EAP actuators aid the quest for the "Holy Braille" of tactile displays

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ABSTRACT

The authors present the worldwide need for electronic Braille displays to promote literacy among the blind. The use of of EAP's to produce Braille displays is encouraged and detailed descriptions of the technology of Braille are presented. Prior art is covered since the early 1950's through present day displays based mostly on piezoelectric technologies. EAP's offer the promise of the “Holy Braille”, the ability to display a full page of Braille electronically. Details on “how not to make a Braille display” are covered in prior art.

Keywords: braille display, braille, piezo bimorph, braille actuator, refreshable braille, EAP actuator

1. BACKGROUND

The Boston-based National Braille Press has recently established a Center for Braille Innovation (CBI), whose mission is to research and develop affordable braille literacy products. The primary focus has been to facilitate the development of dramatically lower cost electronic braille display devices, and the much-sought-after "Holy Braille" of a full-page braille display.

Developing new braille technologies is key to improving the extremely low literacy rate (around 12%) of blind students.

Our CBI team is working to aid developers of braille technology by focusing attention and resources on the development of the underlying braille actuator technologies. We are also developing braille-related information resources to aid braille display developers.

The CBI braille requirements summary is one of these efforts. Available on the NBP web site (http://www.nbp.org/ic/nbp/company/cbi.html), the braille specifications include braille dot dimensions, spacing, displacement, lifting force, and response time requirements. The NBP web site summarizes the technical requirements and specifications for braille and other tactile displays. Additionally, there is a listing of over 100 previous and current tactile display development projects.

Mentoring, helping to evaluate new braille display ideas, and openly sharing braille display technology are all part of the activities of the NBP braille innovation team.

NBP has expanded the CBI project with domestic and international partners including the China Braille Press, World Braille Foundation, National Federation of the Blind, American Printing House for the Blind, American Foundation for the Blind, and many university and research partners.

2. REVIEW OF THE NEEDS

The main challenges our CBI team is addressing are to help improve the extremely low literacy rate of blind students and to reduce the high unemployment among the visually impaired folks who don't read braille. The employment rate of Braille readers is considerably higher than non-Braille readers.

Since commercially available braille line displays are made with many individual braille cells that cost $100 each (US), the typical braille line display of 20 to 40 cells costs several thousand dollars. There is a strong need for compact one-line braille displays that are an order of magnitude less expensive, especially for the educational market. There is also a major need for braille actuator technologies that can produce multiple-line or full-page braille displays.

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Figure 1. Model of 20 Cell Braille PDA

2.1 General Needs for Tactile Displays to Help Visually Impaired Readers

- Affordable, compact, battery powered, single braille line devices for early education
- Multiple line and full page braille displays
- Full page tactile graphics displays
- Image reading systems such as the Optacon
- Vision substitution arrays
- Small displays for watches, calculators, and cellphones
- Tactile virtual reality systems

The CBI team is interested in all manner of tactile displays for visually impaired users, but is currently concentrating primarily on improving braille display technologies.

3. REQUIREMENTS

The NBP web page that has the link to requirements and "specs" for braille display systems is: http://www.nbp.org/ic/nbp/company/cbi_projects.html.

3.1 Summary of specifications for refreshable braille displays

Traditionally, the cells of embossed paper braille have had a format of six dots, arranged in two columns of three rows. A full page of braille typically has 25 lines of up to 40 cells per line.

Most modern paperless, or refreshable, braille displays have eight dots per cell, arranged in two columns of four rows and are limited to a single line of braille.

Table 1. Specifications for Braille Dots

Parameter	Minimum	Nominal	Maximum	Typical
Braille dot base diameter	1.4mm	1.5mm	1.6mm	1.5mm
Dot height (assuming no depression force from user's finger)	0.48mm	0.5mm	0.9mm	0.7mm
Dot Spacing				
Distance between centers of perpendicularly adjacent dots in the same cell	2.3mm	2.5mm	2.6mm	2.45mm
Distance between centers of corresponding dots in horizontally adjacent cells	6.1mm	6.35mm	6.5mm	6.42mm
Height of 6-dot braille cell lines	10mm	10.75mm	11.15mm	10.55mm
Height of 8-dot braille cell lines	12.25mm	13.25mm	13.75mm	13mm

Dot height uniformity for adjacent dots: ±0.05 mm.

Minimum displacement below the reading surface of the top of an unraised dot: 0.025mm.

Braille line spacing, or height, is measured between the centers of a top dot of a cell and the dot in the corresponding position of a vertically adjacent cell.

The tops of braille dots are domed, with a radius of curvature that is unspecified, but usually larger than the radius of the base of the dots.

3.2 Force

Under loading, such as the touch of the braille reader's finger, a dot should provide a minimum of five grams holding force, while being depressed <0.1mm from its top height.

Generally, a raised dot should be supported with a blocking force of >10 grams, and 15 grams force (approximately 0.15 Newtons), or more, is preferable.

Note: The minimum fingertip pressure needed for users to feel a dot clearly is about 2 grams.

Because the force and displacement performance of braille displays is complex and difficult to measure, there is a lot of disagreement in published values for optimal blocking and holding force requirements.

A small 2.5 by 2.5mm actuator footprint is needed for dense multiple line braille arrays, and horizontal cantilever bimorph reed assemblies won't fit this footprint.

3.3 Cell Height

Cell height should be less than 30mm, especially for portable applications such as notetakers, PDAs, etc. Typical piezoelectric braille display modules are now approximately 18mm high.

3.4 Timing

Maximum dot setup time of 50 ms is desired for some applications.

Minimum dot cycling rates as high as 10 Hertz is recommended for most applications, but 1 Hz may be tolerable for some applications with limited interaction, such as continuous reading of long pages of text on multiple-line or full-page displays.

Some systems find it desirable to blink braille cursors or characters on and off with a frequency of several hertz.

Most applications require that braille units be quiet enough to work in classrooms, libraries, meetings, and other noise intolerant settings.

3.5 Voltage and Power

The operating voltage should be <300V, both for safety and electronic driver circuit requirements, but, if higher voltages are needed, a matching safe high voltage drive method should also be developed.

Most applications call for battery power, but some of the full-page braille display applications may tolerate a requirement for operating only while the unit is connected to AC lines.

3.6 Touch Sensing

It is highly desirable to include touch position sensing with tactile displays. This is already being used on modern braille line displays, for cursor routing and "clicking" on displayed menu options. Touch position sensing is also important for supplying additional attributes or information about a position, and for combining the advantages of using both tactile and audible outputs together in a complementary manner.

3.7 High Reliability

Lifetime should be on the order of 10^7 cycles for single-line displays and correspondingly less for larger, multiple-line or full-page displays that are updated less frequently. Certain braille actuator mechanisms might be more appropriately rated in terms of tens of thousands of (10^4) hours of operation, rather than number of dot cycles.

3.8 Serviceability/Cleaning and Fault Repair

Routine cleaning and maintenance should be something that can be done by the user.

Requiring that a personal PDA/notetaker device be sent back to the factory creates a severe hardship on users who may not have any alternative method to access their notes and information.

3.9 Low Cost

Our goal is to get the prices of braille devices down into the few hundreds of dollars, rather than the thousands. With prices in this range, the devices would be affordable enough to be purchased for young students by their family members, church groups, elementary school systems, and others.

Note: New braille actuator technologies should not be ignored simply because they do not perfectly meet all the requirements listed above.

3.10 The Incompatibility between Tactile Graphics and Braille

Good tactile graphics dot spacing makes for bad Braille text dot spacing and vise versa.

A braille display might also be used as a tactile graphics display, if it has additional dots to fill in the gaps between lines of braille cells and the gaps between cells within each line of cells. For example, the display might be an array of evenly spaced dots, with 2.5mm separation between the centers of all perpendicularly adjacent dots. However, braille text on such a display would not have the normal spacing between braille cells and might feel a bit strange to some braille readers.

Displays to be used only for tactile graphics and not for braille text should have even smaller dot separation than normal braille dots (preferably <2.3mm) and should have correspondingly smaller dot base diameters.

4. LIMITATIONS OF VARIOUS TECHNOLOGIES AND ASSUMPTIONS THAT LED MANY PREVIOUS DEVELOPMENTS ASTRAY

At our NBP web site, we have a prior art listing of over 100 tactile display development projects, including the good and the not-so-good ideas.

We hope to help researchers avoid re-inventing the "square wheels" of prior unsuccessful braille display attempts.

4.1 Limits of a Single Braille Cell Display

To begin where many others do, we might ask why user needs can't be met with just eight tactile actuators making up a single braille cell that can be multiplexed to sequentially present a whole page of information.

In 1973, at the IBM Los Gatos Lab[2], the limitations of single cell braille displays were finally investigated thoroughly. In this IBM research, we learned that there were three major limitations in trying to use a single braille cell for general information displays.

One company, Telesensory Systems, actually tried briefly to sell a braille notetaker product that used a single cell braille display for their notetaker, hoping that its single cell would be adequate for editing and minimal braille reading tasks. The TSI Braille Mate single cell display product was not a success.

First, spatial page or screen format information is difficult to interpret through a single braille cell, usually resulting in the user becoming lost about their position on a screen or page of text.

Secondly, dynamic navigation control of the text presented on a single braille cell is slow and awkward. Controlling information flow to a single cell display requires many separate keys or command controls for navigating through a page or screen of text and can easily take several seconds just to back up and reread a word that was displayed just a moment earlier.

The third major limitation of a single braille cell is that rapid reading of braille on a fixed single braille cell with only 6 or 8 actuators is not possible, primarily because rapid reading requires sweeping of the tactile image across the fingertip, either by moving the fingertip over the tactile image or by moving the tactile image under the fingertip.

Image blend effects limit single character sequential flashing display rates to around seven characters per second, for either tactile or visual single character displays[3].

Users have to slow down their reading on a fixed single cell braille display, in order to "scrub" or scan their finger tip around on the tactile image, to feel "a clearer image"[4].

Character exposure time is also limited on a single character display, unlike text on a moving Times Square display, and is another factor limiting the reading rate for a single character display.

Vibrating tactile stimulators at 250 Hz, as in the Optacon Reading Machine, helps improve the stationary tactile image some, but is not enough for most reading applications.

Simulating movement of tactile images by scanning braille images across the fingertip with high resolution lines of tactile actuators was also tried at IBM (using an Optacon), but was found to be unsatisfactory.

A useful model for understanding the awkwardness of using a single character display is to imagine placing a square meter sheet of cardboard over a visual screen or print page. Then imagine a small hole in the middle of the cardboard, just big enough to show one character of the text at a time, the rest of the cardboard blocks out all the other text and also makes it difficult to know where on the page or screen the small window is allowing you to read. Finally, to better simulate the dynamic navigation control issues, you might further imagine that you are only allowed to move the cardboard around by bumping it with your elbows.

You can similarly simulate reading with a short one line braille display by changing the small hole in the cardboard to a thin slit, showing just 20 characters at a time.

Now imagine trying to read a spreadsheet or other highly formatted data through that tiny window.

4.2 Limitations of Some of the Most Notable Past and Current Display Approaches

The IBM Wheeler rubber belt loop display[5] with friction gripped pins was patented in 1950. It was somewhat noisy, driven by punched paper tape input, worked well, with firm feeling braille, and had a hermetically sealed actuator mechanism, but it did not offer appropriately prompt, interactive response or navigation controls for the planned typing application.

The Grunwald/Argonne belt loop display[6] had preformed dots in the moving plastic belt loop, but the belts only lasted for about 10,000 cycles for each preformed dot, and it did not allow easy back up or other needed

navigation controls. Additionally, viscous drag or stiction of fingers on dots formed in plastic makes braille formed in plastic difficult for most users to feel and read.

The IBM Ball bearing moving belt display[2] had very nice feeling rolling dots, but it was prone to failure from dirt and oils that made the ball bearings stick to each other and not feed into the setup mechanism properly.

The IBM pneumatic inflated dots with electrostatic valves[2, 7, 8] had thin plastic membranes that suffered wear problems, and some valve systems would probably have leaked too much for driving large arrays. Additionally, the necessary air pumps would be unacceptably noisy for most braille reading applications.

The Rose Reader[9] had thermal expansion of bimetallic latches that were electrically heated to release spring loaded braille pins. It had very slow setup times of a minute or 2 per page, high drive current requirements, and extreme aggregated mechanical loading from the pin lifting springs that caused bending of the top plate (so much so that dots in the middle of the page could not be reset).

Thermal actuators that use paraffin wax expansion[10, 11, 12] or use shape memory alloys such as Nitinol[13, 14] have been found to have slow response times for dot setup and even slower for dot reset, have high drive current requirements, have aggregated heat dissipation issues, and need a reliable latching mechanism to reduce their high power consumption.

The American Foundation for the Blind's 64X64 dot sequential mechanical setup shared actuators braille display[15] was expensive to manufacture, noisy, had slow response time, and was vulnerable to dirt build up.

The first documented EAP tactile display development appears to have been that of Fred Murphy at TSI, around 1981. The PVFD actuator prototypes were rolled "straw" assemblies that were expensive to manufacture, had low displacements or strain (compared to modern materials), and appeared to offer few advantages over the piezo actuators TSI was already using for the Optacon display. The limited strain performance of those early EAP actuators caused TSI to also lose interest in it as a piezoelectric bimorph braille display actuator replacement.

4.3 Generic Considerations

Noisy operation is a characteristic that has severely limited the applications of some braille display attempts.

If a unit is too slow and/or noisy, a user might as effectively use a paper braille printer.[15]

Slow tactile display setup or response times have been found unacceptable by users, and several prototype braille display units[16] have progressed too far down costly development paths before discovering that.

Most of the thermally actuated braille display approaches require excessive peak drive power to quickly energize enough actuators to obtain reasonably short response or setup times. They also have problems associated with overheating due to accumulated heat dissipation of large numbers of closely packed actuators. This heat build up severely limits the dot cycling times, as it can take a long time for the thermal elements to cool down enough to allow their dot to reset.

It appears to be easier to force energy into thermal actuator systems than it is to rapidly cool them to get the energy back out.

The behavior of an isolated single dot actuator can be very different from the behavior of a whole tightly packed array of thermally interacting actuators.

Similarly, Interference of the magnetic fields from adjacent actuators clustered in Robert Petersen's magnetic rotor cam pin driver display[17] is another example of why aggregated effects must be considered carefully, before costly prototype developments are begun.

We heartily recommend that developers of new actuators take a moment to just do some simple math, to get an understanding of the basic aggregation issues such as peak drive power, heat dissipation, magnetic or electrostatic field cross interference, and accumulated mechanical forces.

For example, as part of our CBI project, we did a lexical analysis of the number of dot set/reset state transitions for a 40 cell braille display, being used to read standard braille texts. We found an average of 11.6 dot transitions per word (including the blank trailing each word), and 9.7 dots raised per average braille word

(with or without any trailing blanks). We derived both types of average values, as some actuator designs use very little energy to reset dots, while other designs may require as much energy for reset as for setting up dots.

Using a nominal braille reading speed of 100 words per minute, simple multiplication indicates that 1160 dot state transitions or 977 dot setups might be expected during continuous reading at a modest rate. Actually, braille reading rates several times higher than this can be expected.

Multiplying the average dot setup or transition rate by the corresponding setup or transition energy gives a continuous power value that can easily be in the range of watts for displays using actuators that only require a few millijoules to change the state of each single dot.

It was surprising to our CBI team, to discover that many developers of braille display actuators had never done similar power requirement calculations!

When shown these simple power dissipation models, several current developers of braille displays decided that they ought to change their designs to include some sort of latching mechanism, in order to reduce the predicted exorbitant average power consumption levels.

4.4 Latching Versus Direct Drive of Pins

Most thermal actuators, such as SMA or wax expansion devices need latching mechanisms to reduce their high average power consumption.

Because of pull-in break down and other failures associated with many highly stressed EAP actuators, it might be possible to achieve better reliability and long life time of EAP systems by using a latching or bistable mechanism that would allow the EAP element to be driven in a binary mode with only a short activation duty cycle[18].

Another of our CBI projects is attempting to find a good general design for a latching mechanism that could be driven with any one of a number of different types of actuator technologies.

We've found that push-push or pull-pull toggle mode latches are interesting, because of their simplicity, but they require some extra mechanism to force dots to reset or to sense the true up/down state of each dot. Otherwise it might be impossible to assure that all the dots are in their proper state.

Most mechanical braille latching designs incorporate many small moving parts that may be vulnerable to contamination by dirt, skin oils, and spilled liquids.

At CBI, we have been considering designs for a braille cover plate that contains the braille dot elements and latch mechanisms, is installed just above the actuator arrays, and can be easily removed for cleaning, maintenance, or replacement.

As an alternative approach to latching, a friction gripping elastomer sheet, as was used in the IBM Wheeler rubber belt and rubber plate displays, is an interesting and extremely simple latching system that also provides hermetic sealing, which keeps the actuator elements under the elastic surface clean and protected.

An additional design concern for latching mechanisms is the ability to correctly latch the braille dot in the correct state, even when the user's fingertips are reading the braille and possibly depressing the dots. It is highly undesirable to require the users to lift their fingers clear of the braille display whenever it is setting or resetting dots.

In the past, some companies attempted to sell braille line display products that required hands off during braille setup, but those products have all been failures. However, many braille readers so desperately want a full page braille display that they might be willing to put up with the problems of keeping their fingers off the full page display during setup.

Starting around 1975, latching miniature solenoid braille cells were made by Shaefer and Schonherr, and later by Metec Ag. The latching mechanism was very clever, but had two serious drawbacks.

The user had to remove their hands from the braille display whenever the displayed text was changed. Any finger pressure on the dots prevented them from being set and latched properly.

The second problem with those latching solenoid displays was more serious. The small actuator components were too vulnerable to dirt, skin oils, and other contaminates. In the case of the Schonherr displays[15], even small amounts of dirt could cause the dots to not setup and latch correctly. In an attempt to protect the actuator elements, Schonherr placed a removable/replaceable flexible cover film over the braille dots. This cover film made the braille dots feel so weak and hard to read that typical users removed the films, only to find that the exposed and vulnerable actuator mechanisms clogged up with dirt and seriously failed within a month or so of average reading use.

Over the years, the piezo bimorph braille displays have proven to be more acceptable then the latching solenoid displays, but the piezo actuators are also vulnerable to some types of contaminant exposures.

Some examples:

The current chairman of NBP was very careful to protect his braille notetaker from spills, but a hapless airline flight attendant lost her balance and poured a cup of apple juice into his piezo braille display, destroying the $6000 unit.

Another former NBP board member had an office visit from his four-year-old son, who was eating a peanut butter and jelly sandwich. When he said, "See Daddy, I can read braille too!", he swiped a sticky finger across his dad's $7700 braille display and ruined it.

As has happened to many others, the same member of the NBP board stumbled and accidentally poured his coffee into his braille display unit (the one that replaced the previously ruined display).

In many other cases, tree pollen from an open window, volcanic ash from Mount Saint Helen's eruption, and other airborne dust has conspired to clog up braille displays.

In general, a standard visual display with a hundred or more pixels forming each character can still be usable, even when several visible dots or pixels fail to display properly. The braille code lacks similar redundancy, so a braille character displayed with a single dot failure will typically feel and be read as a completely different character. This means that braille displays must be extremely reliable, as the users have a near zero tolerance for even a single dot error anywhere on a line or full page braille display.

5. CAPABILITIES OF CURRENT SYSTEMS

Braille watches have been available for a long time, but they are not digital, and they don't actually display braille, just fragile hands pointing to tactile bumps marking the hours. Currently, there are no refreshable braille cells available that are compact enough for small devices such as a true braille digital watch.

Virtually all currently sold refreshable braille displays are built up from single-cell braille modules of 8 dots in two columns of 4 dots.

Virtually all braille modules available today use piezoelectric ceramic bimorph reeds to actuate the braille dots. The piezo reeds are mounted as a stair stepped stack of cantilevers, each with a braille pin resting on its free end. Each reed can lift the dome top of its 1.5mm diameter braille pin approximately 0.5mm above the reading surface.

As shown in Figure 2, a typical module has 4 layers of side-by-side pairs of reeds mounted horizontally, below and parallel to the top reading surface.

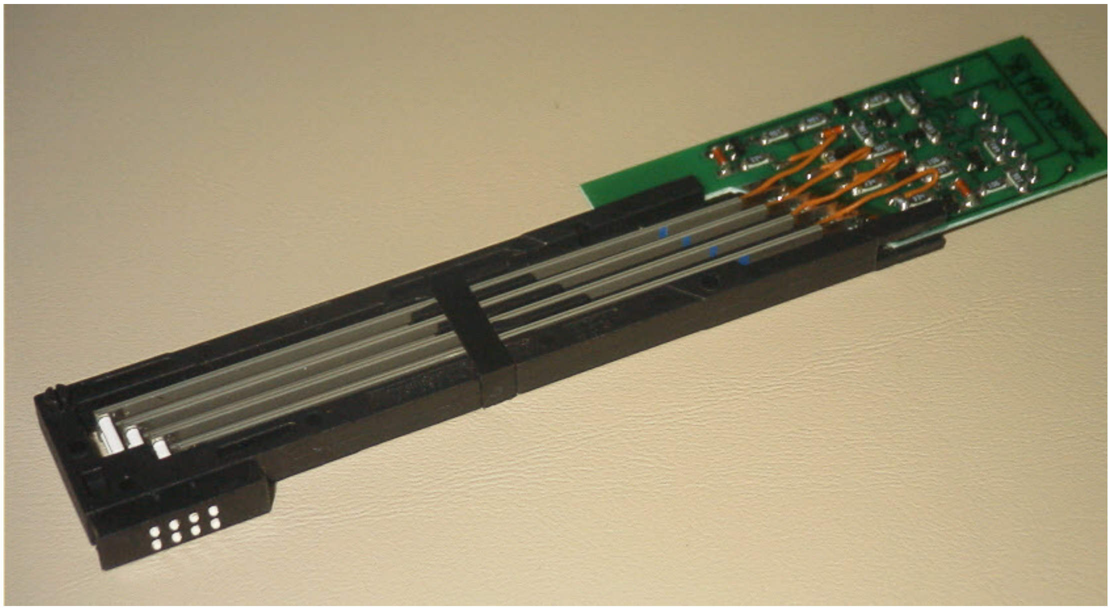

Figure 2: Typical Piezo Braille Cell

The circuit board on the cell module also contains the associated data latch and 200V driver circuitry required for, and integrated into, each braille cell module.

These modules are horizontally mounted next to each other in arbitrarily long lines (typically 20, 40, or 80 cells).

Although it may be possible to mount two of these lines together, in nose-to-nose fashion, for a two-line display, packaging size and high costs limit most displays to a single line.

These long, cantilevered piezo actuators can not be reasonably packaged into larger multiple-line displays because the footprint of each braille dot's actuator mechanism would need to be in the range of $2.5mm^2$ or less.

There are no full page braille display products currently available on the market. Until recent years, it was not considered at all possible to make a full page display, regardless of cost, size, noise, or response time.

Over the last 20 years, the costs of braille displays have not been significantly reduced. They still cost the end user several thousand dollars for a small, single line braille display.

6. REMAINING CHALLENGES TO DEVELOPING PRACTICAL TACTILE DISPLAYS

6.1 Size

For braille displays, we need small tactile actuators that can be packed on 2.5mm centers.

For "tactile vision" systems such as the Optacon Reading System, actuators with even smaller footprints of 1.25mm are needed.

6.2 Response Time

Response times of braille actuators need to be shortened to less than a second, preferably less than a tenth of a second.

In contrast to the relatively low cycle times of around 10 Hz for braille actuators, the Optacon and other vision substitution devices will need actuators that can respond well at 250 Hz.

Penn State[19] and other workers have been able to make EAP braille discrete actuators with good enough force and strain, but the fabrication of such discrete braille actuators will need to be simplified considerably, to begin to be price competitive with piezo braille actuators.

In order to make full-page or multiple-line braille displays that are affordable, large braille actuator sheet systems need to be developed with force and strains that are several times that of the flexible sheet systems developed at the University of Tokyo[20]. The response times of such systems have been in the range of seconds, and need to be reduced to tenths of a second or less.

6.3 Lowering EAP Drive Voltage Requirements

In order to make real products using large arrays of EAP or other tactile actuators, we will need researchers to also develop the necessary methods for electrically driving the large arrays of cells.

It usually isn't as simple as just putting a series of parallel conductor rows on one side of an EAP sheet and putting perpendicular conducting columns on the sheet's back side. Such X-Y matrix or grid selector systems usually need diodes or active drive elements at each intersection, to protect against the sneak path currents or voltages.

Using standard electronic circuits for switching the several thousand volt drive signals required for many current EAP materials is extremely challenging. Actually, switching voltages higher than 300 volts with today's available ICs is not very practical. Switching voltages in the range of 300--700 volts usually requires discrete high voltage FET components.

If very high voltages must be used on large arrays of braille actuators or sheets of actuator material, it may be possible to form optically switched drivers using coatings or pockets of photoconductive materials.

One of the authors (Runyan) has experimented with organic and other photoconductive materials for localized switching of large arrays of actuators, but so far has not found an adequate organic material.

Photoconductive high-voltage switches of thin film amorphous silicon for EAP drivers has been considered and reported on by Lacour, et al[21].

The NHK Laboratories Ultrahigh-Sensitivity HARP camera tube has, for some time, been successfully using "large" area 25 micron thin films of amorphous silicon at voltages of up to 2.5 Kilovolts[22].

Although it may be possible to develop high voltage driver systems for large arrays of EAP materials needing drive voltages of several kilovolts, we are hopeful that it will soon be possible to form large arrays from EAP materials that use much lower drive voltages in the range of 200 volts or less[23].

6.4 Reliability

As mentioned above, the needed tactile actuator arrays must have extremely high reliability and freedom from defects.

We need EAP actuators that supply the needed force and displacement without having to be driven so hard that they are unreliable, due to dielectric failures.

To increase manufacturing yields and maintain reliable operation through long life spans, more good ideas such as self-healing mechanisms[19] will probably be needed.

Significantly lowering manufacturing costs will require actuator technologies that are amenable to simplified and inexpensive manufacturing processes.

Instead of all the labor-intensive manual soldering and handling of discrete actuators, as is currently done for piezo bimorph braille cell manufacturing, it would be desirable to have processes that use photo etching, silk screen, inkjet printing, and other manufacturing processes like the electric circuit printing techniques now used in organic LED and other large visual display screen fabrication[20].

7. FUTURE PROSPECTS

As a major near-term project, the CBI team is developing a more affordable braille notetaker/cellphone/PDA device. Through the use of open software and open hardware designs, to limit development costs, we plan to produce a feature rich unit that uses the latest in bimorph display technology and sells for a fraction of the cost of current units.

As soon as EAP-based braille cells can offer lower priced braille displays, we hope to use them in our braille unit, to further drop the manufacturing costs, and make it an even more affordable product.

A major difference in our approach to developing braille devices is that our primary motive is not for profit; rather, it is to make significantly more affordable braille products available, in order to increase braille literacy and thereby increase employment.

We feel that the exciting field of EAP technology has matured to the point where it can start to provide real solutions for braille displays.

In the two year time frame, we hope to see discrete EAP actuators replacing piezo bimorph reeds as braille cell actuators.

In the 3- to 5-year time frame, we are hopeful that someone will be offering the first multiple line or full-page braille display products.

We suspect that these large array devices will be fabricated as integrated plates or sheets, perhaps using an approach similar to the University of Tokyo's flexible braille display, in which electrical circuits are printed onto large sheets of actuator material[20, 24].

The authors have both been involved in the braille development field for most of their careers, and have heard many optimistic predictions for braille innovations that never bore fruit. We have also observed that the market of braille display products has been stagnant for the last decade.

However, today, primarily because of the maturity of EAP material science, we are cautiously optimistic that we may be nearing real resolution to the quest for the holy braille of low cost and full-page braille display products.

We welcome and encourage anyone who wants to take part in this exciting field of braille innovation.

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