Overview of Microprocessor-Based Controls in Transit and Concerns About Their Introduction

David J. Mitchell
Battelle Columbus Laboratories
Columbus, Ohio

Microprocessor-based devices that perform control and monitoring functions are all around us. They are being incorporated every day in consumer, automotive, and transit products among others. For example, in consumer products they monitor the operation of refrigerators. In automobiles they control operations of the engine. In transit vehicles they perform functions such as propulsion, braking, and automatic train control. The trend is well established. The benefits of small size, low power consumption, flexibility, improved diagnostic capabilities, and low cost are expected to aid transit operators in improving service and reducing cost (both operating and capital).

With the introduction of any new technology, transit authority personnel ask themselves three main questions:

- How do I know that the equipment will operate safely and reliably?
- How do I maintain the equipment?
- How can I modify the equipment, if needed?

The purpose of this paper is to stimulate discussion on this subject by acquainting the reader with present and possible future uses of microprocessors in light rail transit (LRT) and identifying concerns associated with such uses.

PRESENT USES OF MICROPROCESSORS IN TRANSIT

The use of microprocessors has evolved in rail transit and has spread to all the major subsystems. This evolution is most evident in automatic train control (ATC) equipment. ATC functions associated with railroad and transit control systems have been primarily implemented with discrete component technology. Such circuitry has been commonly based on established designs and, in most cases, has used proven components (e.g., relays) in their implementation. Equipment that uses such circuitry has been readily accepted by the transit industry because it is based on concepts and components that have evolved over many years and that have been well proven in actual service.

In recent years the levels of complexity and sophistication of train control systems have increased dramatically. Not only is there a trend toward greater levels of automation, but the means of implementing these systems have changed as well. Initially, relays were displaced by solid-state devices. In time, digital circuitry, based on the use of integrated circuits, was employed. Now, because of their potential for low cost and design flexibility and their ability to perform large numbers of complex functions, software-based computers are being used in transit control systems. The present trend is clearly in the direction of using computers (microprocessors in particular) to perform ATC functions throughout the entire range of transit controls: central, wayside, and vehicle borne.

This evolution has spread to other major subsystems as well. Presented hereafter are several examples of how microprocessors are used in controlling and monitoring rail transit. These are examples only; the list is not meant to be all inclusive. Applications in both heavy and light rail are cited because much interchangeability of equipment is possible between these two modes, which further demonstrates the flexibility of such equipment.

Train Control

Microprocessors are used throughout train control equipment. The most safety-critical applications have been in automatic train protection (ATP) equipment. Computer technology has been employed for the second and third generations of the vehicle-borne ATP equipment (supplied by Westinghouse) at the São Paulo, Brazil, Metro. The Atlanta Airport people-mover system and the Miami downtown component of the Metrorail (also Westinghouse systems) use similar on-board safety equipment. In these systems, a dual channel configuration with identical hardware in both channels is used for some functions. Dissimilar software in the two channels is used for independence. A fail-safe checker, using discrete component technology, compares the outputs of both channels and allows train motion only if both agree (1).

Standard Elektrik Lorenz AG (SEL) has developed a computer-based train control system called SELTRAC, which is now under demonstration on Line 4 of the Berlin O-Bahn. These controls have also been selected by the Urban Transportation Development Corporation (UTDC) for their advanced LRT systems to be deployed in Vancouver and Toronto and their automated system in Detroit (2). One subsystem of SELTRAC uses three channels of hardware with identical software in each channel. A two-out-of-three voter allows train motion if any two of the channels agree.

Computer technology is also being used in Europe and Asia. Ericsson of Sweden has used computer-based designs for rail transit interlockings in Gothenburg and Malmo, Sweden, and in Denmark (3). The Japanese National Railway has been testing computerized interlockings on their Joetsu line, as has British Rail at Leamington Spa (4-6). In France, Interelec, along with Jeumont Schneider, is designing System Aid to Driving Operations and Maintenance (SACEM) (discussion between the author and Marc Genain, SOFRETU, October 1984). This device will compute safe stopping distances for trains while they are in motion (in essence a moving block system). It is based on two microprocessors with different hardware and software plus extensive cross-checking. Both microprocessors must agree before the safe-to-proceed signal is given.

In the United States microprocessor-based safety controls are now being applied to railroad use. The Union Switch & Signal (US&S) Division of American Standard, along with the Union Pacific Railroad, tested prototype control systems near Modena, Utah. This led to their microcode system, which is a microprocessor-based track circuit system now in service on the Norfolk & Western Railroad (7-12). It provides train detection as well as detection of broken rails and failed insulated joints. The device uses a single central processing unit (Motorola 6809). Exhaustive self-checks, such as wrapping the outputs back to the input so they can be checked, and interleaving diagnositc routines in the operating software are used to verify proper operation. Figure 1 shows a microcode unit.

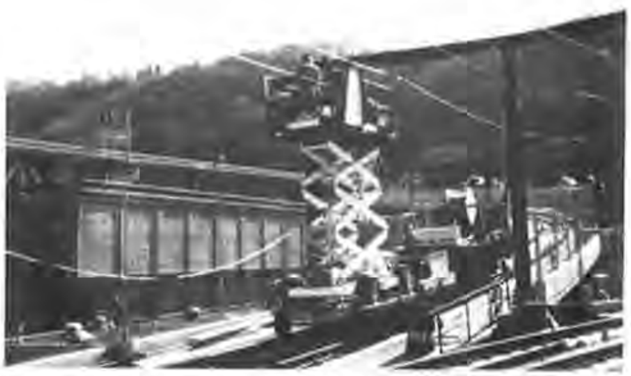

FIGURE 1 Microprocessor-based ATP equipment.

The General Railway Signal (GRS) Company is also marketing a similar device--the Trakode II. The safety of the device is assured through "safety assurance logic," a separate program running in the same central processing unit as the operating program (13-15 and General Railway Signal promotional material on safety assurance logic and vital processor interlocking). The safety assurance logic verifies that the inputs and outputs of the processor are correct and that the program is executed correctly. Inherent to the proper functioning of the safety assurance logic is the generation of checkwords. For the device to continue operating, new checkwords must be generated every processor cycle and appropriate tests passed. Otherwise, the device ceases operating and reverts to a state known to be safe.

Both GRS and US&S are extending microprocessors to interlocking circuits. The US&S device is called Microlok and the GRS device Vital Processor Interlocking. Both devices are now being demonstrated on railroads.

Microprocessors are also being used in non-safety-critical equipment. Here they control train operations and assist in transmitting large amounts of data from stations to a central point. Santa Clara is expecting microprocessor-based preemptive signaling equipment for grade crossings.

Brakes

Westinghouse Air Brake Division (WABCO) is providing a microprocessor-based unit to interface the train-line electrical signals and the friction brake control valves for the new Washington Metropolitan Area Transit Authority (WMATA) Breda cars (16). Two complete microprocessor units, which use the Intel 8080A central processing unit (CPU), are provided on each car. Each unit controls a separate truck.

Vehicle Information Systems

SEL has designed a new vehicle information system called Integrated Vehicle Information System or IVIS for short (17). Its purpose is to receive, process, and transit supervisory and information data for passengers and train operators. SEL has proposed that this equipment be used in LRT vehicles for the transmission and reception of digital data and voice information. The unit is based on an Intel 8085 CPU. As many as 32 items on board the vehicle can be controlled through one IVIS unit.

Propulsion

Westinghouse Transportation Division has supplied microprocessor-based propulsion control logic for several transit systems (18). These include Rio de Janeiro Metro, São Paulo Metro, Southeastern Pennsylvania Transportation Authority (SEPTA), Baltimore Metro, Miami Metro, Washington Metropolitan Area Transit Authority (WMATA), Vancouver Transit Authority, Niagara Frontier Transit Authority (NFTA), and Bay Area Rapid Transit System (BART). These microprocessor-based control systems operate power switching devices that in turn apply power or brakes; condition the train-line signal to provide smooth, jerk-free motion; operate the chopper thyristor circuits; and protect against abnormal conditions such as overcurrents. Early Westinghouse equipment was based on the 8-bit Intel 8080 CPU and later systems have been based on the 16-bit Intel 8086 CPU. Brown Boveri is supplying microprocessor-based propulsion control for the Portland light rail system.

Fare Collection

Microprocessors are being used increasingly in fare collection equipment. For example, the fare box system manufactured by General Farebox (Figure 2) uses a microprocessor to count coins or currency, display this amount, signal when the correct fare has been tendered, and allow the motorman to accept discount fares. These devices also permit more efficient collection of ridership data and revenue profiles, performance of audit trails, and preparation of management information reports. Because of its small size, microprocessor-based fare collection equipment can be easily installed on LRT vehicles.

Destination Signs

Destination signs (such as that used on the Baltimore Metro and provided by Luminator) are controlled

FIGURE 2 Microprocessor-based fare collection equipment.

by microprocessors (19). The memory circuit--Erasable Programmable Read Only Memory (EPROM)--displays specific messages or destinations based on preprogrammed data. Luminator has recently introduced MAX, which uses an Electrically Erasable Programmable Read Only Memory (EEPROM) (20). Such devices can be erased and rewritten without being removed from the circuit. This reduces the probability of lost, damaged, or incorrectly inserted EPROMS.

Vehicle Identification

Microprocessors are also used in equipment for train tracking and routing. On trains using such equipment, the motorman enters his run number and destination at the dispatch point before departure. At fixed locations along the route this information is transferred to a central control location by wayside receivers. There the information is processed so that the train position can be displayed to a central operator or used to activate track switches, or both. In the GRS equipment that performs this function, the microprocessor controls the transmission of interrogation pulses and radio frequency (RF) power to activate the on-board transponder and checks the received data for errors before passing it along (21,22). This vehicle identification equipment can also be used to activate an on-board annunciator system as has been done at Toronto. On the basis of information received from the wayside transponder, the on-board annunciator identifies the next station to the passengers.

TRENDS FOR THE FUTURE

The future of microprocessors in rail transit (both light rail and heavy rail) is well established. They are being used more and more in new LRT installations. At NFTA, the propulsion control equipment uses microprocessors. The new systems at Vancouver and London's docklands are two examples of the extensive use of microprocessor-based equipment for safety and operating functions. Microprocessor-based equipment for various safety-critical functions is being tested at the San Diego LRT.

Also, transit equipment manufacturers are changing their product lines to microprocessor-based equipment to remain competitive. When the useful life of existing equipment is reached, the cost of obtaining exact replacements will become prohibitive. New, microprocessor-based equipment will have to be purchased at this time. Thus such equipment will find its way into older LRT systems.

Further, there will be increased emphasis placed on having the latest technology when a question of potential liability is involved. Union Carbide is being sued for $15 billion as a result of a chemical plant leak that killed at least 1,600 people (23). The lawsuit says, in part, that Union Carbide "negligently failed to install [a] computerized early warning system" in place of existing electromechanical equipment. Transit authorities may find public opinion forcing the use of microprocessors instead of vital relays in safety-critical equipment such as ATP.

Technical societies and others are also addressing the evolution of microprocessors in transit. For example, the Institute of Railway Signal Engineers held an international conference in September 1984 on "Railway Safety Control and Automation Toward the 21st Century." More than 50 papers were presented; many of them addressed microprocessors. Topics included electronic interlocking, traction and control systems, data transmission and communications, track circuits, train detection and identification, and train control. A joint American Public Transit Association/Urban Mass Transportation Administration (APTA/UMTA) Microprocessor Liaison Board was recently established to address the concerns of U.S. transit authorities. Safety, reliability and maintainability, training, and electromagnetic compatibility were subjects addressed at the Liaison Board's first meeting in December 1984. Further technical meetings of this nature are being planned.

CONCERNS ABOUT THE INTRODUCTION OF MICROPROCESSORS

Transit authority personnel ask themselves three main questions when equipment that uses new technology is introduced to their system:

- How do I know that the equipment will operate safely and reliably?

* How do I maintain the equipment?
* How can I modify the equipment, if needed?

These questions create a set of concerns that must be alleviated for the new technology to be accepted. In the course of conducting the research for this paper, more than 40 such concerns relative to microprocessors used to control and monitor transit equipment were identified. This list is based on several items including work Battelle has conducted with transit authorities both in the United States and in foreign countries, discussions with transit and supplier personnel, reviews of reports and other printed material (manufacturers' brochures, equipment manuals), and technical seminars and sessions. A few of these concerns (and those believed to be most critical) are discussed next.

Single Versus Multiple Microprocessors

As previously described, some suppliers are designing (and have in operation) microprocessor-based vital circuits that use two microprocessors. They selected this configuration because it was believed necessary for safety. During the design process, it was hypothesized that, should a single microprocessor system be used, some hardware failures might result in an unsafe situation. Thus these suppliers selected a design that uses two microprocessors. In this configuration there is a fail-safe device that checks the outputs of both microprocessors. Assuming that the two microprocessors are completely independent and that all failures are detected, a single failure in either results in a fail-safe stop of the equipment being controlled. The upper half of Figure 3 shows one possible implementation of a multiple microprocessor system.

More recently, some suppliers have been designing single microprocessor systems and these are in operation also. These suppliers are relying on extensive built-in tests and other means of ensuring proper hardware operation. They believe that the probability of undetected hardware failures or software errors is acceptably low (24). One foreign-based supplier has concluded that one microprocessor may be used but two different versions of software made by two different programming teams are needed for safety (3,p.1007). The lower half of Figure 3 shows one possible implementation of a single microprocessor system.

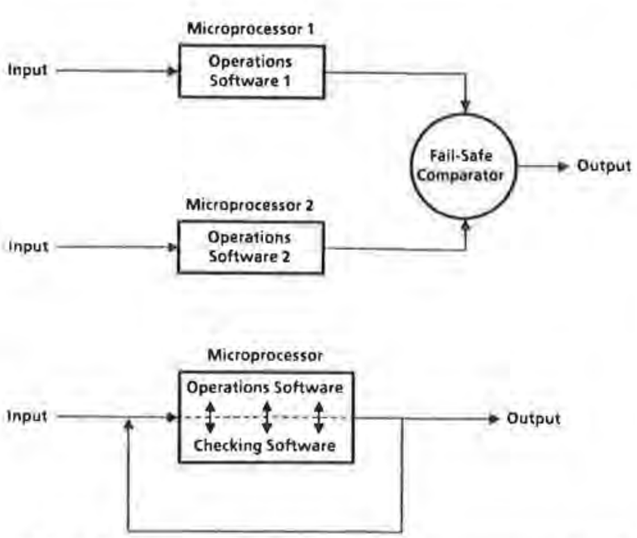

FIGURE 3 Conceptual multiple and single microprocessor-based equipment.

Obviously, each supplier is confident of the safety of their equipment. However, because different approaches have been taken, questions are being asked about the relative merits of each approach.

Safety Analysis Methodologies

In the past such standard analysis techniques as failure modes and effects analysis (FMEA) and fault-tree analysis were used to determine whether or not control systems using discrete components were fail-safe. Because the circuitry was based on single-thread designs and used discrete components, it was possible to perform exhaustive analysis of the effects of all plausible failure modes and, thereby, analytically determine the safety of the subject control systems with a high degree of confidence.

Today, however, the hardware in control systems is more complex. The use of integrated electronics makes it virtually impossible to perform a comprehensive FMEA of the system. Also, reliability data are usually available only on entire integrated circuits, which makes it currently impossible to calculate meaningful failure rates for individual circuits or functions. Further, not only has the analysis of hardware become difficult, but the introduction of computer technology has required the development of analysis techniques to ensure the integrity of the software. Software testing, analysis, and validation techniques have evolved out of years of research in computers and computer programming and, more recently, software engineering. But these techniques are not mature. Because, in some applications, the computer hardware is time shared to perform several functions, the complexity of any safety analysis is compounded. Finally, there is the issue of how to deal with the extreme interdependence of hardware and software. Traditionally hardware and software have been analyzed separately. Recent experiences with analysis of transit control circuits have indicated that hardware and software should be analyzed as a single entity. With the use of computer technology in safety control equipment the complexity of the safety analysis task has grown immensely and the tools the safety analyst should use are not clearly defined.

The Urban Mass Transportation Administration (UMTA) Office of Technical Assistance has a program directed at developing a methodology for such analyses. Figure 4 shows the activities planned in this program.

Lack of Data on Current Systems

Extensive data are available on the safety and reliability of current transit systems, but such data are collected at a high level only. That is, they reflect safety or reliability of the entire transit system rather than safety or reliability of specific subsystems and components (e.g., interlockings and vital relays). For example, an extensive data base on the safety of the vital relay as used in various applications is not readily available. When comparisons between the safety and reliability of more traditional equipment and the newer microprocessor-based equipment are desired, subsystem and component performance needs to be compared. More data at this level is needed.

Also, if it is assumed that the procuring transit authority wishes to specify safety quantitatively, the issue of defining what that number should be must be dealt with. Various numbers have been sug-

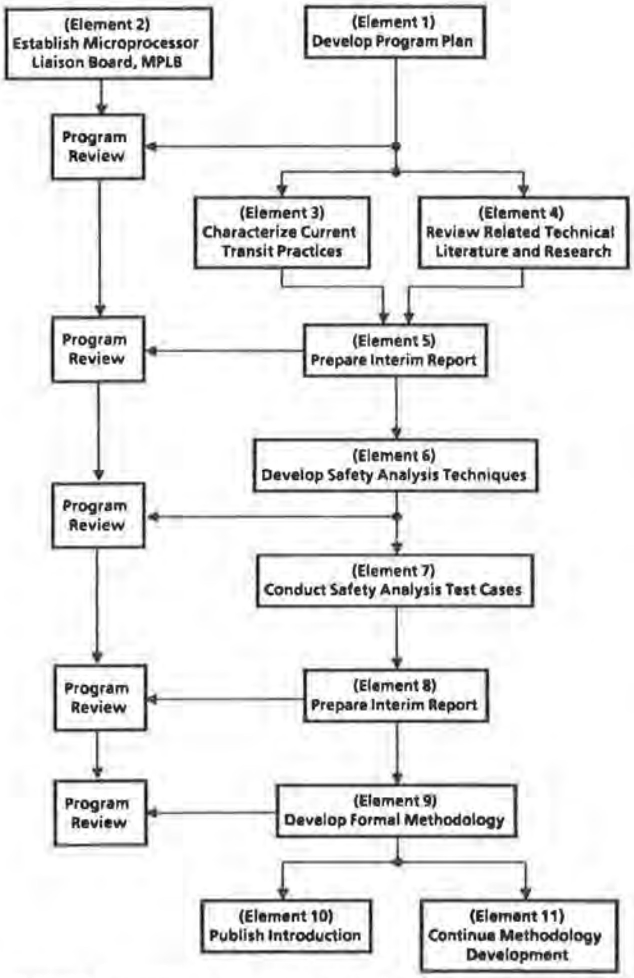

FIGURE 4 Program plan for development of a safety analysis methodology.

gested for safety-critical circuits and, as recently as March 1984 at the TRANSPAC 84 Conference, at least four different numbers were proposed. They are listed in the following table. The rate believed applicable to vital relays is also shown.

	Mean Time Between Unsafe Failures
Vital relay	1 million years
Microprocessor	10 million hours?
	250,000 years?
	1 billion vehicle-operating-hours?
	1 million years?

Obviously, agreement does not exist on a single number. Further, it is not clear whether such a number should be based solely on the failure rate of the equipment or should include the possibility of operating failures. More research is needed here.

Diagnostics

The more traditional failures are well known. Mechanical linkages break due to excessive forces and resistors become open circuits due to excessive power dissipation. But microprocessor-based equipment does not always fail in this conventional sense: The software in the microprocessor may contain errors that may remain hidden for some time. These errors may become evident only under a specific set of operating conditions. For example, the Baltimore Metro has experienced problems with their microprocessor-based supervisory control system. Equipment has ceased operating without evident cause (discussion at the first Microprocessor Liaison Board meeting, American Public Transit Association Offices, Washington, D.C., December 1984). After resetting the equipment, proper operation is restored. A software error could be the cause. Certain hardware failures may also remain undetected for an extended period of time.

Because of problems such as those just described, microprocessor-based controls may require the addition of built-in test or diagnostic equipment. This equipment (and the software programming that accompanies it) monitors the microprocessor and provides operating personnel and technicians with failure management and troubleshooting information. However, such additional equipment and complexity may result in a lower overall reliability than is obtained when the microprocessor is used without diagnostics. For example, in a recent study of an army helicopter using extensive diagnostic equipment to monitor helicopter operation, most aborted missions were due to the failure of the diagnostic equipment (25). Either the reliability of the diagnostic equipment needs to be greater than that of the equipment it is monitoring or a human must be given sufficient information to determine when the diagnostic equipment is faulty.

Further, the diagnostic equipment must also be able to discriminate between potential and imminent failures. Reaction to a potential failure may be allowing the train to proceed to the next station. On the other hand, notification of an imminent failure might require immediate cessation of vehicle operation. Thus microprocessor-based diagnostic systems can require relatively large computing power (compared to the equipment being monitored) and large amounts of memory.

Progress is being made with diagnostics in transit. Some present microprocessor-based propulsion control systems contain extensive diagnostic equipment whereas earlier versions did not. Further, WMATA has tested various ways of storing failure data on board the cars. However, these are only examples--diagnostic equipment has not been applied throughout rail transit. More attention to diagnostics could result in higher transit reliability.

Proprietary Data

Before safety analysts can make their review, they must obtain a detailed understanding of the equipment they are reviewing. This requires that the supplier of the equipment divulge the details of his design to the analysts. Some manufacturers have expressed reluctance to do so because they believe that exposing their design would destroy their competitive edge.

Specific approaches to handling this concern have been suggested. One is that the safety analysts review the supplier's data at the supplier's facility. This would require that the analysts spend considerable time (weeks and possibly months depending on the complexity of the equipment) at the supplier's facility. Another approach is that the materials be given to the safety analysts through a confidentiality agreement. This agreement, which is legally binding, binds the safety analysts to not disclosing the details of the circuitry. A third approach is a licensing agreement between the manufacturer and the procuring transit authority. This allows the transit authority (and its safety analysts) access to the detailed design information. All of these approaches have been used and have met with varying degrees of acceptance. More effort is needed to identify and evaluate other alternatives and to obtain an industry consensus on the preferred approach.

Documentation and Configuration Control

In the past suppliers of transit equipment provided detailed schematics showing the electrical configuration of their equipment. Such schematics were well organized and easy to follow and thereby facilitated troubleshooting and modification by transit authority personnel. However, now these electrical schematics do not always show how a microprocessor-based circuit operates; documentation on the software is needed. To date there have been instances in which the software documentation supplied with a new product was sorely lacking or delivered late, or both. For example, Miami, which started operations in the spring of 1984, does not have full documentation for their new rail cars. In other cases the documentation supplied has consisted of high-level flow charts (the equivalent of block diagrams for hardware circuits) without the details of the software implementation. Without complete and detailed documentation, maintenance and modification activities are extremely difficult.

Also, there is a concern that equipment configuration (that is, knowing exactly how the circuit is connected) is no longer readily obvious. In a hardware-based circuit, the wiring can easily be traced to determine connectivity of components. Modifications to the wiring were usually readily obvious. Now, however, personnel can make unauthorized modifications to the software. These modifications reside inside the microprocessor equipment and are not readily obvious. Possibly new configuration control procedures are needed.

Repair and Modifications

There are several issues that are central to concerns about repair and modifications of microprocessor-based equipment. This first relates to who performs the repairs. When repairs are needed, a transit authority can perform the necessary work in-house or outside under a separate contract. Each of these options has two suboptions. If the repair action is kept in-house, maintenance personnel can perform their activities at the printed circuit board level and leave identification and replacement of the failed part to an outside source. Or transit authority maintenance personnel can perform repairs at the part level. When equipment is sent outside the transit authority for repair, the authority can contract with the original equipment manufacturer or a contract maintenance organization. For all these options the two deciding factors appear to be assuring the safety of the circuit being repaired and minimizing the cost of the repair. One approach might be to have all part-level maintenance on vital circuits performed by the original equipment manufacturer. In this way the transit authorities' liability is minimized. However, this may not be the most cost-effective approach.

There is also concern about obtaining replacement parts. The technology of microprocessors is changing rapidly. The product life of new microprocessor components is approximately 10 years whereas the life of the equipment that uses the microprocessor is often 15 to 20 years. Thus transit authorities need sufficient information to be able to select alternative replacement parts when original parts are no longer available.

Transit authorities also need the flexibility to modify equipment as application needs change. With a vital relay-based circuit, this was relatively simple to do. Transit authority personnel could rewire the vital relay circuits yet leave the vital relay itself untouched. It is possible that a parallel might exist in microprocessor-based circuits. Here, equipment suppliers might separate the safety-critical components (hardware and software) from the non-safety-critical components. For example, the application software could be made separate from the safety-checking software. Transit authority personnel could change the application software as the application needs changed and leave the safety-checking software untouched. For relatively simple applications of microprocessors in safety-critical circuits this approach might be acceptable. However, for complex systems in which the microprocessor is performing several calculations using data that can take several states (for example calculating speed error on the basis of commanded and actual speeds) it might not be possible to separate the applications and safety-checking software. A different approach might be needed.

Finally, new and different skills are needed for technicians who must maintain or modify this new microprocessor-based equipment. However, several issues must be addressed first. Training programs (included classroom training and on-the-job training) need to be conducted. Further, existing labor agreements may prevent certain key personnel from maintaining microprocessor-based equipment and new labor agreements might need to be prepared. Also, qualifications and appropriate pay rates should be established for such personnel.

Environmental Aspects

Rail transit equipment is subject to electromagnetic interference (EMI); some sources of transit EMI are shown in Figure 5. Special techniques for measuring interference levels and mitigating potential EMI problems may be needed. Further, new microprocessor-based equipment must be able to withstand extremes in temperature and humidity, rough handling, and electrical shocks. For example, special maintenance techniques (e.g., rubber mats under technicians and special grounding circuits) are required when certain sensitive microprocessor components are being replaced. WMATA has experienced static electricity-induced failures of equipment during removal and replacement of printed circuit boards (discussion at the first Microprocessor Liaison Board meeting, American Public Transit Association Offices, Washington, D.C., December 1984). Training for technicians may be needed.

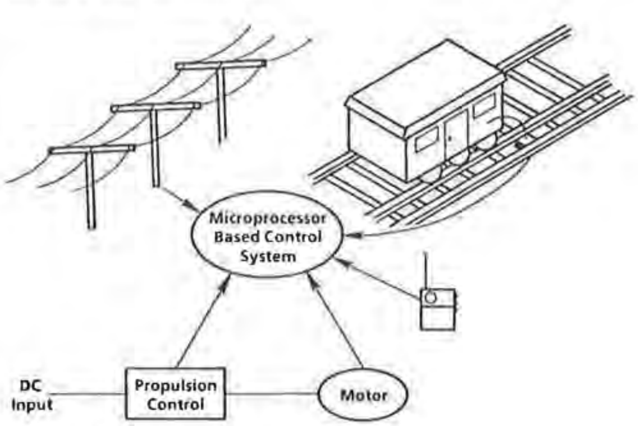

FIGURE 5 Sources of transit EMI.

SUMMARY

The present and future uses of microprocessors in transit have been described and the concerns expressed by transit industry personnel about their introduction have been identified. Further discussions and research on several of these concerns need to be conducted. Microprocessor-based control equipment also needs to be implemented in test settings on operating transit systems and its performance monitored. Such efforts will ease the introduction of this new technology and prove its safety and reliability in operating environments.

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