System controls for a resistive ribbon printer

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The system controls for a printer using the resistive ribbon print technology involve conventional requirements, such as moving the print mechanism relative to the paper, with a new requirement, controlling the electrical energy to the ribbon, an electrothermal component. Other special requirements are dictated by using the same ribbon for hard copy print/erase while ensuring that the print and erase operations are acceptable to the user. This paper discusses the design and performance of the system controls for a resistive ribbon printer that was developed for use in an interactive typewriter application and as an output printer for a personal computer.

Introduction

The design of the system controls for a printer is primarily governed by its print/erase technology, performance, and applications. The printer which uses the resistive ribbon technology operates as a "letter-quality" unidirectional serial printer at a maximum print speed of 4 in./s (101.6 mm/s): 40 characters per second (cps) at 10 characters per inch. The applications for the printer are a key-to-print typewriter with hard copy erase or an output printer for a device such as a personal computer.

The resistive ribbon (RR) technology is a "contact," but nonimpact, print technology and is an extension of the thermal transfer print technology. The technology components, the printhead and the ribbon, are used in the dual functions of hard copy print/erase. The ribbon consists of a conductive layer and a transfer (ink) layer. The printhead has 40 electrodes arranged in a linear array and provides the electrical contact to the conductive layer of the ribbon through which the input power is supplied.

The typewriter application requirements governed most of the design decisions. High standards for print/erase quality and ergonomics had been established by the impact print technologies such as the printwheel and the IBM ®SELECTRIC typewriters. For comparable performance, the system controls had to balance ergonomic factors such as key-to-print time, noise levels, and print line visibility with the print/erase requirements of the technology. The latter involved positioning the printhead in contact with the ribbon and controlling the relative motion of the printhead, ribbon, and paper.

With special design considerations, the RR print technology can be utilized in a typewriter application with performance comparable to that of the impact technologies. The technology offers potential advantages, lower noise levels, higher print rate, and easier access to different character styles and pitches. The system design considerations, in conjunction with a functional and performance description of the RR printer, are presented in subsequent sections.

Resistive ribbon printer system overview

- *Control functions*

The basic objectives of the system controls are to perform high-quality print/erase operations in an acceptable manner, especially when the RR printer is used in a key-to-print application. Five basic functions (**Figure 1**) are controlled during a print or erase operation to meet these objectives: 1) printhead in/out position and velocity, 2) carrier velocity V_c and carrier position, 3) printhead electrode selection, 4)

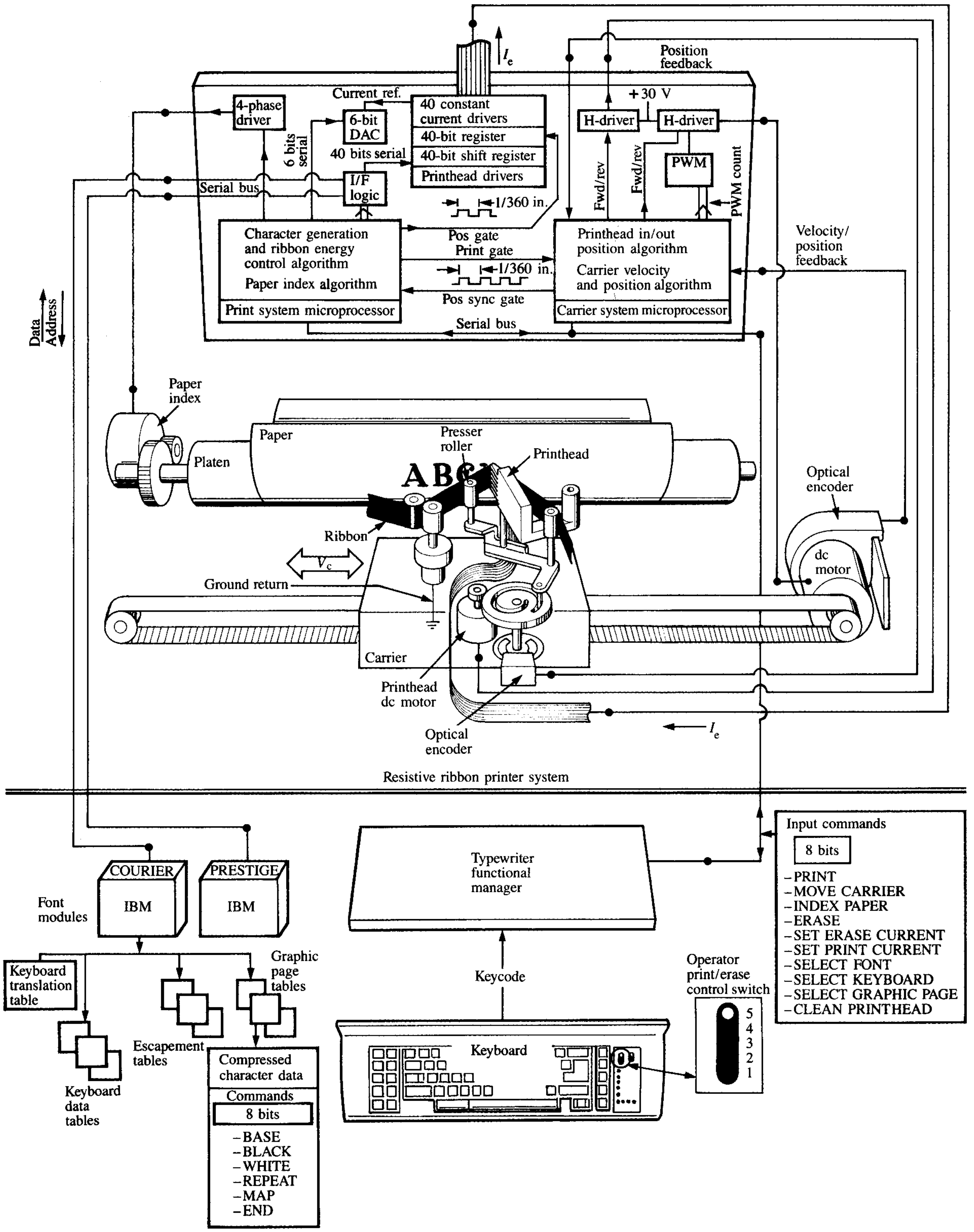

Figure 1

Resistive ribbon printer system used in a key-to-print typewriter application.

electrode current I_e, and 5) paper index. The algorithms controlling these functions have been divided between two microprocessors (the print system and the carrier system) that are functionally self-contained and require minimal communication with the other functions.

The input commands to the RR printer system, listed in Fig. 1, have been designed to allow the printer to be controlled by either of two functional managers: key-to-print typewriter or output printer. This paper focuses primarily on the case in which the functional manager is a typewriter, since this application involves the more demanding control requirements.

The RR technology is a nonimpact print technology but does require the printhead to be positioned in contact with the ribbon while printing or erasing and to be retracted otherwise. An important printhead control requirement is to minimize the acoustical noise generated while the printhead is being positioned to prevent interference with the typing rhythm of the operator. This is accomplished by controlling the velocity and position of the printhead, using a dc motor with an optical encoder for feedback, with an adaptive control algorithm designed to minimize the noise level.

The ribbon and printhead are mounted on and transported by the carrier; therefore, carrier velocity and position correspond to print velocity and position. The carrier velocity V_c is an important technology parameter. This parameter, along with the printhead electrode current I_e, determines the ribbon input energy per electrode and consequently the print/erase temperatures generated within the ribbon. The velocity of the carrier is controlled by a closed-loop servo consisting of a dc motor with an optical encoder for velocity and position feedback.

The print velocity affects not only the electrode input energy but also the imaging characteristics of the RR technology. The print quality increases with print speed up to a range of 3 to 5 in./s (76.2 to 127 mm/s), but the printer cost also increases with print speed. A print rate of 4 in./s (101.6 mm/s), chosen as the operating point, balances the requirements of print quality, throughput, and printer cost.

The system has the capability of selecting which of the 40 printhead electrodes will supply current to the ribbon at each horizontal print boundary. These boundaries are spaced at 1/360-in. intervals and are defined by pulses from the optical encoder on the servo motor for the carrier control. The printhead electrodes are spaced on 1/240-in. centers, allowing a maximum print resolution of 240 × 360 pels per inch. This resolution is high enough to minimize the visual effects of character digitization but does not require extensive storage for font data or system capabilities for character generation. Character generation, controlled by the print system processor, accesses data to build a character from either of two customer-pluggable font modules. Each module contains the data for approximately 220 characters, stored in a compressed form.

The printer controls the input power to the ribbon by using 40 constant current drivers to regulate the ribbon current flow for each electrode. The print system processor can adjust the electrode current in one-milliampere (mA) increments over a range from 0 to 63 mA.

• *Print operation*

Printed images on a page are generated by positioning the 40-electrode printhead in contact with the ribbon, forcing the ribbon against the paper. While the printhead is moving from left to right at a speed of 4 in./s relative to the ribbon and the paper, current is passed via the selected electrodes through the ribbon to the ground return. The electrode current causes heat to be generated within the conductive layer of the ribbon under the electrode. This thermal energy heats the ink, lowering its viscosity. The ink is bonded to the paper and released from the ribbon when it is peeled away from the paper. A printing electrode draws a line approximately 0.1 mm wide. Printed images are formed by turning the selected electrodes on or off at the horizontal boundaries of the image matrix.

The functional manager initializes the print process, sending the print system processor a SELECT FONT command which instructs the processor to select one of the font modules. The processor accesses all subsequent character and keyboard data from this module. If the functional manager is the typewriter, it initializes its keyboard by sending to the print system a code which identifies the keyboard layout. The print system uses this code to select one of the keyboard data tables within the font module. This data table contains special information relevant to the keyboard, such as dead and repeat keys, and identifies the graphic page table where the compressed characters are stored. This information is passed to the functional manager. A keyboard translation table is also passed to the functional manager. This table allows the functional manager to convert each key code from the keyboard into a standard code point (EBCDIC) uniquely identifying the graphic or character on the key-top.

The font character data are compressed and stored within the graphic page tables in the form of run-length coding commands [1]. Each command (Fig. 1) is a single byte, with the three high-order bits identifying the command. The five low-order bits define the "run," or number of consecutive white or black bits to be shifted into the printhead drivers during the decompressing process. The commands are accessed and decompressed one at a time until a 40-bit column has been built. The commands define the base (BASE) of the character (the number of white bits under a character), the number of electrodes to turn on or off in a run (BLACK, WHITE), the number of bytes to be mapped (MAP) directly to the printhead drivers, and the number of columns to repeat REPEAT.

The functional manager starts the print process by sending a PRINT command followed by an EBCDIC code to the RR printer. The print system uses the EBCDIC code as an indirect address pointer to access from the selected graphic page table in the font module the starting address of the first byte of compressed character data. Printing a character is a sequential process of transforming compressed character data stored in the font module into a character matrix of 40 bits per column times N columns. N is a function of the pitch, equal to 24, 30, or 36, corresponding to 15, 12, or 10 pitch, respectively. As each column is being built, the print system transfers the 40 bits serially to a 40-bit shift register in the printhead drivers. The data are transferred from the 40-bit shift register into a 40-bit latch register on the next carrier position encoder pulse. The 40-bit register gates the 40 constant current drivers, permitting current to flow through the selected electrodes and thereby transferring ink to the paper. This process of extracting compressed data from the font module, decompressing them into a 40-bit column, and sending the column to the printhead drivers continues until an END command is read from the font.

The relationships between the controlled parameters as a function of carrier position during an interactive print cycle are illustrated in **Figure 2**. At the start of a print cycle, the carrier system processor has the carrier (printhead) positioned approximately 60 pels (60/360 in.) ahead of the next print window. This positioning gives enough time for the printhead to be positioned against the ribbon and for the initial velocity transient of the carrier to settle out before reaching the next print window. When the printhead reaches the print window, the carrier system synchronizes the print operation to the carrier position.

The print system controls two parameters while the character is being printed: 1) the printhead electrodes within each column that are on and 2) the electrode print current within the column. The print current per electrode is determined as follows:

$$I_e = \textit{operator print/erase control switch} + \textit{font offset}, \qquad (1)$$

where I_e is the electrode current (mA); *operator print/erase control switch* is the input from the functional manager, allowing the operator to set the print current to one of five possible values (Fig. 1) for desired print density or boldness; and *font offset* is an offset current value stored in the font module, automatically providing a print compensation for fine-line fonts.

Figure 2 shows that in printing underscores, the first two columns and the extended two columns are printed at a higher current. The extension eliminates gaps in the underscore when continuous underscores are being printed in an interactive (one-character-at-a-time) mode. The gap is prevented by starting the printing of the next underscore over the extension of the previous underscore.

The high current level at the character boundaries

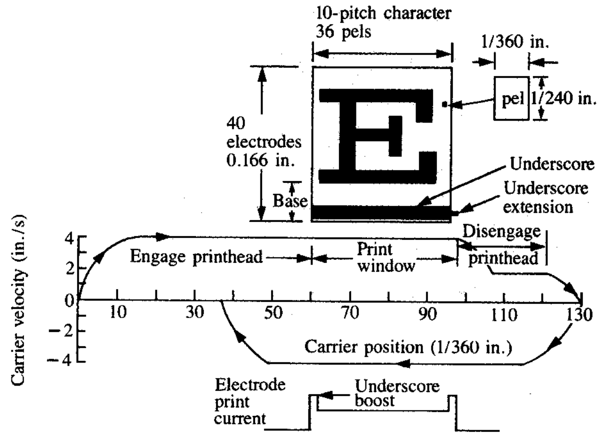

Figure 2

Print cycle—carrier velocity, character generation, and electrode print current as a function of carrier position.

increases the bonding of the underscore at these points. This allows a section of a continuous underscore to be lifted off during an erase operation without disturbing the leading and trailing adjacent sections of the continuous underscore.

• *Erase operation*

Hard copy erase is just the opposite process from print; the objective is to lift a printed image off the paper. The erase process is similar to the print process, except that a special block character is printed over the character desired to be lifted off. The special erase block character covers the character completely and is printed at about half the normal print current. This results in the ink becoming tacky and sticking to the character but not hot enough to release from the ribbon. An additional difference between the erase and print operations is the length of time between the bonding of the ink and the ribbon's being peeled away from the paper. During an erase operation, the peeling of the ribbon from the paper is delayed by the presser roller (Fig. 1), which controls the peel point. This delay allows the heated ribbon to cool down in order for the optimum bonding condition to be established before the ribbon peels away from the paper, lifting off the printed character.

The relationship between the controlled parameters during an erase operation, as a function of carrier position, is illustrated in **Figure 3**. The functional manager initiates the erase cycle by sending an ERASE command to the RR printer. The command defines the dimensions of the character to be erased, not the actual character, since a block erase technique is used.

Key characteristics of the erase block, i.e., its shape and average current levels supplied to the different sections of the block, have been designed for optimum erase performance.

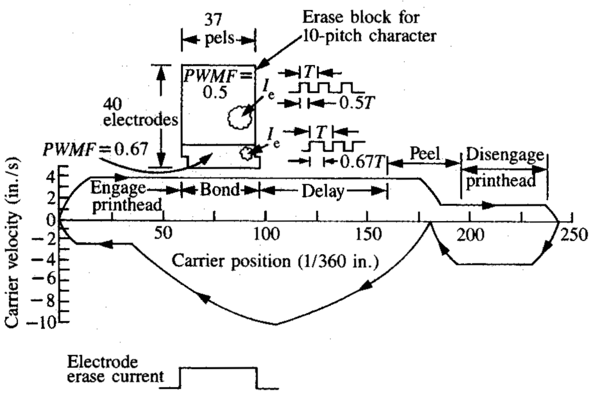

Figure 3

Erase cycle—carrier velocity, erase block, and electrode erase current as a function of carrier position.

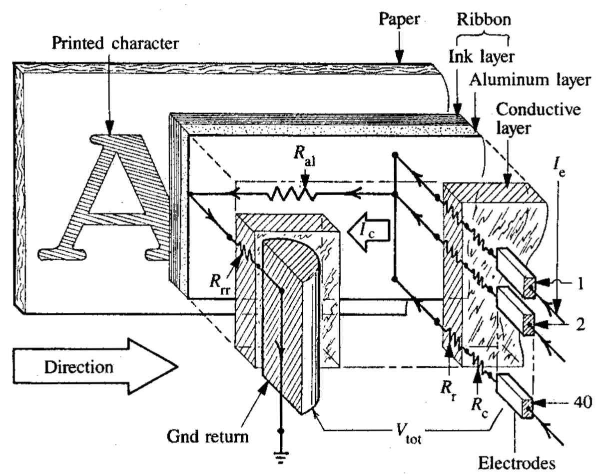

Figure 4

Ribbon equivalent electrical circuit.

These characteristics determine the forces bonding the erase block to the character being erased.

The average printhead electrode current for each section of the erase block is controlled by setting a peak current for each column of the erase block and pulsewidth-modulating this value. The print system sets the column current via a 6-bit control word to the DAC (digital-to-analog converter) for the printhead drivers. Three 40-bit scans per column are generated to set the required pulsewidth modulation factor (*PWMF*) for each electrode:

$$I_e\,(\text{avg}) = \textit{DAC setting}\,(\text{mA}) \times \textit{PWMF}. \qquad (2)$$

The average current level for electrodes 36 through 40 ($PWMF = 0.67$) is about 17% higher than the average current level for electrodes 1 through 35 ($PWMF = 0.5$). The higher current level for electrodes 36 through 40 facilitates the erase of underscores, which are generally more difficult to lift off the paper.

The erase sequence is the same as the print character cycle until the bonding of the erase block matrix is completed. After the block has been bonded to the character to be erased, the carrier continues to move until the character is peeled off the paper. As stated previously, the peel point is determined by the presser roller, and not by the printhead as in a print operation. The presser roller trails the printhead in an erase operation by 6.8 mm. After the presser roller moves past the printed character and the liftoff is complete, the printhead is retracted from the ribbon and the carrier system stops the carrier motion. The carrier is then moved in the reverse direction, to place the printhead in position to reprint at the point where the character was lifted off.

Print and erase electrode current control

• *Ribbon electrical characteristics*

The ribbon comprises a conductive section and a transfer layer. The conductive section is composed of a moderately resistive layer and a thin aluminum layer, which together form an electrical circuit. The thermal energy for print or erase is generated within the resistive layer [2]. The printhead drivers must supply consistent electrical power to this layer of the ribbon for good performance. To better understand how the drivers accomplish this, the electrical characteristics of the ribbon are first reviewed.

As an electrical component, the characteristics of the conductive section can be represented by a simple lumped parameter model, which is shown in **Figure 4**. In this model, the current from each electrode passes through two components. The first is called the "through" component. This component includes the parts of the ribbon between the electrode and the aluminum layer and is the combination of the head-to-ribbon contact resistance R_c and the conductive layer R_r.

The second component of the model is common to all the electrode currents and is referred to as the "common" component. It comprises the parts of the ribbon between the aluminum layer under the electrodes and the ground return. This consists of the sum of the resistance R_{al} of the aluminum layer and the resistance R_{rr} from the aluminum layer to the ground return point. Along this common path flow all the combined electrode currents. Thus, this component becomes more significant as the number of energized electrodes increases and the total current increases.

The total voltage V_{tot} from the electrode to the ground return point is equal to the sum of the voltages across the individual components R_c, R_r, R_{al}, and R_{rr}. The power

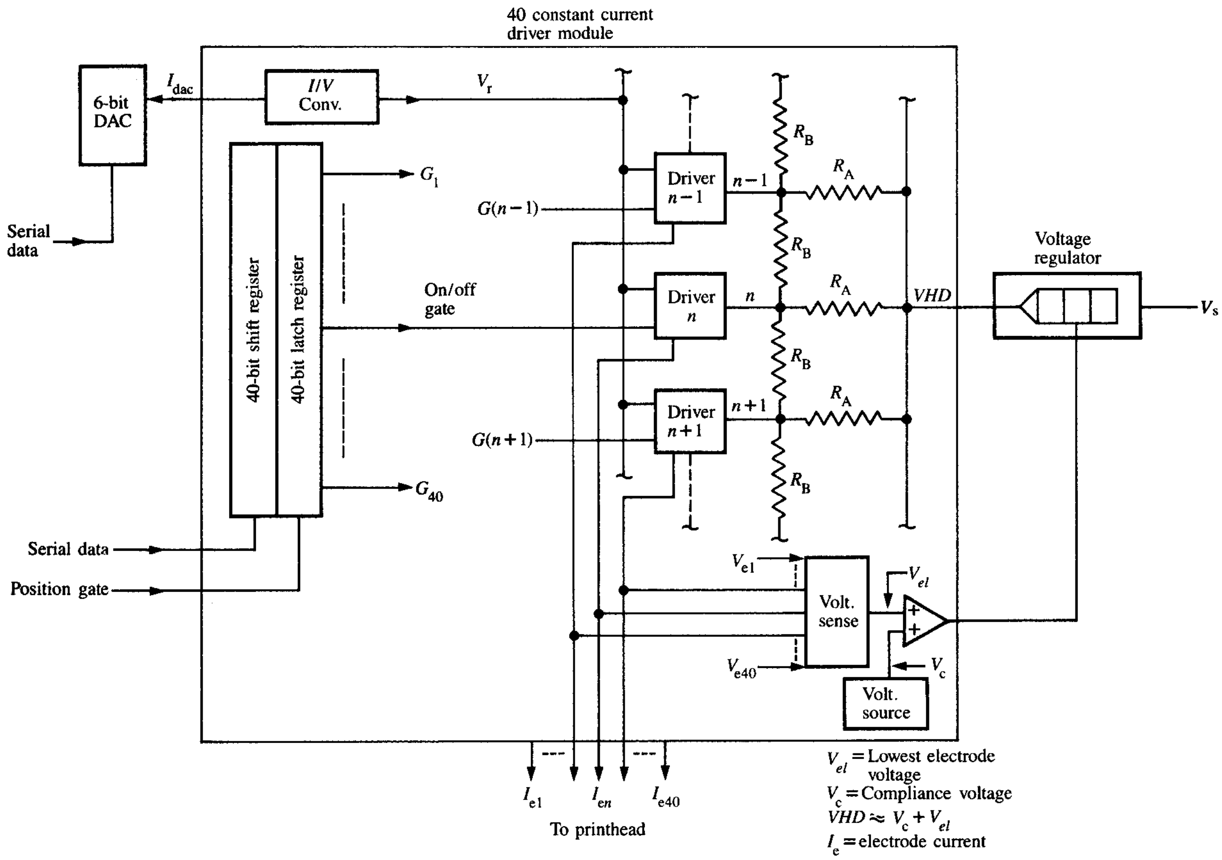

Figure 5

Printhead driver system—6-bit DAC, 40 constant current drivers, and voltage regulator.

dissipated, and consequently, the heat generated in the R_r element of the ribbon, has the most effect on heating the transfer layer. Therefore, the printhead drivers must control the power to this section of the ribbon.

This model of the electrical characteristics suggests that if a constant current were applied to each electrode using a constant current driver, power would be directed to the proper element R_r to produce consistent heating. Resistance in the common return path for electrode currents makes it necessary to increase electrode voltages to maintain the same current, as the number of electrodes that are on increases. There are also potential variations in electrode-ribbon contact resistance R_c, resulting in a variation in the total voltage V_{tot} required by the individual drivers. The drivers must provide the necessary compliance voltage to compensate for this variability.

• *Constant current drivers*

The printhead drivers [3] supply a controlled constant current to each of the 40 electrodes. The driver electronics consists of a 6-bit DAC module, a driver module, and a voltage regulator. These different functions are illustrated in a simplified diagram in **Figure 5**. The DAC receives its digital input for the desired current level from the print system processor. The electrode current can be set in 1 mA increments over a range of 0–63 mA. The DAC generates a current I_{dac} input to the driver module, which is converted to a voltage V_r and used as a reference by the 40 constant current drivers to regulate the current.

The driver module contains a 40-bit shift register, a 40-bit latch register, and 40 constant current drivers. The module receives 40 bits serially from the print system processor, and these are transferred to the 40-bit latch register at the beginning of the print column by the position gate signal. Each of the 40 bits in this register provides an on/off gate to control its corresponding constant current driver.

One of the key features of the drivers is the automatic adjacent electrode compensation [4] provided. The close proximity of the electrodes results in a sharing of thermal energy generated in the ribbon within a group of electrodes, which are energized simultaneously. The region under the inner electrodes of the group is hotter than the region under the edge electrodes. Because of this sharing, an electrode requires less input power to the ribbon to print if one or both of its adjacent electrodes are energized.

The current supplied by a driver I_e is a function of the DAC reference current I_{dac} and the equivalent resistance R_e between the drivers and the output of the voltage regulator VHD: $I_e = I_{dac} \times 1260/R_e$. The adjacent electrode compensation is achieved by using a resistor R_B to connect adjacent current drivers. This produces a change in the equivalent resistance between a driver and VHD that depends upon the state of its adjacent drivers.

If current driver n and both of its adjacent drivers are on, the voltages at the three nodes $n - 1$, n, $n + 1$ are equal and no compensation current flows between these nodes. Therefore, the equivalent resistance between the driver and VHD is R_A. If driver n is on and one of its adjacent drivers is off, the equivalent resistance is lower and the electrode current increases. The equivalent resistance between driver n and VHD is now equal to R_B plus R_A of the off driver in parallel with R_A of driver n: $R_e = R_A(R_A + R_B)/(2R_A + R_B)$. The electrode current is boosted about 16%. If both adjacent drivers are off, $R_e = R_A(R_A + R_B)/(3R_A + R_B)$, and the current supplied by driver n is at its highest level, which corresponds to a 32% boost.

Constant current drivers have a fundamental power dissipation problem because they operate in a linear mode as opposed to a saturated mode. To minimize this problem, the voltage across each driver is restricted to a maximum value. This function is achieved by first sensing the lowest electrode voltage V_{el} of the energized electrodes. This voltage is added to a compliance voltage $V_c \simeq 6$ V and used by the voltage regulator to generate a supply voltage VHD for the 40 drivers which is approximately equal to $V_{el} + V_c$. Therefore, the maximum voltage across a driver plus its series resistance is approximately equal to the compliance voltage. The compliance voltage allows for electrode-to-electrode variation and the dynamic variation due to changing contact resistance between the electrodes and the ribbon.

Printhead actuator control

• *Control objectives*

The RR technology requires the printhead to be positioned in contact with the ribbon, forcing the ribbon against the paper during an erase or print operation. The printhead retracts about 2 mm from the platen for nonprinting movement of the printhead and about 10 mm for print line visibility. Controlling the position of the printhead, the engagement of the ribbon feed, and the correction presser roller is the function of the printhead actuator control. The following are the five control positions:

1. *HOME* Printhead positioned about 10 mm from the platen for print line visibility. Actuator goes to the HOME position if there is no print or erase operation for 150 ms.
2. *I1* Intermediate position with printhead about 2 mm from the platen and the ribbon feed not engaged. This position allows for operations such as space, tab, carrier return, or backspace.
3. *I2* Intermediate position with ribbon feed engaged. The I2 position is used when the carrier is moved in the reverse direction during an interactive print or erase cycle.
4. *PRINT* Printhead in contact with platen and ribbon feed engaged for print operation.
5. *CORRECT* Printhead in contact with platen, with ribbon feed and presser roller engaged for erase operation.

Controlling the noise levels generated by the movement of the printhead became one of the major design considerations. To the user of a key-to-print typewriter, acoustical feedback is an important ergonomic factor. Noise levels that are too high, or even worse, not synchronized with the keyboard entry, can interfere with the typing rhythm of the operator. This can increase the number of typing errors and decrease the typing rate. Because of the characteristics of the print cycle of the RR printer, the movement of the printhead is generally not well synchronized with the keyboard input. In the prototype models, asynchronous noises generated by the printhead movement were high enough to cause some interference with the typing productivity of the user. The objective was to reduce the noise level below that produced by the keyboard in order to avoid any interference.

Acoustical tests demonstrated that gear noise was dominant and was directly proportional to motor speed for a fixed gear ratio. A closed-loop velocity control system would have been a good but relatively expensive solution to the noise problem, especially with a high-resolution encoder for velocity feedback. An adaptive control system, which measures the travel time for a particular move and adjusts the motor voltage accordingly, was chosen as a low-cost method of controlling the motor velocity.

• *System components*

The printhead actuator system consists of a dc motor, optical encoder, cam disc, cam followers, motor driver circuit, and the logic/software to control the encoder position (**Figure 6**). The dc motor drives a cam disc through an 85/11 gear ratio. The top surface of the disc, containing a grooved cam and follower, controls the position of the printhead and the correction presser roller. The grooved cam has dwells for home, intermediate, print, and erase positions.

A face cam on the bottom of the cam disc allows a follower to engage the ribbon feed clutch in the intermediate printhead position. In addition, a code disc on the bottom of the cam disc contains the code pattern for the optical encoder. Stationary light-emitting diodes (LEDs) and integrated photodetectors complete the encoder function.

The encoder is a three-bit absolute optical encoder. By virtue of changing only one bit between adjacent codes, timing problems due to eccentricities in the encoder shaft and disc are avoided.

• *Control algorithm*

The printhead actuator motor controls the position of the encoder, and hence the printhead, by means of two software-generated drive signals and three positional feedback signals from the encoder. The software-generated drive signals (forward and reverse) cause the motor to be driven clockwise (CW) and counterclockwise (CCW), respectively, as viewed from the pinion end of the motor. CW motion of the motor corresponds to the printhead being driven toward the platen.

The normal printhead drive sequence requires the processor to read the present encoder position, set up the target position code, and start a timer to check that the encoder reaches the target position within a fixed period of time.

The travel time allowed for moving from one position to another position is 200 ms, assuming that the encoder is initially at a valid position. If the encoder move is in progress and the timer value expires, the printhead actuator will perform a retry operation.

After the target position has been reached, the drive signal is turned off, and the other drive signal is turned on for a period of time to apply a reverse brake to the motor. After this period, a shorting brake is applied to the motor to reduce coasting of the motor, in case its velocity is not zero when the reverse brake is removed. The values for reverse brake time for the different actuator moves are taken from a lookup table within the processor. For the adapted moves, the brake times vary with the duty cycle of the motor voltage.

The adaptive algorithm defined below modulates the motor voltage and hence limits motor speed and gear noise:

- Motor voltage on time = T_{ON} = constant = 3 ms.
- Motor voltage off time = T_{OFF} varies between 0 and 26 ms.
- Initial T_{OFF} = 0 ms to prevent stalls.
- T_{OFF} incremented in 1 ms steps until travel time for master move (I2 to PRINT) is greater than 70 ms.
- T_{OFF} decremented in 1 ms steps until travel time for master move is less than 100 ms.
- Moves PRINT to I2, I1 to HOME, and I2 to HOME are slaved off master move at the same duty cycle on the motor voltage.

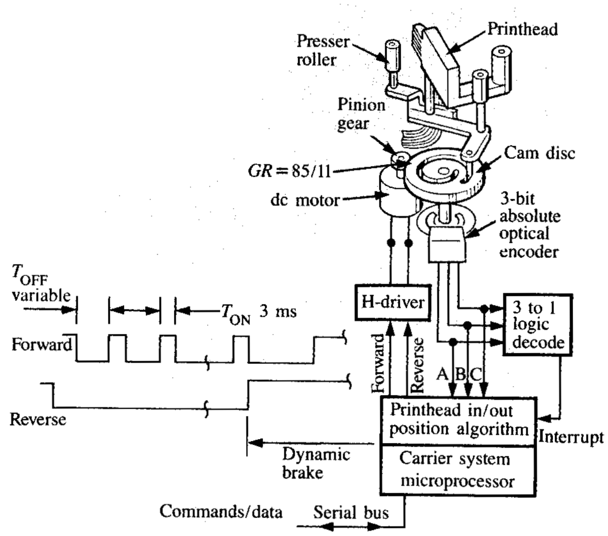

Figure 6

Printhead actuator system—forward and reverse shown for forward move of the printhead.

- T_{OFF} reset to 0 ms for travel time of master move greater than 140 ms.
- T_{OFF} reset to 0 ms for retry on any adapted move.

This particular method of controlling the motor voltage waveform was chosen over other methods, such as fixed period with varying duty cycle, because it offers the most linear control over travel time.

The master/slave concept was used to reduce code space. The move I2 to PRINT was chosen for the master move because it experiences the largest load torque changes and is therefore the most susceptible to stalling.

The adaptive velocity control algorithm reduced the noise level 4 dBA (decibels adjusted to reference level), dropping the level of noise generated by printhead movement below that of the keyboard. This eliminated the problem of printhead actuator noise interfering with the typing rhythm of the operator.

• *ASTAP model*

An Advanced Statistical Analysis Program (ASTAP) simulation model of the printhead actuator system was developed to determine the motor speed, required brake time, travel times, stopping accuracy, peak or average motor current, and power for each system move. **Figure 7** illustrates the model and consists of three equivalent circuits: motor, load, and encoder.

The equivalent ASTAP circuit for the motor can be drawn directly from the motor equation

$$E_m = I_a R_a + L_a d(I_a)/dt + K_e \omega. \qquad (3)$$

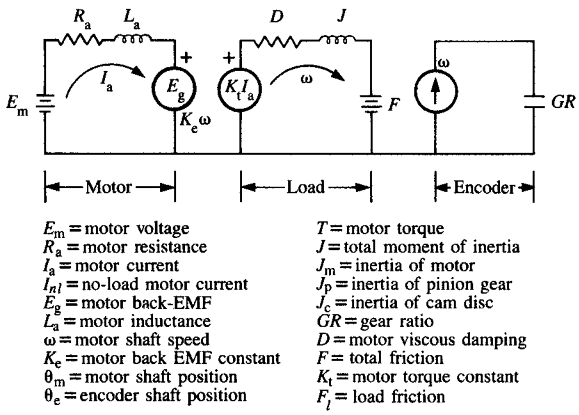

Figure 7

ASTAP model of printhead actuator system.

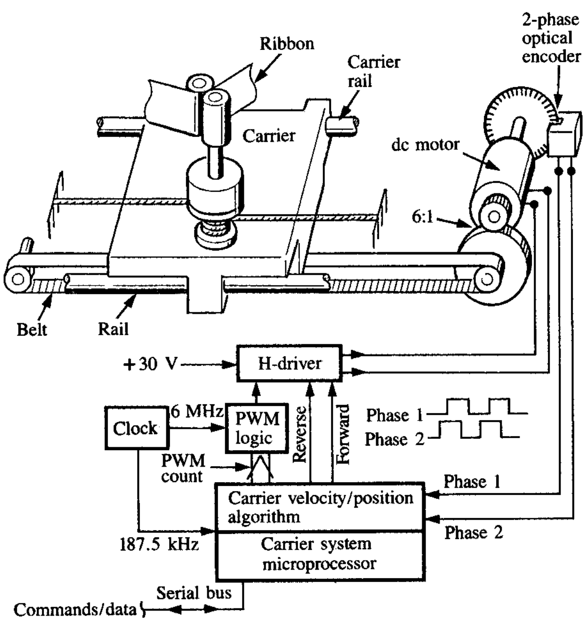

Figure 8

Carrier velocity/position control system.

An analogous "load circuit" can be drawn from the torque equation

$$T = K_t I_a = J d\omega/dt + \omega D + F, \tag{4}$$

where

$$J = J_m + J_p + J_c/GR^2, \tag{5}$$

$$F = F_l/GR + I_{nl}K_t. \tag{6}$$

$K_t I_a$ becomes a dependent voltage source coupling the motor equation and the torque equation. The "current" in this circuit is simply the motor speed ω.

The encoder angle θ_e, which is needed as both an input and an output parameter, can be modeled as a voltage V_c across a capacitor with a value equal to gear ratio GR,

$$\theta_e = V_c. \tag{7}$$

E_m can be listed in a table as a function of either time or encoder angle. F can be listed in a table as a function of encoder angle. The encoder angle is simply the voltage across the capacitor.

Carrier velocity and position control

- *Design objectives*

The dominant design objective was to provide accurate control of the carrier velocity. The carrier transports the print mechanism (printhead and ribbon) during a print or erase operation. Therefore, carrier velocity corresponds to printhead velocity relative to the ribbon and the paper. The energy per electrode delivered to the ribbon is a function of the printhead-ribbon relative velocity and is an important factor for high print/erase quality.

A second objective was to desensitize the carrier system to system variables such as load variations and motor parameters, necessitating a combination of closed-loop and adaptive controls in acceleration, steady state, and deceleration modes.

A third objective was high printer throughput. This was accomplished by a 4-in./s (101.6 mm/s) print speed matched with 20-in./s (508 mm/s) tab and carrier return operations. In addition, an optimizing position algorithm for intermediate-length carrier moves enhances throughput by taking the fastest path to the stop point.

These design objectives were met by using a number of control algorithms, including the following:

- Closed-loop Type 1 (defined in the Velocity Control Algorithm section) digital velocity control.
- Closed-loop Type 0 (defined in the Velocity Control Algorithm section) digital deceleration control.
- Optimal high-speed intermediate-length moves.
- Adaptive low-speed velocity acceleration.
- Adaptive low-speed stopping control.

- *System components*

Figure 8 illustrates the system hardware. The carrier is driven with a dc motor via a belt drive. A dc motor drive was selected early in the development cycle to provide flexibility in generating the complex velocity profiles required for the interactive print and erase cycles. The velocity profiles evolved into a 13-to-1 speed range (1.5 to 20 in./s), requiring several velocity changes within the cycle. A dc motor also offered low acoustical noise levels, excellent velocity control, and registration accuracy.

The Carrier System Processor is the heart of the transport digital control system and is shared with the Printhead Actuator System. The carrier position and velocity control functions performed by the processor are the following:

- Determining moves and corresponding velocity profiles.
- Performing digital Type 1 velocity control.
- Tracking carrier position without additional external logic.
- Providing error detection and recovery or shutdown.

An H-driver (motor connected to four transistors arranged in an H pattern) efficiently regulates the motor voltage by pulsewidth-modulating the 30-V supply. The processor outputs 8 bits (PWM count) to the PWM logic which controls the average voltage the H-driver supplies to the motor over a modulation interval of 42.7 μs:

$$E_m = \frac{PWM\ count}{255} \times 30\ \mathrm{V}, \tag{8}$$

where E_m is the average motor voltage and the PWM count is 8 bits supplied by the processor (0–255).

Carrier velocity and position feedback are provided by an optical encoder. Generally encoders are expensive and require electrical or mechanical adjustments that would cause assembly and maintenance problems. However, an encoder was developed which eliminated these adjustment problems at a relatively low cost.

The optical encoder, consisting of a 120-slot disc and encoder circuitry, generates two 90° out-of-phase digital signals. The spatial convolution of the disc and a stationary mask create an analog waveform which appears half-wave-rectified. A high-gain amplifier combined with a low voltage threshold converts the waveforms into digital signals without requiring any electrical adjustments. Mechanical part tolerances and the assembly process align the mask and disc radially and axially, totally eliminating any mechanical adjustments.

Encoder phase 1 is used for velocity detection and position updates; encoder phase 2 is used to check direction. With three motor revolutions per inch of travel, the encoder provides 360 different addressable carrier positions per inch.

- *Carrier motion profiles*

The RR printer requires several different carrier-move operations to satisfy its typewriter requirements. The primary types of move operations performed in 10, 12, and 15 pitch are:

- Print cycle,
- Correction cycle,
- Space, backspace,
- Tab, carrier return,
- Unit move,
- Head clean move, and
- Error recovery moves.

Figure 2 illustrates the velocity/position profile for a print cycle, Fig. 3 for an erase cycle. As illustrated in Fig. 2, the carrier is moved a relatively large distance before and after the print window. An early objective was to have a much shorter print cycle to avoid distracting the operator with the motion of the carrier. However, the short cycle was difficult to achieve without adding cost to the printer for a very stiff system. An alternate method was to add carrier motion before the print window and to allow a steady state velocity to be reached before entering the print window. The short print cycle would also have required faster movement of the printhead, creating acoustical noise problems. Slower movement of the printhead was chosen and extra carrier motion was added after the print window to allow time for the printhead to be retracted before the carrier was stopped. Extensive human factors testing has not revealed any problems with these compromises in the length of the print cycle.

- *Velocity control algorithm*

Accurate control of the carrier velocity is essential to the performance of the RR printer. A Type 1 velocity control scheme, having a theoretical velocity error of zero for a constant load, is used.

The motor velocity is controlled by the processor, which measures the time interval Δt between consecutive encoder pulses. The average motor velocity equals $\Delta x/\Delta t$, where Δx is the distance between adjacent slots on the encoder disc. A Type 0 system derives a voltage applied to the motor which is directly proportional to the difference between the measured velocity and the desired velocity:

$$E_m = K(V_0 - V) + E_{mb} \text{ or } E_m = KV_0(1 - V/V_0) + E_{mb}, \tag{9}$$

where E_m is the motor voltage, K is the gain factor, V_0 is the desired velocity, V is the measured velocity, and E_{mb} is the bias voltage equal to the nominal motor voltage at a velocity equal to V_0.

Since the calculation of $V = \Delta x/\Delta t$ is difficult in a microprocessor, the implementation of the $E_m = K(V_0 - V) + E_{mb}$ function is simplified by using a nonlinear approximation [5] around the operating point V_0:

$$E_m = K'(\Delta t - \Delta t_0) + E_{mb}, \tag{10}$$

where E_m is the motor voltage, K' is the new gain factor, Δt is the actual time between encoder pulses ("inverse" velocity 1/s), and Δt_0 is the desired time between encoder pulses ("inverse" velocity reference 1/s). This equation can be expressed in the following form:

$$E_m = K'\Delta t_0[(V_0/V) - 1] + E_{mb}, \tag{11}$$

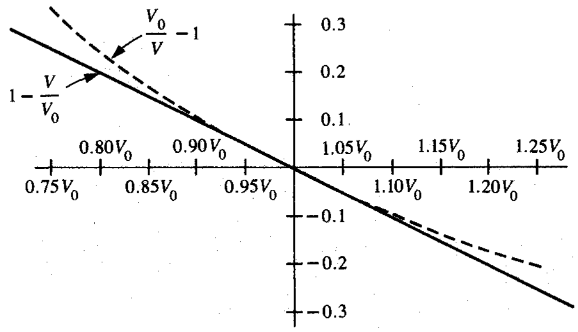

Figure 9

Nonlinear approximation of $1 - V/V_0$.

Equations (9) and (11) differ only by a constant and the terms $[1 - (V/V_0)]$ vs $[(V_0/V) - 1]$. **Figure 9** illustrates how well $[(V_0/V) - 1]$ approximates $[1 - (V/V_0)]$ around the operating point.

This algorithm provides only Type 0 velocity control. An integrator must be added to the forward loop to achieve Type 1 control and a compensation zero added to maintain stability. This integration and compensation require the use of digital filtering by the processor. The Type 1 control reduces to the implementation of Eqs. (12) and (13):

$$E_{\mathrm{mb}} = \omega z T K'(\Delta t - \Delta t_0) + Z^{-1} E_{\mathrm{mb}}\,; \tag{12}$$

then

$$E_{\mathrm{m}} = K'(\Delta t - \Delta t_0) + E_{\mathrm{mb}}\,, \tag{13}$$

where E_{mb} is the bias voltage, ωz is the compensation zero frequency, T is the sample interval, Z is the Z transform operator, and E_{m} is the motor voltage.

The Type 1 implementation, which provides a motor bias voltage E_{mb}, is calculated by taking the previous E_{mb} $(Z^{-1}E_{\mathrm{mb}})$ and adding a fraction of the error signal to it. This error fraction is determined by the zero frequency (ωz) and the sample interval (T). The voltage to the motor is the addition of the bias voltage and the error signal.

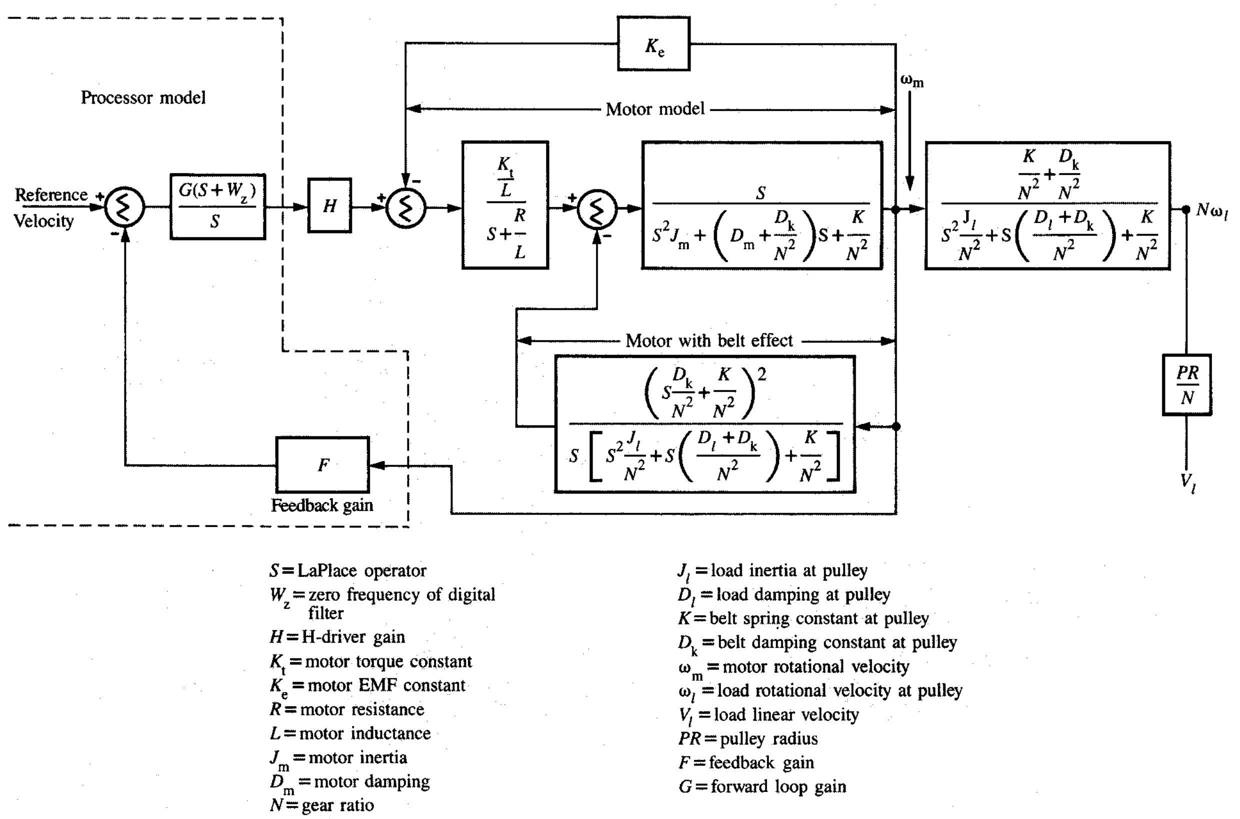

Figure 10

System block diagram for Type 1 control.

In the processor implementation of the velocity control algorithm, E_m and E_{mb} are in the digital form of a PWM count, as defined in Eq. (8). In addition, the inverse velocities Δt and Δt_0 are in the digital form of counts:

$$\Delta C = \Delta t f_c, \quad (14)$$

$$\Delta C_0 = \Delta t_0 f_c, \quad (15)$$

where ΔC is the inverse velocity measured by counting the number of clock pulses of f_c between encoder pulses for Phase 1, ΔC_0 is the reference inverse velocity in counts of f_c, and f_c is the frequency of clock used for encoder time interval measurements.

Within the processor, the digital representation of Eq. (13) would be

$$E_{mc} = K_c(\Delta C - \Delta C_0) + E_{mbc}, \quad (16)$$

where E_{mc} is the motor voltage in PWM counts, K_c is the gain constant (PWM counts/frequency counts), and E_{mbc} is the motor bias voltage in PWM counts.

- *Velocity control linear analysis*

The digital velocity control system can be easily understood if it is assumed to be linear and continuous. These assumptions are a good approximation since the sample rate is high and the belt can be linearized over small regions. **Figure 10** summarizes this linearized system. A single spring rate is assumed for the belt, and belt-carrier effects are reflected into the feedback loop.

Note that a second-order response exists between the motor and load velocities, as would be expected from a belt (spring) and a carrier (mass). A fifth-order response exists within the feedback loop. These poles consist of the integrator, the motor electrical and mechanical poles, and two poles resulting from the motor-load interaction. A root locus of this system versus loop gain is shown in **Figure 11**. The integrator pole and the motor mechanical pole move together before going imaginary and circling counterclockwise back to the real axis. One of these poles terminates on the compensation zero. The other pole and the electrical pole move toward each other along the real axis before they become a complex pair moving toward infinity. This system has approximately 50 degrees of phase margin.

- *High-speed deceleration control*

A Type 0 closed-loop deceleration algorithm is used to decelerate for tab and carrier return operations. This algorithm uses a digital position control loop to provide tight deceleration control and thus ensure a high throughput. It also utilizes velocity feedback as a stabilizing influence to prevent excessive deceleration while the motor back-EMF (B_{EMF}) is high.

Figure 12 illustrates the defined deceleration profile as a function of distance. The deceleration is a linear function of time. For each discrete carrier position (D_c in units of 1/360 in.) moving down the deceleration profile, a reference velocity is compared to the actual velocity. This velocity difference is used as an error signal to control the deceleration rate of the motor. Thus, the motor tracks a constantly changing velocity in a Type 0 loop.

The algorithm uses inverse velocity calculation as in the constant velocity control. A generalized relationship between the reference inverse velocity (ΔC_0) as a function of distance (D_c) is given in Eq. (17) and plotted in **Figure 13**:

$$\Delta C_0 = \sqrt{\frac{B/A}{1 - D_c/A}}, \quad (17)$$

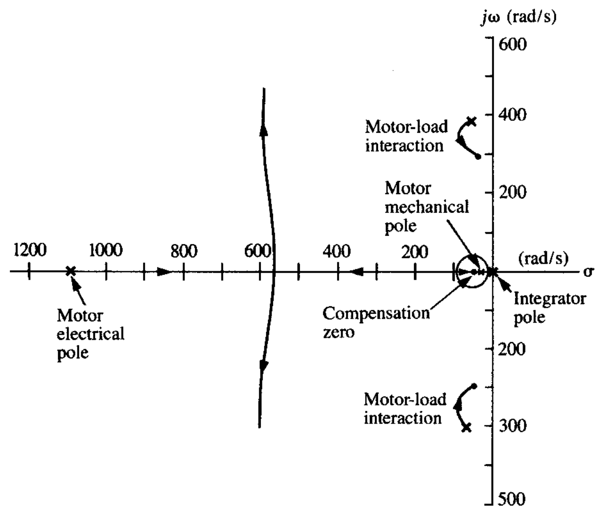

Figure 11

Velocity control root locus.

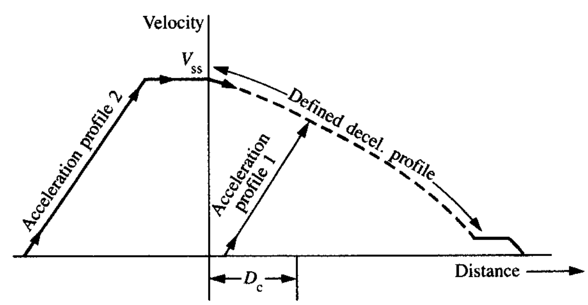

Figure 12

Carrier velocity control vs distance.

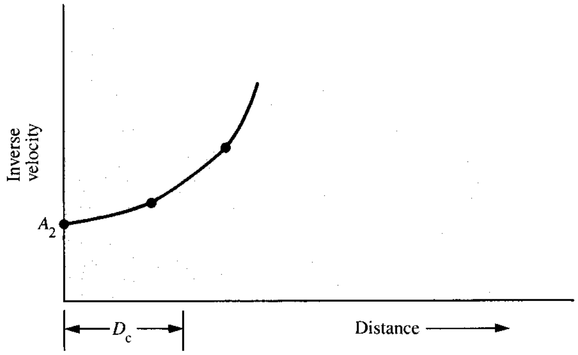

Figure 13

Inverse velocity vs distance.

where

$$A = \frac{V_{ss}^2 K_1}{2a}, \tag{18}$$

$$B = \frac{f_c^2}{2aK_1}, \tag{19}$$

V_{ss} is the initial carrier velocity (see Fig. 12), K_1 = encoder pulses/inch = 360, and a is the constant deceleration rate.

Since Eq. (17) is difficult to calculate in a processor, two second-order approximations are used. The processor uses Eq. (20) if the carrier velocity is in the range of 20 in./s (508 mm/s) to 7 in./s (177.8 mm/s) and Eq. (21) if the carrier velocity is below 7 in./s:

$$\Delta C_0 = A_2 + \frac{D_c^2}{2^{n_1}}, \tag{20}$$

where $A_2 = \sqrt{B/A}$, the inverse velocity intercept, and n_1 is an integer used to obtain the best fit;

$$\Delta C_0 = A_3 + \frac{D_c^2}{2^{n_2}}, \tag{21}$$

where A_3 is the inverse velocity at 7 in./s and n_2 is an integer used to obtain the best fit.

The algorithm calculates the velocity error at each carrier position D_c as follows:

$$V_e = K_c(\Delta C_0 - \Delta C). \tag{22}$$

This velocity error V_e is used to adjust the average braking voltage to the motor. The motor is braked for a time proportional to V_e and then allowed to coast until the next encoder count.

• *Printer optimum move algorithm*

This carrier move algorithm increases system throughput by minimizing the time required to perform a tab or carrier return. The algorithm achieves minimum move times by always accelerating to the maximum speed possible for the length of move. The algorithm essentially triangulates to the stop position, as shown in acceleration profile 1 in Fig. 12. This optimization is possible since deceleration is closed-loop, providing a tightly controlled deceleration. An equation is calculated during acceleration that defines the point at which the deceleration profile is intersected. At this point deceleration begins.

Figure 12 illustrates the acceleration-deceleration decision process. To make the decision during acceleration to begin deceleration, a linear approximation of Eq. (17) is used to obtain a simple relationship between carrier position D_c and inverse velocity ΔC:

$$D_c \geq 1/B_1(\Delta C - A_2), \tag{23}$$

where A_2 is the inverse velocity intercept and B_1 is the integer chosen to obtain the best fit. The algorithm switches from acceleration to deceleration when Eq. (23) calculates that the acceleration profile has intersected the deceleration profile, as shown with acceleration profile 1 in Fig. 12. If steady state speed is reached before Eq. (22) is satisfied, a constant velocity is continued until the deceleration profile is reached, as shown in acceleration profile 2.

• *Adaptive low-speed acceleration algorithm*

The velocity acceleration is open-loop but adaptive to increase throughput. Velocity acceleration consists of an initial voltage step applied to the motor to overcome friction, plus a voltage ramp to accelerate the carrier to final velocity. The acceleration is partially adaptive, in that the initial voltage step is adjusted for frictional differences. This routine enables the high-friction system to apply an initial voltage to move the carrier immediately, instead of waiting until the voltage ramp increases to where friction is overcome.

The Type 1 control enables the initial voltage step to be adaptive, since a motor bias voltage is maintained for each speed. This bias voltage is the motor voltage to overcome friction and B_{EMF}:

$$E_{mb} = E_{mb}\,(\text{friction}) + E_{mb}(B_{EMF}). \tag{24}$$

Since B_{EMF} is tightly controlled for a given speed, and especially when the motor bias voltage is dominated by the friction term, changes in E_{mb} are due primarily to changes in friction. The change in E_{mb} (ΔE_{mb}) is determined for each carrier move operation and is used to adjust the voltage step:

$$\textit{Voltage step} = \textit{default voltage step} + \Delta E_{mb} \tag{25}$$

(ΔE_{mb} can be positive or negative). A positive ΔE_{mb} helps overcome friction quickly and increases throughput, while a negative ΔE_{mb} prevents carrier overshoot by not overdriving a low-friction system.

• *Adaptive low-speed stopping algorithm*

In a digital servo motor control system, the sample rate at low speed becomes inadequate for closed-loop control, necessitating an open-loop algorithm for the final stopping. Open-loop stopping in a system without detenting results in a wide tolerance as system parameters and loading conditions change. An adaptive algorithm is used to reduce the stopping tolerance. The algorithm stores a running average of the previous three stopping distances (SP_{DIS}) and then initiates the next stop, a distance SP_{DIS} from the desired stopping position. The algorithm applies a fixed voltage until the worst-case minimum detectable speed is detected, and then stores SP_{DIS} after a fixed time out. This stopping accuracy solves several problems in the RR printer:

- It allows the character pointer to define accurately the edge of a character that is 24 to 42 columns wide.
- It ensures sufficient ramp-up distance to the next print point.
- It ensures that a minimal amount of ribbon is wasted while avoiding overprinting on the ribbon.

Summary

The RR technology offers the flexibilities and advantages of other nonimpact, matrix print technologies along with the unique capability of hard copy print and erase using the same ribbon. The RR printer capitalizes on these technology capabilities for two distinct applications: a key-to-print typewriter and an output printer for a personal computer.

Controlling the electrical energy to the resistive ribbon, an electrothermal component, was the key requirement unique to the RR technology. This was achieved by regulating the current through 40 printhead electrodes, providing the electrical contact to the ribbon. In addition, the relative velocity of the printhead and the ribbon was accurately maintained since this parameter, along with electrode current, determines the electrical input energy to the ribbon.

The RR technology requirements for the print/erase cycles, along with some compromises in the hardware implementation, resulted in both the print and erase cycles' requiring more carrier motion and time than originally established by early objectives. However, when the acoustical noise levels (particularly those generated by the movement of the printhead) were limited, these longer cycles did not create any significant problems.

The RR technology requirements for interactive print and erase cycles, together with the large dynamic range in carrier velocities, necessitated extensive carrier velocity and position control. Several control algorithms were implemented to meet these needs. In addition, special attention was given to simplifying the algorithms wherever possible, to allow them to fit within the resources of a low-cost microprocessor and to require minimal external hardware.

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