ON THE CHOICE OF TACTILE CODE

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ABSTRACT

Tactile codes and devices are widely used in virtual reality, robotics, telemanipulation, by blind and sighted people. Based upon the Braille code, we provide a rigorous analysis of tactile spatial codes, and propose a code that is improved in the information theoretical sense. Based upon the criterion of a minimum average code word weight, we derive a code that provides improved reliability and longer lifetime of tactile devices. Such an approach can be also employed for robot hands, and tactile feedback in virtual reality and dextrous telemanipulation.

1. INTRODUCTION

For more than half a century, the cutaneous senses have been studied in an attempt to use them as communication channels. Some success has been achieved in utilizing these channels and an upper bound has been placed on the information channel capacity for vibrotactile stimulation of human fingertips [1]. Some applications of tactile communication include a fingertip tactile vocoder for the deaf [2], hand masters for teleoperation of multifingered robot hands, control of graphics displays, interfaces for computer games [3], and a tactile display for tele–existence robots or virtual reality [4]. Most of these have been designed using ideas first enunciated by Louis Braille. Nowadays, there is a variety of existing tactile displays, which represent the information from the computer's screen to the reader in form of a Braille representation of text. The Braille characters are obtained by an one–to–one mapping of alpha–numeric text characters on the screen.

At present, with all the facilities of multimedia, and virtual reality, tactile communication still appears to be under–explored, even when considering the blind. New technologies, such as telemedicine, robotics, and virtual reality demand feedback, which is provided via data–gloves, or some other means of tactile Braille–like feedback. In addition, there is a need for robots with soft fingertips that are able to feel texture of surfaces [5].

This paper investigates tactile Braille–like communication strictly, both from a cognitive and engineering point of view, and offers solutions which could lead to more reliable tactile devices as well as a tactile code better adjusted to the needs of new technologies.

2. SKIN AS A RECIPIENT OF INFORMATION

As a communication channel, the tactile sense is often considered inferior to sight and hearing. However, the tactile system possesses some of the attributes as both of the "primary" senses. With over 10000 parallel channels (receptors) capable of responding to stimulus interruptions as short as 10 ms, the tactile system may be capable of processing a great deal of information provided information was properly presented. The rate at which humans process tactile information is (2–56 bits/s) at the perceptual level. This shows its importance when compared with information processing in understanding spoken speech (40 bits/sec), and reading (30 bits/sec). The approximate maximal rates of information flow at the receptor level for eye, skin, and ear are respectively 10^7, 10^6, and 10^5 bits/sec. The fingertip amplitude sensation threshold corresponds to a skin indentation of about $10\mu m$ [6, 7]. Both peripheral (tactile receptors) and central mechanisms (cortex) determine tactual sensation thresholds.

3. COGNITIVE PROCESSING OF TACTILE SIGNALS

From a cognitive point of view, the navigation through a complex text while reading is eased by the use of a specific mental image of the underlying text structure (meaningful reading), where the cortex plays a role of a specific signal processor. The human cortex embodies functions of a Perceptual processor, Cognitive Processor, and Motor processor with appropriate average response times respectively of $\tau_P = 100ms$, $\tau_C = 70ms$, and $\tau_M = 70ms$ [8]. This

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means that an average reading speed for Braille becomes

$$\bar{v}_{braille} = \frac{1}{\tau_P + \tau_C + \tau_M} \approx 4-5 \; \frac{symbols}{second} \qquad (1)$$

It should be mentioned explicitly that the spatial resolution on the fingertip depends on whether the task is one of recognition or localization of a set of tactile stimuli.

4. MATHEMATICAL DESCRIPTION OF BRAILLE

Let A denote the English alphabet

$$A = \{A_1, A_2, \cdots, A_{27}\} \qquad (2)$$

with 26 letters and a space between words in a sentence. The Braille code is a spatial and relief one where every element of the alphabet A (2) is represented by a combination of raised dots on six possible fixed spatial positions which make a Braille cell represented by a matrix

$$A_k = \begin{bmatrix} a_{11}^k & a_{12}^k \\ a_{21}^k & a_{22}^k \\ a_{31}^k & a_{32}^k \end{bmatrix}, \quad k = 1, 2, \dots, 27 \qquad (3)$$

In the plane, the distance between tactile dots is 0.1 inch. For every dot with coordinates (i, j), $(i = 1, 2, 3;\ j = 1, 2)$, an event of a raised dot $(a_{ij} = 1)$ or a non-raised dot $(a_{ij} = 0)$ can be defined. In Figure 1, several Braille letters are shown, with black dots denoting raised, or active dots in some spatial position, and a plane circle denoting an inactive position within a Braille cell. With the Braille cell

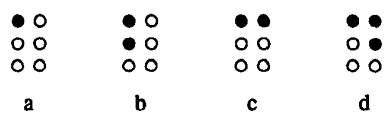

Figure 1: Several Braille letters

given in (3), it is possible to represent $2^6 = 64$ different symbols. For Braille code words we can introduce a code word weight $w(A_k)$, as the number of its non-zero components (i.e. the number of raised dots). It is now straightforward to determine the number of code words C_i^6 with weight i, $0 \le i \le 6$

$$C_i^6 = \binom{6}{i} = \frac{6!}{(6-i)!\, i!} \qquad (4)$$

which are binomial coefficients $C_6^0 = 1$, $C_6^1 = 6$, $C_6^2 = 15$, $C_6^3 = 20$, $C_6^4 = 15$. The standard Braille code for the English alphabet is shown in Figure 3.

Denoting a distance between two code words A_m and A_n, by $d(A_m, A_n)$, a greater metric $d(A_m, A_n)$ leads to reduction of the probability of wrong detection

$$p_e(A_n) = p(A_m | A_n), \; m \neq n \qquad (5)$$

The distance is determined by the number of the component pairs (a_{ij}^m, a_{ij}^n), $i = 1, 2, 3;\ j = 1, 2$ for which $a_{ij}^m \neq a_{ij}^n$. Unlike the common approach in the algebra of binary codes, we expect that it is necessary to take into account also the spatial placement of tactile "ones" and "zeros" within the matrix (3) in order to take into account the perceptual features of the tactile sensors in the fingertip, and therefore improve the mechanism of tactile reading.

As an example to verify the need for such an approach, an illustration of the three Braille code words with the weight one is shown in Figure 2. From Figure 2, the number of non-

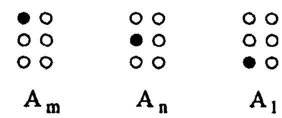

Figure 2: Three codewords of weight one

coincident elements for all the possible pairs of given code words is 2. However, it is to be expected that in a perceptive sense, the following inequality holds

$$d(A_m, A_n) < d(A_m, A_l) \qquad (6)$$

5. INFORMATION THEORETICAL APPROACH

To evaluate characteristics of the Braille alphabet, we rewrite (3) into a one dimensional form

$$A_k = (a_1^k, a_2^k, \dots, a_6^k), \quad A_k \in A \qquad (7)$$

In the technical sense, concerning reliability, energy consumption and other relevant features, it is important to take into account relative frequencies of raised tactile pins while reading the tactile display. For a tactile pin, the quantitative measure can be the firing probability $p(a_i = 1)$, $i = 1, 2, \dots, 6$. Knowing the a priori probabilities of the elements A_k of alphabet A (2), the firing probability of the i th tactile pin, $p(a_i) = 1$ becomes

$$p(a_i = 1) = \sum_{k=1}^{27} p(A_k) p(a_i^k = 1 | A_k) \qquad (8)$$

This means that the probability of firing for every tactile pin i, $i = 1, \dots, 6$ can be found by summing the underlying a priori probabilities for those elements of alphabet A which contain "one" at the $i-th$ position in its matrix representation (3). The firing probabilities for the tactile pins are given in the Table 1. The probability of the zero–weight interword space p_{SP} in standard letter frequency tables is $p_{SP} = 0.1753$. The reliability of a tactile display can be estimated by the average number of active tactile pins, e.g. the average number of tactile pins used to represent a letter within the alphabet. This leads to

$$E\{w(A_k)\} = \overline{w(A_k)} = \bar{w} = \sum_{k=1}^{27} w(A_k)p(A_k) \quad (9)$$

For the known probabilities $p(A_k),\ A_k \in A$, the result is

$$\bar{w} = 2.4093 \quad (10)$$

The probability distribution in Table 1 shows that the information content for pins on the tactile display is highest for the first tactile pin, and lowest on the sixth tactile pin. If every tactile pin position is considered as a binary information source without memory, then each position has the entropy

$$\begin{aligned} H_b(i) &= p(a_i = 1)ld\frac{1}{p(a_i = 1)} \\ &+[1 - p(a_i = 1)]ld\frac{1}{1 - p(a_i = 1)} \end{aligned} \quad (11)$$

where $ldx = log_2 x$. The appropriate numerical values are shown in Table 1. A rough insight into the numerical values in Table 1 shows that the tactile pins are highly unevenly used, as e.g. the first tactile pin a_{11} with $p(a_1 = 1) = 0.6457$ is roughly six times more used then the sixth tactile pin a_{32} with $p(a_6 = 1) = 0.1209$. From the point of view of an optimal coder, the entropies for all the pin positions should be the same, or as close as possible regarding system constraints. Looking at the entropies in the fourth row of Table 1, that is not the case. Having in mind that entropy is a logarithm measure, even the slight differences in pin entropies means significantly different underlying firing probabilities. Our further analysis will be directed towards an improvement of a spatial code based upon the commonly adopted six-dot tactile cell.

6. A PROPOSITION FOR NEW TACTILE CODE

In order to define our goal analytically, a criterion function is introduced

$$F = \sum_k w(A_k)p(A_k) \quad (12)$$

According to the criterion function (12), the aim is to find a code that preserves

$$F_{min}|_{variation(code)} \quad (13)$$

In order to optimize the code in the maximum entropy sense, which turns out to be equal to looking for the minimal energy consumption code, or equivalently high reliability, and having in mind that sum (12) is a sum of non-negative elements, such a constrained minimization task can be assessed by minimizing each element of (12) separately. This means that, apart from the code word with zero weight (interword space), it is necessary to use 6 code words with weight 1, 15 code words with weight 2, and 6 code words with weight 3. Code words with lower weight should be joined to the more probable elements of the alphabet A. Thus, the six more frequent letters should be joined to code words with weight 1, then the following 15 most frequent letters should be joined with code words with weight 2, and eventually the least frequent 5 letters should be joined with code words with weight 3. According to the probabilities of letters in written English, the optimal code weight after such an optimization becomes

$$\bar{w}_{opt} = 1.2118 \quad (14)$$

which is 49.7% smaller than for standard Braille. After some heuristics, in order to make the tactile pin frequencies as close as possible, with restriction related to the energy consumption premises, such a code which satisfies well both the information–theoretical and energy consumption criteria is given in Figure 4. The average code word weight for such a code is

$$\bar{w} = 1.2316 \quad (15)$$

That, in turn, means that the average lifetime of all the available tactile equipment could be twice as long as at present, with a better statistical code.

Comparing the appropriate rows in Table 1, it becomes apparent that after undertaking the proposed optimization, the activity of tactile pin is significantly balanced. The first position is not so extensively used any more, and the sixth position becomes more active and wealthier in the information theory sense. Appropriate entropies, given in the last row of Table 1 have the same first significant number, which shows the quality of the newly proposed code. The

Pin i	1	2	3	4	5	6
Braille						
$p(a_i = 1)$	0.65	0.36	0.44	0.36	0.39	0.12
$H_b(i)$	0.94	0.94	0.99	0.94	0.97	0.53
New Code						
$p(a_i = 1)$	0.23	0.21	0.22	0.23	0.20	0.19
$H_b(i)$	0.77	0.75	0.76	0.78	0.72	0.71

Table 1: Probabilities and entropies for tactile pins

new code shown in Table 1 may be optimal in a technical sense but as suggested by Figure 2, it is not optimized in the perceptual sense. However, such optimization is certainly possible, but, of course, there are many possible optimality criteria. Such criteria are nonlinear functions of the Hamming and Euclidean distance between codewords. In [9], we have made an attempt to incorporate such a perceptual metric.

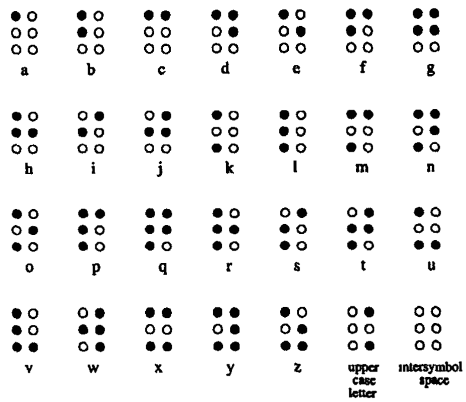

Figure 3: Standard Braille code for English

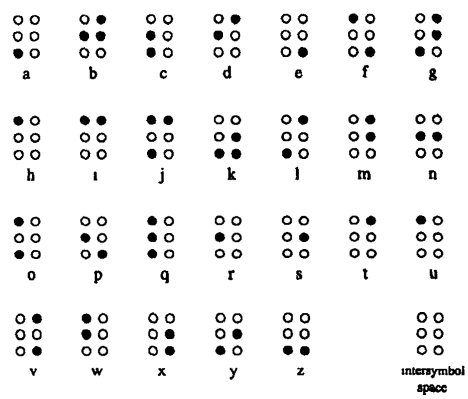

Figure 4: Optimized code under energy consumption constraint

7. SUMMARY

An insight into a Braille–based tactile code is provided. Such a code has been optimized with respect to the minimum average code weight. This also means improved reliability of actual tactile devices. We have halved the mean code length, and hence halved the energy consumption. Such a code is useful for data-glove based devices, robotic hands with soft fingertips, virtual reality with tactile feedback, and Braille–like reading for people with lower skin sensitivity. This paper has focused on a technical aspect of the problem. However, perceptual aspects are important as well, but subjective. The ideas presented in this paper have been incorporated into a commercial system, PC–BRAILLER [10].

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