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STReSS: A Practical Tactile Display System with One Millimeter Spatial Resolution and 700 Hz Refresh Rate

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Abstract. A tactile display system is described which can produce 'tactile movies', that is, rapid sequences of tactile images refreshed at a rate of 700 Hz. The display uses an array of one hundred laterally moving skin contactors designed to create a time-varying programmable strain field at the skin surface. The density of the array is of one contactor per millimeter square, resulting in a device with high spatial and temporal resolution. The paper describes the construction method and the drive electronics. It also reports informally on initial test patterns and on the resulting tactile sensations.

1 Introduction

Tactile displays are devices meant to artificially create sensations that resemble, for example, those arising from sliding a fingertip on a textured surface, or from brushing over Braille characters. For a variety of reasons, such devices are not yet available. Nevertheless, the demand for tactile displays capable of creating a reasonable subset of the gamut of all possible tactile sensations is significant. Potential applications include virtual training for surgeons, remotely touching materials via the internet, sensory substitution devices among many others.

While most tactile displays are designed to stimulate the skin of the fingertip, there exists vibrotactile devices that cause tactile sensations at various places of the body including the back, the arm, the phalanges or the feet [12, 17, 5, 24]. Other displays often employ miniature transducers arrays to cause tactile sensation via skin indentation and other methods. Typical stimulation mechanisms involve arrays of moveable pins or inflatable miniature bladders to either indent the skin or vibrate it locally [16, 6, 27]. Actuation techniques include electromechanical actuators, piezoceramics, servomotors, shape memory alloys, fluids, and others [11, 29, 18]. Other systems, generate friction electrostatically when a user slides a finger over the display [20]. Some devices avoid direct solid contact with the skin by using air jets [1]. Many devices are or were based on electrostimulation, e.g. [2]. Devices that use electrogel bristles brushing against the skin have been introduced [13]. Yet some others require miniature magnets to be glued to the skin for electromagnetic activation [26]. For a more complete survey, please refer to [23].

In [8], it was suggested that normal skin indentation and normal vibrations are not essential to many tactile sensations. Lateral skin strain induced by an array of discrete contactors moving laterally can give rise to a variety of sensations, including those given by small-scale geometrical features moving against the skin. This observation motivated the development of a tactile display array which relied on the deformation of a membrane to determine the swinging movements of a dense array of pins [8]. In the intervening period, it was found that inherent structural and manufacturing limitations made it difficult to use this technique to achieve sufficient strain levels at the skin surface [19]. This and other factors prompted the development of a new generation of surface strain devices. This paper introduces the "Stimulator for Tactile Receptors by Skin Stretch" or STReSS, an efficient and practical tactile device which achieves high spatial and temporal resolution.

2 Requirements for Practical Tactile Displays

The slow development of tactile displays can be attributed to poor usability. Most existing systems are cumbersome, bulky, expensive, and often focused on the optimization of one single feature. In order to be successful, devices should conform to a large set of requirements and be capable of causing a variety of sensations. Moreover, they should stimulate a reasonable skin area, say of fingertip size, and be capable of refreshing it at a high rate to match the skin's sensitive bandwidth (about one kHz).

They must be safe. They must be compact so as to be embedded in other structures such as computer mice or steering wheels. Most crucially, they should be able to resist prolonged exposure to skin abrasion and be impervious to various pollutants including dirt and skin secretions.

It is generally accepted that in order to give meaningful tactile information, displays should conform to a spatial resolution of one transducer per mm^2. The central problem is then to pack of the order of 100 robust transducers in about one cm^3, each capable of substantial movement at about one kHz.

The skin receptors adapt rapidly as can be readily observed when attending to the sensations coming from a stationary finger pressing on fabric or on paper. Therefore, a tactile display which by principle remains stationary with respect to the skin it contacts, should be capable of replicating the interaction of the skin sliding on a surface. More generally, it is clear that active touch — which involves voluntary movement — provides more information than passive touch does, although in some cases both result in the same tactile sensation for the same surface [14]. So ideally, the display should allow the freedom of active exploration.

The present prototypes were designed empirically because a preferred design depends on many unknown factors which fall under the following headings:

Biomechanical factors. Fingers are mechanically highly variable. Their properties vary according to the owner's age group, occupation, habits, gender, and most evidently, plain individual differences. The skin is both tough and deformable and has peculiar biomechanical properties [28]. These properties do not provide much useful design information at this stage of the development. Presently, we are interested in large strains (of the order of 10%) for small 1 mm^2 patches.

Neuroanatomical factors. The nature, distribution, and specificity of various touch receptors is still an open issue, see for example [22, 21]. Therefore, this gives little information as to a preferred design.

Psychological and behavioral factors. The respective roles of biomechanics and neuroanatomy to conscious touch perception is also open to debate, see for example [4]. Previously published studies of the behavioral response to skin stretch were obtained with different stimuli (e.g. only one contactor [3]). The stimuli that we are creating result from an ensemble of organized time-varying patterns which are presumably subject to further processing centrally or at the periphery (e.g. [7]). This also, provides little design guidelines.

Cognitive factors. It is highly probable that learning, training, and more generally, prior knowledge of the sensations given by touch and other modalities play a role in touch perception.

Factors related to the application. Even if all of the above issues where settled, designs would depend on the application. For example, a display designed for representing fine textures would obey different rules than one designed for reading Braille, since an actuator design relies, among others, on a displacement-bandwidth tradeoff.

3 Actuator Array Structure

Piezoceramic actuators constitute a practical choice to build an actuator array. They can be operated over a large bandwidth and are relatively easy to form in a desired miniature structure. Moreover, they are widely available from a variety of sources for a reasonable price. Unfortunately, piezoceramic actuators still require high operating voltages. However, the technology is mature and piezoceramic properties continue to improve steadily year after year.

The objective is to create a deformable structure capable of causing programmable strain fields in a patch of skin in contact with it. The exposed side of this structure should thus be made of an array of contactors each moveable tangentially. Among the different piezoelectric elements available, bimorphs can achieve substantial displacement via bending of a cantilever. This bending motion can directly be used to stretch the skin without the need for extra motion amplification mechanisms. Figure 1 and caption show the manner in which a collection of bending elements can be arranged to create a two dimensional array of contactors.

One advantage of this design is the creation of a sturdy, yet modular, structural configuration made of the same part replicated ten times. Of course, all

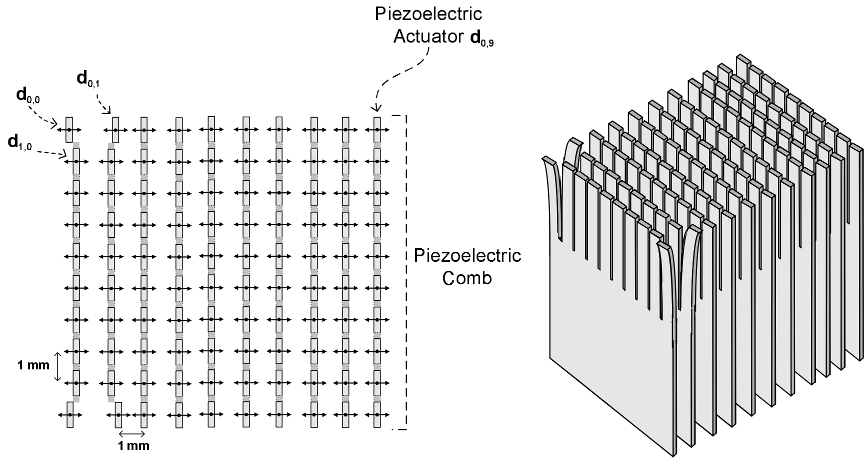

Fig. 1. Structural configuration of the piezoelectric actuator pack. Ten piezoelectric combs, each cut to form ten tooth-like actuators, are packed one next to another to form a matrix with one mm pitch in both directions. Four actuators are shown with an exaggerated displacement. The upper side is in contact with the skin.

the actuators bend around the same axis, and hence, all contactors move along the same direction. Nevertheless, this was not found to be a limitation since at such a small scale, the resulting sensations seem to be indifferent to the details of skin stretch/shear orientation. In any case, other more complex configurations are possible by simply interlocking the combs orthogonally or at 30^o angle. In the meantime simple stacking simplifies fabrication and assembly.

4 System

The design problem was, in a compact and reliable system, to provide for computer communication, individual amplification of the driving voltages for one hundred actuators, and tactile image buffering for precise synchronous refreshing of all actuators. The driving electronics are thus not unlike those needed for visual displays.

The STReSS device is presently controlled by a programmable logic device (PLD) available as part of a development board supporting USB communication. Ultimately, once a satisfactory design will be reached, the PLD could be replaced by an application specific integrated circuit (ASIC). Figure 2 and caption summarizes the main components of the STReSS system.

At the time writing, the software components of the system include a 'Tactile Player' application which accepts sequences of tactile images, that is, tactile movies and relay them at a rate of 700 frames per second via Universal Serial Bus (USB) communication to the PLD. The system latency is about 20 ms. It also includes functions to configure the device.

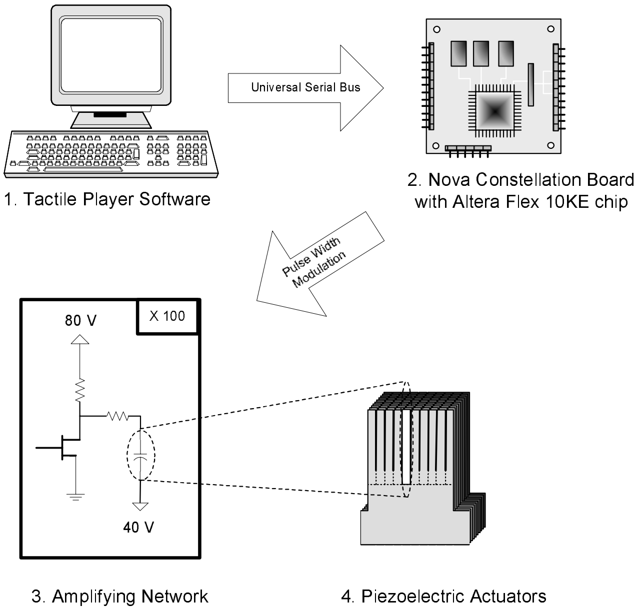

Fig. 2. The STReSS system is composed of four subsystems: A tactile player application (1) sends tactile images to the PLD (2). The PLD converts the tactile data into pulse width modulation (PWM) control signals used to drive a network of 100 switches (3). The switching amplifiers control voltages to drive the piezoelectric actuators forming the tactile array.

4.1 Programmable Logic Device Board

A developement board (Constellation™ from Nova Systems) operates an Altera™ Flex 10KE chip and a Universal Serial Bus (USB) interface. Incoming tactile image frames transmitted in serial format are buffered into a first-in-first-out (FIFO) queue in order to reconstruct individual frames. Buffering makes reliable transmission possible despite MS-Windows™' poor performance under real-time operation. Tactile images stored in the buffer are then displayed using parallel refresh of all hundred actuators at a maximum controllable rate of 700 Hz. The device outputs one hundred simultaneous PWM switching signals clocked at 156 kHz which are used to drive a network of one hundred individual switches.

4.2 Amplifying Network

The network operates concurrently to carry out one hundred simultaneous amplification operations. Each individual amplifier is driven by the 0-3.3 V digital pulses generated by the PLD which must be amplified to ±40 V to drive the piezoelectric actuators in bipolar mode. There must be one hundred of such amplifiers, it is therefore crucial to minimize their complexity. Standard bipolar Class D amplifiers require at least two transistors (push-pull), a voltage shifter

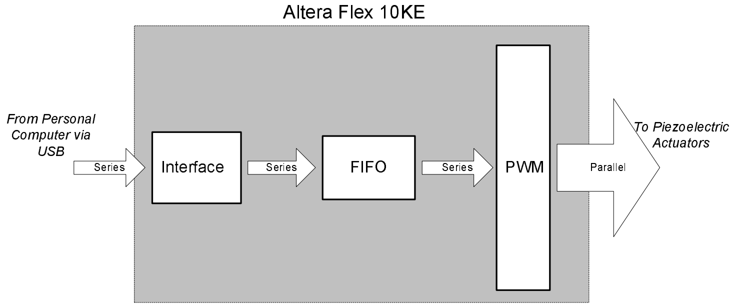

Fig. 3. The Flex 10KE is programmed to accomplish three functions: accept serial data from the USB interface, reconstruct images in a first in first out (FIFO) buffer, and generates 100 pulse width modulation (PWM) control signals.

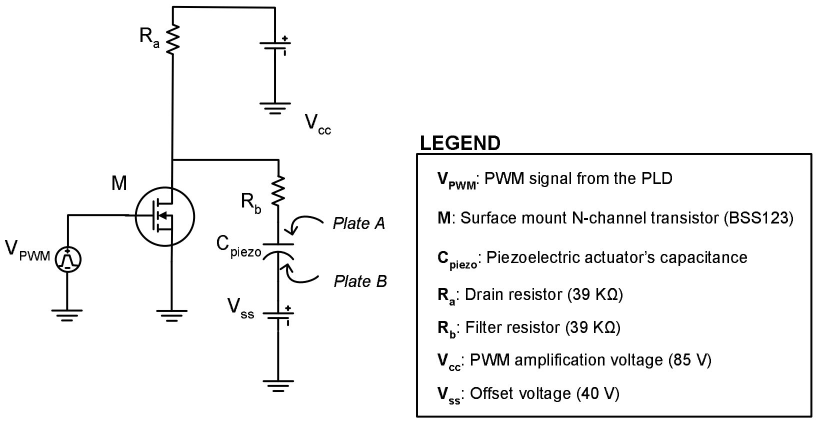

Fig. 4. An amplifying element comprises one transistor, two resistors and the piezoelectric actuator's capacitance. The 3.3 V PWMs are amplified to 80 V pulses before being filtered by the actuator. One of the piezoelectric's electrode (plate B) is offset by 40 V so that bipolar potentials of ±40 V can be set across the actuator.

and an inverter. Seemingly infeasible at first sight, a design was found that could provide bipolar output voltages with only one transistor and two resistors per amplifier, and yet, which could achieve reasonable resolution. Such design could therefore be termed a "Class $\frac{D}{2}$" amplifier.

Switching amplifiers require at least three elements: an energy throttling mechanism, a dissipative element and an energy storage element. The energy throttling mechanism is accomplished by a single transistor. The energy storage element is provided by the capacitance of the actuator, and therefore does not

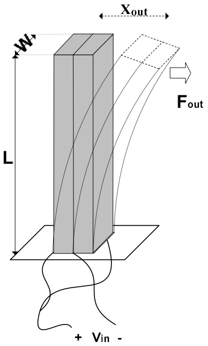

Fig. 5. Applying a differential voltage V_{in} between the middle electrode and the outside electrodes results in a lateral displacement X_{out} and a force F_{out} applied to the load at the tip of the bimorph. The bimorph has resonant frequency F_0. From basic cantilever mechanics, it is known that $X_{\text{out}} \propto L^2$, $F_{\text{out}} \propto W/L$ and $F_0 \propto 1/L^2$. Likewise, from basic electrical relationships, $C_{\text{piezo}} \propto W \times L$

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require any component other than the actuator itself. The dissipative element is represented by two resistors.

Refering to Figure 4, when the transistor is open, the capacitor charges up as dictated by an RC circuit of time constant $(R_{\text{a}} + R_{\text{b}})C_{\text{piezo}}$. When the transistor is driven to conduction to reverse the polarization on the actuator armatures, the time constant $R_{\text{b}}C_{\text{piezo}}$ is actually increased by the slew rate of the transistor, balancing the two phases of a cycle. A careful selection of the components and of the manufacturing of the actuators allowed us to achieve 4 bits of amplitude resolution with this simple circuit. The first-order RC dynamics, plus the lowpass nature of the actuators, are sufficient to smooth the output signal switched at 156 kHz. The price to pay for this simplicity is a dual-voltage power supply. A more precise conventional push-pull bipolar design would have required a two-rail power supply anyway, and a much larger component count to accomplish essentially the same function.

The actuator's central armatures are grounded, so users cannot be exposed to voltages greater than ±40 V. Moreover, the resistors limit accidental currents to a small value. The resulting amplifying network fits on a middleware PCB roughly the same size as the PLD board and therefore can be mounted on it in a piggy-back configuration.

4.3 Piezoelectric Actuators

The piezoelectric bimorphs are used as bending motors. They are fixed at one end and therefore obey cantilever mechanics loaded at the free end, as illustrated in Fig. 5. A basic bimorph model is sufficient to address all the design issues. For a complete mathematical and physical model of piezoelectric materials, refer to [10]. A piezoelectric actuator's electric behavior can be modeled with an equivalent circuit [9, 25], see Figure 6. The load Z is unknown, however. When unloaded, that is when not touched, around resonance, a Van Dykes RLC model represents well the electro-mechanical behavior of one tooth. When loaded and/or far from resonance, an RC circuit in parallel with the load is sufficient to model the actuator. Since the device is designed to operate well below its resonant frequency, an unloaded actuator's displacement is directly proportional to the applied voltage. When loaded, the displacement is also determined by the load, by the electromechanical properties of the bender, and by its shape.

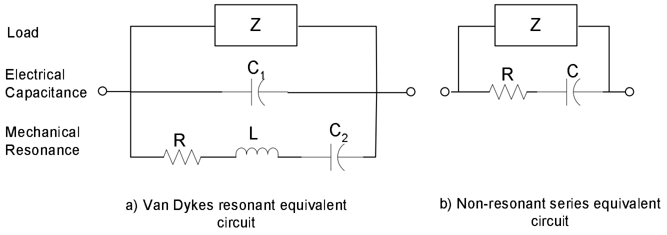

Fig. 6. Equivalent circuits modeling the frequency response of a piezoelectric actuator (a) around resonance and (b) far from resonance.

4.4 Manufacturing

Manufacturing one hundred independent piezoelectric milli-actuators, so that they can be assembled on a 1 cm^2 PCB surface is a challenge. All actuators should be identical in shape, be electrically accessible, and be sturdily fixed to the PCB. Manufacturing the piezoelectric material in a comb shape leads to a practical structural configuration that is easy to assemble (Figures 7 and 8).

The manufacturing of a single piezoelectric comb led to a procedure from which a solid mini-actuator structural configuration was obtained. Once ten piezoelectric combs are manufactured, it is possible to assemble them on a PCB to create a 10 x 10 actuator display, using a system of sockets, see Figure 8.

5 Tactile Movies

The tactile player software relays sequences of tactile images, that is, 'tactile movies' at a rate of 700 frames per second via Universal Serial Bus (USB) communication to the display system. There does not exist yet a systematic method to create these movies from first principles. To date, one approach being explored consists of directly measuring the skin deformations as it slides over transparent surfaces. In the companion paper [15], an apparatus and a method are described to perform this function. This will allow for more direct mapping between what is observed and what is displayed by the STReSS system. To date however, only empirically designed patterns were tried.

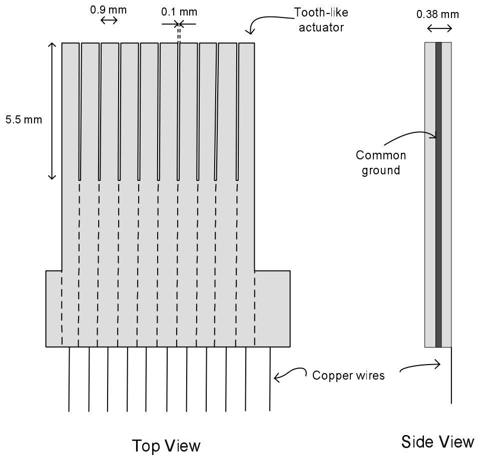

Fig. 7. Comb shape. Each tooth-like actuator is isolated from its neighbors by selectively removing the external electrodes. They all share the brass center shim as a common ground. Electric connections to the PCB are by small copper wires. Two shoulders are provided for clamping each comb in its socket slot. Sockets are made of two opposite racks attached to the PCB, as illustrated in Figure 8.

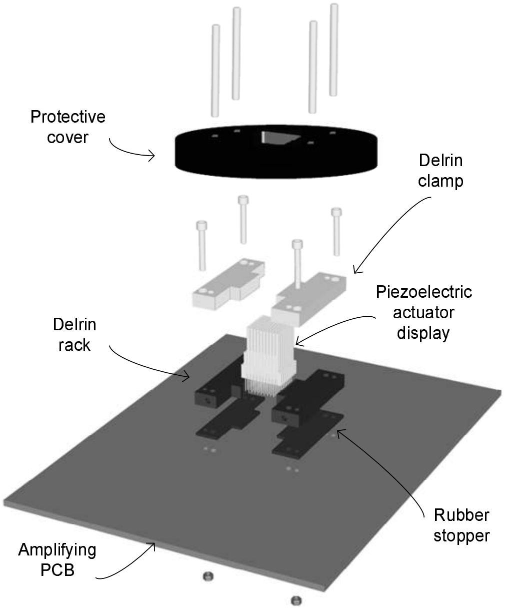

Fig. 8. A PCB supports one hundred amplifiers. The outputs are routed via an 8 layer board to a 1 cm^2 pad having one hundred connections. The individual combs are held collectively using two racks and two clamps, forming 10 sockets.

6 Preliminary Results

From a functional view point, these results are better described by inspection of Figure 9 and caption. They indicate that indeed distributed skin strain of 5% could be achieved with a device of form factor 1 × 1 × 1.5 cm for the complete actuation sub-system.

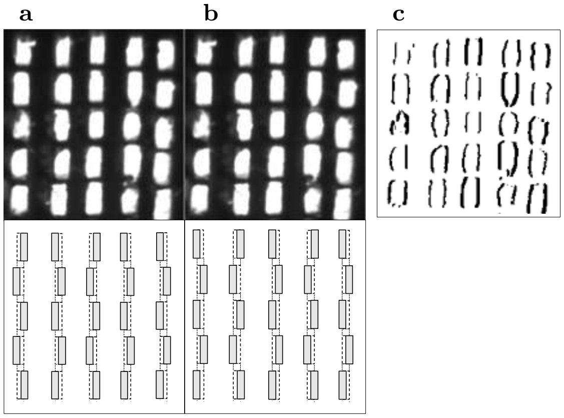

Fig. 9. Panels (a) and (b) show the top right quadrant of the display enlarged 5 times (the average distance between two rows is one mm) where a sub-array of 25 skin contactors can be seen. Panel (a) shows the actuators activated in a checkerboard pattern so half of them move to the right while the others move to the left, as indicated by the bottom panels. In panel (b), the directions of movement are inverted. The binarized difference between images (a) and (b) shows more clearly the actuators' relative movements. Using this simple technique, the maximum actuator's movement could be evaluated to be around 25 μm in each direction.

At the time of writing, only very few of all possible tactile patterns could be tried, so only very preliminary observations could be made.

One pattern that was tried was such that a pair of adjacent actuators was activated to cause successive stretch and compression of an enclosed patch of skin. This was achieved by driving the actuators in phase opposition as illustrated in Figure 1, where the variables $\mathbf{d_{i,j}}$ represent actuator displacements indexed by rows and columns. A progressive wave was created by time-overlapping strain changes in successive neighboring patches, as shown in Figure 10. The waveform (smoothly represented by 60 samples of period of 1.4 ms) was traveling from row 0 to row 9 at a speed of about 2.5 cm/s (a typical tactile scanning speed). This particular pattern has the property that the rate of change of strain is roughly constant within a small space-time neighborhood. Informally, for most subjects, the conscious experience could be described at that caused by one (sometimes two) small raised dot(s) sliding under the fingertip.

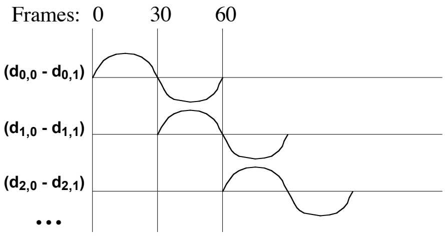

Fig. 10. Progressive wave activation for pairs of actuators, indicating the gap size variations through time and space.

Another pattern that was tried was created by replicating the above sequence for each 5 pairs of actuators on the same row. Thus, at any given instant in time, if one patch was stretching, its row neighbors were compressing at the same rate (and vice-versa). As above, the pattern was made to travel column-wise at 2.5 cm/s. In this case, the experience was that of a uniform horizontal edge scanning the finger vertically. Moreover, there was no ambiguity whatsoever regarding the direction of the edge movement.

While is would be inappropriate to draw strong conclusions from these informal tests, they do seem to vindicate the notion that that liberties can be taken with millimeter-scale details of time-varying skin deformation in order to create meaningful sensations (c.f. Section 3).

7 Conclusion and Future Work

A practical and compact system was described that could create under computer control distributed strains patterns at the finger tip with high temporal and high spatial resolution. The results are sufficiently encouraging to motivate systematic behavioral investigations that take advantage of the unique capabilities of the device.

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