CONTROL CONCEPTS FOR DIGITAL CLAY

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Abstract: Digital Clay is a new generation of 3D computer input and output device for surface shape. Its three control levels are introduced in this paper. The device consists of arrays of fluidically actuated cells under the control of valves, that are connected to two pressure reservoirs in a manner ultimately suitable to an implementation in MEMS technology. Preliminary research on control related behaviour is described including testing of a single cell under a proposed control scheme. Based on these tests, control methods are presented and discussed that achieve elastic, plastic and elastic-plastic material behaviours.

Keywords: digital clay, preliminary research, control

1. INTRODUCTION

Shape is a key element in successful communication, interpretation, and understanding of complex data in virtually every area of engineering, art, science, and medicine. The Georgia Institute of Technology is developing a novel haptic computer interface that will enable both user-specified display of shapes as output from a computer, as well as the user-directed input of shapes to a computer. This proposed haptic interface is referred to as Digital Clay. Like ordinary clay, digital clay will allow an area of moderate size to be touched, reshaped with pressure, and seen by the user in true three-dimensional form as illustrated in Figure 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 also portrayed in Figure 1.

Some previous implementations of digital clay-like devices have focused on reshaping of non-physical volumes of 'virtual clay' using glove-like or haptic manipulator interfaces to a computer in which the virtual clay is stored. This is not the approach of this work. Instead, the Digital Clay proposed herein comprises an instrumented, actuated, computer-interfaced physical volume bounded by an actuatable surface that acts as the haptic interface. This surface is displaced by rows or arrays of controllable interconnected fluidic-driven actuators which together act to convey the surface topography of three-dimensional 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 two-way miniature valves. Ultimately each valve will be integrated with a pressure sensor, manufactured by MEMS technology that also under development at Georgia Tech but not the focus of this paper.

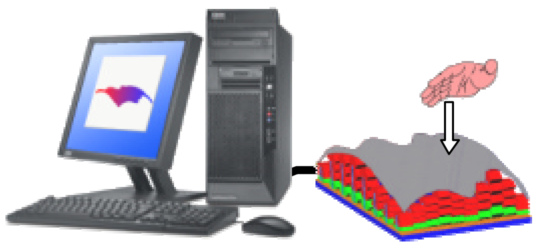


Fig. 1. Digital Clay

The focus of this paper is the control of discrete actuators connected to two pressure reservoirs by simple valves of variable restriction intended to achieve the functions necessary for the ultimate digital clay. Since several technologies are under parallel development, it is essential to verify these concepts on conventional components: valves, actuators and sensors.

Ultimately, digital clay will be realized through the complementary efforts of a multidisciplinary team of researchers from the Schools of Mechanical Engineering and Electrical and Computer Engineering, and the Colleges of Computing and Architecture. Successive refinement will not only allow development of improved fabrication techniques and control approaches, but also will allowing the opportunity for feedback from selected user communities and human-computer interface (HCI) experts.

1.1 Control Structure

Digital Clay's control 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 control, considers cell-cell interaction and commands actuation of the cell control level. The bottom level, cell control, incorporates sensor feedback to drive individual valves in response to commands and sensed pressure.

A general function block diagram is provided. (Figure 2) The part enclosed by a double dotted line is the control system.

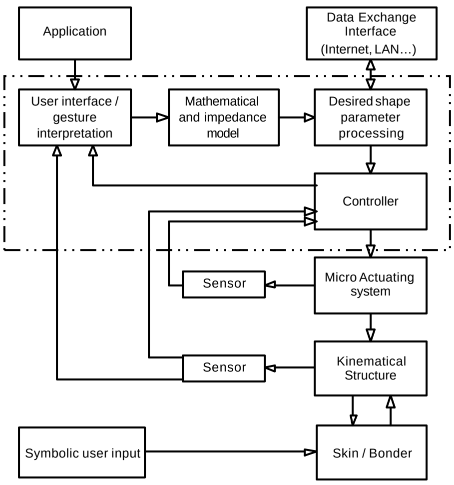


Fig. 2 General Function Block Diagram of Digital Clay

The whole system will work in two modes: display mode and editing mode. In display mode, the API will translate a digital representation of a 3-D shape to the corresponding parameter values that can be read by the low-level control unit. The low-level control unit will then regulate the fluid flow until the digital clay has taken the desired shape. In this mode, the low-level control unit is responsible for all the haptic interactions.

In editing (input) mode, Digital Clay allows the user to modify the displayed model (3-D shape) by haptic interactions. Users can produce a shape either by forcing fluid out of cells when the pressures inside cells rises above a specified level, or by applying certain gestures to indicate the control unit to inflate the cells. Both Low-level control unit and API will take part in the haptic interactions. All the haptic interactions are digitally recorded by the API for later analysis.

The surface level control is dependent on the implementation of clay under control but that should 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 neighbouring cells might be critical for reliable operation. The surface level will be responsible for achieving the best fit to the ideal surface. Surface level control also determines the shape when requested.

The cell level control is responsible for inflating and deflating individual cells with certain pressure to achieve a specified dimension as well as providing a haptic interface. Pressure differential, valve actuation and time are the parameters in the integral relationship that determines the extension of the cell. Initially this logic will be placed in a central computer, but it is desirable to embed as much of this capability in a cell or group of cells as possible. The forces applied by the user are not under our control and hence the pressure must be monitored frequently to estimate the integral of flow that corresponds to cell dimension. External measurements for calibration and verification of shape will also be used to determine the shape.

The experiments described in this paper pertain to the bottom (cell) level control and part of the top (API) level control. Experts from the computer science will mainly focus on the research relating to the top-level control. The proposed control system includes the hardware (control and data bus systems, middle and low level controllers) as well as the algorithms covering the haptic display, communication, and command generation.

2. PRELIMINARY RESEARCH ON CONTROL

The preliminary research is aimed to find out the basic requirements and the possible principles and methods to control the system. More specifically, objectives of the preliminary research are (1) investigating the possibility of using simple on/off valves as the control valves in the system, and if confirmed then (2) the basic requirements for these valves, and (3) figuring out a simple, efficient and user friendly communication method between the user and computer.

The preliminary research starts from the investigation of a single cell. Though finally most of the components will be the MEMS devices under development, the research on a similar system composed of conventional but carefully chosen devices will also provide useful results.

2.1 *Experimental Devices*

The experimental system schematic diagram is given in Figure 3. An ultra-low friction cylinder is chosen to represent the cell actuator. Solenoid valves are chosen as the control valves. The working fluid is pressurized by regulated compressed air. A pressure sensor is attached to the cylinder chamber to measure the pressure. A linear potentiometer is used to measure the displacement of the rod tip. A computer directly controls the whole system. A digital control card provides the interface between the computer and the experimentation system. To improve the performance, Real-time Linux is adopted as the operating system.

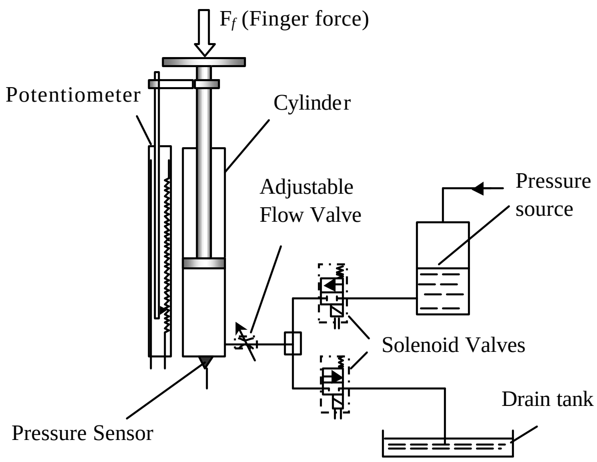


Fig. 3. Schematic Diagram of a Single Cell

2.2 *Solenoid Valve Noise*

Two conventional 2-way solenoid valves are used in the system. These valves have an open and close time around 10ms and 20 ms respectively.

A main drawback of solenoid valves is the big pressure surge caused by the sudden opening and closing, as shown in Figure 4. This big pressure surge can dramatically affect the pressure sensor when trying to detect the finger force acting on the cylinder rod tip. To solve this problem, filters are considered to suppress the noise. This is feasible based on the fact that the solenoid valve noise usually has a frequency higher than 60 Hz while the finger force change is normally lower than 6-7 Hz.

Two types of filters were investigated. One is the fluid filter composed of a small orifice and an accumulator.

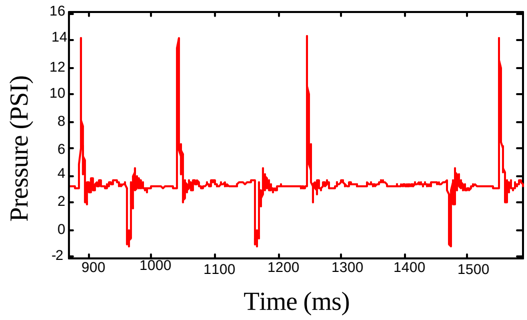


Fig. 4. Solenoid Valve Noise

Another is the electronic filter composed of inductors, capacitors and resistors or equivalent active components.

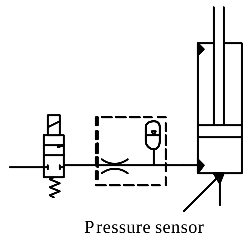


Fig. 5. Fluid Filter

The inlet hydraulic circuit with a fluid filter is shown in Figure 5. The experimental result of this system is not satisfying, because the filter is basically first order filter and the frequency difference between the noise and the finger force change is only one decade. Hence a second order electronic filter is placed between the pressure sensor and the digital control card to filter the signal. The efficacy of the filter is shown in the Figure 6.

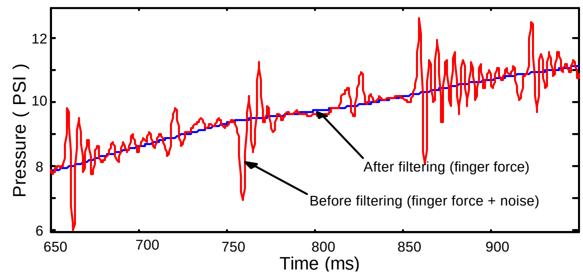
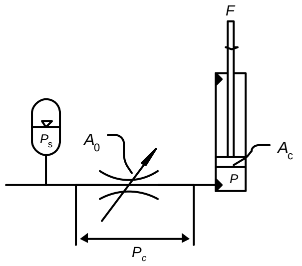


Fig. 6. Efficacy of the Filter

2.3 *Pressure Lead Control vs. Position Lead Control*

As a haptic device, the cell's displacement is related to the force acting on it. There are two methods to control the cell's displacement: the pressure lead method and the position lead method. The pressure lead control is to regulate the cylinder's pressure according to the displacement of the cylinder rod.

The pressure lead control method is shown in Figure 7. By dynamically adjusting the orifice area A_0 according to the flow rate q, the pressure inside the cylinder chamber is regulated. Obviously, this method cannot be directly applied when using simple on/off solenoid valve because of the discontinuous orifice change. Hence control using the Pulse Width Modulation (PWM) has been investigated.



$P=P_s-P_c;$
$P_c=f(q,A_0);$
$P=F/A_c;$

Fig. 7. Inlet Circuit for Control using Pressure Lead Method

As shown in Figure 8, PWM controls the valve duty cycle on a fixed base frequency, and a fluid filter suppresses the solenoid valve noise. Simulation shows that with a base frequency higher than 200 Hz, the solenoid valve noise is suppressed quite well. But additionally considering response time over 30 ms (10 ms to open, 20 ms to close) for the selected valves, the base frequency is too low. This method is found inapplicable by experiment.

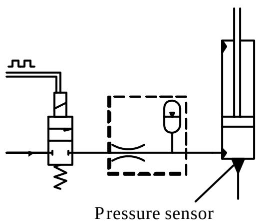


Fig. 8. Inlet Circuit for Control using PWM

The position lead control method is to adjust the cylinder rod position according to the finger force acting on the cylinder rod. A second order electronic filter is placed between the pressure sensor and the computer to filter the pressure signal. Given that the second order filter can give a -40dB/decade effect on the pressure signal, it is quite effective in discriminating the difference between the solenoid valve noise and the finger force signal. (Figure 6) In addition, during the whole process, the solenoid valve only opens and closes several times, so there isn't much vibration of the rod, which gives the user better feels. Moreover, there is no small orifice A_0, so the rod's speed can be quite high, which is quite important for the system's performance. (150mm/s when using the position lead method; 50mm/s when using the pressure lead PWM method)

2.4 Cell–level Control Structure

A point model of a material is shown in Figure 9. When one pushes the point with a force F under a certain limit (F_y), the material is in the elastic state. If F exceeds F_y, the material will yield, the point will keep moving inwards, and the displacement of the point is no longer proportional to the force F. When pushing the point with different speeds, one can feel the damping effect. Research discussed in this paper is focused on the simulation of elastic and plastic states; the damping simulation is not studied yet.

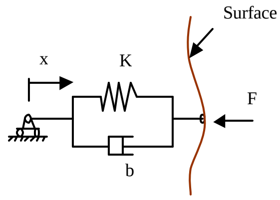


Fig. 9. Model of a Point on a Material

Based on the real material behaviours, the control structure of current experimental system is organized into two working modes: (1) the display mode, consists three possible working states: *a. elastic state*; *b. plastic state*; *c. elastic–plastic state*; and (2) the editing mode, consists three working states above and a special state---shaping state. The shaping state allows the user to "add" or "subtract" volume from the displayed 3D model.

Under both the display mode and the editing mode, the user is allowed to view the shape, feel the properties of the displayed material. But only under the editing mode, the user can "add" or "subtract" volume from the displayed 3D model and the selected interactions between Digital Clay and the user will be digitally recorded for further editing actions such as "undo" and "redo".

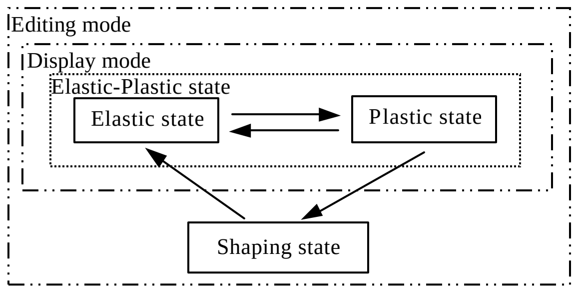


Fig. 10. General Control Structure

The general control structure is shown in Figure 10, and details of these working states are described in the following parts of this paper.

2.4.1 Elastic State

In the elastic state, the system is controlled to perform like a spring, i.e. the displacement of the cylinder rod is controlled proportional to the finger force acting on the rod's tip. The position lead control method is used to realize this working principle.

2.4.2 Plastic State and Elastic-Plastic State

In the plastic state, the cylinder rod keeps moving inwards until the plastic state is terminated (i.e. finger force < yield force F_y).

When the finger force is less than the yield force F_y, the system works in the elastic state (Line ***ab*** in Figure 11) with the zero load position X_c. If the finger force becomes greater than F_y, the rod keeps retracting until the finger force is smaller than F_y again. (Curve ***bc***) Then the new zero load position X_c' is calculated, the elastic modulus is restored and the system switches back to the elastic state (Line ***cd***).

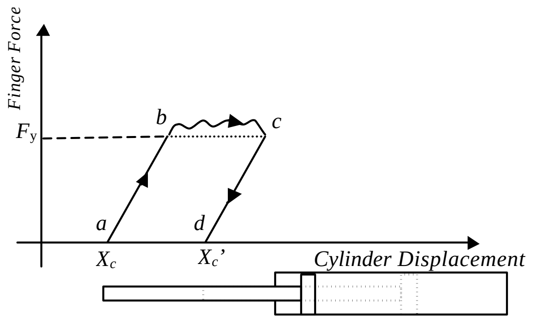


Fig. 11. Perfect Elastic-plastic Working State

2.4.3 Shaping state

Shaping state is not a part of the behaviours of a real material. It allows the user to "add" or "subtract" volume from the system by the means of "pulling" or "pushing" the surface. In this working state, if the finger force is larger than the upper limit force F_p, the cylinder rod will retract (Curve ***ab*** in Figure 12). If the finger force is smaller than the lower limit force F_l, the cylinder rod will stretch (Curve ***cd***). If the finger force is between F_p and F_l, the cylinder rod will stay stationary. (Curve ***de*** and ***bc***) This working state looks like the plastic working state except that (1) the force limits (F_y F_p and F_l) are different and (2) the user can "pull" out the rod in shaping state (actually offering a controlled expansion).

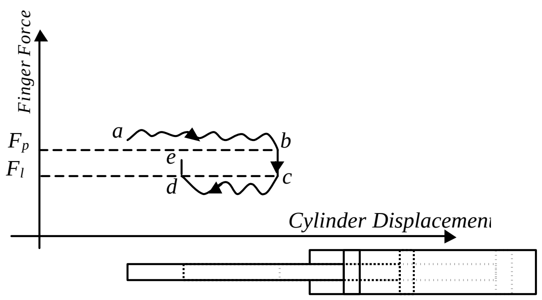


Fig. 12. Shaping State

2.5 *User Gesture Interpretation*

Digital Clay is an input/output device, so an effective, simple and friendly communication method between user and Digital Clay is critical.

The control system uses the three working states (described above) to deliver the information from the computer to the user. And the user can use preset gestures to express his/her intention.

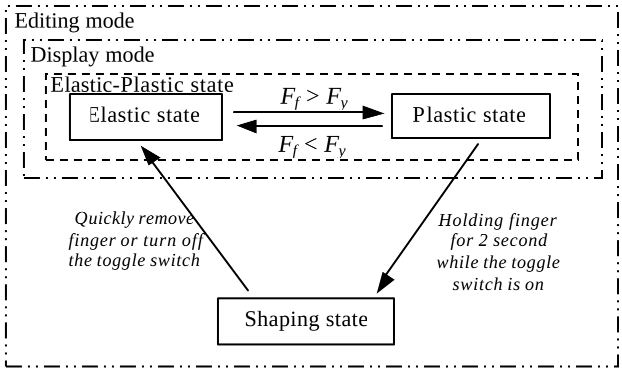


Fig. 13. User Gesture Interpretation. F_f -- *finger force;* F_y -- *yielding force limit;*

The final solution is subjected to the following requirements: (1) Simple, i.e. both the hardware and the software should be as simple as possible; (2) Reliable, i.e. the computer must correctly detect the user's intention; (3) Easy to operate, i.e. the preset user gestures should be easy for the user to perform; and (4) Easy for user to remember. Based on above requirements several methods were investigated and the one selected is described below and its general block diagram is provided. (Figure 13)

2.5.1 Switch between Display Mode and Editing Mode

A toggle switch is used to toggle between the editing mode and the display mode. The switch could be a software switch controlled by the computer. Only when the switch is on, is it possible for the user to edit the model, i.e. the user can use the shaping state.

2.5.2 Switch between Elastic State and Plastic State

To switch the system from the elastic state to the plastic state is very simple: exert a force larger than the yield force F_y. If under display mode, when the finger force is less than F_y again, the system goes back to elastic state.

When under editing mode, to shape the model, the user firstly has to reach the plastic state, i.e. exert a force bigger than F_y on the cylinder rod, and then keep the finger stationary for a short while, for example, 2 seconds. Then the system will go into the shaping state. In the shaping state, the cylinder rod tip will follow the finger until the finger is quickly removed (or turn off the toggle switch). This set of user gestures is quite easy to remember: Pushing hard (till it yields), waiting for the rod tip to "stick" to the finger, shaping the surface (currently only one point) with the finger and, if finish, quickly removing the finger to "get rid of" the rod tip.

The above user gestures are realized using the following method. When the toggle switch is on (i.e. in editing mode) and the system is in plastic state, a software thread will start to monitor the movement of the cylinder rod. If the rod keeps stationary for a certain time, the system will switch to the shaping mode. In the shaping mode, if $(-dF_f/dt)$ is detected to be bigger than a certain value, the system will record the rod position and go back to the elastic state. Here, F_f is the finger force. The recorded rod position will be the new zero-load position for the elastic state.

2.5.3 Experimental Results

This method is tested on the experimental device described above. The result is shown in Figure 14. The data were recorded under editing mode and the experiment process is described as below:

Under editing mode, push the rod with gradually increasing force until the system went into plastic state. (Line ***ab*** indicates the elastic working state and curve ***bc*** indicates the plastic working state) Then hold the finger's movement until the system goes into the shaping state. (Line ***cd***) In the shaping state move the cylinder rod back and forth by controlling the finger force. (Curve ***de***, ***ef***, ***fg***, ***gh***, ***hi***, ***ij*** and ***jk***) Then quickly remove the finger, (Curve ***kl***) let the system go into 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 F_p and lower limit force F_l, the cylinder rod keeps stationary. This can be seen from the vertical line ***S***, ***gh***, ***ef***, etc.

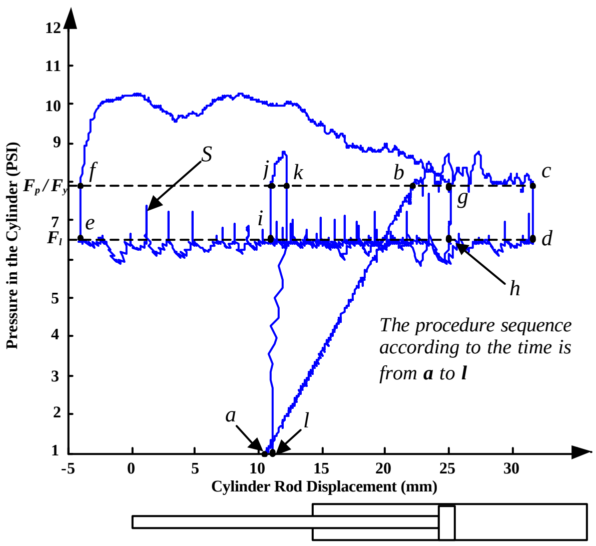


Fig. 14. Experimental Result

Though the experimental result is obtained under the editing mode, the result is also applicable for the display mode. Since this experiment focused on testing the user gesture interpretation method, two high-speed solenoid valves instead of the conventional solenoid valves were used to make the working states clearer and easier to identify.

3. FUTURE WORK

There is still much work left to reach the final target. Future efforts will be placed on (1) refining the actuator's performance in elastic state through control (2) investigating the control relating to cell-cell coupling events (3) effective control and data bus design/selection (4) other problems linked to MEMS devices and inter-cell communication.

4. CONCLUSION

Control of the Digital Clay encounters a lot of challenges. Three levels of control tasks are introduced in this paper. Preliminary research on the control methods for system working states, working mode and user gesture interpretation are reviewed and discussed. Several basic solutions for the realization of the four working states, two working modes and user interpretation methods are selected for further research and investigation.

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