XII. COGNITIVE INFORMATION PROCESSING*

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A. CONTROL OF A READING MACHINE BY THE BLIND

During the past year members of our group have constructed a character-recognition type of reading machine. This system consists of a two-dimensional document handler that is capable of positioning an 8-1/2 × 11 sheet of paper in front of a flying-spot opaque scanner. The character-recognition algorithm that is used was implemented by combination of a computer program and a special-purpose digital system. The output mechanism now used consists of spelled speech which has been processed so that the maximum output rate is 120 wpm. As the character-recognition process is alternated with the spelled-speech output, the average speed of the machine is approximately 80 wpm.

In order for such a machine to be useful, provision must be made for the effective control of its operation by a blind person. Experiments have been conducted to compare different modes of specifying the reading speed and the location on the page of the text to be read.[1] A computer simulation was made of a character-recognition type of reading machine with a spelled-speech output. Since this same computer is a portion of the reading machine, the major simulation was to store a page of English text instead of utilizing the character-recognition routines. Blind subjects were allowed two means of controlling the reading process. First, they could initiate a character sequence by pointing to a page location with a probe. This was simulated by using a light pen and an oscilloscope display. The simulation program allowed the experimenter to vary the resolution of the probe by effectively partitioning the page into an

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arbitrary number of rectangles. The smallest possible rectangle enclosed a single character. When a probe was positioned within a rectangle, the rectangle's area was increased by a factor of four to permit the subject to be less precise in the task of maintaining the probe position and to require a rather definite motion to move to a new rectangle. Immediately after the acquisition of a rectangle, the location of the next letter to be spelled was computed by searching back through the stored text until a marker was encountered. The experimenter had previously specified this marker to be a space, a carriage return, a punctuation mark, or other special character. The speech output was then under the speed control until (a) another marker was encountered in the forward direction, (b) a specified number of characters had been spelled out, or (c) the probe was removed from the rectangle. This speed control determined both the speed and the direction of progress through the text. In the middle position nothing happened. As the knob was turned clockwise the output speed increased to a maximum rate of 45 wpm. As the knob was turned counterclockwise from the middle position the speed was the same for the clockwise, but in the reverse direction. For this backward traverse the letter sounds were suppressed. Instead a beep was emitted for every word boundary encountered.

Four different control modes were investigated with three different types of text. A literary review was used as a practice page. Comprehension tests in the form of a paragraph followed by a series of multiple-choice questions and the Tinker Speed of Reading Test[2] were also used.

The simplest mode that gave the blind subject the most control over the exact character to be spelled was one in which the rectangles were set to their minimum size and the speed control knob was disabled. This required the subject to actively move the probe to each new character that he desired to read. A horizontal guide which could be positioned vertically was provided to facilitate movement of the probe on a line. The four subjects who tried this mode found it very tedious and fatiguing. It was extremely difficult for them to control the reading speed. They tended, at first, to go too fast for the machine, thereby causing the output buffer to overflow, and they were not able to maintain a correlation between the characters that were being spelled and the location of the probe. They experienced a distinct bewilderment when they pointed to a blank area, for example, end of line, in between paragraphs, and indented lines. They had to concentrate on the exact position of successive letters and could not effectively coalesce letter strings into words. They had even greater difficulty understanding the meaning of word sequences. Average reading rates when they were constrained to understand the text were approximately 2 wpm. The major reasons for this were that words longer than 5 or 6 letters were repeatedly retraced, and the subjects had difficulty in maintaining smooth enough hand and arm motions to emit a steady stream of letters and retain correlation of the probe location to the letter being spelled.

In the second mode the probe location effectively specified words and the subject was allowed to use the speed control knob. If the subject continued to point to any letter of the same word, then that word continued to be spelled out. If the probe was moved to a letter in another word, the next letter spoken was the first letter of the new word. The beginning of a word was found by scanning backwards until a space was found, and letters were spelled until another space was encountered. Word-at-a-time operation was about the same as letter-at-a-time, with words still being retraced repeatedly.

A third mode was tried in which the rectangle height was limited to one line and the width was equal to the page width. A beep was sounded when the probe was moved to a new line. When the last letter on a line had been spelled, the word "next" was spoken. The subjects immediately turned the speed control up to the maximum rate, and within one-half hour were reading at the rate of approximately 15 wpm. Subsequent practice did not improve the speed significantly.

A sentence-by-sentence mode was tried in which the mechanisms of operation were identical to those of the word-at-a-time mode. The subjects' performance was indistinguishable from that of the line-at-a-time mode.

The maximum reading rate the subjects could possibly attain with this system was 45 wpm. The major reasons for their not achieving this maximum rate were the following.

1. Long words had to be retraced frequently. This was especially severe for the first two modes.

2. The excess spaces at the end of a line introduced uncertainty about when the line was completed.

3. Considerable time was required to move from one line to another. This was especially difficult when the new line was the beginning of a paragraph, or some other indentation.

The reading speeds attained with the line-at-a-time mode are rather low. They are, however, only 25 per cent less than those attained by sighted readers in an earlier experiment[3] in which text was presented visually in a manner similar to the line-at-a-time mode. In this earlier experiment the subjects could control the speed but did not have the capability of retracing a word. This operation consumes a lot of time, and it seems reasonable to attribute a major part of the 25 per cent speed reduction to this factor. These low rates are encouraging, however, because of the extremely short training time required to achieve them.

In all reading tasks, the reader should take an active role; but these exploratory tests indicate that when spelled speech is an output the blind person should not be required to specify each letter as it is read. Rather, the selection of a line, a speed control, and the ability to interrupt and retrace, are sufficient involvement.

D. E. Troxel, E. Rosenfeld

References

1. E. Rosenfeld, "A Line Selector for a Reading Machine," S. B. Thesis, M. I. T., June 1967.
2. Copyright 1947, 1955 by Miles A. Tinker, Published by the University of Minnesota Press, Minneapolis, Minn.
3. D. E. Troxel, "Comparison of Tactile and Visual Reading Rates," Quarterly Progress Report No. 67, Research Laboratory of Electronics, M. I. T., October 15, 1962, pp. 267-272.

B. DIGITAL LINEAR TIME-VARIANT FILTERING

1. Introduction

Suppose we want to calculate, on a digital computer, $g(t)$, the output signal of a linear time-variant filter $h(t, \tau)$, which is due to an input signal $f(t)$:

$$g(t) = \int_{-\infty}^{\infty} d\beta\, h(\beta, t-\beta)\, f(\beta). \tag{1}$$

The first problem that we face is how often we should sample f, h, and g. The purpose of this brief report is to try to provide some insight into this problem by graphical means.

2. Mathematical Formulation

In the case of linear time-invariant filtering, the sampling rate can be determined by Fourier analysis. In the time-variant case, Fourier analysis can also be used in an indirect way.[1]

Let the Fourier transforms of $f(t)$ and $h(t,\tau)$ be $F(u)$, and $H(u, v)$, respectively. Let

$$f_1(x, y) = \delta(x+y)\, f(y), \tag{2}$$

where δ is the Dirac delta function. The Fourier transform of $f_1(x, y)$ is

$$F_1(u, v) = F(-u+v). \tag{3}$$

Let

$$G_1(u, v) = F_1(u, v)\, H(u, v) \tag{4}$$

and

$$G(v) = \int_{-\infty}^{\infty} G_1(u, v)\, du. \tag{5}$$

Then the inverse Fourier transform of $G(v)$ is $g(t)$.

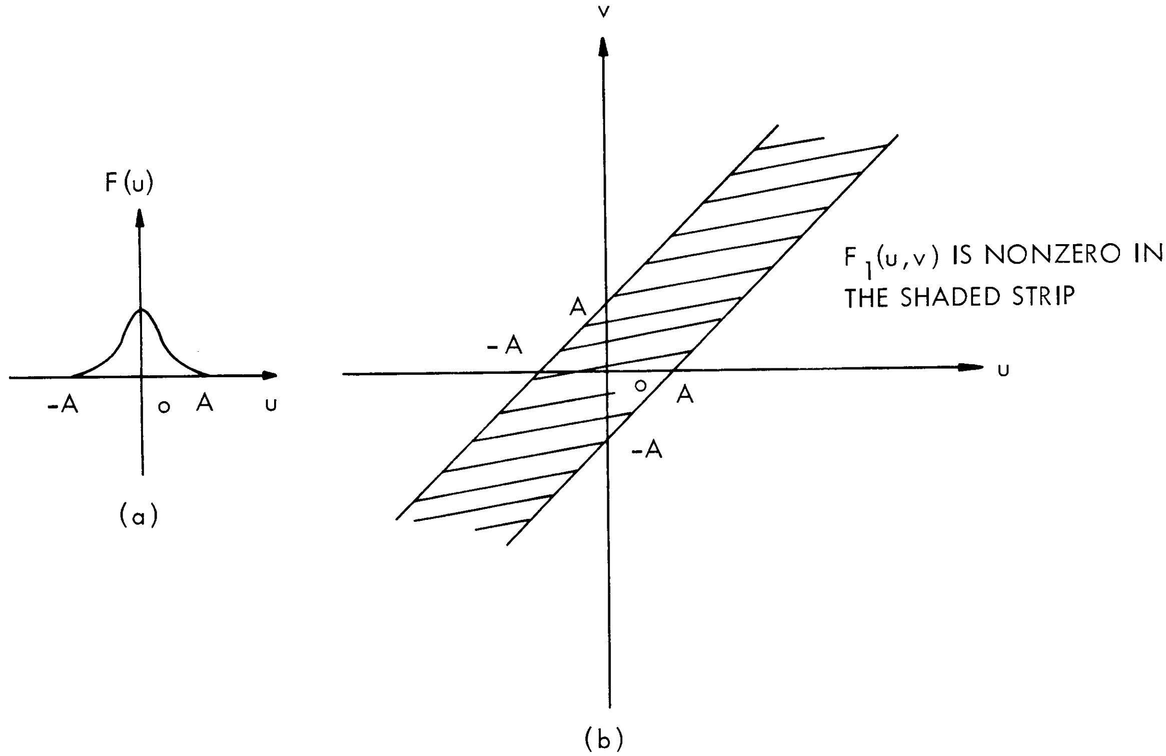

Fig. XII-1. F(u) and $F_1(u, v)$.

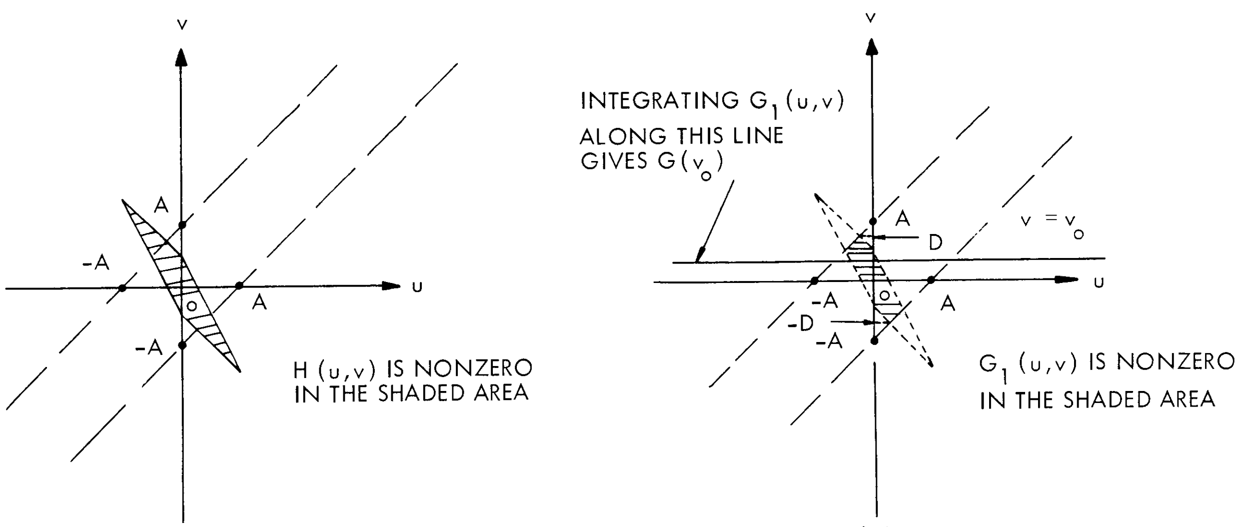

Fig. XII-2. H(u, v) and $G_1(u, v)$.

3. Graphical Interpretation

Assume that f(t) is bandlimited and has a bandwidth 2A, that is, $F(u) = 0$ for $|u| > A$, as shown in Fig. XII-1a. Then $F_1(u, v) = F(-u+v)$ is zero outside an infinite strip bounded by the straight lines $-u + v = \pm A$, as shown in Fig. XII-1b. Now, if H(u, v) is zero outside the shaded region of Fig. XII-2a, then $G_1(u, v) = F_1(u, v)\, H(u, v)$ is zero outside the intersection of this region and the infinite strip, as shown in Fig. XII-2b. Integrating $G_1(u, v)$ along the straight line $v = v_o$ gives $G(v_o)$ whose inverse Fourier transform is g(t). Therefore the bandwidth of g(t) is equal to the vertical extent of the shaded region of Fig. XII-2b namely 2D.

4. Determination of Sampling Rate

Now, let us sample f(t) and $h(t, \tau)$ with sampling periods T, and $T \times T$, respectively, to get $f^*(t)$ and $h^*(t, \tau)$. The Fourier transforms of these latter functions, $F^*(u)$, and $H^*(u, v)$, consist of periodically repeated versions of F(u) and H(u, v), respectively. Let

$$F_1^*(u, v) = F^*(-u+v) \tag{6}$$

$$G_1^*(u, v) = F_1^*(u, v)\, H^*(u, v) \tag{7}$$

and

$$G^*(v) = \int_{-\infty}^{\infty} G_1^*(u, v)\, du. \tag{8}$$

Equation 7 is illustrated graphically in Fig. XII-3.

A sketch such as Fig. XII-3 is a convenient way of determining the sampling rate when we perform Eq. 1 on a digital computer. If we want the calculated values $g^*(t)$ to be equal to the sampled values of g(t), and g(t) to be recoverable from $g^*(t)$, then T should be chosen small enough so that $G_1^*(u, v)$ consists of nonoverlapping periodically repeated versions of $G_1(u, v)$. Let the bandwidth of f(t) be 2A, and let the size of the smallest square which encloses the nonzero region of H(u, v) in the u-v plane be $2B \times 2B$. Then one might think that it is sufficient to choose $T = \frac{\pi}{C}$, where $C = \mathrm{Max}(A, B)$. Not so. For example, if we let $\frac{2\pi}{T} = 2B$ in Fig. XII-3, then $G_1^*(u, v)$ will contain extraneous components in addition to periodically repeated versions of $G_1(u, v)$.

If we do not require that $g^*(t)$ be equal to the sampled values of g(t), but only require that g(t) be recoverable from $g^*(t)$, then T should be chosen small enough so that $G^*(v) = G(v)$, wherever G(v) is nonzero. This can be achieved by requiring that in the strip bounded by $v = \pm D$ in the u-v plane, $G_1^*(u, v)$ consists of only nonoverlapping periodically repeated versions of $G_1(u, v)$. For the example in Fig. XII-3, it is sufficient to

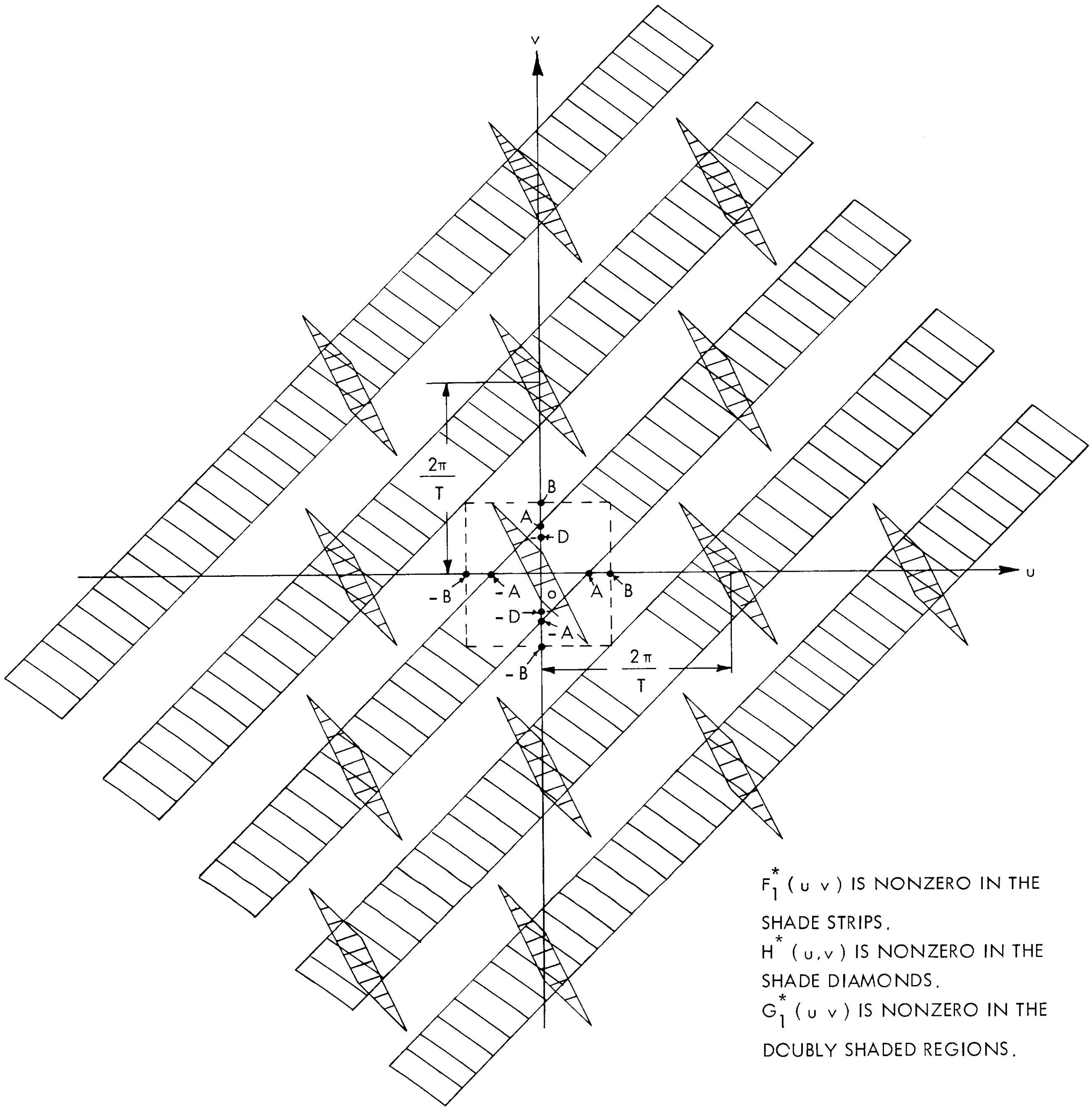

Fig. XII-3. Transforms of sampled functions.

choose $\frac{2\pi}{T} = A + B$.

To require that $g^*(t)$ be equal to the sampled values of $g(t)$ obviously demands a higher sampling rate than to require only that $g(t)$ be recoverable from $g^*(t)$. The former is probably more convenient, however, since in the latter case, complicated interpolation (lowpass filtering) may be needed to obtain sampled values of $g(t)$ from $g^*(t)$. In the former approach, the sampling rate can be reduced, if we modify $h(t, \tau)$ by setting the value of $H(u, v)$ to zero for all (u, v) not lying in the infinite strip determined by the bandwidth of $f(t)$.

T. S. Huang

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C. SURFACE RECONSTRUCTION FROM CONTOUR SAMPLES

The problem is the following: Given the constant elevation contours of some surface, how should one reconstruct the surface. If the surfaces of interest may be characterized statistically and, in particular, as a Gaussian random field, then the problem can be approached.

Before going into the statistical approach there is another approach that is actually reasonable. The contours are treated as boundary conditions on which the value of the surface is known. From these boundary conditions, the surface is reconstructed by solving Laplace's equation. This reconstruction technique is not really as arbitrary as it may seem, at first. One of the most useful properties of a contour map is that the height of the surface at any point is bounded above and below by the heights of the neighboring contours unless the neighboring contours have the same height. A solution to Laplace's equation achieves its maximum and its minimum on the boundary, making the solution consistent with the property of a contour map.

A workable computer simulation of this idea is not yet successful. One of the biggest difficulties is in representing the contours on a grid. A fine grid requires too much computation, while a coarse grid may not be capable of representing all of the contours. One possibility is to use a fine grid where the contours are dense and a coarse grid where the contours are sparse.

Suppose now that the surface is a sample function, $x(t_1, t_2)$, from a Gaussian random field. The reconstruction problem may now be considered a statistical estimation problem. If a minimum mean-square-error criterion is chosen, the estimate will be the mean of the density of $x(t_1, t_2)$ conditioned upon the contour information. It is difficult to take into account all of the information in a contour map. In particular, at any point (s_1, s_2) of the region where contour information is known, there is an inequality: $\alpha(s_1, s_2) \leq x(s_1, s_2) \leq \beta(s_1, s_2)$. This information is difficult to include in the condition for the density so the condition will be simplified to apply only to the point (t_1, t_2) at which the estimate is desired.

Let the heights at which contours have been extracted be $-\infty = x_o < x_1 < \dots < x_n = \infty$. Suppose that curves implicitly defined by $x(t_1, t_2) = x_i$, $i = 1, \dots, n-1$ may be parameterized into the form $(t_{1i}(u), t_{2i}(u))$ $0 \leq u \leq U_i$. If (s_1, s_2) is a point in the region of interest, let x_j, x_k, $(k = j-1,\ j$ or $j+1)$ be the heights of the contours "neighboring" the point (s_1, s_2). The boundary functions $\alpha(s_1, s_2)$ and $\beta(s_1, s_2)$ mentioned before may now be defined.

$$\alpha(s_1, s_2) = \begin{cases} \min(x_j, x_k), & \text{if } x_j \neq x_k \\ x_j, & \text{if } x(s_1, s_2) > x_j = x_k \\ x_{j-1}, & \text{if } x(s_1, s_2) < x_j = x_k \end{cases}$$

$$\beta(s_1, s_2) = \begin{cases} \max(x_j, x_k), & \text{if } x_j \neq x_k \\ x_{j+1}, & \text{if } x(s_1, s_2) > x_j = x_k \\ x_j, & \text{if } x(s_1, s_2) < x_j = x_k \end{cases}$$

These two functions are constant except for discontinuities on the contours.

The information contained in a contour map may now be written as the intersection of two events: $\{x(t_{1i}(u), t_{2i}(u)) = x_i,\ \text{for } 0 \leq u \leq U_i,\ i = 1, \dots, n-1\}$ and $\{\alpha(s_1, s_2) \leq x(s_1, s_2) \leq \beta(s_1, s_2)\}$. The two events in brackets are the conditions imposed on the random process $x(t_1, t_2)$. The first event contains the information that would have been obtained had the process been sampled on the contours; call this event S. The second event is information derived from the fact that all of the points are known at which the surface achieves any of the heights $x_1, \dots x_{n-1}$.

If one knew the conditional density $p_{x(t_1, t_2)|S}(X|S)$ and only the simplified version of the second event, $C = \{\alpha(t_1, t_2) \leq x(t_1, t_2) \leq \beta(t_1, t_2)\}$, were used, then the mean of $p_{x(t_1, t_2)|S, C}$ would serve as the estimate of the field $x(t_1, t_2)$. The Gaussian assumption for the random field enables one to find, conceptually, the density $p_{x(t_1, t_2)|S}$. The density for the estimate would then be

$$p_{x(t_1,t_2)|S,C} = \begin{cases} \dfrac{p_{x(t_1,t_2)|S}(X|S)}{\displaystyle\int_{\alpha(t_1,t_2)}^{\beta(t_1,t_2)} p_{x(t_1,t_2)|S}(U|S)\, dU}, & \alpha \leq X \leq \beta \\ 0, & X < \alpha,\ X > \beta \end{cases}$$

To find $p_{x(t_1,t_2)|S}$, one uses the fact that it must be a Gaussian density. The mean value function $m(t_1, t_2)$ must be a linear functional of values of $x(t_1, t_2)$ along the contours and the variance $\sigma^2(t_1, t_2)$ may be found by knowing this linear functional. To simplify the notation, let $\vec{t} = (t_1, t_2)$ and let $\vec{t}_i(u) = (t_{1i}(u),\ t_{2i}(u))$. The mean value function may be written as

$$m(\vec{t}) = \sum_{i=1}^{n-1} \int_0^{U_i} h(\vec{t}, \vec{t}_i(u))\, x(\vec{t}_i(u))\, du$$

$$= \sum_{i=1}^{n-1} x_i \int_0^{U_i} h(\vec{t}, \vec{t}_i(u))\, du.$$

Here the contours have been assumed to be parameterized by arc length u. The function $h(\vec{t}, \vec{t}_i(u))$ must satisfy an integral equation:

$$R(\vec{t}, \vec{t}_j(v)) = \sum_{i=1}^{n-1} \int_0^{U_i} h(\vec{t}, \vec{t}_i(u))\, R(\vec{t}_i(u), \vec{t}_j(v))\, du,$$

where $R(\vec{t}, \vec{s})$ is the autocorrelation function of the random field. The variance may be written as

$$\sigma^2(\vec{t}) = R(\vec{t}, \vec{t}) - \sum_{i=1}^{n-1} \int_0^{U_i} h(\vec{t}, \vec{t}_i(u))\, R(\vec{t}, \vec{t}_i(u))\, du.$$

The conditional density, $p_{x(\vec{t})|S,C}$, may now be written as

$$p_{x(\vec{t})|S,C}(X|S,C) = \frac{\exp\left(-\frac{1}{2}\left[\dfrac{X - m(\vec{t})}{\sigma(\vec{t})}\right]^2\right)}{\displaystyle\int_{\alpha(\vec{t})}^{\beta(\vec{t})} \exp\left(-\frac{1}{2}\left[\dfrac{X - m(\vec{t})}{\sigma(\vec{t})}\right]^2\right) dX}, \quad \alpha(\vec{t}) \leq X \leq \beta(\vec{t})$$

and the estimate is the mean value of the density above:

$$x(\vec{t}) = m(\vec{t}) + \sigma(\vec{t}) \frac{\exp\left(-\frac{1}{2}A^2\right) - \exp\left(-\frac{1}{2}B^2\right)}{\int_A^B \exp\left(-\frac{1}{2}z^2\right) dz},$$

where $A = \dfrac{\alpha(\vec{t}) - m(\vec{t})}{\sigma(\vec{t})}$ and $B = \dfrac{\beta(\vec{t}) - m(\vec{t})}{\sigma(\vec{t})}$. Because the density is restricted to $[\alpha(\vec{t}), \beta(\vec{t})]$, the estimate must satisfy: $\alpha(\vec{t}) \leq x(\vec{t}) \leq \beta(\vec{t})$.

To simulate such an equation on the computer or to synthesize a device to realize such an estimate would require the integral equation to be solved for each such contour map. For this reason, a simpler approach is used by scanning the random field $x(t_1, t_2)$ to obtain a random process $x(t)$. The contours now become level-crossing times, and the integral equation becomes a set of linear simultaneous equations. The equation for the estimate remains essentially the same as before.

Assume that $x(t)$ is to be estimated on a finite time interval, the level-crossing times are t_j, $j = 1, \ldots, m$ and $x(t_j) = l_j$, where l_j is one of the x_i levels. Now

$$m(t) = \sum_{j=1}^{m} a_j(t)\, l_j$$

and the $a_j(t)$ satisfy a set of linear simultaneous equations:

$$\sum_{j=1}^{m} a_j(t)\, \rho(t_j, t_k) = \rho(t, t_k), \qquad k = 1, \ldots, m$$

and $\rho(t, s) = E[x(t)\, x(s)]$. The variance is

$$\sigma^2(t) = \rho(t, t) - \sum_{j=1}^{m} a_j(t)\, \rho(t, t_j).$$

The estimate is the same as before, except now t replaces $\vec{t}$.

The simplest version of this equation has been simulated; the mean value, $m(t)$, and variance, $\sigma(t)$, are permitted to depend only upon the two neighboring crossing times. The results of this simulation will be presented later.

G. M. Robbins

D. COMPUTER-CONTROLLED TACTILE DISPLAY

The display system described here is designed primarily as a research tool for tactile experiments to determine the feasibility of word-at-a-time presentation of Braille to the Blind. The system consists of the hardware and software necessary to simultaneously present up to 8 Braille-like cells to a person's 8 fingers, one cell per finger.

1. System Hardware

A block diagram of the display system is shown in Fig. XII-4. The system utilizes

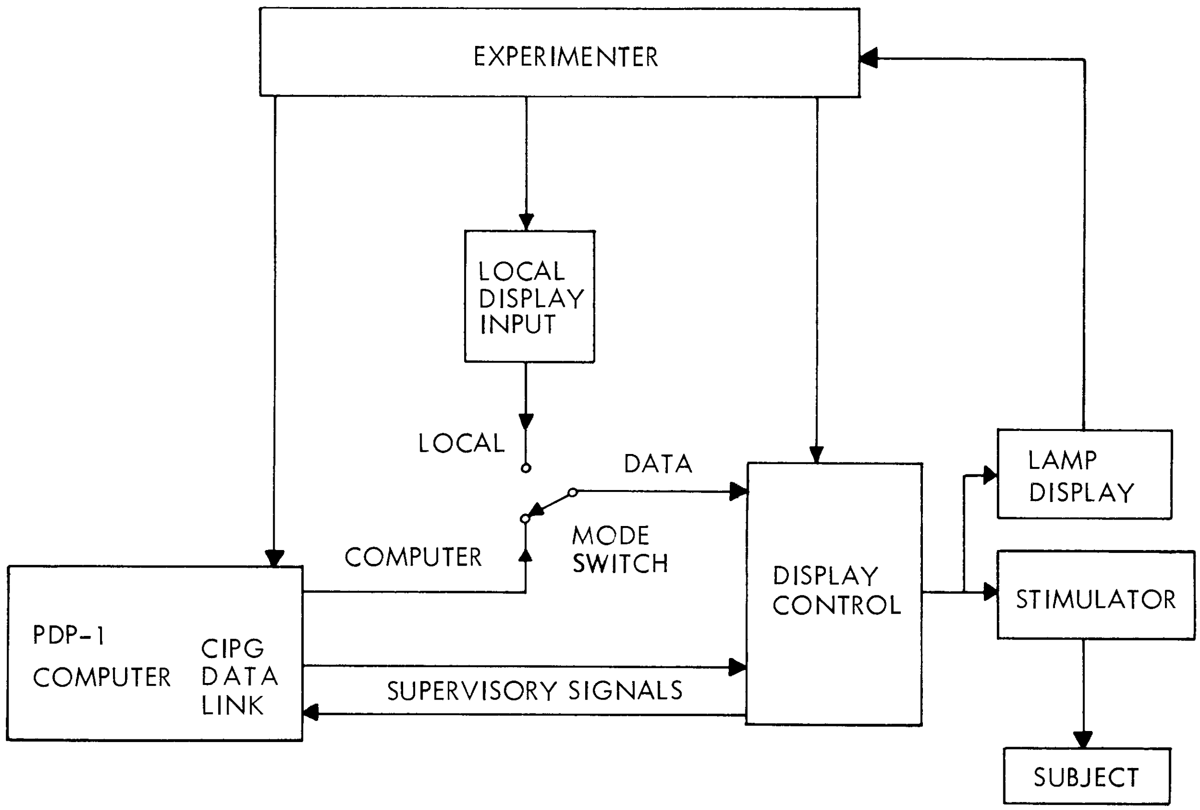

Fig. XII-4. Diagram of the Display system.

the PDP-1 computer through the Cognitive Information Processing Group's data link. The local display input is a set of 18 switches that permit operation of the display independently from the computer. The mode switch selects whether data are to be received from the computer or from the local display input. The display control operates on these data to set up the corresponding patterns on the stimulator. In "computer" mode the display control also receives and sends back supervisory signals to the computer. The stimulator presents the information to the subject. The lamp display receives the same information as the stimulator, and serves as a monitor for the experimenter.

The display is capable of presenting up to 48 bits simultaneously to the subject. The information is received 12 bits at a time from either the local display input or the computer, and is stored in buffer registers in the display control before being gated to the stimulator. An individual Braille cell is presented to each finger by six solenoid-driven poke probes arranged in the 6-dot Braille cell configuration. Up to 8 characters may thus be presented simultaneously. Although the system uses, at present, this word-at-a-time Braille pattern of presentation, it can easily accommodate a variety of stimulator patterns and devices.

2. System Software

The software of the system consists of a library of subroutines which can be used as building blocks to construct programs for specific tasks. The subroutines currently planned or available are summarized in Table XII-1. They are classified into Input, Processing, and Display subroutines. Input subroutines are used to read in data to the computer, either from punched paper tape or directly from the computer console. Processing subroutines convert the data to a standard format which is then used by one of the Display subroutines to present the necessary signals to the Display control to operate the stimulator.

Table XII-1. Summary of subroutines.

	Subroutine Name	Abbreviation	Function*
Input	*Type-Input	TI	Text input from computer console.
	Punched Paper Tape Input	PI	Text input from punched paper tape.
	Pattern Input	PA	Non-text pattern input from computer console.
Processing	*Word-Centering	WC	Centers up to 8 characters in an 8-position table.
	*Flexo-to-Braille	FB	Converts flexo characters to their Braille equivalent.
	*Pile Buffers	PB	Piles up 8-character textwords in storage for use when a Display Subroutine is called.
Display	*Simultaneous Display	SD	Displays the pattern to all fingers simultaneously.
	Ripple Display	RD	Displays the pattern a finger-at-a-time; the pattern "ripples" across the fingers.

*Subroutines marked with an asterisk are currently available.

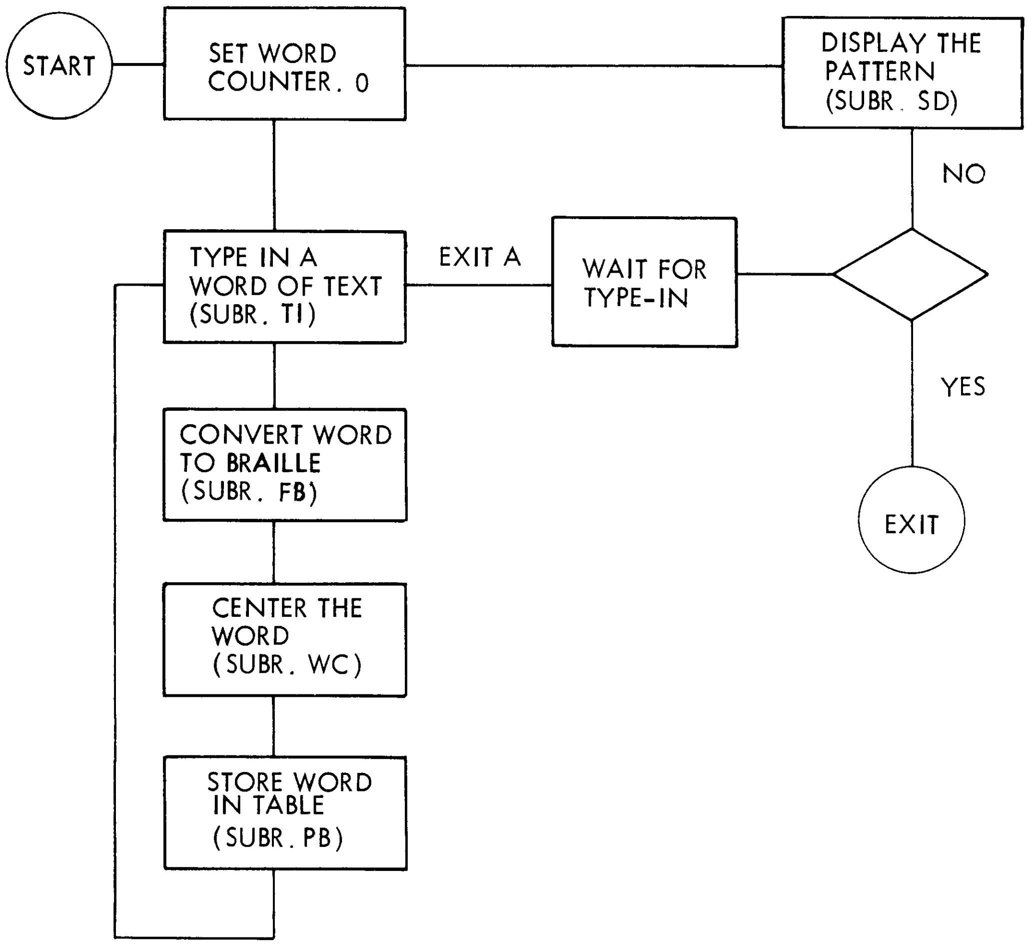

Fig. XII-5. Typical program, built from subroutines.

Other subroutines may easily be added to accommodate future experiments and applications.

An example of a typical program is presented in Fig. XII-5. This program receives text typed into the computer console and displays it on the word-at-a-time Braille stimulator. After each word of text is typed in, it is converted to the Braille code, and centered with respect to the 8 fingers; the resulting centered Braille code is stored, and the next word of text can be typed in. After the desired text is completely typed in, typing a 'center dot' on the console followed by any other typed character (except '/') causes the coded text to be displayed on the stimulator. Typing 'center dot' followed by '/' causes the program to exit.

An immediate application of the system would be as an output to a computerized reading machine for the Blind. By using a modified stimulator, the system could be applied to the study of tactual motion perception.

D. L. Peterson

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