

An advanced tactile inkjet printer: Enhancing tactile map design and production methods

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Following the development and testing of a unique and novel printing methodology, this paper proposes a conceptual supplement to Pugh's 'Total Design methodology' (see figure 14). [1] Sequenced Drop Placement (SDP) is a printing method devised to achieve control over the cross-sectional profile of printed symbols in tactile maps. Achieving such control was thought to be imperative for additional discriminability between tactile symbols. Results from our initial experiment did not fully meet our hypothesis and introduced further depth to future experiments in this specific subject. As producing tactile maps using inkjet and the ability to control line profiles of individual symbols is new, forecasting complicated haptic outcomes with very little to no previous records, is not straight forward! As the paper will go on to show, failing to test and verify the effectiveness and drawbacks of line profiles at the stage of Conceptual Design would have resulted in an incorrect assessment of machine requirements and functions hierarchical order. If significant advancement in technology was made during the conceptual design stage, effecting one of more functions, there is a clear need for testing with end-users rather than relying on the design team intuitive decision making. This proposition must be taken into consideration along side issues such as Time To Market (TTM) schedules and costs.

1. Introduction

Significant improvements in accuracy, repeatability, speed and cost of inkjet printheads over the last decade have led to a rapid growth in the number of areas in which the technology can be applied. In particular, using this technology to create tactile maps and diagrams has proved desirable due to its advantages over parallel technologies. A tactile map is a set of symbols either attached to a medium or pressed into a substrate, so that they are raised above the surface in low relief. Most tactile map productions use thermoform (figure 1), swell paper and Mixed Media technology. Although the use of these technologies is widespread, an assessment of their production process and quality [2] reveals lack of:

- A. Durability for repeated use.
- B. Robustness for outdoor conditions
- C. Efficiency for high production levels at reduced production time and cost.

Indeed, from a systems design point view, the need for two or more manual processes, which cannot take place concurrently, present the most significant drawback.

These issues have led to the Tactile Inkjet Mapping Project (TIMP), which aims to change and enhance tactile map design and production processes using an innovative technology of inkjet to overcome some of the drawbacks of parallel production methods as well as reducing production cost and increasing availability to end-users. The design of such technologically advanced, novel and multi-faceted system requires placement of end users at its centre. This is achieved by our close collaboration with the Royal National Institute for the Blind (RNIB), The Royal National College for the Blind (RNC), Ordnance Survey (OS) and the National Centre for Tactile Diagrams (NCTD).

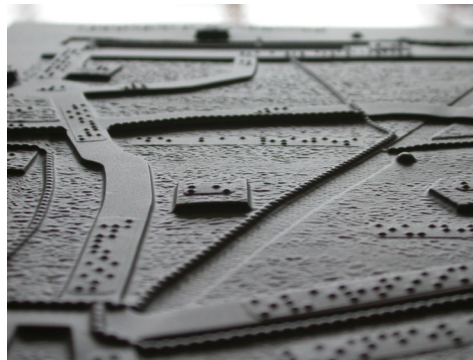


Figure 1: Thermoform tactile map, Courtesy of Bibliotheek Le Sage Tem Broek

1.1 Background and Motivation

Two different attempts to produce tactile maps using inkjet technology were made in the past. The Phaser 300x and the Non-Impact printer and plotter both used a thermal printhead and a wax based solvent injected onto a medium. [3] Due to low adhesion, robustness and lack of detail, both projects were said to have significant limitations.

Extensive research on tactile maps has indicated that no consistent guidelines exist for their design. However, one common factor shared by most was the need to vary different tactile map symbols by more than one defining characteristic, preferably two or three to increase their discriminability to a maximum. Examples of tactile symbol characteristic include: size, value, form (shape), orientation and elevation. In order to increase tactile discriminability it was thought that the introduction of *profiles* (change in shape over elevation) will help. A unique and novel printing technique was devised to achieve this and it is referred to as ‘Sequenced Drop Placement’ (SDP). Using this method both cross-sectional and longitudinal profiles can be created on both lines and area symbols.

Introducing the ability to produce different line-profiles using ink-jet technology, has also paved the way to the suggested introduction of *slope* as a new tactile variable to Vasconcellos existing 7 tactile variables. [4] Although it could be argued that line-profiles can be applied to tactile symbols using Thermoform, no evidence of such have been observed, most certainly not as a design tool. The tactile variable, *profile*, is not to be confused with line structure.

2. APU – Tactile Inkjet Printer

The development printer at the centre of the TIMP research programme contains six main sub-systems:

- Xaar XJ500 piezoelectric binary printhead;
- Ink plumbing system;
- A curing system;
- Mechanical actuation and Software driver;
- Printing algorithm controlling image;
- Substrates.

The division to sub-systems is made with reference to Pond's (Pond, 2000) [5] ink, printhead and substrates triumvirate.

The printer is able to print on all common medium sizes up to A3 (297mm * 420mm). Some of the types of substrates used include: PVC, polystyrene, acetate, foam boards, although adhesion of the ink may vary depending on the type of substrate.

In principal, the printing process is achieved through printing multiple layers of ink, one on top of the other to form an elevated feature. In between each print session (also known as a *pass*) the substrate is exposed to ultraviolet light which causes a partial solidification of the ink, rendering the substrate and ink for the next print session.

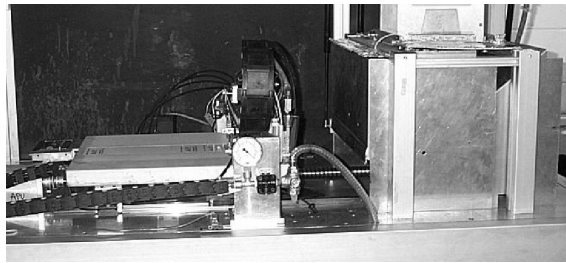


Figure 2: APU-Tactile Inkjet Mapping Printer

3. Methodology

3.1 Background

Printing a line using the 'conventional' process described in section 2 results in a line which has a domed shape cross-sectional profile. This is due to surface energy interplay between drops on cured ink and drops on substrate during initial passes. [6] The challenge in controlling the cross-sectional profile of a line to achieve any other profile such as a square or a triangle is therefore large, and additional strategies have been used to achieve this. One example is the use of a supporting gel, which is printed wherever ink is not. By doing so the gel supports the 'wall' (the edge of the printed feature) of the printed area to form a straight edge. Another example is the use of a cutter that shaves off a small part of the top of each printed layer, preparing the surface for the next layer of ink. Both methods, often used in conjunction, aim to achieve a flattened top and sides in order to control the line profile. The use of such additional processes complicates the design, is wasteful of resources, increases printing time and requires maintenance which should be reduced to minimum. Sequenced

Drop Placement (SDP) uses an algorithm embedded in the software layer to control both the position of individual drops on the substrate and the sequence in which they are ejected and cured. The algorithm analyses the outline of the structure being printed and according to the required cross-sectional profile, strategically places drops within the boundary of the printed object. By doing so, newly ejected drops are confined to the required position by being ‘locked’ between previously ejected cured drops. Using this method the location and the order of drop ejection can be altered to achieve numerous profiles. Thus far we have established three SDP models, resulting in a controlled build up of lines, circles and symbols of a waved nature. The image stored as a monochrome file taking the lowest possible storage space. Similarly, the processing power required in order to analyse the image is insignificant compared with mechanical printing time. As the algorithm can produce up to 4 images from the original one, it increases the overall printing time. However, this methodology has no implications on the machine design, its cost or maintenance procedures.

3.2 Implementation

In order to produce a straight edge profile (see figure 8b) an algorithm analyses the image and each object (line/symbol) within it, to determine their cross-sectional orientation in respect to the printhead. Each shape identified is then divided into one pixel-wide line (‘single lines’ hereafter). Depending on the shape, the division can occur in horizontal, vertical or both directions. Once the file has been processed the ‘single lines’ are saved in separate files. (See figures 3, 4 and 5 respectively)



Figure 3: Full Image



Figure 4: 1st part



Figure 5: 2nd part

The printing process starts by printing the first image containing the one set of ‘single lines’, creating the form of a ‘zebra crossing’. This is immediately followed by exposure to the ultraviolet lamp, which partially solidifies the printed drops, forcing the next layer of ink (2nd image) to flow into the interstices between, created by the drops printed previously. The process is repeated until the required elevation is reached.

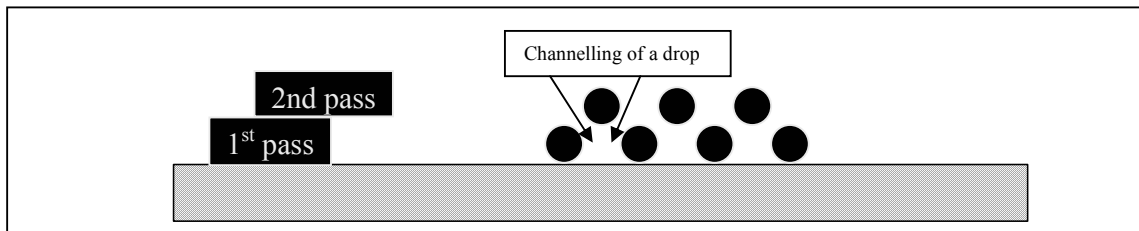


Figure 6: Drop placing, channelling drops – cross section view.

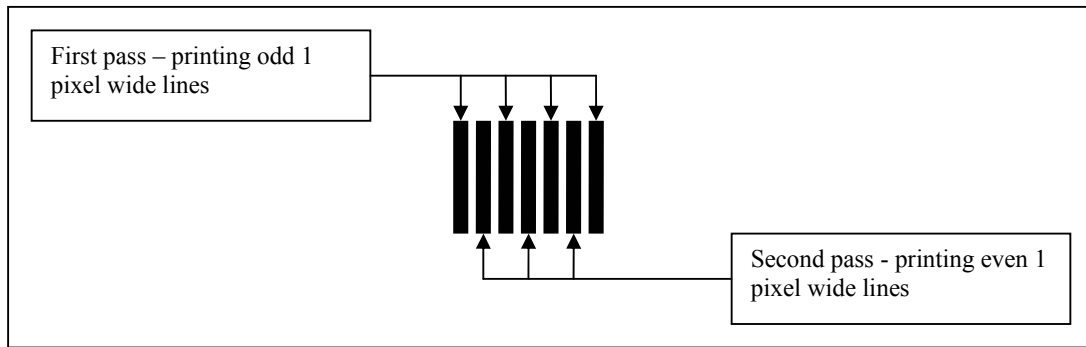


Figure 7: Plan view showing the print sequence for a 7 pixel wide line image composed of 1-pixel wide line members (separation is for clarity). Each line member would print as a sequence of longitudinally coalesced drops.

Figures 8a and 8b shows microscopic images of the cross-sectional profile of lines 13 pixels wide, printed using Xaar XJ500. Across the x axis drops are printed at 180 dpi, where each drop is 80picolitre and 50 μ in diameter. The number of drops per inch along the longitudinal axis of the lines (z axis) varies from 360 to 720 DPI. (These profiles are achieved using a single additive process.)

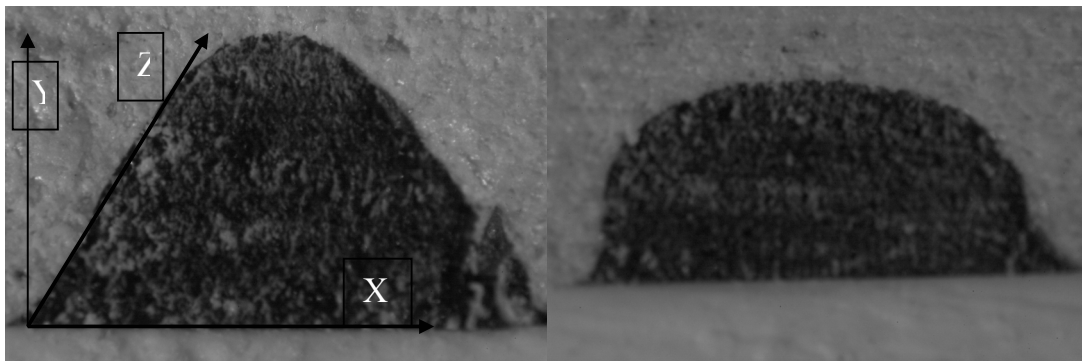


Figure 8a/8b: Images of two line profiles achieved after 160 passes. Left image shows line printed normally with height of 1300 μ , right image shows line printed using Sequenced Drop Placement with height of 860 μ .

Although the full effects of printing using SDP have not been fully investigated, we have observed a reduction in volume between normally printed lines and those printed using SDP. The comparison was made on two lines covering equal areas, ejected with the same amount of ink onto the same type of substrate. Environment and machine settings were identical. The differences in recorded volumes ranged between 18 and 23 percent. [7] Due to the fact that a normally printed line is exposed half the number of times a line printed using SDP method, the reduction in volume can be attributed to the increase in chemical cross-links occurring due to greater number of exposures to ultraviolet light. This however, is an abnormally high level of shrinkage compared with other polymer inks.

4. Adhesion and Psychophysical Evaluation

Although there is no set standard by which tactile map quality can be assessed, end-users preference to the feel of the substrate and the raised material is incredibly important. Contrast in texture between the printed material and the substrate as well as the rigidity and adhesion between the two materials has also been rated as very important. The following three experiments were carried out to record differences between the two printing methods:

- I. The adhesion of lines to different substrates;
- II. Users' performance in identifying and discriminating between available objects printed using the two methods;
- III. Users' preference to a specific printing method.

4.2 Ink to substrate adhesion

To conduct this experiment four lines were printed on each of the eight substrates tested at four different elevations. The experiment was conducted on two line widths, 5 and 15 pixels lines printed at 180 DPI. The types of substrates used in the experiment are: APET250 (a form of thick acetate), Brailleon (used in Thermoform), Polyester, Aluminium, High Impact Polyester (HIP) shiny and matt, PVC shiny and matt. Following the printing process a bending experiment was conducted to record the adhesion between the ink and the substrate. This was carried out by applying pressure along the longitudinal axis (figure 9) of the printed lines. Changes in adhesion between the lines and the substrate are recorded at regular intervals. Any occurring change in adhesion recorded the distance between the vice lips.

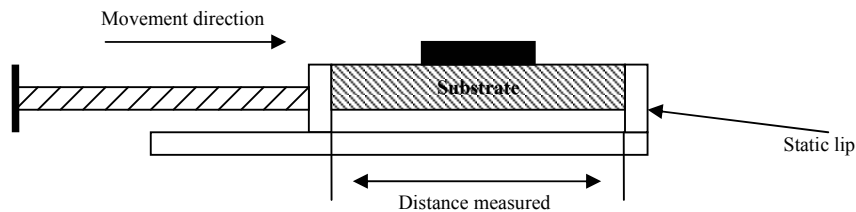


Figure 9: Diagram demonstrating delamination experiment using a vice.

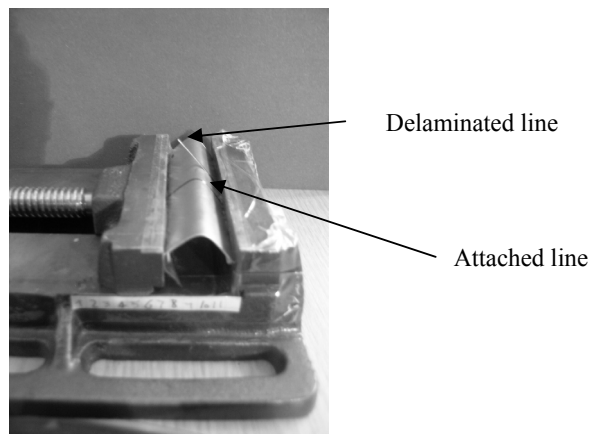


Figure 10: A photo of the vice used to deformed sample substrate which has two print lines, one of which has delaminated.

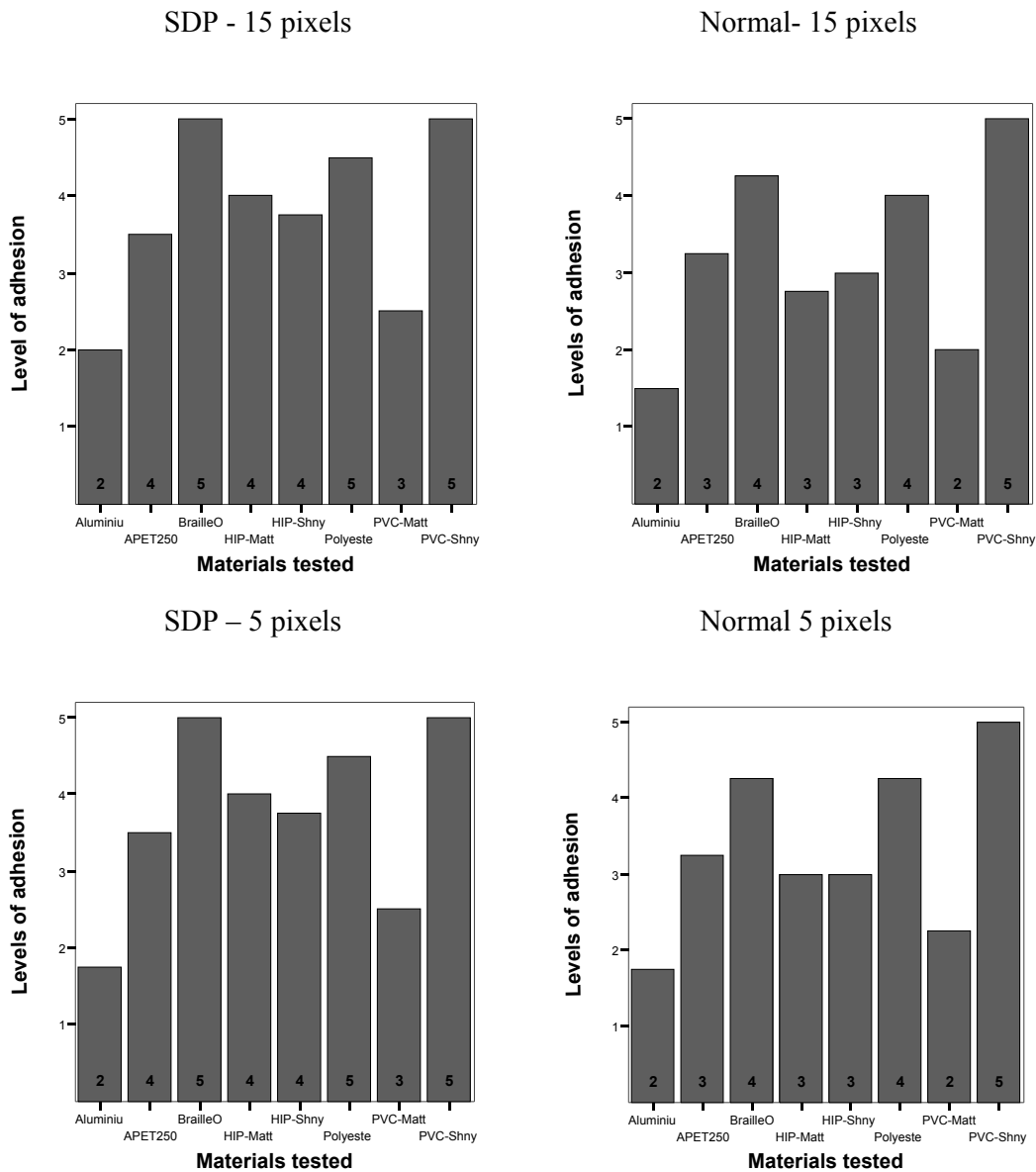


Figure 11: Results of the delaminatiton experiment, comparing normal and SDP substrate/ink adhesion.

The results of the delaminatiton experiments are recorded in Figure 11. The graphs represent average delaminatiton point of specific line width on a given substrate. The average combines the delaminatiton point across four elevations tested. (100, 200, 300 and 400 microns) The higher the value of bars, the greater deformation occurred prior to delaminatiton, yielding greater substrate-ink adhesion.

Analysis of the graphs indicates higher adhesion levels with lines (15 pixels wide) printed using SDP. This is with the exclusion of Aluminium and the shiny PVC.

4.2 Users' Performance

An initial experiment to test the effectiveness of tactile line profiles and textures against normally printed shapes was devised. A matrix of circles (6 * 6) was printed using 3 different profiles at 6 different elevations. The three profiles used were *domed* (referred to as smooth), *triangle* (referred to as sharp) and *rough* (a series of Braille dots forming the symbol's shape). The matrix contained full circles and incomplete circles. Seven incomplete circles were randomly located in the matrix and acted as target symbols. Participants were asked to scan the matrix from top left to bottom right, searching for incomplete circles. Scanning time was measured. Seven sighted and 11 visually impaired participants took part in the experiment.

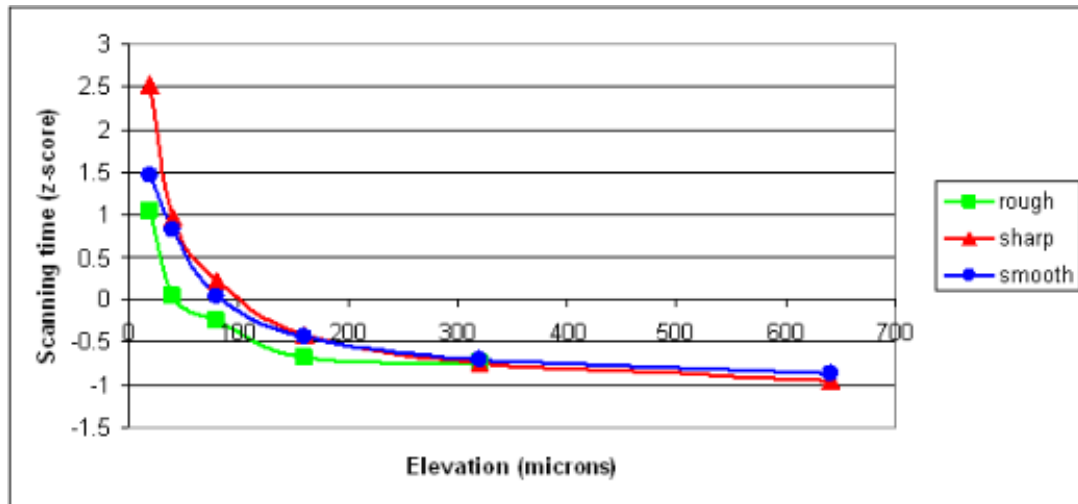


Figure 12: Graph showing users' scanning time with three different profiles – with kind permission from S. Jehoel's

The three profiles used were *miniscoid* (smooth), *triangle* (sharp) and *rough* (textured line). Figure 12 shows the scanning times expressed as a difference from sighted and visually impaired control groups in units of standard deviation (Z score) against elevation for all target symbols. Although these results are not conclusive, do not cover all possible profiles and involve only 18 participants. The graph clearly shows that scanning time of objects did not improve significantly much after 160 microns. It also indicates that the effectiveness of the triangle profile is limited up to roughly 80 microns. This is due to the limited effectiveness of the profile at low elevations. It must be stressed that this experiment took into account only one symbol at a time, simply looking at scanning times. It did not however take into consideration symbols in combination as well as combination of different types of symbols (i.e. point, area and line symbols) [8]

4.3 User Preference of line profiles

After completing the above search tasks, participants were asked to rate all displays based on how much they liked them.

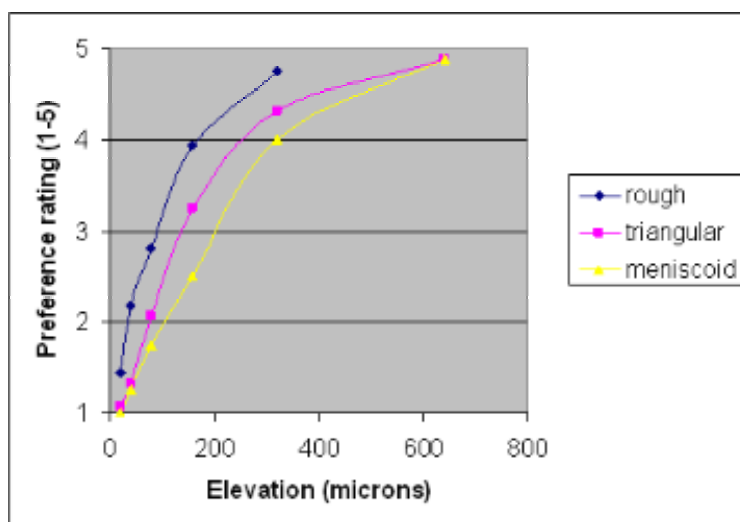


Figure 13: User preference to the different profiles split by elevation - with kind permission from S Jehoel's

Figure 13 shows clear users' preference to the *triangle* profile over the normal domed shape profile despite poorer performance. Contradiction between users' preference and performance only strengthen the need for end-users testing. [8]

5. The Effects on Design Methodology

From early beginnings TIMP research programme identified the successful implementation of line profile as a highly desirable outcome amongst other highly rated features (i.e. printing speed, miniaturisation, high adhesion and relative low cost). As these features are very much dependant on each other they had to be prioritise in clusters, satisfying 'Concept Design' Pugh's third major phase in 'Total Design' [9]

As the issue of haptic effectiveness of line profiles, in different scenarios, is not straight forward, the lines were tested with end-users. As this paper has shown results from these experiments did not match our initial hypothesis and yielded surprising results. These results have made a direct impact on the weight these features carried in the importance hierarchy list. Further more, the line profile experiment has revealed further depth to future experiments in this area, forcing a set recursive experiments combining different profiles, combination of symbols and levels of conveyed information. The achievement of controlling the cross-section of line profiles was marked as significant progress in the production of tactile maps using inkjet technology. This advance was made long after users' requirements has been collated and from our experience had the design team made their judgement base purely on intuition it would have almost certainly lead to an incorrect prioritisation of functions in the final product.

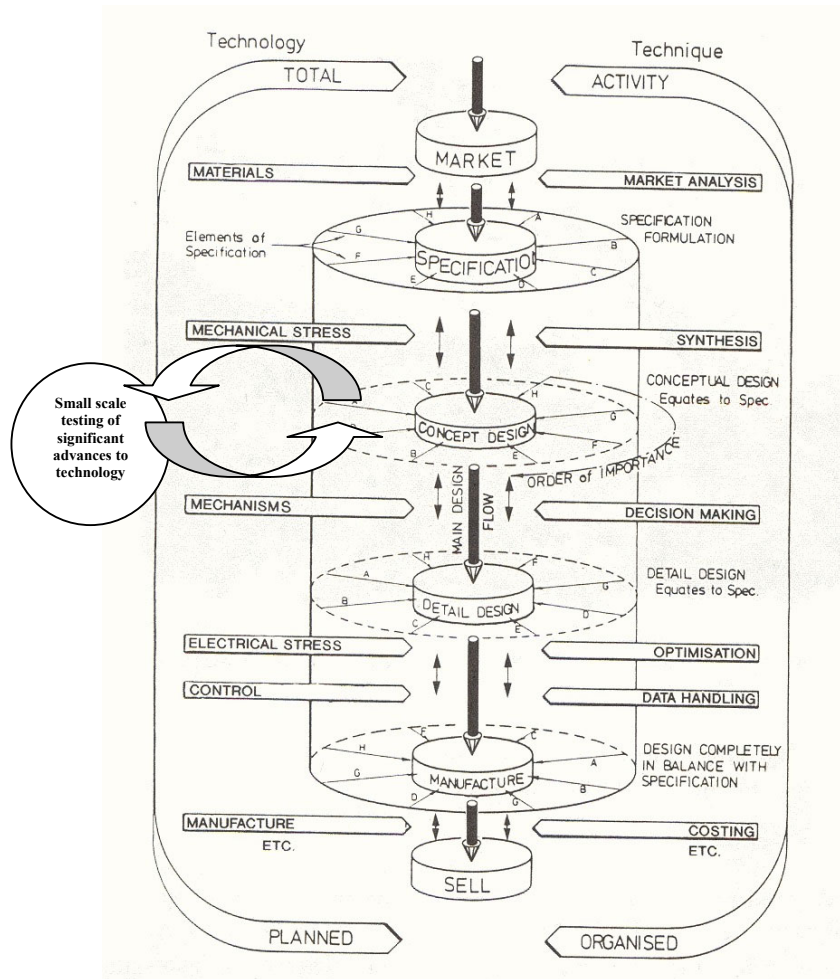


Figure 14: Pugh's 'Total Design' activity model – with additional proposed supplement.

Having analysed and worked to Pugh's Total Design methodology, in our experience an optional route (see figure 12) to end users, for the purpose of testing/re-testing major advances in the relevant technology be drawn. This route is strictly possible if the progress to be tested has occurred after *PDS* was generated and before the stage of *Concept Design* has culminated. This is subject to an assessment of Time to Market schedules versus the consequences of not reflecting users' performance and preference accurately in the final product.

When designing a product where members of the design team cannot count themselves (individually) as part of the end user group, intuitive decision making becomes harder and more risky. In the case of the TIMP, all researchers are sighted, designing a tactile inkjet printer to produce tactile maps for visually impaired. Often we can use our judgement to make informed decisions based on past knowledge, parallel technologies and using our own tactile abilities. However, when making these decisions on complex haptic issues spanning over several disciplines without testing/consulting end users may result, from our experience, in an inaccurate design, negatively affecting on the chances of success of the product in the marketplace.

6. Conclusion

The creation and control over cross-sectional and longitudinal profiles of tactile objects has been achieved using inkjet technology using a novel process defined in this work as Sequence Drop Placement, which also enhances line adhesion. After the initial collation of requirements, flow of information between researchers/designers in a multi-disciplinary project must be efficient and bi-directional. This is clearly demonstrated in Pugh's Total Design methodology. In our experience, when a major advance in technology occurred during the 'conceptual design' stage, perceived end users' performance and preference information may be no longer correct on a particular issue, spelling potential and an unnecessary mismatch between the final product and target users' requirement. Additional route to end users for testing (on small scale) anecdotal issues will help ensure accurate functionality of the product, increasing its chances in the marketplace.

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