# Research Directions in Computer Networking for Manufacturing Systems[1]

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*This paper identifies and discusses pertinent research problems in the design and development of communication networks for Computer-Integrated Manufacturing (CIM). The conclusions and recommendations presented here are largely the outcome of the workshop on Computer Networking for Manufacturing Systems [1]. The workshop was conducted in November 1987 under the sponsorship of the division of Design, Manufacturing and Computer Engineering of National Science Foundation. Both basic and applied research in computer networking for integration of all manufacturing-related functions is recommended in three general areas of efficient networking architectures, accommodation of equipment and environmental heterogeneity, and distributed network management and control.*

## I Introduction

In view of the worldwide competition for productivity, research in computer-integrated manufacturing (CIM) has a major impact on the infrastructure of our national economy. Computerization of office and factory operations and engineering design tools has created islands of automation in the current state-of-the-art of manufacturing technology. The ultimate goal of CIM is to integrate the production processes, material inventory, sales and purchasing, administration and accounting, and engineering design information into a single, closed loop, and interactive control system. Essential to this distributed total manufacturing system is an integrated communications network over which the information leading to process interactions, status checking, and plant management and control will flow. The architecture and performance of the network that interconnects these diverse functions are of paramount importance to the efficient and reliable operation of CIM processes. Lack of interoperability, reliability, and flexibility in the network design can cause chain reactions of delay and congestion resulting in loss of control of safety and productivity. Research in computer networking should be oriented with the objective of significantly improving productivity and quality in manufacturing by eliminating the inefficiency of manual actions.

In November 1987 the division of Design, Manufacturing and Computer Engineering of National Science Foundation sponsored the workshop on Computer Networking for Manufacturing Systems to assess the state-of-the-art, identify and characterize research needs, and to recommend directions for future research in CIM networking. This paper describes pertinent research topics which were recommended by different specialist groups in the workshop.

The paper is organized in four sections including the introduction. Section II discusses general problems in CIM networking. Section III identifies five broad areas and provides recommendations for research in these areas. Summary and conclusions are given in Section IV. A short bibliography of related research publications is attached in Appendix A.

## II CIM Networking Requirements

The general requirements which distinguish CIM networks from other applications can be broadly classified into the following three areas: (*1*) Efficiency and Flexibility of Real-Time Multi-Process Communications; (*2*) Accommodation of Equipment and Environmental Heterogeneity; and (*3*) Distributed Network Management and Control.

**Efficiency and Flexibility of Real-Time Multi-Process Communications.** Although the technology of computer networking is quite advanced, its specific application to CIM has not yet been well characterized. A large body of analytical research exists in the general area of network control and communications, focusing on modeling and performance analyses as well as on designing flexible systems for accommodating future growth. However, it seldom addresses the needs for real-time communications between the factory floor equipment such as multi-robot and multi-machine systems where delays (even of the order of tens of milliseconds) could disrupt the process, resulting in loss of production time and product quality. Formal characterizations and modeling of the entire manufacturing process will lead to efficient network architectures which provide operational flexibility and rapid error recovery.

**Accommodation of Equipment and Environmental Heterogeneity.** The computerized equipments for autonomous manufacturing, engineering design, and office management may have their own individual control

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languages, data structures, and operating systems which are not mutually compatible. The problems of incompatibility can be partly handled by adopting a standardized layered network architecture whereby individual computers can communicate to peer level counterparts in their own languages. To this effect the seven-layer Manufacturing Automation Protocol (MAP) [2] and Technical and Office Protocols (TOP) [3] are under development as standards for factory and office automation, respectively. Furthermore, the U. S. Government Open Systems Interconnection Profile (GOSIP) Federal Information Processing Standard (FIPS) [4] is compatible and interoperable with MAP and TOP. There are, however, potential problems and many unresolved issues in the interoperation of office and factory communication protocols, which require systematic anaytical and experimental research.

**Distributed Network Management and Control.** Since the objective of CIM is to unify the administrative, engineering, and manufacturing processes, the management and control functions of the integrated network must be designed to support the distributed organizational structure. The network should serve as the essential communication link for overall management of the integrated manufacturing process and, at the same time, provide a certain amount of autonomy within local areas. The CIM network must continuously adapt to environmental changes resulting from design modifications and reassignment of manufacturing processes, market demand, movement of people within the organization, introduction of new equipments, and malfunctions. Therefore, the management and control functions should be formulated on the basis of (*1*) the design specifications of equipments which the network integrates, (*2*) the users' needs, and (*3*) the general operating environment.

In order to provide timely communications between a large number of heterogeneous processes in a dynamic environment, the network management and control system must be aware of the status of all available resources over which decisions have to be made. These decisions include efficient utilization of resources in situations of competing demand as well as detection, isolation, and recovery from failures. This can be achieved by incorporating human expertise into automated network management tools to diagnose, monitor, and dynamically adapt to failures or planned changes in the CIM environment. The principal benefits of applying artificial intelligence (AI) techniques to network management and control are the abilities to (*1*) handle problems with ill-defined characteristics and (*2*) assimilate and integrate information from a variety of heterogeneous sources. Conventional techniques such as simulation experiments and capturing programmed rules and heuristics would not be appropriate for knowledge acquisition unless sufficient expertise about network management is developed. Under these circumstances the machine learning approach which does not rely on heuristics could possibly provide solutions to prototypical problems.

Another major concern, as networks provide electronic access to sensitive databases from remote nodes, is the security of the data. This concern cannot be overemphasized in considering CIM network architectures. Technological advances being made in the banking and defense applications should be utilized to protect the information that traverses the CIM network.

## III Research Problems in CIM Networking

Research in CIM networking should be oriented with the objective of vastly improving productivity and quality in manufacturing for a wide cross-section of industry by eliminating the inefficiency of manual actions in the loop and utilizing human resources outside the manufacturing process for management of the process.

Five major research areas in CIM networking are identified below. Problems requiring basic or applied research are presented in each of these major areas.

**Research Area 1: Specification and Analysis of Network Protocols.** Technologies and tools are needed for development of CIM network protocols to assure transparent communications between heterogeneous processes and to allow for exception handling without disrupting any real-time operations. Therefore, protocols are to be specified in view of requirements of the processes that are served by the network, and these protocols must be analyzed to verify whether the specified requirements are indeed satisfied. This should be done prior to implementation and testing.

**Specification.** Research needs in the area of specification fall into two broad categories. First, there is a need for good descriptive techniques that can model protocols, environments, and requirements. To study the network protocols in a manufacturing environment, each of these components need to be specified in a common descriptive language. The second broad area in which there is a need for further research is design or architecture, i.e., how to build a description of the integrated system. For example, to study issues of network protocols in a new automated factory, it is necessary to have: (*1*) a model of the factory environment including the requirements for its operations, and (*2*) a network architecture. Research in the area of protocol specification essentially emanates from the need to develop the formalism for capturing the design and architecture of an integrated manufacturing system.

Since time critical operations are important in a manufacturing environment, the modeling tools should be able to explicitly refer to time in the model and make decisions based on passage of time. As an embedded part, non-time-critical behavior should also be modeled. The operational aspects of design require more research into the issue of levels of abstraction. It is possible to model the CIM system at several levels and relate these levels formally—that is, the integrated system software can be constructed from more basic components, much as hardware is constructed today.

Many classical disciplines in which research work has been done (or is being done) could be useful in exploring powerful and expressive models. Specification techniques, as used in large-scale computer systems, provide the ability to model parallelism and coordination which are essential for describing integrated manufacturing processes. The area of logic and temporal logic is another example. Discrete event simulation captures one type of specification. A fairly powerful paradigm that could be explored is the condition/action approach from artificial intelligence.

**Analysis.** The classical techniques for protocol analysis, such as finite-state modeling, Petri net modeling, and discrete-event simulation, are largely independent of the characteristics of any particular network. However, an increasingly common view is that analysis of a system must be integrated with the specifications. That is, there should be a common environment in which both specification and analysis can be carried out. This is a fertile research area for protocol analysis for all types of integrated networks.

First, there is functional or logical analysis. The question one asks is *does it work?* That is, a major problem is simply ensuring that the protocol works. In this regard, one could investigate ways for sanity checking, i.e., verifying the specifications that would check the self-consistency of the description. This might be a compiler that could look at the static description of the protocol and decide if there is any inconsistency in the description. Similarly, it should be possible to analyze the protocol description to check if it meets the minimal requirements. Analysis could be iterative in which the model description and analysis tools aid in checking more and more elaborate constraints. Research could be done in the area of proof checking in the sense that a suggested proof that the system meets given requirements could be provided. The analysis tools would then aid in checking if the proposed proof makes sense. This is related to work on liveness and safety in protocols which are critical for reliable communications within a CIM network.

The second component is performance analysis. The question one asks is *how well does it work?* Research in this area would be related to measuring and observing a system that is composed of the network and the manufacturing environment. Generally, performance tools for evaluating a protocol or an architecture consisting of several protocols have relied on external analysis of simulation runs. It should be possible to embed more of the observation task into the description of the model itself. This might also yield insight into how to modify the system description if it does not meet performance constraints. An aspect of research is to see to what extent the performance analysis can be done concurrently with the operation of the system, without incurring any penalties due to the observation.

The third component related to protocol analysis is understanding the impact of exceptions. The tools should be able to treat such incidents as breakdowns and fault conditions. For example, a research problem is to determine where the fault lies once an exception has been raised.

Finally, tools are needed for integrating the results of analysis at various levels of protocols. These tools would also be useful for analyzing critical parts of the integrated network. This is related to being able to describe the specification in a hierarchic fashion. The tools should make it convenient to analyze a given system at several levels of detail.

Appropriate analysis tools depend on the particular specification approach. Once such an approach has been adopted, the area of software engineering offers many insights into better tools. As analysis becomes more complex due to the complexity of the system, more work needs to be done on software that can provide high-quality input/output to the system.

**Research Area 2: Testing and Standardization of Network Protocols.** Testing and evaluation of protocols can be either *model-based* or *implementation-based*. The model-based approach is viewed as an extension of protocol analysis and can be carried out as a continuation. The implementation-based approach is essentially product-oriented and has the following test objectives.

*Interoperability*: This ensures that the product indeed interoperates with the manufacturing environment.

*Conformance*: This ensures that the product conforms to the specification, thereby increasing the confidence in interoperability.

*Performance*: This ensures that the product meets the expected level of performance.

Reseach in this area is *applied* in nature and is essential for standardization of protocols. Topics are discussed below.

**Interoperability Testing.** Success of many critical operations such as exception handling and distributed database management is contingent upon interoperability between host processes in the network. Since interoperability is not defined precisely, it cannot be quantified by developing an accurate measure. Also since it is not a transitive property, each potential pair of processes that need to communicate with each other must be tested for interoperability.

Complete testing for interoperability in a large manufacturing system may not be possible. Development of analytical methods for evaluating interoperability and its testability is a major research area.

**Conformance Testing.** The concept of conformance is closely related to that of interoperability but conformance testing procedures are more complex than those for interoperability. A major problem in conformance testing is to develop methodologies for handling exceptions. There is also a need for fundamental research in the area of provability and verifiability of logical properties of the interoperability and conformance test tools.

Since conventional techniques like finite-state machine modeling may not be applicable to interoperability and conformance testing, a probabilistic approach appears to be a good choice. This is particularly true for an integrated network system.

**Performance Analysis of Integrated Networks.** The performance criteria for integrated network systems vary with different user requirements and viewpoints, e.g., functional requirements at the system level and equipment level are significantly different. Typical research areas for network performance analysis are modeling of workload and control variables, selection of configurative variables and parameters for MAP/TOP modules, and optimal design of ISO/OSI functional modules.

Data distribution among heterogeneous sources in the CIM environment has a major impact on network loading. Modeling of network loading requires decomposition strategies for defining basic network management and control functions. Since the structure of function/data modules could significantly influence network performance, research efforts should be focused on topological decomposition of the network into subnetworks.

**MAP and TOP Specifications.** The future MAP specifications could be largely influenced by the outcome of research in the following areas: (*1*) redundancy for enhanced system reliability; (*2*) capability to meet the needs for CIM evolution; (*3*) priority options and scheduling of tasks within protocol modules; and (*4*) real-time operations.

Implementation of TOP in transaction processing in manufacturing environments is a general research area. Examples of specific problems are distributed/remote database access, forms mode in virtual terminal protocols, and network security.

MAP and TOP have similar architectures with the exception of the medium access control (MAC) layer and the application layer. The MAC layers protocols are designed to be different because of the different traffic characteristics in the factory and office environments. The application layer protocols in MAP and TOP are discussed under user services.

A potential problem in interfacing MAP with TOP lies in the exact implementation of the two MAC protocols (developed by different manufacturers) at the bridge. This difficulty can be circumvented by a hybrid link-layer protocol which does not require any bridges for interconnecting factory and office communication networks. The research in this category will enhance integration of MAP and TOP with other standard (such as, SNA and DECNET) and nonstandard architectures.

Fiber optic communication media with very high bandwidth capacity could accommodate heterogeneous network traffic such as data, voice, video, and facsimile to be transmitted over the same medium. This justifies research for improving the existing MAC layer protocols in MAP and TOP.

**User Services.** It is generally agreed that user services are a major research issue in the development of application layer protocols. Simple software links may not be adequate for accessing these protocols but object-oriented languages could be very beneficial. In that case, appropriate compilers must be developed to conform with the needs of specific CIM applications. This is deemed essential for handling distributed database systems.

The role of forms made within the virtual terminal protocol is an important issue as future extensions beyond the current languages and graphics, as used in TOP and MAP, may load the imaging specifications. There is also a need for developing a common language at the equipment level since the relay ladder logic used in programmable logic controllers (PLCs) is often the only way to interface with heterogeneous equipments.

**Human Factors.** Industry is faced with ever increasing complexity of equipment and diminishing human resources to manage and maintain automated systems. Researchers should consider human factors, training of personnel, and organizational design.

**Research Area 3: Lightwave and Wireless Communication Media.** Local wireless communication in manufacturing plants is necessary when terminals are mobile. Problems that arise when radio communication is used for local communication in plants are caused by the multiple access and broadcast properties of the medium as well as by its regulated nature. These problems manifest themselves as severe degradation of the quality of the link (in terms of bit-error-rate, bandwidth, delay, power, etc.), and are caused by multi-path and other user interferences. Techniques used to overcome these problems include:

(*1*) Spread spectrum signaling
(*2*) Infrared communication
(*3*) Antenna diversity
(*4*) Improved modulation and pulse shaping, and
(*5*) Dynamic assignment of the communication channel capacity.

It turns out that the architectural and functional design of a manufacturing plant can have a significant effect on the quality of the wireless communication that can be achieved. The building structure affects the radio communications in a manner similar to theater acoustics. The spatial configuration of the terminals used in the manufacturing process can also have a dramatic effect on the interference levels. Finally, care in the job scheduling can considerably reduce the maximum bit rate needed for interterminal communications.

The main advantage of wireless communication is mobility. Both radio and infrared transmission are currently used for wireless communication in manufacturing applications but interference and multi-path effects limit the scope of applications. The key research issues in mobile communications for manufacturing are:

> *Radio Communications in Manufacturing Environment:* The initial factory layout can be adapted to the characteristics of radio and infrared transmission in order to reduce shadow areas where transmission is poor. In a closed environment, attenuation and fading can be reduced appreciably if the factory architecture is properly chosen. Research is needed to develop architectural design rules which will minimize the effects of architecture on radio and infrared transmission. In addition, location of factory machinery can have major effects. Factory layout recommendations with quantitative predictions of multi-path, attenuation, and fading characteristics are needed.
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> *Incorporation of Communication Issues into Manufacturing Architecture:* Modeling is necessary for characterizing the properties of statistical channels. It also provides measures of the effects of electromagnetic interference due to stationary components like machine tools and computers, and mobile components like robots, automated guided vehicles, and human beings.

An important research issue is interference effects resulting from multiple accessing by mobile users. Protocols that are currently used for accessing networks are designed for general communication systems and do not consider the special requirements of manufacturing applications.

Another important research topic is determination of modulation and coding techniques to allow for bit-rate increase and reduction of interference and multi-path phenomena.

Lightwave communication using optical fiber as the transmission medium has many characteristics which are well-suited to the factory environment. The fiber medium has low transmission loss, is resistant to electromagnetic interference, resists corrosion, and is easily maintained. In addition, since it does not carry current, it would not create sparks in explosive environments and does not cause ground-loop problems.

The characteristics of electro-optic components used in conjunction with fibers impose certain limitations on the network architectures to be implemented in a factory environment. Some of these restrictions are fundamental to the medium while others are transitory and are due to the state of development of the optical components.

**Fiber-optics in Manufacturing Systems.** Continuing research is needed into the topologies best suited for use in manufacturing system networks because the characteristics of available electro-optic components are changing so rapidly that optimum topologies must be reevaluated regularly. The relative performance of star, ring, and bus topologies in manufacturing systems is also strongly affected by the medium access protocols. The access protocol used in MAP does not apply the available high fiber optic data rate efficiently and therefore new access protocols need to be considered. In addition to high data rates, these access protocols might also require a different topology to work most efficiently. In particular, improved lower layer protocols are needed to provide adequate real-time performance.

**Considerations for CIM Networking.** The optimum use of computer networks in manufacturing systems will require an interdisciplinary approach in order to optimize the interaction of manufacturing process components with message volume and communication connectivity. It is important to properly include the effects of lower layer protocols on the delivery of upper layer services. This means that chemical, electrical, industrial, and mechanical engineers' expertise should be combined in research on issues which involve finding cost-effective trade-offs among protocol layers for network communication in factory applications.

**Research Area 4: Real-Time Communications, Control, and Fault Tolerance.** Although communication networks involving multiple computers offer enhanced flexibility in real-time distributed control of manufacturing operations, they are accompanied by induced complexities like data latency, mis-synchronization, loss of data due to network failures, noise contamination and buffer saturation, etc. Product quality and operational safety in manufacturing systems could be seriously degraded unless these phenomena are adequately understood and appropriate actions are taken. Analytical and experimental research is needed to resolve these problems for manufacturing system automation.

**Network-Induced Delays.** In distributed data communication and control systems, network-induced delays occur in addition to the sampling and data processing delays that are inherent in all digital control systems. The impact of network-induced delays on dynamic performance and robustness of real-time control systems need to be investigated for computer-integrated manufacturing.

Data latency in computer networks is randomly varying as it is dependent on the intensity and distribution of network traffic and specific characteristics of the protocol. Therefore, conventional frequency domain techniques that are used for linear time-invariant systems are not applicable to these systems which are subject to time-varying delays. Under the present state-of-the-art, combined discrete-event and continuous-time simulation techniques are suitable for understanding and verifying the characteristics of network-induced delays as well as their impact on performance and stability of control systems. Techniques for interpolating and extrapolating useful information from simulation results at selected operating points need to be developed. An example is the perturbation technique for discrete-event system simulation.

In addition to the simulation tools, rigorous analytical techniques are required for analysis and design of real-time control systems that are subject to network-induced delays because extensive simulation runs could be expensive and may not prove to be the exhaustive means for assuring stability and robustness. Application of advanced analytical techniques such as those cited in Appendix A should be investigated.

**Time Synchronization of System Components.** Time-varying data latency coupled with mis-synchronization between system components could have a devastating effect on both performance and stability of real-time control systems. It is important to note that this synchronization is between the network system components and is, therefore, relatively loose compared to that required for internal operations of tightly coupled computer systems.

In order to circumvent the above problem of mis-synchronization between system components, several methods such as time synchronization and time-stamping based on global clocks could be applied. However, in distributed real-time applications, it may not be easy to implement and maintain accuracy of global clocks in physically dispersed system components. An alternative is periodic transmission of the synchronization message which carries a special bit pattern instead of time values. As soon as a synchronization message is received, system components reset their clock to a predetermined value. Effectiveness and reliability of existing methods should be investigated along with the development of new techniques.

**Fault Tolerance.** Both communication and control systems must be fault-tolerant as their functions are critical for real-time operations in a manufacturing environment. Efficient and reliable methods for fault detection, isolation, and reconfiguration (FDIR) should be studied by considering various aspects such as the degree of fault-tolerant functions. Fault diagnosis implies not only finding the erroneous component but also determining the cause of error. Isolation of the faulty components should not affect the performance of other normally functioning components, and must allow the system to operate in a gracefully degraded mode. Error recovery/reconfiguration may be achieved by time redundancy and/or space redundancy, (e.g., by installing redundant buses, network terminals, and processors).

**Task Assignment and Message Scheduling.** These are critical in real-time systems. Each task should be properly scheduled so that an intra-workcell process completes its operations in time. Also the message should be scheduled such that the throughput is maximized and the data latency is minimized. Different workcells may have different message scheduling patterns according to their performance characteristics. For example, an inner control loop with fast dynamics has to sample their data fast. On the other hand, a control loop which has slower dynamics does not have to sample its data frequently. Since the network environment is not static, message scheduling and task assignment should be performed dynamically. These problems may not have direct analytical solutions and it is usually difficult to solve them numerically; therefore heuristic approaches need to be developed.

**Message Prioritization.** Individual workcells may have different priorities which could vary with time according to their functional characteristics. On the other hand, station management messages such as a synchronization message or a fault-recovery message must be transmitted as soon as possible and should have a higher priority than others. However, the notion of a priority scheme is not well defined for real-time applications partly because there are not many systems in operation and the impact of priority of a message upon the system performance is not well understood. Therefore, research efforts should be devoted to find out what difference a priority scheme can make.

**Real-Time Programming Languages.** One of the key aspects for networking in the manufacturing environment is the ability to model time appropriately. As time-critical operations are very important, the meaning of real time needs to be defined in a formal way. Thus, standard programming languages that do not have the capability of modeling time explicitly may not be suitable. On the other hand, many operations in this environment might not care about real time, and so everything should not necessarily be slaved to real-time clock(s). Periodic operations, such as those in an assembly line, are an important component in manufacturing, and this again relates to how time is handled. Similarly, the notion of priorities and being able to interrupt an on-going operation is a question of properly handling the *real-time* problem.

**Research Area 5: Network Management and Control.** The research topics in management and control of CIM networks are discussed below.

**Network Control Center (NCC) Architecture.** A critical factor in maintaining control of automated manufacturing processes is its ability to support real-time communications between physically dispersed and functionally distributed elements including engineering design, product distribution, and customer interface. Network management and control, in this context, provide dynamic monitoring and allocation of available communication resources among competing heterogeneous nodes. The CIM network manager should be aware of the status of these resources and, on the basis of this information, must make appropriate decisions. The policies that these decisions implement are derived from the design specifications of the equipment, performance criteria, characteristics of the users' requirements, and the real-time operational environment.

In the dynamic environment of flexible manufacturing systems, the same robot, machine tool, or intelligent CIM terminal may be assigned to different manufacturing processes. The common equipment could be interconnected by a reliable high-speed network which facilitates dynamic reallocation of resources. A centralized network control architecture for this environment may not be cost effective. On the other hand a totally distributed network control center (NCC) may itself generate enough traffic to degrade the overall performance of the network. A suitably distributed network control architecture needs to be developed as an optimal choice for the CIM environment.

**Fault Management.** Managing faults is an essential function of manufacturing system networks. In the CIM environment, the network must be designed to communicate the failure information for both manufacturing components and network elements. The management and control of a large network from a remote control center is an area that incorporates both fault analyses and quality control. This is especially important in an integrated production environment where one failure can cause chain reactions of delay and congestion resulting in loss of control of safety and productivity. Characterization of instabilities in manufacturing networks is recommended as a major research area which would lead to realistic error models.

The traditional AI approach to fault diagnosis is not always effective in automation tasks, even at a preliminary level, which rely on dissimilar sensory activities. A viable alternative is the neural network [5, 6] which is rapidly gaining importance in diverse disciplines and particularly in situations that require multi-sensor data fusion [7]. A neural network is a parallel processing architecture where knowledge is represented not only algorithmically in individual processors but also in terms of connections between these processing elements. Research in formulation and resolution of the fault management problems, in terms of neural network implementations, has a potential for enhancing reliability and flexibility of CIM network operations.

**Performance Management.** Performance measures for manufacturing networks are not well characterized. Identification of these performance parameters along with other typical parameters like throughput and data latency is essential for establishing acceptable network performance criteria on the factory floor. The network control center design can then be enhanced to monitor performance and bring performance improvement activities on-line whenever the performance degrades to unacceptable levels.

**Adaptive Resource Management.** Flexibility in a fully automated manufacturing plant may often require physical or logical reconfiguration of the integrated networks. Resource modules specific to different manufacturing environments need to be developed for optimal utilization of the factory equipment. A fully automated manufacturing facility is highly dynamic in nature due to rapid changes in network traffic and operational requirements. To this effect systematic research is needed for developing station management functions which could extend from the link layer up to the application layer.

**Network Security.** Communications between databases for manufacturing and marketing via a distributed network provide potential access to this information base by any user of the network. Security of this sensitive data is a major concern. Access control, encryption, authentication of the users, and formal verification of software are some of the techniques which have been developed and implemented by defense and commercial networks to deal with the problems of network security. An example is the *Network Security Evaluation Criteria* that are being developed by the National Security Agency. Transferring this technology from the defense and commercial sectors to the manufacturing sector is an important research topic.

**Network Operator Issues.** The network control operator in the CIM environment will need real-time access to distributed network control information which might only be available at distinct physical locations in possibly incompatible databases. Also, the operator must respond to and track all the status and alarm information. The complexity of this information, and the need to respond to failures and reconfiguration requests has recently instigated research in the areas of:

- Distributed Database Access
- Data Compression, Fusion, and Display
- Intelligent Computer-Aided Instructions

The use of artificial intelligence techniques for design automation, knowledge capture, and self-learning is a fertile area of research. The use of natural language voice interface for access to distributed databases and to input network control commands is a promising area for simplifying human interfaces to a diversified CIM network management and control system.

Another important area of research is the design of the network operator's console which receives and displays status and alarm data from all elements of the network. Rule-based techniques to diagnose faults remotely and to make inferences from correlations in reported alarm conditions can be incorporated in the operator's console to reduce human labor.

## V Summary, Conclusions, and Recommendations

Although networking is essential for providing reliable communications between heterogeneous functions in computer-integrated manufacturing (CIM), research in this field is not yet established. The paper identifies pertinent research problems and discusses research topics as well as provides recommendations for research in several areas of CIM networking. The materials, presented in this paper, are expected to be useful for enhancing both basic and applied research in computer networking for manufacturing systems.

Problems of CIM networking have certain similarities with those encountered in other applications including defense and commercial communications. Therefore, programs of national importance like battle management, communications architectures for air/space defense, and integration of commercial information services may directly benefit from CIM networking research and vice versa. An efficient approach to achieving the goals of CIM is to: (*1*) formulate the manufacturing system network specifications and select pertinent problems for collaborative research between universities, industry, and government institutions, and (*2*) transfer technology from the military and commercial worlds for resolution of common issues.

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# APPENDIX A

## Bibliography of Research Materials in CIM Networking

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