[7] D. Teichrow, "Computer-aided structured documentation and analysis of information processing system requirements," in *Proc. SHARE XLVII*, 1976.
[8] B. Langefors, *Theoretical Analysis of Information Systems*. Stockholm: Auerbach, 1973.
[9] R. Chin, "The utility of system models and developmental models for practitioners," in *Management Systems*, P. Schoederback, Ed. New York: John Wiley, 1971.
[10] A. K. Hennessey, "Aer Lingus airline reservations system; an on-line system case study," in *Final Examinations for B.Sc. (Honours) Combined Studies in Computer Science*, Manchester Polytechnic, England, June 1975.
[11] B. Wilson, "An Approach to Re-organization," Department of Systems, University of Lancaster, England, 1975, unpublished.
[12] P. Checkland, *Systems Thinking and Practice*. Lancaster, UK: University of Lancaster, 1975.
[13] A. K. Hennessey, "Marshall Ward order processing system: an on-line transaction processing case study" in *Final Examinations for H.N.D. Computer Studies*, Manchester Polytechnic, England, June 1978.
[14] ——, "Trustee Savings Bank teller transaction system: an on-line system case study," in *Final Examinations for B.Sc. (Honours) Computation*. University of Manchester, Institute of Science and Technology, Manchester, England, June 1980.
[15] J. Brittan, "Design for a changing environment," *Computer Journal*, vol. 23, no. 1, 1980.
[16] J. Miller, *Living Systems*. New York: McGraw-Hill, 1978
[17] D. R. Mace, T. Crowe, and J. H. Jones, "The econometrics of data validation," in *Management Datametrics*, vol. 5, no. 2, 1976.

Simulation of Typing Process on Different Layouts with Emphasis on Distance and Motion Issues

ISMAIL EL-AZHARY, MEMBER, IEEE, AQIL M. AZMI, MEMBER, IEEE, AND SAAD M. A. SULIMAN

***Abstract*—A new computer simulation for a typist is described. This is unique in the sense that it is based on decisions made by the typist during the look-ahead process, takes care of hand overlapping during typing, and handles simultaneously the shifted and unshifted characters. The simulation is applied to several layouts (two of which are suggested by the authors). The results cover the classical topic of productivity and other topics discussed for the first time. These include distance traveled by the hands, number of hand motions, and alterations.**

Introduction

Since its invention a century ago, Shole's QWERTY design of the typewriter keyboard has faced many challanges. Numerous physical designs were proposed to facilitate the process of typing and to increase the productivity of typists. Examples of these designs are the wipe keyboard [1], chord keyboard [2], and the K-keyboard [3].

On the other hand, it was thought that reassigning letters to keys, without changing the physical design of the Shole's keyboard, could increase the productivity (i.e., more words per minute) compared to Shole's. One of the first attempts was the Dvorak simplified keyboard (DSK). It was claimed to increase productivity by more than 30 percent because it had better hand alterations, better finger loads, and minimum finger motions [4], [5].

Manuscript received May 2, 1984; revised December 17, 1984.

I. El-Azhary is with the Department of Electrical Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia.
A. M. Azmi is with the Department of Computer Engineering, College of Computer and Information Sciences King, Saud University, P.O. Box 51178, Riyadh 11543, Saudi Arabia.
S. M. A. Suliman is with the Department of Mechanical Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia.

For practical and economical considerations, it is difficult to retrain typists on every proposed layout till they gain adequate experience. Therefore, modeling the typing process is a reasonable alternative to evaluate the typist's performance with new layouts. It is assumed that model parameters derived from the typing process based on the Shole's layout held true for any given layout with the same physical structure.

Ramakrishna [6] suggested a one-finger typist model. But due to the absence of the effect of parallelism, his model could not predict the typist's performance using all of the ten fingers.

Kinkead [7], with the help of a computer, collected real data about keystrokes during a speed-typing test, and hence he was able to find the overall time for each key. He constructed a model using the above approach in conjunction with frequencies of possible combinations of letters to find the overall time to type a text. However, this model has drawbacks in several aspects. For instance, the effect of shift keys is neglected, no adequate analysis is made for the effect of look-ahead and overlapping, and finally, he assumed an equal reach time to reach all the keys within a row.

Gershoni *et al.* [8] used the methods–time measurement (MTM) technique to establish the overall typing time for each key and hence built a model similar to that of Kinkead's. Again this model neglected the complex effect of overlapping and look-ahead processes.

Rumelhart and Norman [12] developed a computer simulation of a skilled typist. The fact that the overall typing time was given in units of time independent of the actual time is a drawback in his model. In addition to that, the model did not take care of the combined shifted and unshifted characters. In spite of this, Norman and Fisher [9] implemented the same model to compare between a few layouts.

All of the above-mentioned models agreed that the productivity of a typist could not be improved by more than eight percent, and none of them has tackled the distance and motion issues.

In this correspondence a new computer simulation for a ten-finger typist is constructed based on decisions made by the typist during the look-ahead process. The model takes care of mixed shifted and unshifted characters, overlapping, and look-ahead effects. This model also covers the issue of productivity, in addition to the new topics of the distance traveled by the hands, the number of finger motions, and the number of hand alterations for several layouts (two of which are suggested by the authors).

The Typing Process

The one-finger hunt and peck operation was the earliest method used in typing. To improve the speed, the touch method was developed. In the latter all of the fingers of both hands are involved. Each finger is assigned certain keys to type. The typist should not look at the keyboard, but from a home position he should know where to get the required character. At the same time, the typist should be able to return from everywhere to the home position.

Sometimes, when there is a long string to be typed, the typist will not deal with each character as a separate entity. Instead, he will look at a group of characters simultaneously with a certain look-ahead buffer width. So, it is possible that one hand is processing a character while the other hand is reaching the position of the next. Here, overlapping between the times of each character takes place, and the overall time is reduced.

In some cases, the typist may decide to stay at the current key position in order to reduce work and effort. As an example consider the case of typing the word "que". After typing "q" the left hand, due to the look-ahead process, will not go directly to

0018-9472/85/0500-0416$01.00

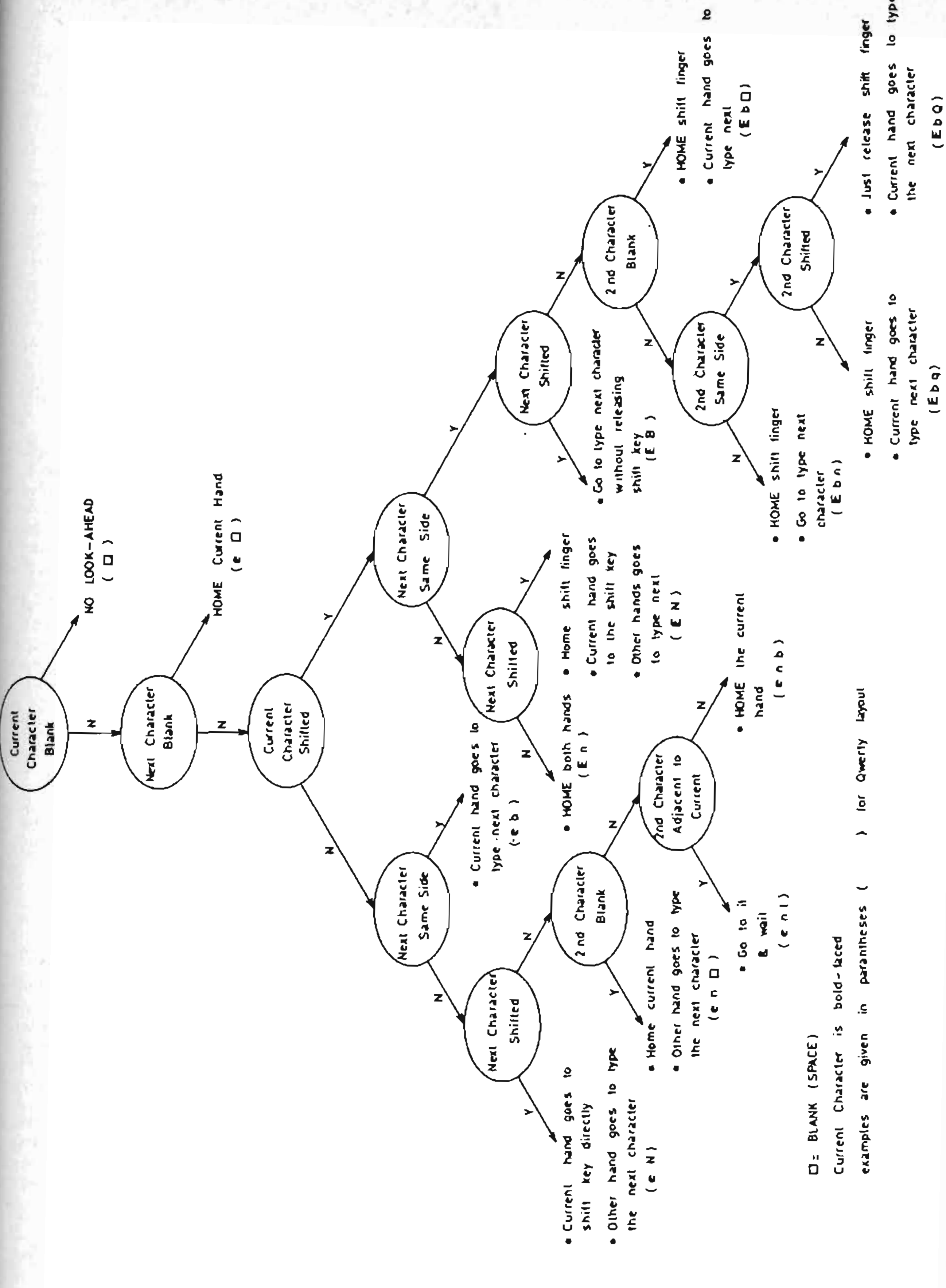

Fig. 1. Look-ahead decision process (buffer width = 2 characters).

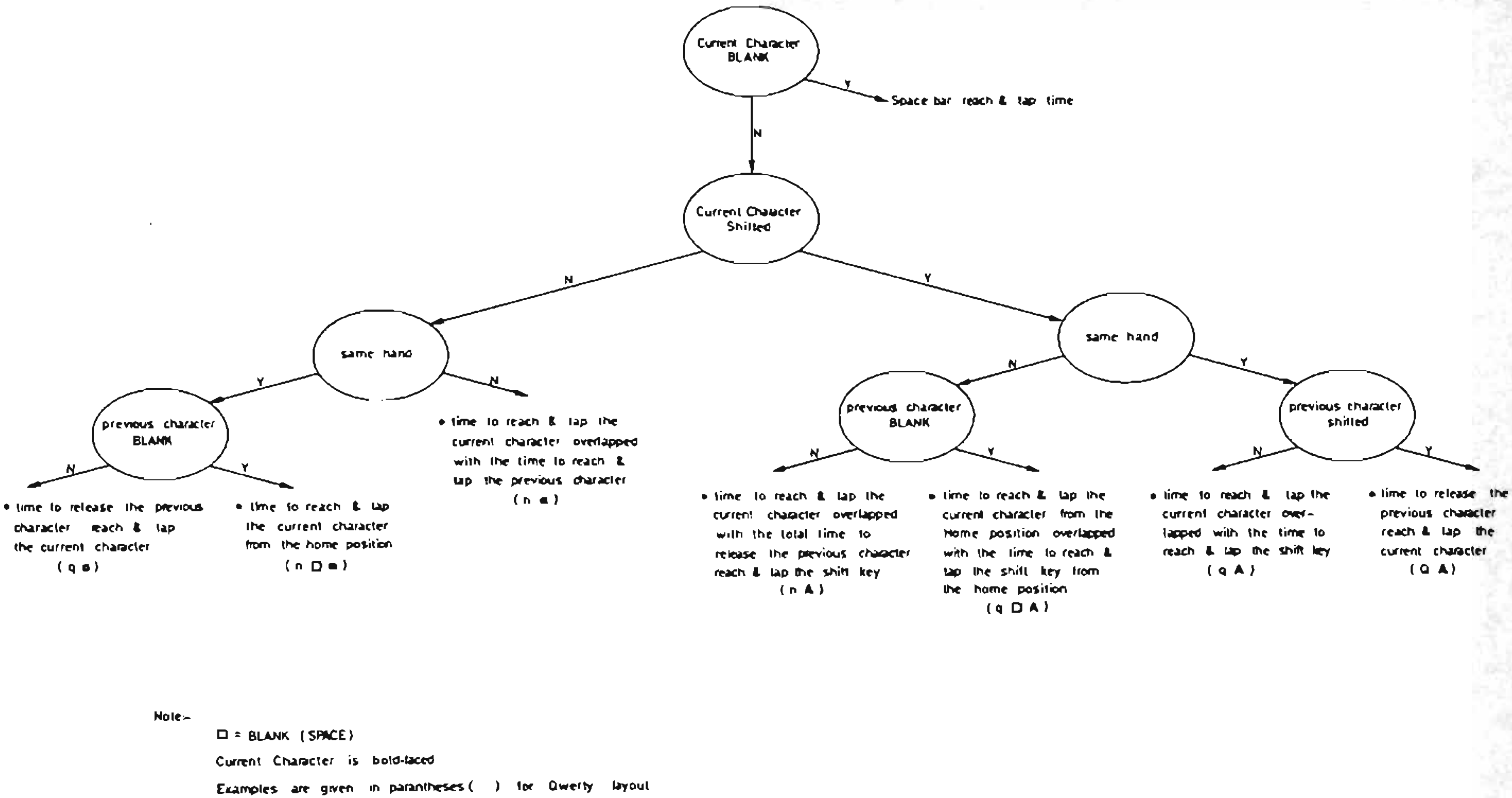

Fig. 2. Reach and tap tree.

TABLE I
THE REACH-AND-TAP TIMETABLE (MILLISECONDS)

Rows up or down	Reach to side (Keys): 0	1	2	3	4	5
0	136	174	192	192	216	252
1	174	174	192	216	216	252
2	192	192	216	216	252	306
3	192	216	216	252	306	306

the home position. Instead it will stay until the other hand types "u", then it will proceed to type "e".

Finally, the typist might prefer to home his hand(s) whenever he encounters some complex combination of characters. This case happens for some clumsy keystrokes, like the shifted characters.

Decisions based on look-ahead taken by the typist during the typing process were observed for many typists and were found to have the structure of a binary tree (Fig. 1).

The timing of each keystroke depends on the decisions to be made by the typist about the next motion(s). Due to the overlapping and the look-ahead processes, the times of all keystrokes cannot be added in a sequential manner. Timing was also found to follow the structure of a binary tree, as shown in Fig. 2. Overlapping takes place whenever there is a hand alteration. The following formula can be used to find the next character's reach time with the overlapping effect:

$$\text{next character's reach time after overlapping} = \begin{cases} 0, & \text{if it is reached before the current key has been tapped;} \\ \text{the difference between the next and current keys reach time (without overlapping),} & \text{otherwise.} \end{cases}$$

ESTIMATION OF THE MODEL PARAMETERS

For the sake of analysis we can divide the cycle of typing a single character into three operations: reach, tap, and release the character.

The work factor method [13] and Kinkead's real data [7] were used to establish the actual time of each operation of the cycle. The combined reach and tap times for each key (excluding those at the home position), without an overlapping effect, were determined using the work factor method [13]. The time for a reach motion depends upon four variables: the body member employed, the distance moved, the manual control required to make the motion, and the resistance involved. The following is a brief description of how these major variables were obtained.

1) The dominant body member used in the reach motion is the finger–hand combination.
2) The actual distance between the keys of the Shole's layout were measured.
3) Manual control is required to direct the finger–hand combination toward a specific key and to terminate the motion at a definite stop. Thus, both steering and definite stop work factors are involved in the reach motion.
4) Since the finger–hand combination is moved for the purpose of reaching a key without resistance to overcome, no time is involved.

The tap motion is analyzed as a contact grasp motion occurring as a result of pressing a finger against a key. No time is involved in such a contact grasp, since it is actually made during the final portion of the reach motion.

Using these definitions, the combined reach and tap times for each key (without an overlapping effect) were established in milliseconds. The results are tabulated in Table I.

To complete the data for the model, Kinkead's real data [7] were used to deduce the following:

1) tapping time (at home position) = 136 ms,
2) release time = 47 ms,
3) space bar typing time = 155 ms.

Some manipulation of Kinkead's data is required to deduce the above values from his table.

1) The tapping time at the home position is obtained from the "alternate key" entry (136 ms). This is because the alternate hand will be ready to tap the next key without any reach operation.
2) The release time is deduced from the "same key" entry (183 ms). The typing of the same key requires two operations, releasing it and then tapping it again. Therefore it is a matter of subtraction to get the release time (47 ms).
3) The space bar typing time is obtained from the "space bar" entry (155 ms).

Many observations were performed to determine the look-ahead buffer width. It was taken to be two characters after the current. If a blank is within the buffer, the look-ahead is terminated at that blank.

THE MODEL IMPLEMENTATION

A program to simulate the typing process described earlier was written in PASCAL (a flowchart is shown in Fig. 3). The program was run on an HP3000 computer system.

A sample text (more than 15000 characters) was extracted from many nonscientific magazines and newspapers to ensure randomness.

The program was run to simulate the process of typing the sample text using Shole's layout. This gave the following statistics: the typing speed in gross words per minute (gw/min), finger loads for each hand, loads for each row, the average time to type

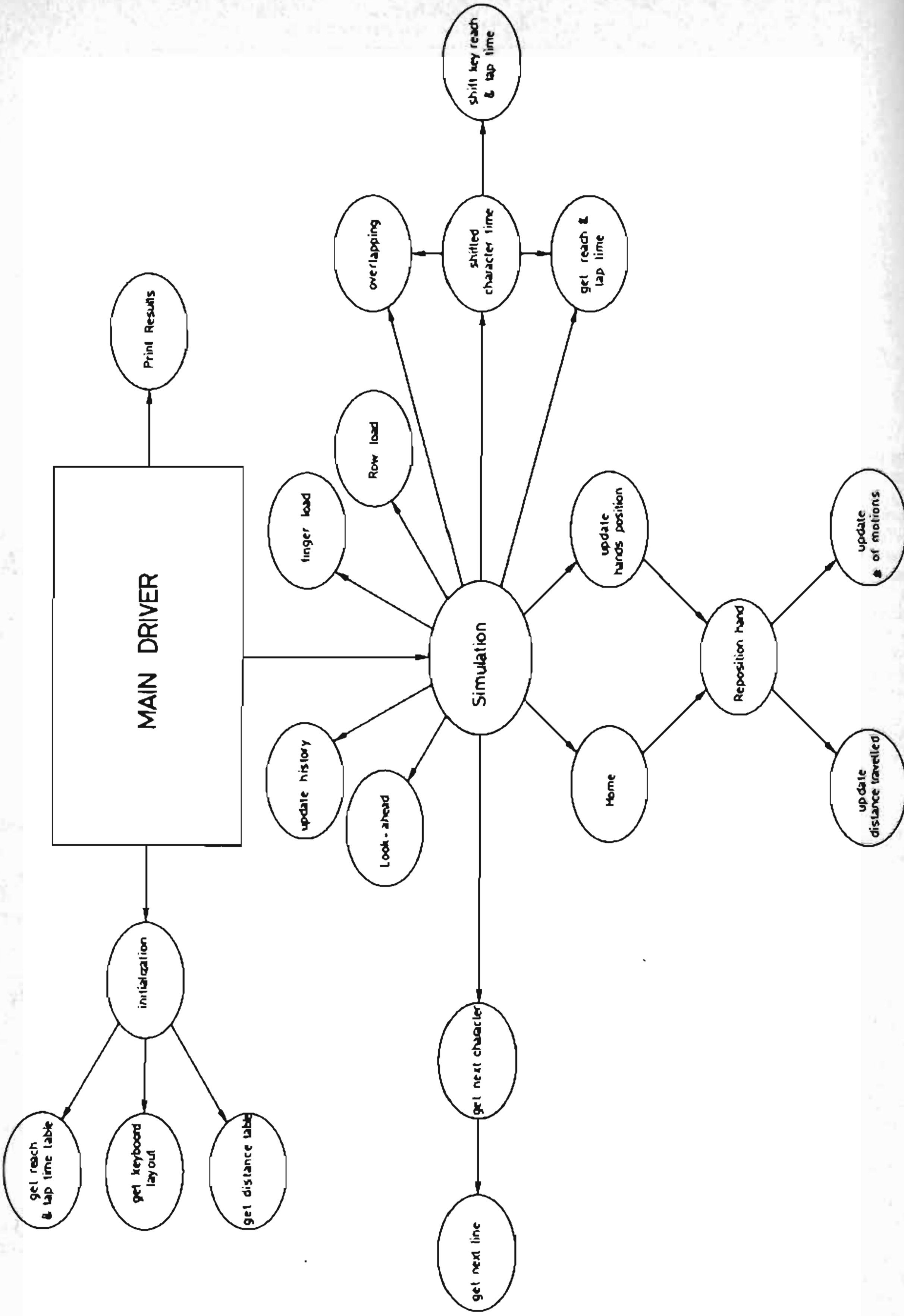

Fig. 3. Implemented programs flow diagram.

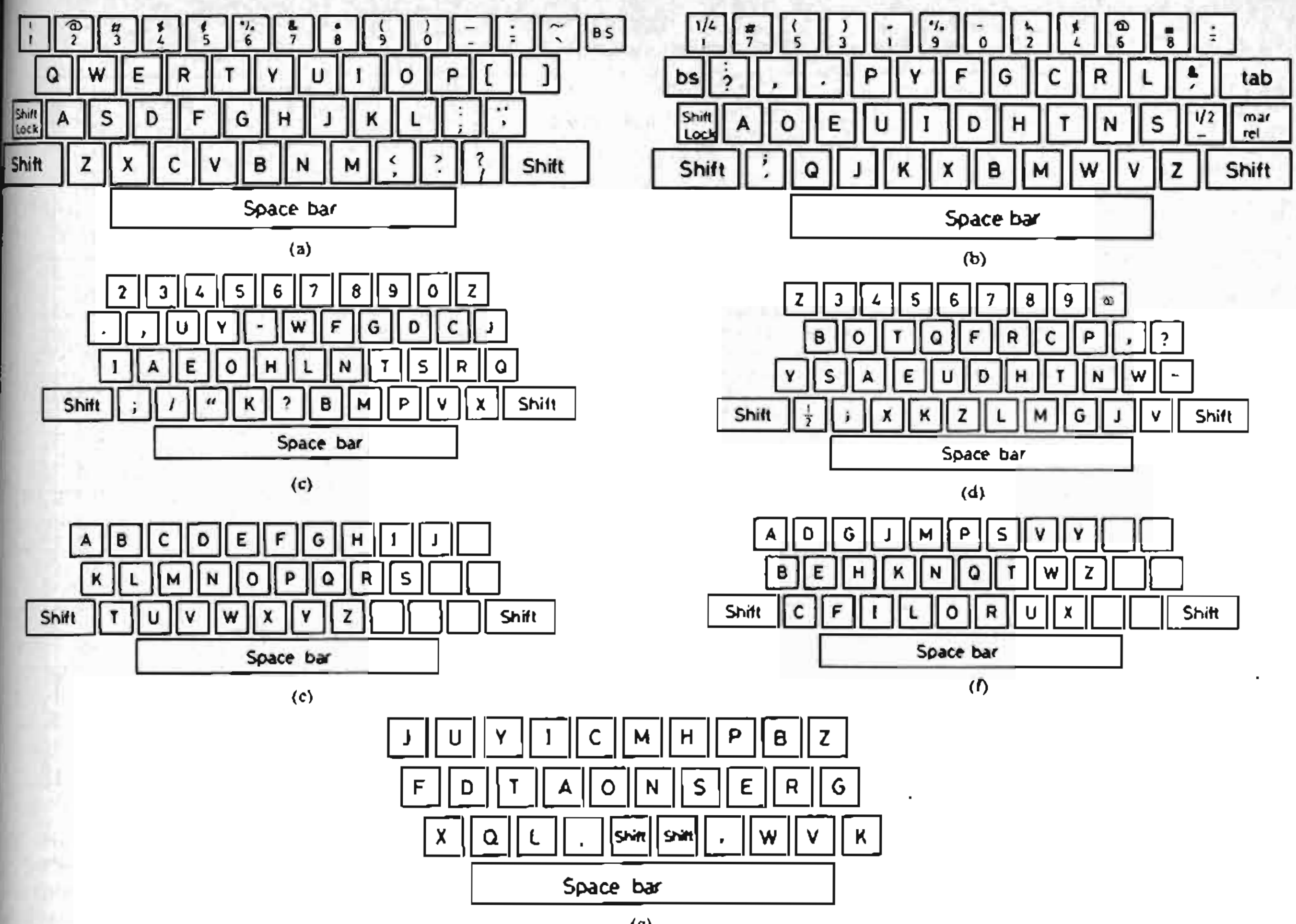

Fig. 4. (a) QWERTY layout. (b) Dvorak simplified layout. (c) Minimotion layout. (d) Rhythmic layout. (e) Horizontal layout. (f) Diagonal layout. (g) Revised QWERTY layout.

a character, and the average keystroke time. Other statistics were normalized to be independent of the text length (i.e., of the number of characters typed). These include average distance traveled per character, average distance per motion, and average length of homing. Another set of normalized data was produced: number of characters that could be typed per hand alteration, per homing, and per motion. This last group is important for later comparisons.

The Validation of the Model

To validate the implemented model, results from the model for the Shole's layout were compared to Kinkead's real data [7]. The model gave a mean time of 172.2 ms/character, and 168.2 ms/keystroke (a shifted character requires two strokes), while Kinkead's real data gave a mean of 152 ms/keystroke. It is expected that our model yields slower rates than Kinkead's data because the latter data were collected during speed tests, whereas the former reflect the productivity of an average skilled operator under normal working conditions [13].

Applications

The program was run to evaluate different layouts using the same sample text. These layouts are the Shole (QWERTY), the Dvorak [10], the minimotion [10], the rhythmic [10], the horizontal [9], the diagonal [9], and a revised QWERTY layout [10] (see Fig. 4(a)–(g), respectively). Two new heuristic layouts, a modified Dvorak and a modified minimotion (named so after the layouts they were derived from), which were suggested by the authors and respectively shown in Fig. 5(a) and (b), were also included in the evaluation.

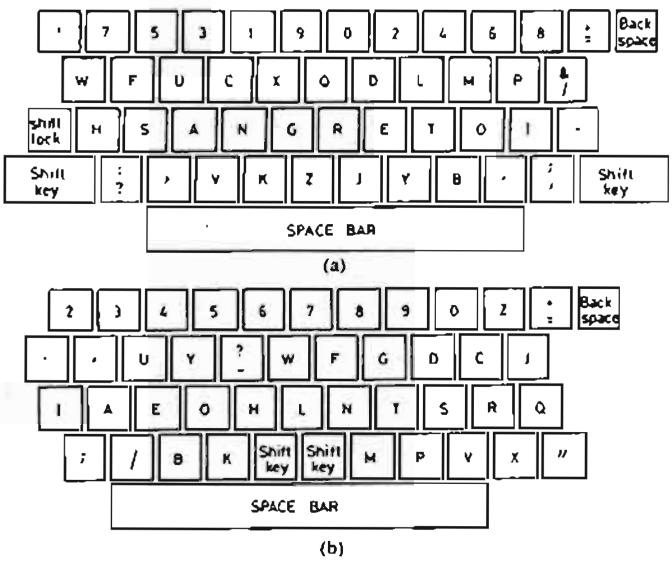

Fig. 5. (a) Modified Dvorak layout. (b) Modified minimotion layout.

Discussion

The results are summarized in Table II. Some of the comparisons, such as speed and distance improvements, were done with respect to Shole's layout.

The model gave a speed of 69.7 gross words per minute (gw/min) based on five characters per word for Shole's layout (172.2 ms/character). According to the by-laws of the international contest of typing [11], this rate falls within the speed of an

TABLE II
SUMMARY OF RESULTS AND COMPARISON OF DIFFERENT LAYOUTS

	FINGER LOAD %										ROW LOAD %				
	LEFT HAND					RIGHT HAND									
	LITTLE	RING	MIDDLE	INDEX	THUMB	LITTLE	RING	MIDDLE	INDEX	THUMB	SPACE	Row # 4	Row # 3	Row # 2	Row # 1
SHOLE (Qwerty)	7.36	6.10	14.47	16.84	7.34	4.13	10.62	6.95	15.85	10.33	17.67	16.84	24.50	40.40	1.39
DVORAK	7.64	7.26	10.69	12.56	9.37	9.53	11.32	10.43	12.93	8.28	17.65	8.66	53.48	19.83	1.17
MINIMOTION	7.82	7.10	12.44	12.58	9.05	8.92	8.00	9.86	15.53	8.62	17.67	8.51	56.52	16.27	1.03
RHYTHMIC	2.88	5.87	12.66	18.57	10.25	6.17	7.53	10.27	18.42	7.38	17.63	11.69	45.11	24.74	0.83
HORIZONTAL	14.55	7.52	4.79	25.63	7.75	2.44	11.02	9.52	6.87	9.91	17.67	17.93	29.15	33.86	1.39
DIAGONAL	10.56	14.11	10.41	17.82	8.18	3.43	2.86	2.23	20.92	9.48	17.66	30.97	29.29	28.69	1.39
Revised QWERTY	3.07	5.70	12.05	20.90	10.10	4.33	6.82	12.68	16.79	7.49	17.67	10.64	49.64	20.67	1.39
Modified DVORAK	6.47	7.43	9.69	10.09	10.92	8.72	8.98	11.51	19.44	6.74	17.67	9.00	54.12	18.04	1.17
Modified MINIMOTION	7.69	7.10	13.55	12.58	9.09	9.11	8.08	9.86	14.33	8.38	17.67	8.50	56.51	16.29	1.03

	Speed in gross words per minute (gwpm) (1 word = 5 chars)	Speed improvement over Shole's %	Avg. time to type a keystroke (mSec)	Avg. time to type a character (mSec)	Avg. distance travelled/char (1/64)"	Distance improvement over Shole's %	Avg. motion length (1/64)"	Avg. homing length (1/64)"	# Chars/hand motion	# Chars/hand homing	# Chars/hand alteration
SHOLE (Qwerty)	69.7	0	168.2	172.2	67.47	0	67.77	64.76	1.004	2.718	2.373
DVORAK	74.5	6.89	157.1	161.0	40.63	39.78	60.69	60.87	1.494	3.833	1.883
MINIMOTION	74.3	6.60	157.8	161.5	37.32	44.69	59.03	61.54	1.683	4.310	1.865
RHYTHMIC	73.3	5.16	159.4	163.6	47.86	29.06	63.62	62.97	1.329	3.305	1.973
HORIZONTAL	69.0	-1.00	169.0	173.8	66.59	1.30	65.46	64.21	0.983	2.001	2.420
DIAGONAL	68.2	-2.15	171.7	175.8	65.27	3.26	69.87	67.52	1.078	3.189	2.661
Revised QWERTY	69.8	0.14	167.9	172.0	47.61	29.44	59.87	58.26	1.258	3.986	2.481
Modified DVORAK	71.0	1.87	165.2	169.1	36.49	45.92	58.27	59.89	1.597	5.087	2.342
Modified MINIMOTION	74.0	6.17	158.4	162.1	35.99	46.66	57.69	58.51	1.603	4.462	1.985

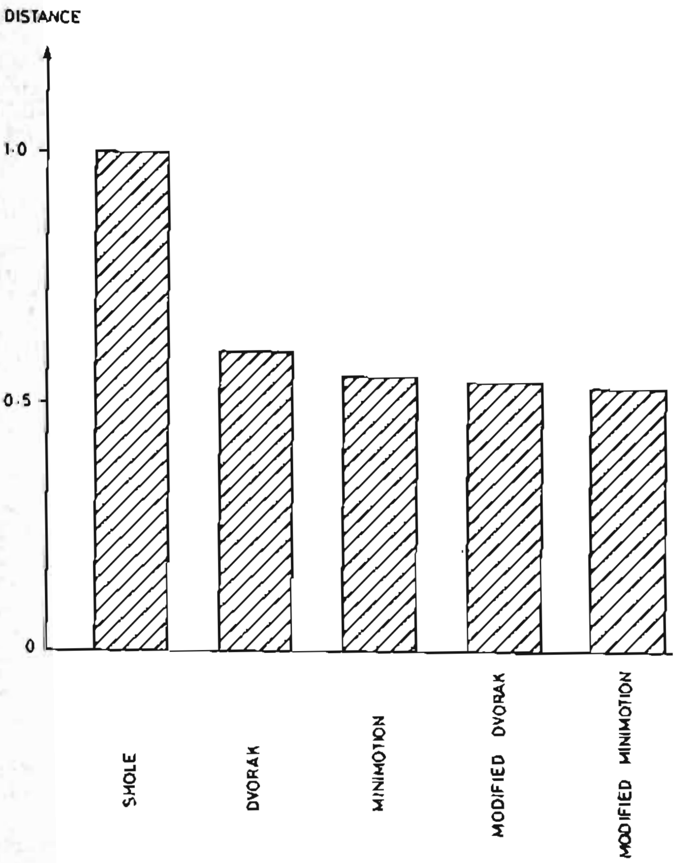

Fig. 6. Distance traveled/character normalized to Shole's = 1.

amateur (average) typist, which starts from 67 gw/min. The speeds for the other layouts varied between 68.2 gw/min for the diagonal layout and 74.5 gw/min for the Dvorak. Compared with the Shole's layout, an improvement of 6.9 percent could be achieved for the Dvorak layout, which is similar to the results given by [9].

The average distance traveled per character for the Shole's layout is more than an inch. This distance is the worst distance per character for the layouts given. For the sake of comparison, consider average typists, working continuously for 8 h/day with the same productivity. The typists would move their finger tips 4900 yd (2.78 mi) over the Shole's layout; using the Dvorak layout would reduce this to 3150 yd (1.79 mi), i.e., a ratio of 1 : 1.55. McCauley and Parkinson [4] had overestimated this ratio to be as high as 1 : 20. Reductions up to 46.7 percent of the Shole's could be achieved for the modified version of the minimotion layout. The distance reductions for some layouts are shown in Fig. 6.

Typists may be unaware of the tremendous number of motions done by their hands during a typical working day (166,600 motions/day for the Shole's layout). To the authors' knowledge, there is no clear indication of the effect of the number of motions with regard to the production and hand fatigue in the long run. However, the best amount of hand motions was calculated for the minimotion and its modified version layouts (110,800 motions/day), i.e., a reduction of 33.5 percent over Shole's. A comparison of the number of characters per hand motion for some layouts is illustrated in Fig. 7.

It is evident that the productivity increases as the number of characters per alteration decreases (theoretically, the optimal is one character per alteration). In this respect the Dvorak layout is the best whereas the diagonal and the revised QWERTY are the worst.

Also, it is advantageous to have as many characters as possible typed in a single hand motion. The Shole's layout offers only a single character per hand motion, while the minimotion and its modified version guarantee about 1.6 characters per motion.

The number of characters typed per homing is another criteria for comparison. As stated earlier, typists tend to home whenever

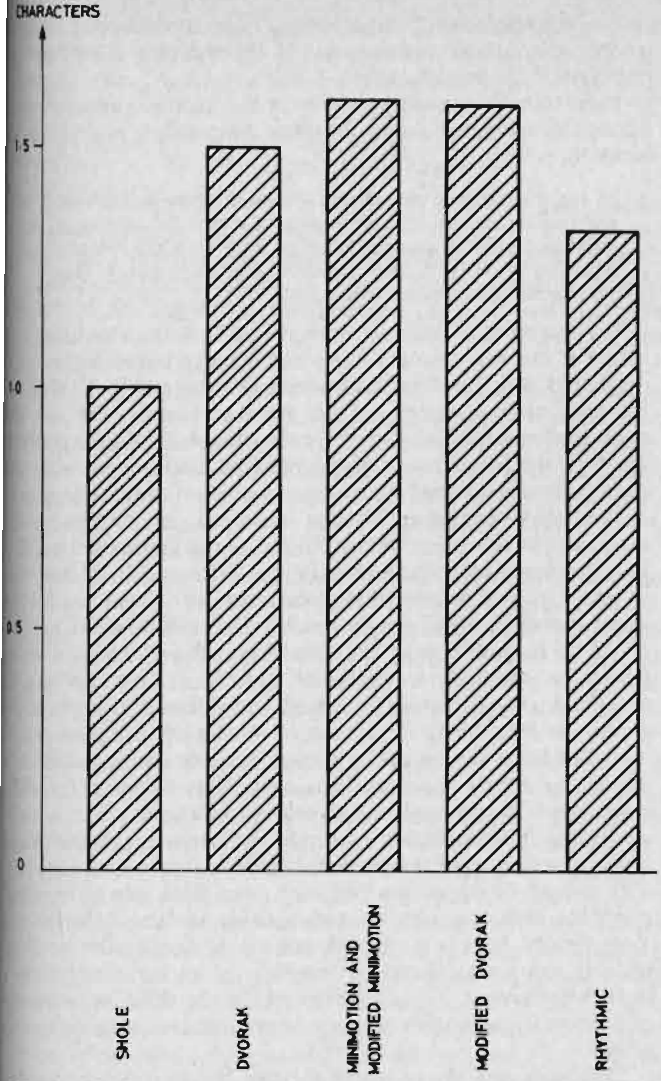

Fig. 7. Number of characters/hand motion normalized to Shole's = 1.

they encounter a clumsy combination of characters. This means that it is beneficial for layout when the number of characters typed before homing is maximized. In this respect the modified Dvorak is the best while Shole's is the worst.

Conclusion

The reassignment of characters to keys on the Shole's layout yields insignificant tangible improvement on typing productivity in terms of gross words per minute. However, regarding its effect on the distance traveled by the typist's fingers and the number of motions, considerable tangible improvement on typing process is realizable in terms of ease of operation and possibly less hand fatigue. This logic is an impetus for further research on new layouts.

Acknowledgment

The authors would like to thank Prof. M. Al-Azami for his support and encouragement. The authors would also like to thank Drs. M. Afifi, Y. A. Rahim, and A. Sharaf for their useful discussions during this research.

References

[1] E. B. Montgomery, "Bringing manual input into the 20th century: New keyboard concepts," *IEEE Trans. Comput.*, vol. C-15, no. 3, pp. 11–18, Mar. 1982.

[2] N. Rochester *et al.*, "The chord keyboard," *IEEE Trans. Comput.*, vol. C-11, no. 12, pp. 57–63, Dec. 1978.

[3] K. H. E. Kroemer, "Human engineering the keyboard," *Human Factors*, vol. 14, part I, pp. 51–63, Feb. 1972.

[4] B. McCauley and B. Parkinson, "New popularity of the Dvorak simplified keyboard," *Computers and People* (formerly *Computers and Automation*), pp. 31–32, Nov. 1971.

[5] R. Parkinson, "The Dvorak simplified keyboard: Forty years of frustration," *Computers and People* (formerly *Computers and Automation*), pp. 18–25, Nov. 1972.

[6] K. Ramakrishna, "Wipe keyboard slick but not practical," *IEEE Trans. Comput.*, vol. C-15, pp. 97–99, Aug. 1982.

[7] R. Kinkead, "Typing speed, keying rates and optimal keyboard layouts," in *Proc. Ann. Meeting of the Human Factors Soc.*, 1975, pp. 159–161.

[8] H. Gershoni *et al.*, "A better Hebrew typewriter," *Ind. Eng.*, pp. 35–37, Oct. 1976.

[9] D. A. Norman and D. Fisher, "Why alphabetic keyboards are not easy to use: Keyboard layout doesn't much matter," UCSD Center for Human Inform. Processing, Rep. No. 8106, Nov. 1981.

[10] J. Noyes, "The QWERTY keyboard: A review," *Int. J. Man-Machine Studies*, pp. 265–281, 1983.

[11] D. D. Lessenbery and T. J. Crawford, *20th Century Typewriting, 5th Ed.* New York: South-Western, 1947.

[12] D. E. Rumelhart and D. A. Norman, "Simulating a skilled typist, a study of skilled cognitive-motor performance," *Cognitive Sci.*, vol. 6, pp. 1–36, 1982.

[13] H. B. Maynard, *Industrial Engineering Handbook*. New York: McGraw-Hill, 1963.

On Systems Theory and Models of Heat Flow

JOHN W. CHINNECK

***Abstract*—System-theoretic models of most physical systems have certain generic characteristics. However, models of heat flow are anomalous in several respects. The product of the through and across variables does not yield power, an inductive component does not exist, and the through variable is not measured in the usual way. A closer study of these anomalies has broad implications for the methods of systems theory in general. Among these implications are 1) for every physical phenomenon there is a variable set that provides all of the generic characteristics; 2) every physical system has an alternate formulation using energy flow rate as the "through variable;" 3) physical systems that would normally be modelled using discrete variable sets can be united in a single model; and 4) methodological advances are required in order to deal with random diffusion processes such as heat flow.**

Further, some insight is gained into the effect of a macroscopic versus a microscopic viewpoint in model building.

I. Introduction

Systems theory has been applied successfully to many types of physical systems including mechanical translation, mechanical rotation, electromagnetic, and hydraulic. The system-theoretic models are based on a pair of through and across variables, so named because of the method of their measurement. Another property of the through- and across-variable pairs for physical systems is that their product yields power.

The through and across variables are used to construct component models, which can be divided into three types: dissipative (resistive elements), capacitive, and inductive. A capacitive element stores energy due to a difference in an across-variable across its terminals. An inductive element stores energy due to a flow of a through-variable through it.

Manuscript received June 7, 1984; revised August 6, 1984.

The author is with the Systems Engineering Department, University of Waterloo, ON N2L 3G1, Canada.