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Embedding and Multiplexing Large Scale Sensor Arrays for Digital Clay

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ABSTRACT

Digital Clay is proposed as the next generation human-machine communication interface with a morphing, tangible and haptic shape / surface. It is composed of a large array of hydraulic actuators in a planar pin-rod style and corresponding control system. It will be constructed using MEMS technology ultimately to satisfy the resolution, manufacturing and cost requirements. Per the ultimate objective, Digital Clay may have 10,000 to 1,000,000 actuators and, consequently, an array of sensors in large amount. In this paper the sensing system of the Digital Clay is investigated and solutions are given for current and future implementation.

Keywords: Human Computer Interface, Haptics, Shape Display, Shape Input, Digital Clay, Large Scale Sensor Array, Bed of Nails

1. INTRODUCTION

Digital Clay provides a new generation human-machine communication method. As depicted in figure 1-1, the CAD model in the user computer can be interpreted by the Digital Clay and output as a 3 or 2.5 dimensional surface. The user can not only visually inspect it but can also touch it with hand to gather more information such as stiffness, flexibility, and other material properties of the object represented by the CAD model.

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 may be preferred in: (1) design of shape, feel, resistance (mechanical impedance), texture, spatial relationship; (2) exploration of models and experimental data for understanding; (3) training of both rare and common skills, retraining/rehabilitation, conditioning; (4) enhancement of motion capabilities in surgery, manufacturing, construction in normal and hazardous environments; and (5) entertainment and communication of emotion. Digital Clay provides a human machine interface based on both shape and haptic interface.

Digital Clay's name comes from the similarity to the clay (a mud used to sculpt or figure). The user can touch, reshape the working surface of Digital Clay, and inspect in a three-dimensional form as illustrated in Figure 1. Beyond ordinary clay, Digital Clay also provides parameters to the computer that will represent the shape to the computer for further actions such as: analysis, editing, etc. The computer can also command Digital Clay to form the desired surface shape. Note that though the concept shown in figure 1 is more likely a 2.5D device, Digital Clay could be a true 3D device if using certain omni directional actuator.

Figure 1 Digital Clay Concept

Digital Clay comprises an actuatable surface that plays the key role of the tangible haptic interface. The surface is formed by an array of controlled hydraulic/pneumatic cells which act together to convey the surface topography of desired 3D objects. Each cell comprises a fluidic actuator that is connected to two pressure sources through dedicated micro-miniature valves. Sensors are also embedded in each cell to collect feedbacks. Currently, "bed of nails" concept is adopted for the structure of Digital Clay as show in figure 2. Eventually, the hardware of Digital Clay will be manufactured by the MEMS technology that is under development at Georgia Tech.

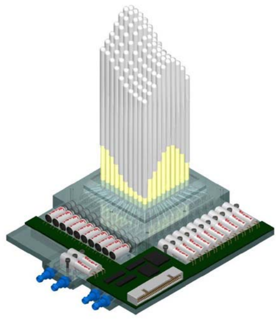


Figure 2 "Bed of Nails" Concept

The size of the cell array ranges from 100 x 100 to 1000 x 1000, with a proposed density around 1 cell per 9 mm^2 (3 mm x 3 mm. To control this kind of large scale system, a modified decentralized control structure and a novel hydraulic matrix drive is utilized. The control of Digital Clay is organized into three levels. The level of top application programming interface (API) generates commands to the level of surface control. The API is designed to simplify validation and development of a target set of applications. The next level, surface level, regulates 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 the commands and sensed pressure.

Several papers and demo are published [1][2][3][4] on the structural design and control of Digital Clay. This paper mainly focuses on embedding and multiplexing the sensor system / array of the Digital Clay.

Digital Clay has two large sensor arrays embedded in the actuator array: the displacement sensor array and the pressure sensor array. Each cell has one pressure sensor and one displacement sensor. Therefore, each sensor array has 10,000 to 1,000,000 sensors and has a density of 1 sensor per 9 mm^2. For the pressure sensor, there is a lot of research on the fabrication and interfacing the sensor array [5] [6] [7]. The challenge faced by Digital Clay is that due to the medium density and high quantity, the total area could be pretty large 30cm x 30cm to 3m x 3m as proposed. (10cm x 10cm to 1m x 1m if the actuator array density is 1 per 1 mm^2) Therefore, it will be impossible to fabricate the whole array on one wafer. Proper mounting technology is necessary to fit several sensor array blocks together if say not every pressure sensor. Two mounting methods are introduced in this paper along with the multiplexing methods.

Very little research can be found on such large scale long working range displacement sensor array (Size > 100 x 100, and working range > 50mm). Rich Boland in ZYGO Corporation [8] reported using a 32 LVDTs array displacement sensor array for measuring surface features of large ground surfaces. However, the amount of sensors is far less than what Digital Clay needs. Challenges lie in the facts that 1) off-the-shelf displacement sensor are expensive (> $100 each); 2) size is big (> 5 mm in diameter when working range > 50 mm; 3) mounting sensors to the actuator one by one is extremely costly, given the large amount of sensors needed. To deal with these challenges, a novel low cost high accuracy displacement sensor is first introduced which is suitable for mass production and makes the construction of the large scale sensor array feasible. Then based on the nature of the displacement sensor, several multiplexing solutions are discussed and one of them is chosen. Multiplexing is not a new concept, but multiplexing a large scale sensor array with a size exceeding 100 x 100 generates some big challenges like static and dynamic crosstalk especially when the sensor output signal is an AC signal.

In this paper, issues on the displacement sensor array will be first discussed followed by issues on the pressure sensor array.

2. NON-CONTACTING RESISTANCE DISPLACEMENT SENSOR ARRAY

The large scale sensor array requires the sensor structure and the integration of sensors to be very simple and suitable for mass production. Hence, a novel displacement sensor is developed which is very easy to manufacture and put into an array. Before further discussion on the sensor array, the structure and actuator of Digital Clay need to be briefed.

2.1 Actuation Structure for Digital Clay

Due to the technical limitation on the fluidic actuator at the current stage, the "bed of nails" concept is adopted to realize the Digital Clay. It is formed by a planar x-y array of linear actuators acting in the z direction as shown in figure 2. Bellows fabricated using MEMS technology provide a solution to the micro linear actuator. However their actuation range is limited due to buckling. Hence a micro cylinder is designed and put into an array in a manner as shown in figure 3. The actuator is composed of a glass tube and a graphite piston. The return can be realized by applying pressure on the common port with constant value.

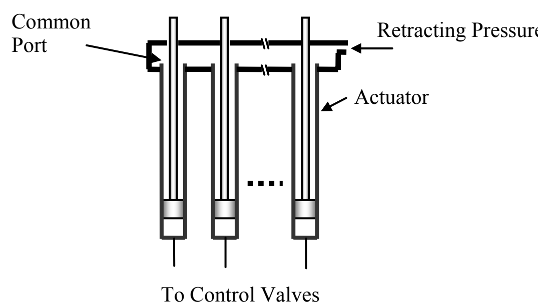
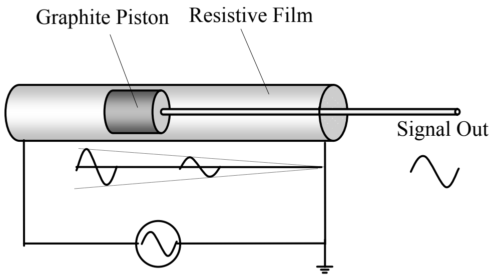


Figure 3 Actuator Array of Digital Clay

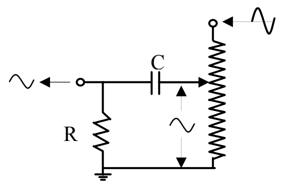
2.2 Non-contacting Displacement Sensor

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. As no such sensor is found on the market, our effort to design a new displacement sensor is highly prompted.

The concept for non-contacting resistance displacement sensor is shown in figure 4. A uniform eclectically resistive film is deposited on the outside wall of the cylinder. A high frequency AC voltage is applied across the resistive film. Therefore the amplitude of AC voltage along the cylinder is linearly distributed as shown in figure 4. The AC voltage is then coupled out by the capacitance between the film and the graphite piston. By sensing the amplitude of the AC voltage collected by the piston, the position of the piston can be detected. Note that, the actual structure includes signal shielding and a wiring mechanism from the piston to the signal conditioner and, therefore, the actual structure is a little more complicated than the concept shown in figure 4.



a. Concept of Non-contacting Resistance Sensor



C — the capacitance between piston and the film
R — the measurement impedance

b. Equivalent Circuit

Figure 4 Non-contacting Resistance Sensor

The accuracy depends on the uniformity of the film, and the resolution is theoretically infinity. Tests show that the performance is comparable to LVDT's. The film can be deposited using sputtering technology (currently used), dipping into a solution such as graphite paste, or e-beam coating. By utilizing these methods, thousands of glass tubes can be coated at one time which greatly simplifies the production and reduces cost. The biggest advantages of this sensor are: (1) taking no extra space (the film is usually < 0.01mm); (2) cost of the sensor is extremely low; (3) high accuracy; (4) mass producible; and (5) simple assembly procedure.

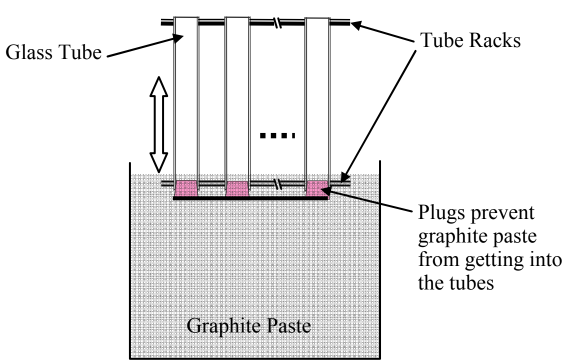


Figure 5 Dip-coating Method for Mass Production

For instance, the coating process using dipping method is shown in figure 5. After the glass tubes (cylinder bores) are assembled, the cylinder bore array is immersed into the graphite paste, and raised until only the bottom of the anode is in contact with the paste to allow momentary drainage, and then removed. The total dip-time is 1 to 2 seconds. No matter how many glass tubes are involved, they can be coated in one time.

2.3 Multiplexing the Displacement Sensor Array

A simple signal multiplexing system is a single output system with a high-speed selector switch accessing input signals from multiple sources or channels. As soon as a reading is taken from one channel, the switch moves on to the next. When dealing with a large scale array of signal sources like the sensor arrays of Digital Clay, switching speeds and the parameters of non-ideal behavior such as static and dynamic crosstalk are critical especially for the displacement sensor used here (since its output is AC). Crosstalk denotes a situation where the signals on other channels couple with the signal on the channel being measured. There are several forms of crosstalk, all inherent to the multiplexing process, and all worsen as the multiplexing frequency and signal frequencies increase. Static crosstalk occurs because parasitic capacitance across each open switch couples a portion of each channel signal to the output to mix with the desired signal. As the impedance of each parasitic capacitance drops with increasing signal frequency, the higher signal frequencies exhibit more static crosstalk. Dynamic crosstalk is primarily a function of the multiplexing speed and the effects of the parasitic capacitance in the system. The multiplexing speed for Digital Clay is relatively slow; therefore the static crosstalk plays a major role.

The signal conditioner used for the displacement sensor is the same as that of LVDTs. Though the displacement sensor is inexpensive, the signal conditioner is relatively expensive and large in size. Therefore, a multiplexing scheme is utilized so that a column of (or all) sensors can share one signal conditioner, by which the number of signal conditioners for an N x N array is reduced from N x N to N (or 1). However, due to the large number of sensors and their AC form outputs, crosstalk greatly affects the multiplexing system. This can be viewed from the analysis in the following section.

2.3.1 Simple Multiplexing Scheme

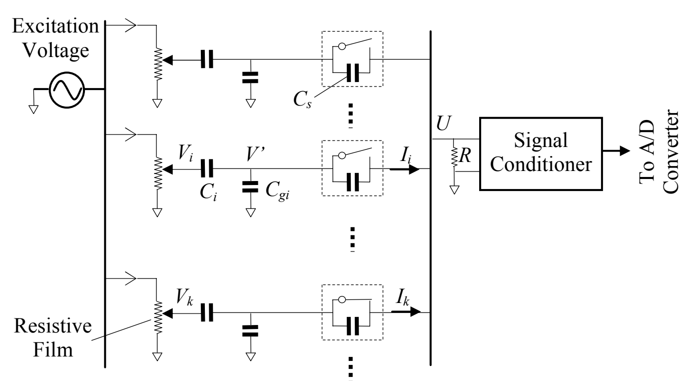


Figure 6 The Simple Multiplexing Scheme

A simple multiplexing scheme is provided as shown in figure 6. The resistive film is represented by a variable resistor. For the ith sensor, the capacitance between the graphite piston and the resistive film is simplified as a capacitor $\boldsymbol{C_i}$. Other capacitances caused by shielding are lumped to a capacitor $\boldsymbol{C_{gi}}$. The parasitic capacitance of the digital switch is represented by a capacitor C_s. R is the resistor used to suppress the noise.

Assume the k[th] switch is activated and all others are deactivated. Then the current I_i from any inactive switches to the signal conditioner can be calculated as:

$$\begin{cases}(V_i - V')C_i s = V' Cg_i s + I_i \\ I_i = (V' - U)C_s s\end{cases} \quad \text{...... (1)}$$

Equation (1) yields:

$$I_i = \frac{C_s s}{C_i + Cg_i + C_s}\left[C_i V_i - (C_i + Cg_i)U\right] \quad \text{...... (2)}$$

The current I_k from the active switch to the signal conditioner can be calculated as:

$$I_k = (C_k V_k - (C_k + Cg_k)U)s \quad \text{...... (3)}$$

U is the voltage presented to the signal conditioner.

Since $U/R = \sum I_i + I_k$, we have:

$$C_k V_k + \sum\left(\frac{C_s C_i}{C_i + Cg_i + C_s}\cdot V_i\right) = \left[\frac{1}{Rs} + \sum\frac{C_s(C_i + Cg_i)}{C_i + Cg_i + C_s} + (C_k + Cg_k)\right]\cdot U \quad \text{...... (4)}$$

Note that, in above summations, i = 1, 2, 3,…n, i ≠ k. (n is the total amount of sensors)

In practice, C_i = C_k = C_1 and Cg_i = Cg_k = C_2. Furthermore, phase angles of V_i and V_k are equal. (i.e. $V_i = \|V_i\|\sin(\omega t);\ V_k = \|V_k\|\sin(\omega t)$). Therefore,

$$\left(\|V_k\| + \frac{C_s}{C_1 + C_2 + C_s}\sum\|V_i\|\right)\sin(\omega t) = \left[-\frac{1}{C_1 R\omega}\cdot j + \frac{(C_1 + C_2 + nC_s)(C_1 + C_2)}{C_1(C_1 + C_2 + C_s)}\right]\cdot\|U\|\sin(\omega t + \phi) \quad \text{...... (5)}$$

Let:

$$a = \frac{C_s}{C_1 + C_2 + C_s}; \quad b = -\frac{1}{C_1 R\omega};$$

$$d = \frac{(C_1 + C_2 + nC_s)(C_1 + C_2)}{C_1(C_1 + C_2 + C_s)}$$

Equation (5) yields:

$$\|U\| = \frac{\|V_k\| + a\cdot\sum\|V_i\|}{\sqrt{b^2 + d^2}} \quad \text{...... (6)}$$

MATLAB simulates the result as given in figure 7. The parameters used in the simulation according the real system are: (1) number of sensors: 10, 100 and 1000; (2) $C1$ = 18pf; (3) $C2$ = 30pf; (4) Cs = 0.3 pf; and (5) R = 1MΩ. The simulation shows a comparison of amplitudes of the desired AC signals with Cs=0.3 pf (solid lines) and Cs = 0 pf (i.e. ideal switch with no parasitic capacitance, the dashed line). Note that the simulation describes the worst situation that is the sensor output of active channel is from 0 ~ 10 volt, while all the inactive channels' outputs are at the maximum value: 10 volt. Please note that, currently, the best digital switch we can find with the smallest parasitic capacitance is made by NEC. Its parasitic capacitance is 0.3 pf.

From figure 7, big offsets are found between the measured values (affected by the crosstalk) and the ideal value. Though the parasitic capacitance is only 0.3 pf, there are large amount of such capacitances linking together in parallel which form a very big capacitance. This big capacitance couples the not desired signal to the signal conditioner.

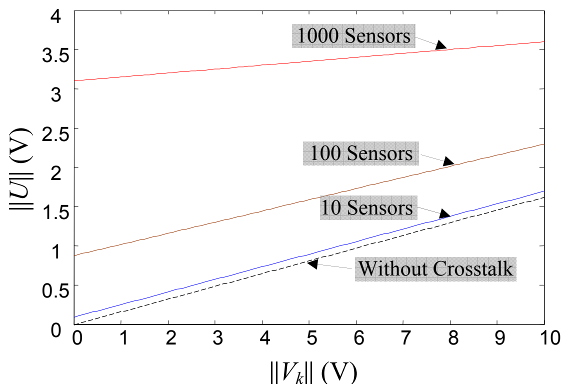


Figure 7 Matlab Simulation Result

2.3.2 Solutions for the Multiplexing Mechanism

Several solutions for solving the crosstalk problem and multiplexing mechanism are investigated. A solution and its schematic circuit are shown in figure 8. The idea is to ground the sensor signal before the digital switch using a grounding resistor R_g.

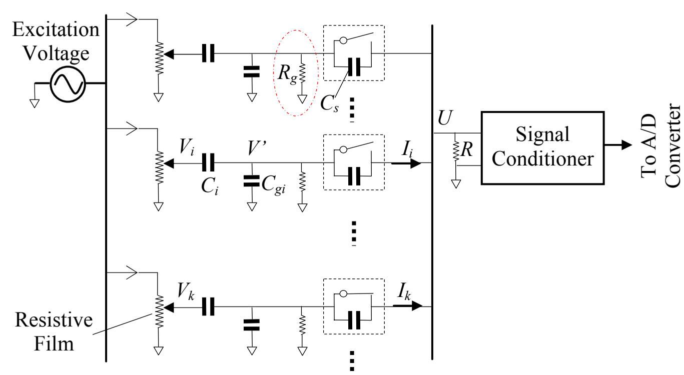


Figure 8 The Multiplexing Scheme of Solution 1

Assume the k[th] switch is activated and all others are deactivated. The current from any inactive switches (I_i) and from the active switch (I_k) to the signal conditioner can be calculated as:

$$\begin{cases}(V_i - V')\cdot C_i s - \dfrac{V'}{\dfrac{R_g}{Cg_i R_g s+1}} = I_i \\ (V'-U)\cdot C_s s = I_i\end{cases}$$

…… (7)

Equation set (7) gives:

$$\begin{cases} I_i = \dfrac{R_g C_i C_s s^2 \cdot V_i - (R_g C_i s + R_g Cg_i s + 1)C_s s \cdot U}{R_g (C_i + Cg_i + C_s)s + 1} \\ I_k = C_k V_k s - (C_k s + Cg_k s + \dfrac{1}{R_g})\cdot U \end{cases} \quad \ldots\ldots (8)$$

Since $U/R = \sum I_i + I_k$, and $\boldsymbol{C_i = C_k = C_1}$ and $\boldsymbol{Cg_i = Cg_k = C_2}$.

$$U/R = \frac{R_g C_1 C_s s^2 \cdot \sum V_i - (n-1)(R_g C_1 s + R_g C_2 s + 1)C_s s \cdot U}{R_g (C_1 + C_2 + C_s)s + 1} + C_1 V_k s - (C_1 s + C_2 s + \frac{1}{R_g})\cdot U$$

…… (9)

Let $V_i = \|V_i\|\sin(\omega t); V_k = \|V_k\|\sin(\omega t); U = \|U\|\sin(\omega t + \phi)$, we have:

$$\begin{aligned}&\{ R_g (C_1 + C_2)(C_1 + C_2 + nC_s)\cdot s^2 \\ &\quad + [(\frac{R_g}{R} + 2)(C_1 + C_2) + (\frac{R_g}{R} + n)C_s\ ]\cdot s \\ &\quad + (\frac{1}{R_g} + \frac{1}{R})\}\cdot \|U\| \cdot \sin(\omega t + \phi) \\ &= R_g C_1 [C_s \cdot \sum \|V_i\| + (C_1 + C_2 + C_s)\cdot \|V_k\|]s^2 + C_1 \|V_k\| s)\sin(\omega t);\end{aligned}$$

…… (10)

Let:
$$\begin{cases} a = R_g (C_1 + C_2)(C_1 + C_2 + nC_s) \\ b = (\dfrac{R_g}{R} + 2)(C_1 + C_2) + (\dfrac{R_g}{R} + n)C_s \\ c = \dfrac{1}{R_g} + \dfrac{1}{R} \\ d = R_g C_1 (C_s \cdot \sum \|V_i\| + (C_1 + C_2 + C_s)\cdot \|V_k\|) \\ e = C_1 \|V_k\| \end{cases}$$

Since $s = j\omega$, We get:

$$(-a\omega^2 + b\omega \cdot j + c)\|U\| = -d\omega^2 + e\omega \cdot j \quad \ldots\ldots (11)$$

That is:

$$\|U\| = \frac{\sqrt{(e\omega)^2 + (d\omega^2)^2}}{\sqrt{(b\omega)^2 + (c - a\omega^2)^2}} \quad \ldots\ldots (12)$$

MATLAB gives the simulation result as shown in figure 9, with all parameters the same as used in the simple multiplexing scheme, and the grounding resistor is 20KΩ. For the array with 10, 100 sensors, the measured signals overlap the ideal signal (i.e. not affected by the crosstalk). Though for the 1000 sensor array, the result at the small voltage (e.g. $V_k < 2$ V) is not good, but given the fact that the initial working position of sensor can be set at 3 V or more, the problem is easy to solve by sacrificing some of the working range as shown in figure 9.

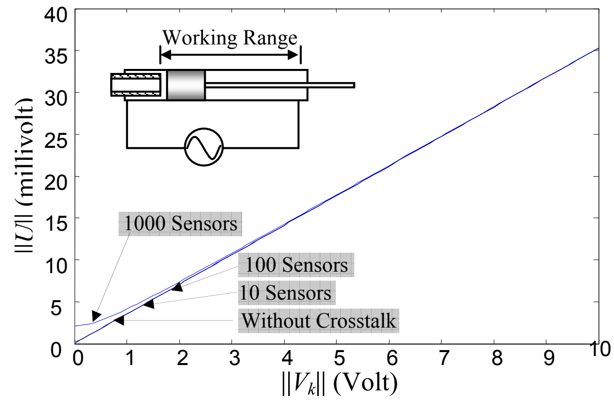


Figure 9 Results of the Multiplexer

Other solutions are also investigated. One solution is to numerically compensate the interference by computer. Since the model of the multiplexing system is known, the desired actual signal can be calculated based on all other inactive channels' outputs sensed and stored in the memory by using certain algorithm. However, this method will increase computation load of the computer and if there is any error in the previous feedback, the current data will be inaccurate and the error will accumulate.

Using two digital switches (or a Single Throw Double Position switch) in one channel is another alternative solution as shown in figure 10. When a channel is deactivated, one of the switches is shut down, and the other is on to ground the signal from the sensor to the ground before it is coupled to the data bus. The main problem of this solution is the cost and the complexity.

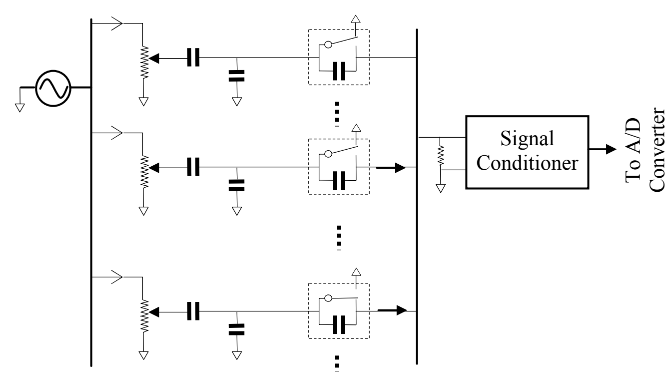


Figure 10 Multiplexing Method using STDP Switch

Therefore, the first solution using a grounding resistor is adopted for multiplexing the displacement sensor array.

3. EMBEDDING AND MULTIPLEXING PRESSURE SENSOR ARRAY

Micro miniature pressure sensors are easy to build using MEMS Technology. An example of such pressure sensor can be found in the PC40 serial pressure sensor provided by

Honeywell. These pressure sensors have the signal conditioner and amplifier built on a small die along with the pressure gauge. Though the small scale pressure sensor array can be built on a single wafer, it is practically impossible to build a large scale pressure sensor array on a single wafer due to the cost and the size limitation of the wafer. However, mounting large amount of micro pressure sensors onto a relatively large size base is possible as discussed below.

Two solutions are investigated. In both solutions, for each pressure sensor, the base provides a main through channel for the working fluid to passing through and a branch channel interfaces the input port of the pressure sensor.

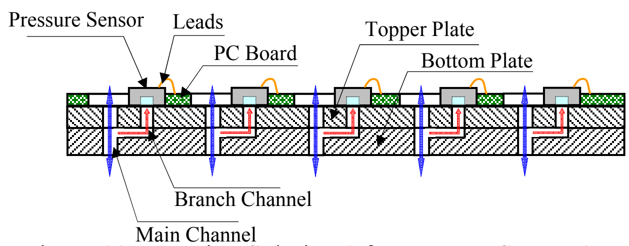


Figure 11 Mounting Solution 1 for Pressure Sensor Array

As shown in figure 11, the base of solution 1 is made of stamped, machined, or cast metal plates. They are bonded to each other by means such as solder or epoxy. The pressure sensor then is bonded onto the upper plate. The leads are connected to the PCB on the top of the upper metal plate.

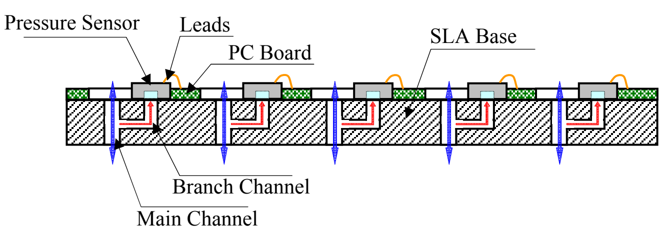


Figure 12 Mounting Solution 2 for Pressure Sensor Array

An alternative solution is to build the base using stereolithography technology as shown in figure 12. The pressure sensor is bonded to the base. The leads are connected to the PCB on the top of the docking base.

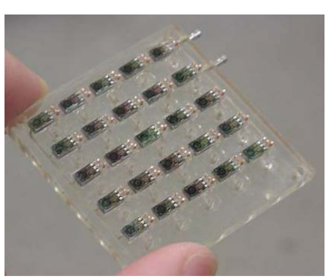


Figure 13 5 x 5 Pressure Sensor Array Assembly

At the current stage, solution 2 is adopted since it is easy to realize due to the small quantity production. An assembled 5 x 5 pressure sensor array is shown in figure 13.

The multiplexing mechanism is conventional as shown in figure 14. To save the multiplexing control resources, the switch arrays of the pressure sensor array and the displacement sensor use the same control signal as shown in figure 14.

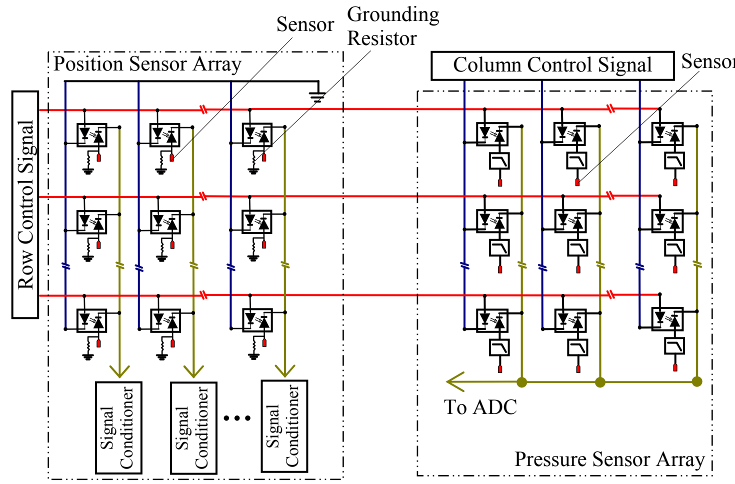


Figure 14 Control Resource Sharing Scheme between Sensor Arrays

4. FUTURE WORK

The sizes of the sensor arrays of Digital Clay are extra large, which are larger than 100 x 100. There is little research reported on this kind of work. Investigations presented in this paper are basically based on theory and computational simulation. Tests and experiments are necessary to validate the proposed methods. A 5x5 prototype of Digital Clay is under assembly, which is equipped with the sensor arrays for the proposed methods.

For the displacement sensor array, though the structural parameters such as dimensions and, consequently, capacitances and resistances of each sensor are assumed to be identical, variances do exist among individuals. Furthermore, the optimized value of grounding sensor is to be determined to achieve the best result.

For the pressure sensor array, though the multiplexing is easier than that of the displacement sensor (since the output of the sensor are an amplified and compensated DC signal), actual efficacy of the multiplexing method still needs further verification.

5. CONCLUSION

As a novel three dimensional human computer interface, Digital Clay provides a more efficient means for man machine communication using an actuated, tangible and haptic surface. Due to its large scale array structure, the sensing mechanism faces big challenges including the sensor mounting and multiplexing methods. This paper presents several methods to solve theses problems based on both practical design and theoretical analysis.

For the displacement sensor, a novel non-contacting resistance displacement sensor and the method to fabricate the sensor array are introduced. Several multiplexing methods are discussed. The solution using the least amount of components while providing adequate results is chosen.

The mounting and multiplexing of the pressure sensor array are also introduced in this paper. A multiplexer control scheme is proposed to reduce the multiplexer control resource.

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