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IMPROVEMENTS TO THE DESIGN AND MANUFACTURE OF TACTILE MAPS PRODUCED USING INK-JET TECHNOLOGY

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1 Abstract

It has been demonstrated that ink-jet processes are capable of producing tactile maps and diagrams for use by people with visual impairments. A prototype machine was built using high resloution industrial print-heads, jetting multiple layers of polymer inks, cured with ultraviolet radiatiation, onto flexible and robust polymer substrates. Three-dimensional structures can be printed that are readily felt by the human finger. By using appropriate design guidelines that pertain to both the cartographic layout and the production capability, it is possible to produce tactile maps that can be effectively used for education, mobility or general information access. Furthermore, recent research has demonstrated efficiency gains and design improvements in the manufacturing process. These advances have been aided by the identification of a set of *haptic* variables by which the output (a tactile map) can be evaluated. Using these haptic variables with a combined design methodology, reductions in input requirements have been brought about.

2 Introduction and Background

Many people are familiar with Braille, a system of raised dots that represent text characters, to be used by people with visual impairment. Tactile diagrams are constructs where other graphical elements such as point symbols, lines and areas are raised, not just the text. It has been shown that tactile diagrams are useful in providing information, increasing mobility and aiding in independent travel [1].

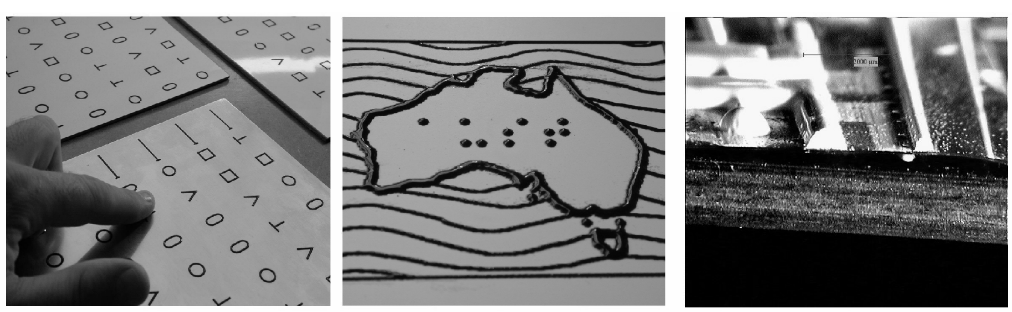

Figure 1: Examples of tactile maps. From left to right; an experimental array, a map and a cross section showing raised structures.

Methods for producing tactile maps are reported in detail elsewhere [2]. *Thermoform,* which is similar to other industrial thermoforming processes, involves deforming a thin (250 micron) film of polymer, over a previously created master mould. Mould production can be expensive, and as a male copy is taken off a male mould there is limited control over feature definition. *Swell paper* (also called Minolta or microcapsule) is particular to tactile diagram production. It is a paper pre-impregnated with expanding, heat-sensitive microcapsules. By designing to raise some areas and not others, tactile graphics are produced. People commonly produce diagrams with *mixed media*, a fundamental approach of bonding string, twigs, cloth and so on, to a substrate. This has advantages but is one of the slowest, least reproducible and dimensionally inaccurate of all methods [3].

Other technologies have emerged. Braille embossers are modified so the hammers can punch out graphics not just the limited set of dotted characters [4]. Screen printing has produced tactile layers of ink [5]. Arrays of movable pins, both static and vibrating [6] have been proposed. And more futuristically, electro-rheological fluids [7] and virtual-reality systems [8] have been touted.

Regardless of the technology, the effectiveness of a tactile map is highly dependant on the design of the tactile maps. Various guidelines exist to aid in good cartographic layout of symbols [9]. Collaborative and future work will investigate technology that will incorporate good cartographic design into the engineering design and manufacture. Psychophysical studies can also aid in tactile feature design by making the designer aware of the limits of tactile sensitivity [10]. The purpose of this research is to investigate the design and production of tactile maps with reference to a set of psychophysically derived output variables.

3 The development of haptic and structural variables.

The output, a tactile map, can be described not only in terms of its structural variables such as its robustness and mechanical properties, but also in terms of a series of haptic variables. This paper considers the haptic variables in detail; the analysis of the structural variables is discussed in greater detail in ongoing work.

3.1 Haptic variables

This research has centred on tactile maps (maps being a subset of a broader set of graphics generally). Cartographers classify all symbols on a map into three groups; point, line and area. In order to differentiate between one symbol and another, the cartographer Bertin [11] described a set of visual variables, namely; *location, form, size, texture, value, hue* and *orientation*. These were developed from the sense of vision to the sense of touch by Vasconcellos and later Griffin [12]. Slightly differing sets of haptic variables have been suggested and it may be controversial to downplay the role of a variable. The role here is not to favour one set over another, but to give the engineer a design tool.

Haptics is the study of that relating to touch, touch sensations and touch as a psychological reference. It is commonly broken into two parts, the *tactile*, which considers the feeling in the outer layers of the skin, and the *kinaesthetic*, which regards the muscle and bone mechanics over the whole body. Griffin considered *vibration, flutter, pressure, temperature, size, shape, texture/grain, orientation* and *elevation* as sources of tactile variation and *resistance, friction* and *kinaesthetic location* as kinaesthetic variables.

Not all of these are of immediate consequence in the use of a tactile map. As we are dealing with static, ambient temperature maps, the variables of *vibration, flutter* and *temperature* are disregarded. Users are likely to adjust their tactile *pressure* so that map use is comfortable [13]. *Orientation* is important as it can give directional cues, but in a production sequence it is only a rearrangement of shape. *Friction* has, perhaps surprisingly, yielded little bearing on some aspects of tactile perception [14]. *Resistance* is important in haptics generally, but in tactile map use is likely to be a function of elevation, line profile or texture.

Size, considers the area covered by a feature; this could include the space taken up by an areal texture, the width of a line or the perimeter dimensions of a point symbol. *Shape* is possibly the most defining characteristic of any tactile structure. It is often not possible to treat shape as a single ordinal variable, as how does one compare a simple geometric symbol with an irregular outline of a country. Probably because the tactile variables have evolved from a set of visual variables that were considering the two-dimensional printed world, shape in the third dimension has not attracted attention. As the way in which three-dimensional structures interact with fingers is likely to be quite important on tactile maps, we have included an additional variable, *line profile,* which allows us to consider many of the ways in which shape will change in the third dimension.

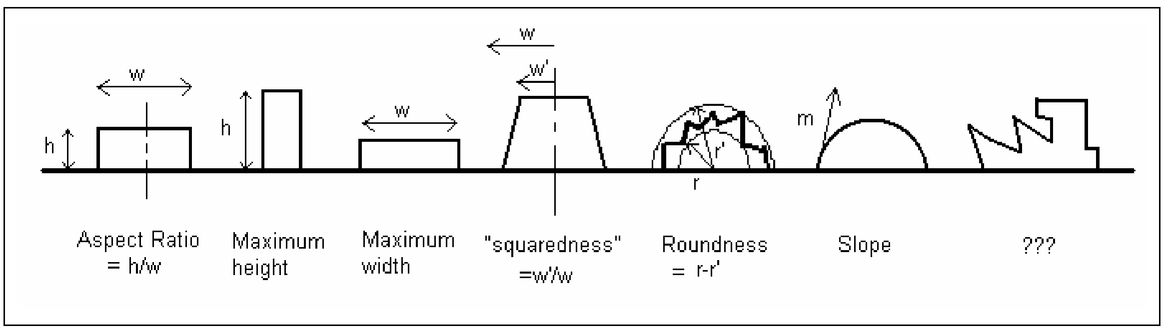

Figure 2: Some of the ways in which line profile may differ.

Texture is an important parameter for identifying perceptual differences [14]. The term covers engineering surface roughness (R_a or R_z), surface macrostructures (wood grain, cloth fibre, etc.) and repeated patterns where texture merges with shape (dots, stripes, etc.) Texture is a complex multi-axis parameter, though it is well understood that roughness is important. *Elevation* is another important variable, somewhat obviously, the height a structure protrudes from a substrate will contribute to its perception. *Location* considers the position and separation of symbols on a map.

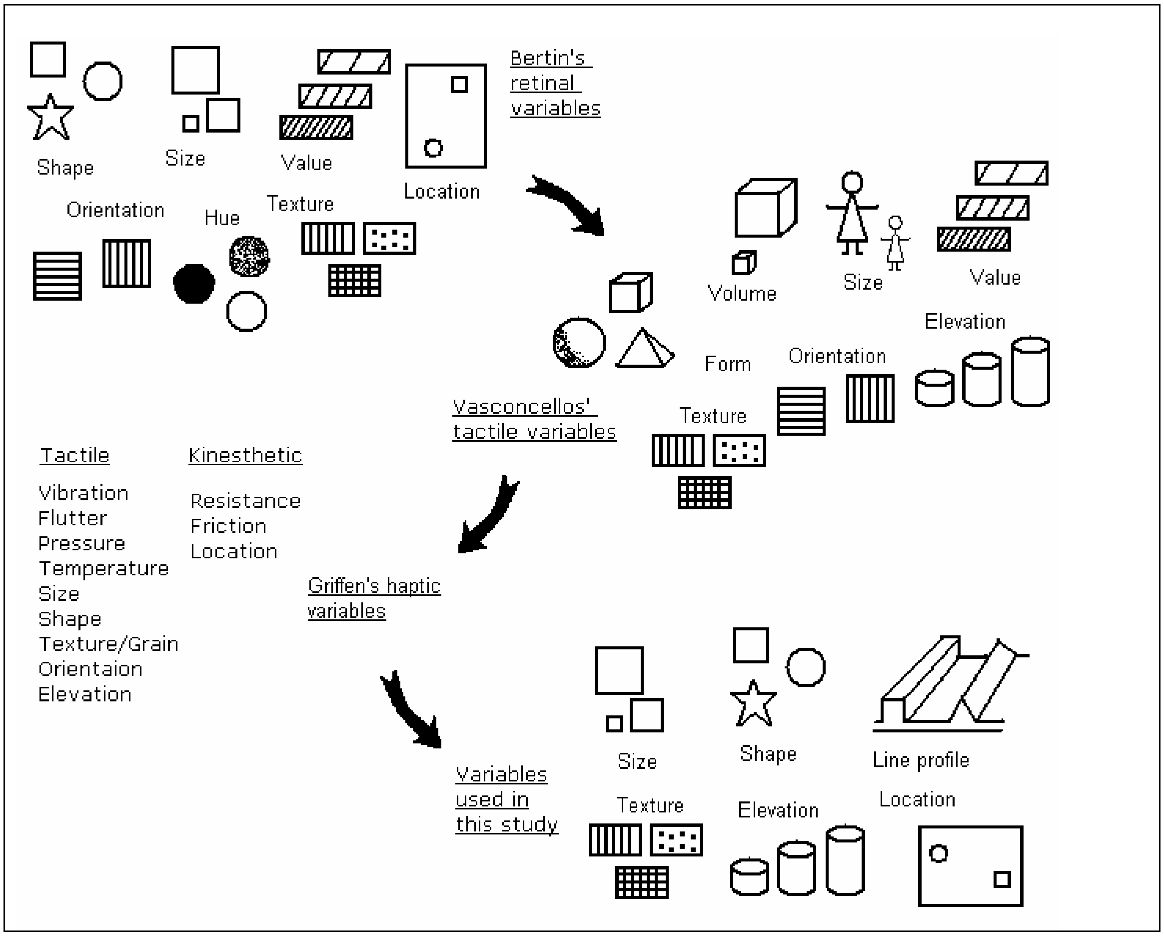

Figure 3: The development of a set of haptic variables from a set of visual variables.

3.2 Structural variables

The term *structural variables,* refers to a more general set of parameters that describe the mechanical and materials engineering properties of a tactile map. For example we could consider the mass of the map and how this impacts on the production infrastructure, e.g. is it light and papery that can be processed using desktop print technology, or are they going to be heavy structures that require, large machine tools. Another structural consideration is the flexibility and how this affects the use, could the map be rolled or folded and bought with a user on a journey, or is it going to be large and static. Of special importance to this project had been the *adhesion* of the ink-jet printed features to the substrate.

4 The identification of a set of inkjet variables

Ink-jet is a process whereby electronic driving signals control the ejection of small (<100 picolitre) ink drops from a nozzle to form an image. Ink-jet has branched out from its origins in the printing industry to be used in a variety of applications, many involving three-dimensional structures. These include printed circuit board marking [15], biomedical models [16], and rapid-prototyping applications [17]. Earlier attempts at producing tactile diagrams using inkjet have been based on wax based inks which were soft, lacking adhesion and definition [18].

A preliminary design overview suggested that of the many formats of inkjet, the research should be based on a piezo-electric drop-on-demand print-head using ultra-violet cured inks. A prototype machine has been built to aid in the research and development, and the identification and classification of the following variables. By passing a substrate under a printhead and repeatedly printing the image the multiple layers of ink will soon become tactile.

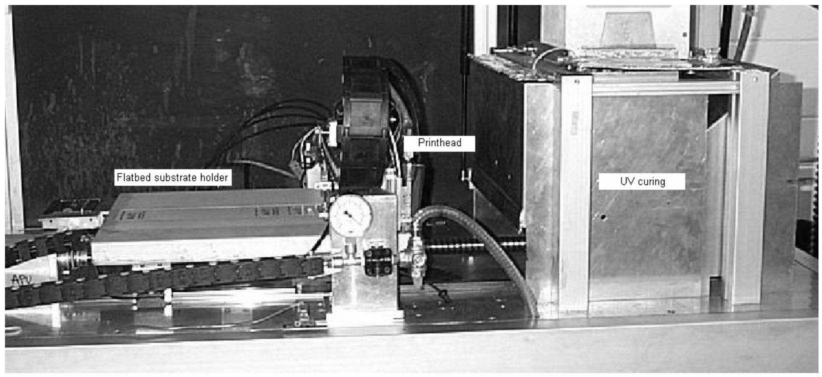

Figure 4: The core parts of the prototype: A substrate held in a substrate holder, which receives the ink as it passes under a printhead and the ink is then hardened on exposure to ultra-violet radiation.

There are a large number of parameters in an inkjet system that could be varied in order to enact changes in the output. Based on the working prototype [19] the ink-jet system has been divided into three primary subsystems; the print-head, the ink and the substrate, and three secondary subsystems; the print algorithm, the UV curing and the motion control.

4.1 The print-head

The printhead used covers a width of 70mm with 500 nozzles, yielding a native *print resolution* of 180 dpi. The perpendicular print resolution can be altered by means of altering the *firing frequency* to suit the substrate table velocity, up to a maximum of 4000Hz for the printhead used, though other makes of printhead can jet at up to 20,000Hz [20]. The ink drops are ejected from the printhead by the motion of the piezo-electric walls of the nozzle chamber. The *voltage* applied to the piezo can be adjusted. The *temperature* can be controlled externally and the *pressure* of the ink supply needs to be regulated also.

Once ejected the drops are generally measured by their *volume, velocity* and *spherocity*.

4.2 Ink

The ink must be suitable for the hydraulic system that channels it from reservoir to the printing chamber. This entails the ink being with suitable ranges of, *viscosity* (pumps are able to force it through correct pipe diameters and so on), *surface tension* (too low and it might seep through fittings) and *composition* (too corrosive and it may degrade materials). Once in the nozzle chamber, the viscosity and density will be the dominant parameters in obtaining the correct acoustic wave to force the ink drop out satisfactorily, though surface tension and chemistry may still contribute. Density is fairly similar for printing inks (~1.1 g/cm^3) and is not treated as a *variable*.

After ejection surface tension will dominate the interaction with the substrate and the build up of ink. From then on the ink's *composition* will determine curing reactions and how the preceding layers of ink behave with subsequent layers. (UV curing inks contain photo-initiators which, once triggered, start off a cross-linking chain reaction which converts the ink to solid.)

4.3 Substrate

How the process will handle the substrate in production will dependant on properties such as mass, density, flexibility, size, which are summarized by the term substrate *mechanics*. Some of these properties will also contribute to user preference of the final product, as will the substrate *type* and *surface roughness*. The ink-substrate interaction will be dominated by the substrate's *surface energy*.

4.4 Print algorithm

The print algorithm will determine the timing and sequence of drop ejection from the printhead, in such away that the relationship with other system parameters is optimised. Firstly a graphical *image design* must be presented to the printhead (in this case a black and white bitmap). The print *resolution* can be manipulated to print differently to the natural resolution of 180dpi. *Stitching*, a process for overcoming nozzle differences and deficiencies, utilises different sets of nozzles on each pass. *Sequencing,* whereby different sections of ink are printed in different passes, can have an affect on feature shape. The height of the printed feature will be a strong function of the number of *print passes* the software requests the machinery to print. By using different bitmaps on different print passe three-dimensional shapes can be generated.

4.5 UV curing

A ultra-violet lamp can be used to excite the photo-initiators in the ink to react and commence solidification. Different lamps can produce different *spectra* and different *intensities*, affecting the curing reaction. The *position* of the light, the geometry of the light beam and the timing of the exposure can also affect the rate, coalescence and geometry of curing.

4.6 Motion control

Motion control. The motion control consists of three axes driven by two servo-motors (X and Y axes) and one stepper motor (Z axis). The primary concerns are the *machine velocity, repeatability* and *accuracy* of the drop placement.

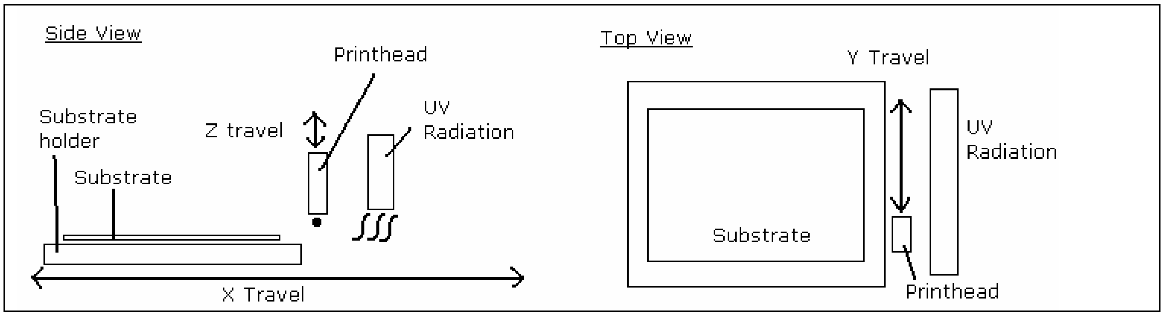

Figure 5: The three axes of motion. As an operator of the machine would see it; the substrate table moves left to right (X axis) passing the substrate under the print-head and the UV radiation. The printhead is able to index, either toward or away from the operator (Y axis), this allows the print-head to cover more of the substrate with more swathes of the image. The distance of the print-head above the substrate is maintained at a safe working distance (Z axis.)

5 Design methodology

The preceding sections have identified six haptic variables and one structural variable, by which to assess the quality of the output.

- Haptic variables: *size, shape, line profile, texture, elevation* and *location*.
- Structural variables: *adhesion*.

Though a large number of design input variables could be investigated, Pond [21] and Clay [15] note 40 and 32 ink-jet parameters respectively, we have reduced the set down to 26 that are readily alterable and are likely to affect the output.

- Printhead variables*: Print resolution, firing frequency, temperature, voltage, pressure, drop volume, drop velocity,* and *drop spherocity*.
- Ink variables: *viscosity, surface tension* and *composition*.
- Substrate variables: *mechanics, type, surface roughness* and *surface energy*.
- Print algorithm variables: *Image design, resolution, stitching, sequencing,* and *print passes*.
- UV curing variables: *Spectra, intensity* and *position*.
- Motion control variables*: machine velocity, repeatability* and *accuracy*.

Given such a large number of variables with potentially complex interactions, a design methodology must be used that is robust and simple enough to aid in system optimisation. The methodology used here is based on the *inkjet triumvirate* [21]. The three primary parts of the inkjet system all have a particular interaction depending on the output variable that is modified (Figure 6).

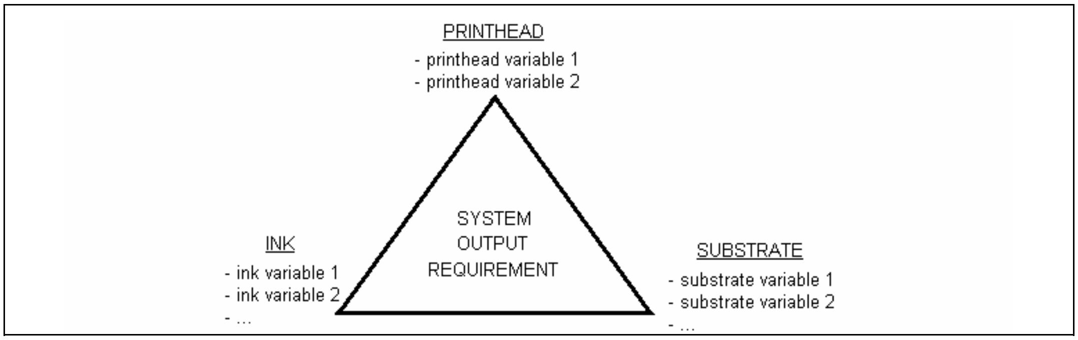

Figure 6: The basic inkjet triumvirate

In this way the triumvirate acts as a visual design aid, giving the designer a better concept of the interactions, and helping to recognise that changing one system input will have a bearing on the others. The triumvirate can be expanded to include the sub-systems. As means of example we expand the triumvirate for line profile.

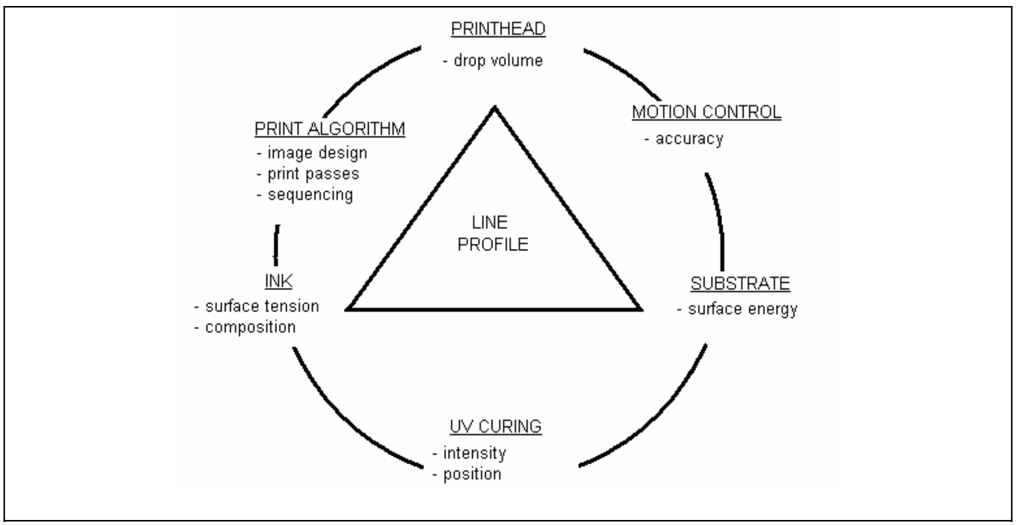

Figure 7: The ink-jet triumvirate expanded to include the secondary subsystems and individualised for line profile.

If we look at Figure 2 we can get an idea for some of the features with contribute to line profile. Starting with the printhead, we qualitatively assess that drop volume is the dominant variable that will affect the generation of line profile features, but drops of certain sizes must wet into a substrate governed by the substrate's surface energy and the ink's surface tension. When these drops fall is governed by the image design and the accuracy will help determine where they land, while the position of the UV curing could help determine the solidification rate. The number of passes will affect the build up of line profiles and it has been observed that image sequencing, ink composition and UV intensity can all change line profile within another subset of interactions.

Given the large numbers of variables the methodology requires a further tool and we introduce a *parameter matrix*, this helps reduce complexity, though can increase management. Table 1 shows the parameter matrix with each of the output variables in the rows. The triumvirate for each was generated [19] and the identified inputs listed across the rows[1]. The matrix also allows the designer to observe each input and gauge the effect they may have on the haptic and structural outputs by going down the columns.

Table 1: Parameter matrix

Inputs / *Outputs*	**1.Printhead**	**1-2. Print algorithm**	**2. Ink**	**2-3.Curing**	**3. Substrate**	**3-1. Motion control**
Size	Drop volume Drop frequency	Image design	Viscosity Surface tension	--	Surface energy	--
Shape	Drop volume Drop frequency	Image design Resolution	Viscosity Surface tension	--	--	--
Line profile	Drop volume	Image design Print passes Sequencing	Surface Tension Composition	Position Intensity	Surface energy	Accuracy
Texture	Drop volume Drop velocity	Image design Print passes	Surface Tension Composition	Position Intensity	Surface roughness Surface energy Type	Accuracy Velocity
Elevation	Drop volume	Print passes Resolution	Surface tension	Position Intensity	Surface energy	--
Location	--	Image Design	Surface tension	--	Surface energy	--
Adhesion	--	Print passes	Composition Surface tension		Surface energy	

Table 1 does not claim to be *correct* in any way, and depending on the level of detail one could argue that every input has an affect on every output. The variables identified have been qualitatively chosen on the basis of experience, pilot experiments and engineering fundamentals. More important is the application of the triumvirate and parameter matrix *design methodology*, further iterations could then go through and test more variable interactions.

6 Discussion

6.1 Size

Size of a tactile symbol is predominately determined by the size of the symbol in the image design. Thus general guidelines on size should be consulted at the design stage; for example, a point symbol should have an edge length greater than 5mm yet lie underneath the finger-pad comfortably [22]. Symbol size may be affected by variation in the amount of spreading at the symbol edges, dependant on the ink surface tension/substrate surface energy interaction. But the size difference due to this is unlikely to be psychophysically noticeable. Changing drop volume or firing frequency may also affect the built up size. Drop volume was identified as having in affect on 5 of the 7 output parameters. In a binary system such as this, drop volume is largely dependant on nozzle diameter, which is fixed and changes to temperature, voltage or pressure offer only modest variation, at the risk of losing reliability [23]. Firing frequency will usually be maximised.

[1] The six further triumvirates are not shown here but follow along the same method as that given for line profile – the elements of the triumvirate are shown in the third row of the matrix.

6.2 Shape

Similar to size, shape is highly dependant on the image design presented to the printhead, and edge effects will be minor. Collaborative studies have suggested that the maximum number of perceivably different (point and line) symbols might only be 12 symbols, and certainly no more than 20. With visual printing, increases in print resolution accompanied by decreases in drop size can help achieve better quality, more photo-like images, this is only partially true with three-dimensional ink-jet printing there is soon saturation as drops fall on top of each other and coalesce. Increasing print resolution means more print drops per pass, enabling a reduction in print passes, and thus dwell times and overall print times. Experiment clearly showed which resolution (dpi) can be increased with minimal loss of drop shape (diameter) and height (Figure 8).

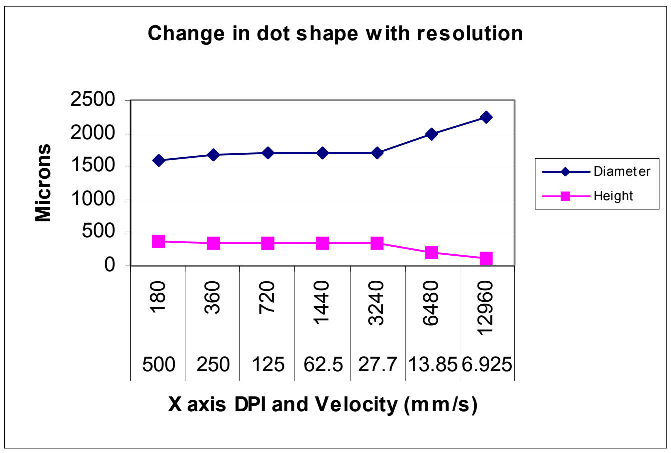

Figure 8: Graph showing affect of print resolution on symbol height and shape.

6.3 Line Profile

Though variation of shape in the XY plane is mostly dependant on the image design, line profile is dependant on a lot more variables, as derived in our example of the triumvirate methodology (Figure 7). This reflects the complexity of three-dimensional ink build-up. Line profile has not attracted a large amount of study; there is not the amount of research and literature that a subject like symbol shape has dedicated to it. Preliminary psychophysical studies of line profile as a means of enhancing the tactile diagram design have been mixed. Ongoing experiments show abrupt, sharp changes in the profile of some arrows and stair symbols can enhance their meaning, while changes in line profile in search tasks did not yield changes in search performance. Line profile (or more generally shape in three dimensions) remains a tantalising and enigmatic haptic variable. Whereas knowledge of the other haptic variables has been used to aid improvements to the machine design, it may well be the machine design will aid in knowledge of line profile.

6.4 Texture

Marco-textures (patterns) where features are in the order of 1mm or greater, are controlled almost entirely by the image design. Micro-textures (<<1mm) operate on different neurological basis, with users more sensitive to variations in the input parameters. The ability of the machine to print accurate repeated structures (due to well controlled drop velocity and machine velocity, accuracy and a good ink-substrate-UV interaction) is important to the production of quality textures. One recent performance task has shown that users have been able to identify symbols at lower heights when those symbols are textured with a dotted pattern. This result has important implications for the product design, the inference is that symbols printed in a textured manner can be lower meaning significant reductions in print passes and thus production time. Experiments have also shown that surface roughness and type of substrate affect tactile performance, with papery, slightly rough substrates being superior to others [24].

6.5 Elevation

Elevation has a great bearing on system production time, as to achieve increased elevations generally means more print passes, given that drop size and drop frequency are typically maximised. Acrylic polymer inks used in this study shrink (~10%) upon curing. Some variation in this shrinkage is bought about by ink composition and UV intensity changes, but this is unlikely to yield great changes in elevation. It is desirable to develop techniques, such as sharp line profiles, or the textured symbols mentioned above, that reduce the elevation requirement.

6.6 Location

The location of symbols relates to their placement on the printed page and is, again, primarily a function of the image design. There is a requirement for minimum separation distances for symbols and enhancing the production technique may allow this to be decreased, enabling more symbols to be placed on a page.

6.7 Adhesion

Adhesion was independent of haptic output variables. It was highly dependant on the ink composition (chemistry), substrate type, and possibly the curing. Adhesion has been mentioned only as an example of how we might use the design methodology to deal with the more engineering traditional structural variable. Hardness and compliance are two related variables that require further study, and a possibly controversial re-assessment of the haptic variables. Variations in the ink composition-UV curing interaction have varied the cured ink from rigid-hard to soft-flexible structures; this is not neatly accounted for in the derived set of haptic variables.

6.8 Output Overview

The process has thus far yielded positive results. The ink-jet process is allows considerable variation of the haptic variables and thus significant psychophysical data can be generated. A real example of this involved using samples in elevation studies, which showed that tactile structures, which are often recommended to be over 0.5mm, still give very good user performance at 0.1mm. The tactile graphics produced using this process have also been utilised as way-finding maps in public spaces, and can meet existing requirements for educational, mobility and information maps.

7 Conclusion

The ability to produce tactile diagrams using ink-jet for people with visual impairments has been demonstrated. Central to the understanding of tactile diagrams and the systems by which they are created is an understanding of the processes of human touch. The touch process has been broadly quantified by a set of haptic variables. A set of engineering input variables for a prototype ink-jet printer was also identified. A design methodology was proposed based on a parameter matrix and the three main ink-jet subsystems; printhead, ink and substrate. This enabled a substantial number of input and output design variables to be considered. Knowledge of the haptic perception of variables, such as texture and raised-line elevation, enabled the design of efficiency gains in the production process, such as time and material usage reductions.

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