure sensor, manufactured using MEMS technology that is under development at Georgia Tech.

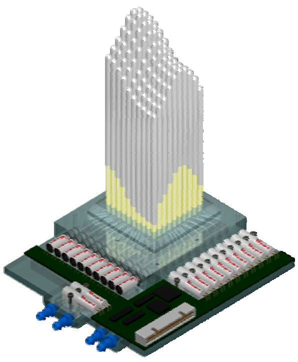


Figure 1-3 "Bed of Nail" Structure Concept

There are two proposed structures for digital clay: formable crust [8] and formable body. One of the main issues discussed in this paper is the design of a practical formable body structure (known as "bed of nail"), its cells' structures and sensor system. (The concept of the "bed of nail" system is shown in figure 1-3.)

The control of Digital Clay will be organized into three levels. The top application level is represented by application programming interface (API) software that generates commands to the surface control level. The API will be designed to simplify validation and development of a target set of applications. The next level, surface level, considers cell-cell interaction and commands the actuation of the cell level control. The bottom level, cell level, incorporates sensor feedback to drive individual valves in response to commands and sensed pressure.

Due to the large scale of the cell array of the Digital Clay, the Surface Level Control has similarities to the control of large scale systems with controlled units distributed over some spatial domain and operating asynchronously. There is a lot of research found in this area. Examples can be found in Intelligent Vehicle Highway Systems and Air Traffic Management Systems [9]. However, with the scale of the systems expanding quickly to millions and even tens of millions of units, centralized control becomes unviable due to the limited centralized information and computing capability. (One million cells for Digital Clay represent a resolution of 1000×1000 in 2.5D or 100×100×100 in 3D.) Decentralized control, on the other hand, using only local information while guaranteeing stability of the entire system is more suitable for this kind of large scale system. There are three types of decentralized control structures: Fully, Partially and hierarchically decentralized control [10]. D. Gavel, and P. Ioannou gave examples of addressing the problem of decentralized control of large-scale systems in the framework of direct model reference adaptive control [11]. However, for tiny devices, because measurements will be subject to considerable noise, precise state information will be difficult and costly to obtain for a local closed loop control. Moreover, the operational time constants trend to be very short, which leads to a need for increased channel capacity in feedback links. J. Baillieul presented a paper with emphasis on general communications and information processing problems [12]. Though it is basically a modified centralized control solution, it touches the constraints on the information carrying capacity in the feedback links connecting the sensors, controller, and actuators for some large scale systems.

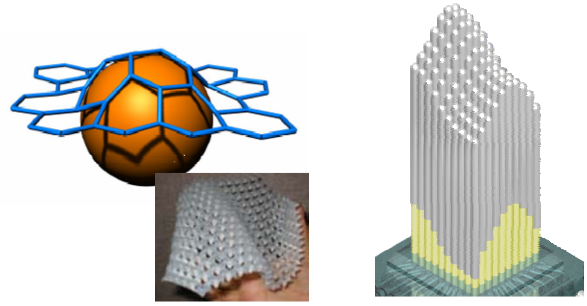
Another related technology is the large scale LED array driving method, which controls each LED using a row and column matching manner. However, since the actuator of the Digital Clay is not a simple "pass through" device, this method will be modified before being applied.

Results of the cell level control and potential solutions for surface level control are presented and the interface between surface level and the user API will also be briefly discussed.

2. CONCEPTUAL DESIGN OF A PRACTIAL MECHANICAL STRUCUTRE FOR DIGITAL CLAY

2.1 Structures for Digital Clay

The structure of the Digital Clay has two solutions: formable crust (figure 2-1 a) and formable body. At the current stage, formable crust and 3D formable body structure are far from practical. Therefore, the 2.5D formable body concept that can be realized by a planar x-y array of linear actuators acting in the z direction is studied here.



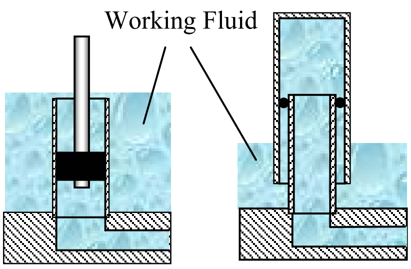
(a) Formable Crust Concept (b) Planar Array Concept

Figure 2-1 Kinematical Structures for Digital Clay

2.2 Concepts for Actuators of Digital Clay

For the 2.5D formable body structure of digital clay, linear hydraulic actuator can be used since the actuation is one dimensional. However, given the requirements on the size (i.e. diameter < 3 mm and stroke > 50 mm), it is very difficult to find a suitable cylinder. Bellows fabricated using MEMS technology provide an alternative solution. However their actuation range is limited due to buckling. Hence it is necessary to design a micro fluidic actuator. As shown in figure 2-2, two solutions for the actuator are proposed and studied at the same time. Experiment shows that either rubber o-ring or graphite seal can provide excellent seal. But the graphite seal can reduce the friction greatly.

For solution a, return force can be generated either by spring or pressurised fluid. For solution b, applying negative pressure (vacuum) can make it retract. Both two structures can easily meet the requirements on diameter and stroke length. The outer glass tubes will be supported by stiff frames to resist the lateral force applied on them.



(a) (b)

Figure 2-2 Solutions for Actuators of Digital Clay

2.3 Position Sensor Solutions

The challenges of displacement measurement lie in both the fabrication of the sensor (diameter < 3 mm, sensing range > 50 mm), and mounting the sensor into the cell. No such sensor is found on the market, prompting our efforts to design a new displacement sensor.

2.3.1 Non-contacting resistance position sensor

An example for capacitive sensor is shown in figure 2-4. It comprises a metal film deposited on the wall of the outer tube and two symmetric metal films deposited on the wall of the inner tube. By measuring the capacitance between those two films on the wall of the inner tube, the relative displacement between the inner tube and outer tube can be detected.

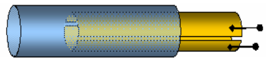


Figure 2-4 Capacitive Sensor Concept

The advantage of this kind of position sensor is its simple structure. The drawback is the capacitance variance due to the eccentricity of the inner and outer tubes. The capacitance variance (of the capacitive position sensor with the design parameters shown in figure 2-5) is analyzed and plotted as shown in figure 2-6. The ratio of capacitance/displacement is around 3.9 pf /mm (for water and 1 pf/mm for oil). Therefore, the calculated capacitance variance will cause 0.5 mm error (for water) and 3.8 mm error (for oil).

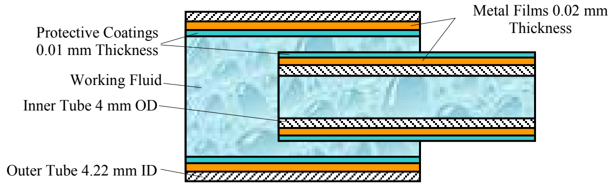


Figure 2-5 Capacitive Sensor

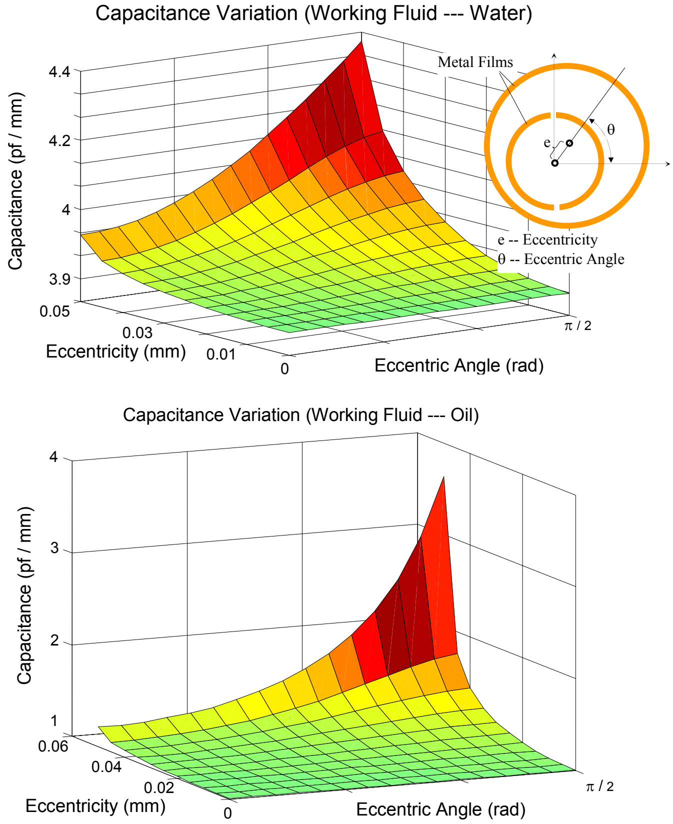


Figure 2-6 Capacitance Variation Due to the Eccentrics

Therefore, a concept for non-contacting resistance position sensor is proposed and depicted in figure 2-8. This concept is not original, but it provides a good combination of the advantages of capacitive sensor and resistance sensor.

As shown in figure 2-8, a resistance film is deposited on half of the outside wall of the inner tube and a conductive metal film is deposited on the other half. A metal ring is deposited on the insider wall of the outer tube. A high frequency alternating voltage is applied across the resistance film.

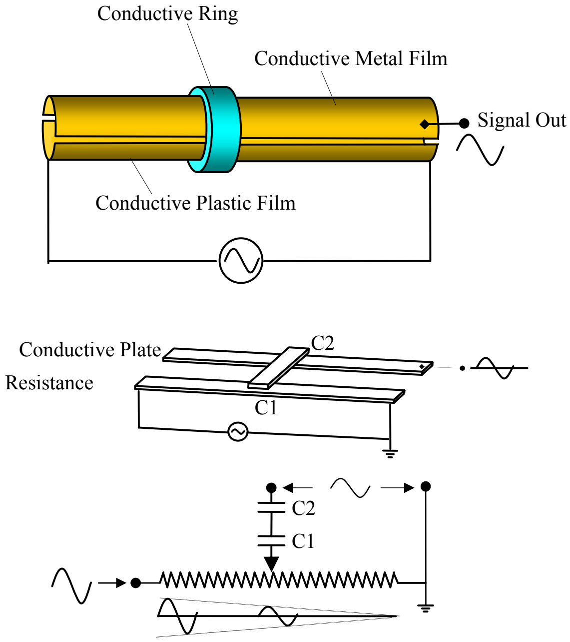


Figure 2-8 Non-contacting Resistance Position Sensor

By sensing the amplitude of the alternating voltage collected from the conductive film on the inner tube, the displacement of the outer tuber can be detected. The electrical schematic circuit of the sensor is shown in figure 2-9, where R is the impedance of the measurement instrument, C1 is the capacitance between the conductive ring and the resistance film, and C2 is the capacitance between the metal ring and the conductive film. This is a high-pass filter. Therefore, if the frequency of the alternating voltage is high enough, a small capacitance variation will have little effect on the amplitude of the output signal.

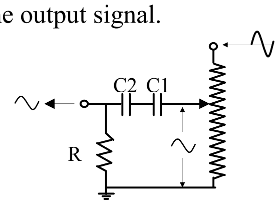


Figure 2-9 Schematic Circuit for Measurement

For example, if measurement impedance R = 1MΩ, for the smallest capacitance calculated for water in Figure 2-5, one can plot the Bode Diagram of this system as shown in figure 2-10. From figure 2-10, one can find that 40 KHz frequency is enough for the system to work. Calculation shows that, even with air getting into the sensing area, 400 KHz frequency is high enough to get rid of the disturbance.

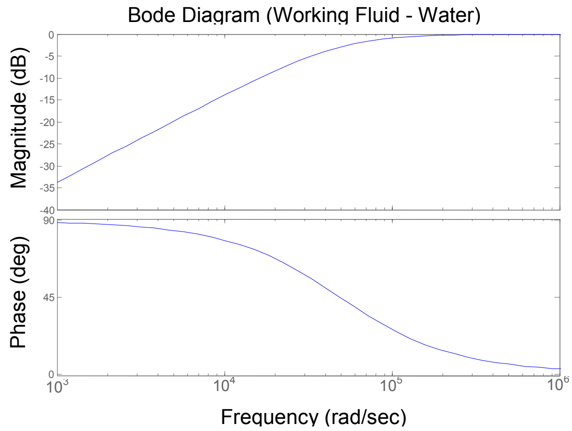


Figure 2-10 Bode Diagram of Measurement Circuit

3. CONTROL ARCHITECHTURE FOR PLANAR ARRAY STRUCTURE OF DIGITAL CLAY

The control structure of digital clay is organized into three levels: Cell Level Control, Surface Level Control and user API. Due to the large scale (100x100 to 1000x1000) of the planned actuator and sensor system, a modified decentralized control structure is proposed to control the system. A general control structure diagram is illustrated as shown in figure 3-1.

The Cell Level Control is responsible for inflating and deflating individual cells to a certain volume according to the cell pressure in order to achieve a specified dimension as well as to provide a haptic interface. Cell pressure, valve actuation and time, and the command parameters from the Surface Level Controller are the parameters in the integral relationship, which determines the extension of the cell.

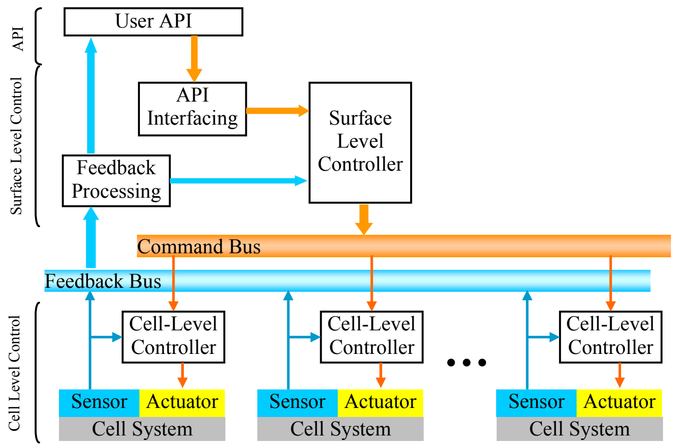


Figure 3-1 Control Structure of Digital Clay

The Surface Level Control will be responsible for achieving the best fit to the ideal surface (i.e. CAD model). The Surface Level Control is dependent on the implementation of Digital Clay under control but that will be hidden from both the higher and lower level of control software. The desired cell deformation would be distributed to multiple layers, if present. Interaction between neighboring cells might be critical for reliable operation. Surface level control also determines the shape when requested.

This paper focuses on the Cell Level Control Structure, Surface Level Control Concept and the Interfacing parameters between the Surface Level Control and User API.

3.1 Cell Level Control

The Cell Level Control adjusts the actuator's extension according to the feedback signals and command parameters. More specifically, the feedback signals are the displacement of the actuator and pressure inside the actuator. The command parameters are the virtual damping ratio, the pressure/displacement ratio, and the initial position.

3.1.1 On-off Valve Flow Rate Control

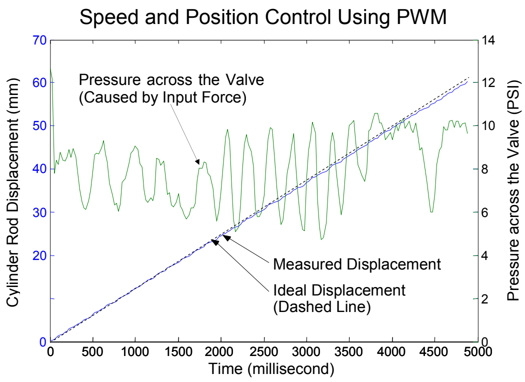


Figure 3-2 Speed and Position Control Using PWM

The control valves used in Digital Clay are on-off valves because the on-off valve is easy to implement using MEMS technology. The problem is the discontinuity of the valve orifice change. This problem can be solved by driving the valves using a PWM (Pulse Width Modulation) command. As show in figure 3-2, though the input force (disturbance) acting on the actuator varies a lot, the speed is nearly constant.

3.1.2 Feedback Sensing

Feedbacks required in the Cell Level Control are the pressure inside the actuator and the displacement of the actuation.

When sensing the pressure, the problem encountered is the big pressure surge due to the discontinuity of the on-off valve orifice change. The problem can be solved by applying a low pass filter when processing the pressure signal, since pressure surge's frequency is higher than 200Hz, while that of human input force is lower than 7Hz.

The displacement feedback can be obtained by several ways. PWM displacement estimation is a good way since it does not need any displacement sensor. By measuring the pressure across the valve orifice, one can estimate the flow rate through the valve given the PWM duty circle applied to the valve. In figure 3-2, the final position of the actuation is commanded and reached with an error less than 2% [13]. The drawback of this method is that it occupies a lot of computer resource and it is subject to drift.

An alternative way is to embed a non-contacting resistance position sensor in the cell as described above.

3.1.3 Logic Control and User Gesture Interpretation

Logic control enables an actuator to mimick a point on a physical material. Inspired by the mechanics of materials, the logic control structure of the Cell Level Control is organized into two working modes: (1) Display Mode, consists of two states: Elastic State and Plastic State; and (2) Edit Mode, consists of Elastic State, Plastic State and Shaping State. The shaping state allows the user to "add" or "subtract" volume from the displayed 3D shape. A general logic control structure is shown in Figure 3-3.

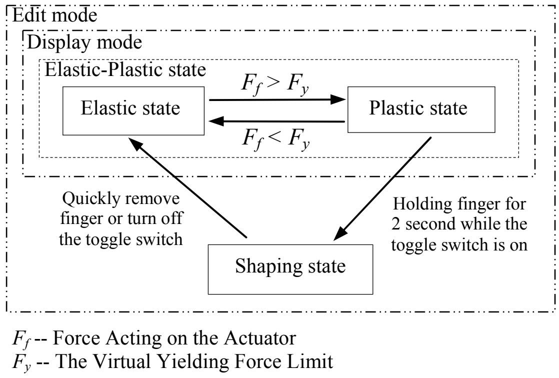


Figure 3-3 Logic Control and User Gesture Interpretation

User gesture interpretation detects the user's intention in edit mode. In other words, it detects when the user wants to start the shaping state and when the user wants to exit the shaping state.

The logical control is realized as follows. To switch between Display Mode and Edit Mode, the user needs to notify the computer by some input device (keyboard, mouse click or toggle switch, etc.) To Switch between Elastic State and Plastic State, the user needs to exert a force larger than the preset virtual yielding force limit Fy. Under display mode, when the input force is less than Fy again, the system will go back to elastic state. Under edit mode, in plastic state, if one keeps the actuator stationary for a short time (e.g. 2 sec), the system will go into the shaping state. In the shaping state, the cell's extension will change to follow the motion of user's finger until the finger is quickly removed. (For details, please refer to paper [14])

3.1.4 Testing Results

A testing result for logic control and user interpretation is shown in figure 3-4. The data were recorded under editing mode and the experiment process is described as below: (in this experiment, the displacement is acquired by potentiometer)

In edit mode, push the rod until the system goes into plastic state. (ab -- elastic state; bc -- plastic state) Then hold the finger until the system goes into the shaping state. (cd) In the shaping state, move the piston back and forth by controlling the input force. (de, ef, fg, gh, hi, ij and jk) Then quickly remove the finger, (kl) let the system go back to the elastic state (with a new zero load position – point l). In the shaping state, when the finger force (proportional to the pressure in the cylinder) is between the upper limit force Fy and lower limit force F_l, the piston keeps stationary. This can be seen from the vertical line S, gh, ef, etc.

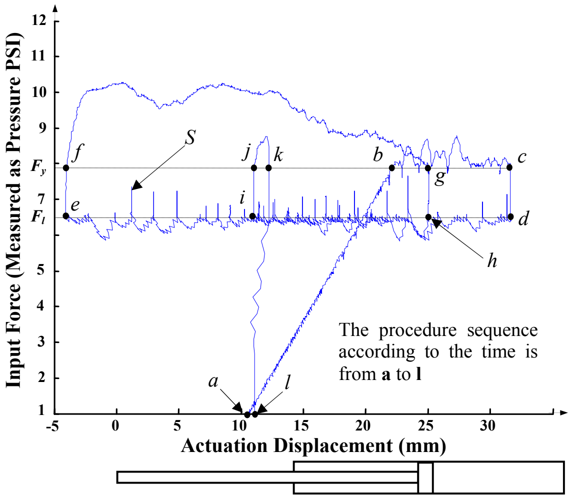


Figure 3-4 Testing Result of Logic Control and User Gesture Interpretation

3.2 Surface Level Control Concept

The Surface Level Control is responsible for achieving the best fit to the ideal surface. The ideal surface is defined by the CAD model and translated by the API into certain parameters which the surface level controller can understand. The Surface Level Control is dependent on the implementation of Digital Clay under control but that will be hidden from both the higher and lower level of control software.

3.2.1 "N^2 by 2N" Driving Structure

Before proceeding to further discussion about the surface level control, it is necessary to introduce the "N^2 by 2N" mechanism for the planar array structure of Digital Clay. The "N^2 by 2N" mechanism is a novel driving structure for a large scale hydraulic actuator array. It is so called because an N x N actuator array can be driven by only 2*N valves (e.g. 200 valves can drive 10,000 actuators). The fluidic schematic circuit is shown in figure 3-5. Note that though here the given schematic circuit is for a 1 port actuator, minor modification can make it work for a 2 port actuation cylinder array.

The working principle of this driving circuit is quite like the electrical driving circuit for an LED array. Only when a certain row control valve is open can the actuators in that row be driven by the flow control valve array. Therefore by refreshing the actuator array row by row, the whole actuator array can be controlled. Note that, refreshing methods are not limited to an entire row. Actually a specific actuator can be addressed by controlling the corresponding row control valve and flow control valve.

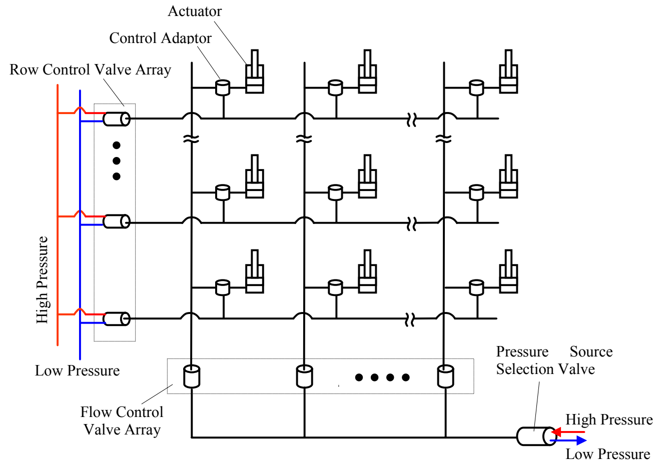


Figure 3-5 "N^2 by 2N" Driving Fluid Circuit

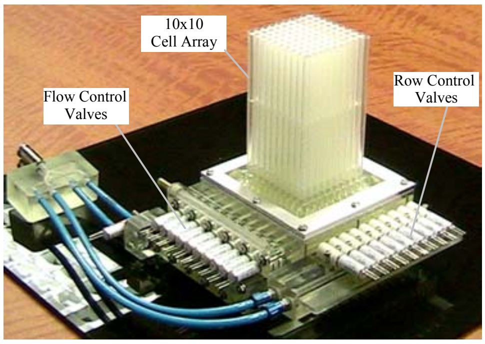


Figure 3-6 Testing Prototype of a 10x10 Actuator System

The advantage of this driving method is the reduction of the number of control valves and related control resources. For a 1000 x 1000 actuator array the amount of control valve needed is cut down from 2,000,000 to only 2000 valves. Corresponding control resources (electrical circuits, computing loads, etc.) also decreases dramatically. The potential problem may be the relatively low speed. However current experiments show that the system can achieve a refresh rate of 100 rows / sec, regardless of the number of columns. The testing prototype is shown in figure 3-6. It's a 10 x 10 actuator array driven by 20 on-off 2 position / 3 port valves.

3.2.2 Surface Level Control for "N^2 by 2N" Driving Structure

For this kind of structure, the actuator array is divided into several sub-arrays as shown in figure 3-7 (the areas divided by the double-dot-dash line). Each sub-array is controlled by a cell level controller and the corresponding row controller under the coordination of the surface level controller. The row controller is a simple device that only takes the command, controls row valves and feeds back their status.

After the User API gives out a set of shape and material property parameters, the information is then processed and distributed by the API Interfacing processor to the surface level controller (figure 3-1). The surface level controller then coordinates cell level controllers and row controllers to fulfill the surface command given by the User API. The size of the sub-array depends on the capability of the cell level controller.

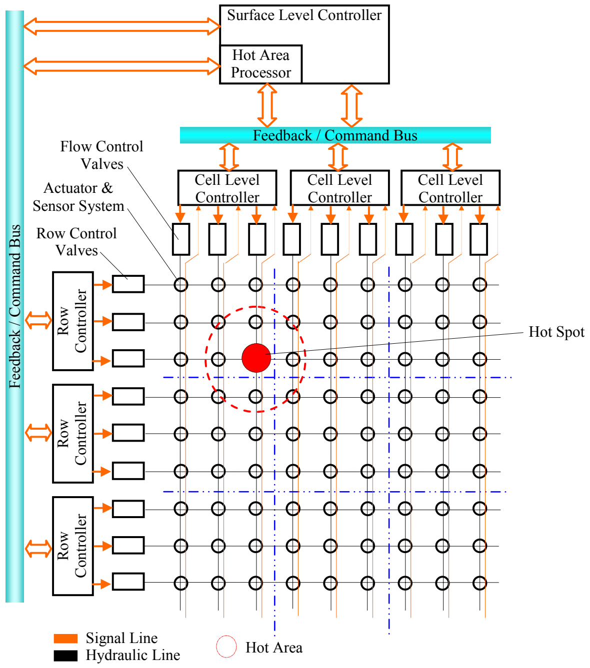


Figure 3-7 Surface Level Control Structure for "N^2 by 2N" Driving Structure

There is an important mechanism in the surface level control, which is termed as hot area processor. Normally, most of the cell array operates as a passive display. Only a small area may be touched by the user (the area of user hands is less than 0.04 m^2, while that of the cell array could be 0.5~2 m^2). That area is defined as a hot spot. When a hot spot is detected, the surface level controller will define a hot area including the hot spot and its neighbours (figure 3-7). Then the surface level controller passes the authority to the hot area processor to deal with the control of that hot area. For a hot area, haptic responses to user input will be controlled by the corresponding cell level controllers, but the interaction between neighbouring cells will be coordinated by the hot area processor. Hot area processing is proposed as follows. 1) Involved cell level controller will be notified by the surface level controller to: only take commands with certain ID# and send feedback messages with that ID#. 2) Hot area processor will be notified to process the feedback message with certain ID# and give command with that ID# based on the command from the API.

3.3 Interface between Surface Level and User API

The top application level is represented by user application programming interface (User API) software, which generates commands to the surface control level. The User API will be developed by cooperating researchers in the College of Computing at Georgia Tech.

The commands/information from the User API are mainly about global surface parameters, as well as the virtual material property for each cell. The API Interface processor (figure 3-1) between the surface level control and User API translates and distributes those information and commands to each surface level controller. Note that, depending on the scale of the cell array and the capability of the surface level controller, more than one surface level controller may be used to control the cell array. Feedback from the cell level controller on the pressure, displacement and moving speed of each cell will be processed by the feedback processor and send back directly to the User API for the host computer's reference and for further editing purpose (i.e. save, undo, redo, compute design aids, etc.).

4. FUTURE WORK

For hardware, the most parts of the 10x10 cell array prototype are working well. However, since the non-contact resistance position sensor is still under fabrication, the system is not yet fully functional. Further work is needed to find out the limit of the refresh rate and the capability of the position sensor once the position sensor is ready.

For the Surface level control, further tests are needed to testify the proposed control method and the interface between the User API and the surface level control.

5. CONCLUSION

Digital Clay is a novel 3D computer input/output device. A variety of mechanical structures are possible to fulfil the objective. This paper describes a planar array structure that is suitable for large scale cell system for digital clay.

Based on the planar array structure (known as "Bed of Nails") for Digital Clay, this paper presents a practical actuator structure and a solution for the embedded non-contacting position sensor. Calculation and simulation have confirmed the viability of this sensor. A prototype is under construction.

Complete cell level control is discussed and good results are shown. For the surface control level, a novel large scale actuator array driving structure, which can drive an N x N actuator array by only 2*N on-off valves, is discussed, and further surface level control concepts based on this novel driving structure are also presented.

Preliminary testing results on the prototype show a good potential for this kind of practical structure and control methods for Digital Clay.

ACKNOWLEDGMENTS

This work is supported by the U.S. National Science Foundation ITR grant IIS-0121663. The assistance of the co-investigators (Mark Allen, Ari Glezer, John Goldthwaite, David Rosen, Jarek Rossignac, Imme Ebert-Uphoff) and their colleagues and graduate students in the Schools of Mechanical Engineering and Electrical and Computer Engineering, and the College of Computing is gratefully acknowledged.

REFERENCES

[1] Fearing, R. S., G. Moy, and E. Tan. Some Basic Issues in Teletaction . In Proceedings of the IEEE Int. Conf. Robotics and Automation, April 1997, pp 3093-3099

[2] Howe, R. “Tactile sensing and control of robotic manipulation.” Advanced Robotics, v. 8 N. 3, 1994, pp245-261

[3] Howe RD, Peine WJ, Kontarinis DA, Son JS. Remote palpation technology. IEEE Engineering in Medicine and Biology, 14(3):318-323, May/June 1995

[4] Kammermeier, P. M. Buss, and G. Schmidt, “Dynamic display of distributed tactile shape information by a prototypical array,” Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robotics and Systems, pp 1119-1124

[5] Cohn, M., M. Lam, and R. Fearing, “Tactile feedback for teleoperation,” SPIE Telemanipulator Technology, 1833:240-254, 1992

[6] Howe RD, Peine WJ, Kontarinis DA, Son JS. Remote palpation technology. IEEE Engineering in Medicine and Biology, 14(3):318-323, May/June 1995

[7] http://intron.kz.tsukuba.ac.jp/vrlab_web/feelex

[8] P. Bosscher and I. Ebert-Uphoff, ``Digital Clay: Kinematic Mechanism Designs and Computational Issues for Haptic Shape Display." Journal of Robotic Systems, Submitted February, 2004 (in review).

[9] G.J. Pappas, G. La®eriere, & S.S. Sastry, Hierarchically Consistent Control Systems," IEEE Trans. Automatic COntrol, 45(6) 1144-1160, June, 2000.

[10] Drouin, M., Abou-Kandil, H., and Mariton, M.,Control of Complex Systems, Plenum Press, New York, 1991.

[11] D. Gavel and D. Siljak, Decentralized adaptive control: structural conditions for stability, IEEE Trans. Autom. Contr. 34 (1989), no. 4, 413-426.

[12] J. Baillieul, Feedback Designs for Controlling Device Arrays with Communication Channel andwidth Constraints, in Lecture Notes of the Fourth ARO Workshop on Smart Structures, Penn State Univ., August 16-18, 1999.

[13] Haihong Zhu and Wayne J. Book, Speed Control and Position Estimation of Small Hydraulic Cylinders for Digital Clay Using PWM Method, Proceedings of 2004 JUSFA, 2004 Japan – USA Symposium on Flexible Automation, Denver, Colorado, July 19-21, 2004

[14] Haihong Zhu and Wayne J. Book, Control Concepts for Digital Clay, Proceedings of 2003 SYROCO, 7 IFAC Symposium on Robot Control, September 1-3, 2003 Wroclaw, Poland