Bibliographic Information

Vadde, S., Kamarthi, S. V. and Gupta, S. M., "Modeling Smart Sensor Integrated Manufacturing Systems", *Proceedings of the SPIE International Conference on Intelligent Manufacturing*, Providence, Rhode Island, pp. 30-37, October 29-30, 2003.

Copyright Information

Contact Information

Dr. Surendra M. Gupta, P.E.
Professor of Mechanical and Industrial Engineering and
Director of Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, U.S.A.

(617)-373-4846   *Phone*
(617)-373-2921   *Fax*
gupta@neu.edu   *e-mail address*

http://www.coe.neu.edu/~smgupta/   *Home Page*

Modeling Smart Sensor Integrated Manufacturing Systems

Srikanth Vadde, Sagar V. Kamarthi[*], Surendra M. Gupta
Department of Mechanical Industrial and Manufacturing Engineering
Northeastern University, 360 Huntington Avenue, Boston, MA 02115

ABSTRACT

Smart sensors and their networking technology when applied in manufacturing environment for monitoring, diagnostics, and control and for data/information collection could dwarf all the advances made so far by the manufacturing community through traditional sensors. Smart sensors can significantly contribute to improving automation and reliability through high sensitivity, self-calibration and compensation of non-linearity, low-power operation, digital pre-processed output, self-checking and diagnostic modes, and compatibility with computers and other subsystem blocks. There is a huge gulf between the existing models of manufacturing systems and the computational models that are required to correctly characterize manufacturing systems integrated with smart sensor networks. This paper proposes a multi-agent model for S^2IM system. The agent characteristics and the expected model behavior are presented.

Keywords: Intelligent manufacturing system, smart sensors, multi-agent model

1. INTRODUCTION

The modern manufacturing system is a complex network of workers and machines interacting in a multitude of ways. Models of manufacturing systems are needed to study the effects of workers, machines, and their interactions and to develop validation and verification techniques. The other drivers for modeling manufacturing systems are the need for high quality products and demand for a steady flow of information in the manufacturing system. It is important to model and simulate manufacturing systems to study their behavior. Many existing models in literature are restricted to theory and only a few have really been implemented in practice. Models that truly capture the behavior of manufacturing systems are difficult to develop, implement, and maintain[1].

1.1 Traditional Sensors

A sensor is a device that is capable of responding to a stimulus and produces an electrical signal that corresponds to the stimulus. It is typically made of a sensing element and an electrical circuit to sense a stimulus and provide a measure of the stimulus as output. Traditional sensors provide output signals which have to be interpreted further to understand what the sensors are registering.

1.2 Smart Sensors

A smart sensor is one which consists of a sensing element, a signal processor, and a microprocessor all coupled into a single system. The characteristics and functionalities of a smart sensor are listed below.

- Smart sensors are capable of performing information processing locally. This feature is normally absent in traditional sensors. When conflicting observations are sensed by either an individual smart sensor or different smart sensors, they are capable of choosing the correct observation.
- Through a network, smart sensors can communicate and receive signals (real-time data) from other smart sensors in the network, make collective decisions, distribute tasks among themselves, and set common goals for the entire network[2]. Smart sensors commonly use a multi-drop bus system for communication.
- Smart sensors can convert analog sensor signals to digital signals and make amends for non-linearities arising because of A/D conversion of signals.

---

[*]Correspondence – e-mail: sagar@coe.neu.edu; phone: 617-373-3070; fax: 617-373-2921

- Smart sensors are expected to enhance the communication network design flexibility and lessen the burden on centralized servers.
- Smart sensors are capable of self-diagnosis and self-calibration[3]. They can periodically perform tests on important internal sensor elements and suggest any preventive maintenance necessary and/or the deployment of a new sensor to replace a faulty one. The sensors in the network can recalibrate themselves to incorporate changes in the network (for example when a new sensor is added). That means there is no need to manually enter sensor parameters; instead the calibration can be performed automatically by the on-board memory chip placed in the sensor[4].
- Re-programmability of smart sensors facilitates remote software updates in order to incorporate new processing and maintenance techniques. This feature allows updates to the system with minimum operational disruption and hardware changes[5].

Advantages of smart sensors as reported by Ranky[4] are as follows: (a) elimination of sensor look-up tables, (b) elimination of cable connection errors, (c) location identification, (d) instant transducer substitution, (e) full scale output automatically matched to A/D converter, and (e) improved product quality and shortened market timing.

2. ADVANTAGES OF SMART SENSORS IN MANUFACTURING

The advantages of smart sensors in manufacturing can be found in three categories, process monitoring and diagnostics, condition based monitoring, and product quality monitoring.

2.1 Process monitoring and diagnostics
The main role of sensors in process monitoring and diagnostics is to monitor the condition and parameters of a process being performed on the machine. The sensor should be able to recognize any deviation from the normal process parameters and take necessary control action.

With smart sensor network, each machine in the shop floor can be monitored in real-time. If the network is web-based, then each machine's status can be monitored anytime, anywhere, anyplace to improve the manufacturing processes and to enhance the self-diagnostic and reporting capabilities for production and quality control.

Because prognosis of machine failures is possible through smart sensors, the limitations of diagnosis can be overcome. Diagnosis only provides possible reasons for machine failure after it has already occurred, whereas prognosis predicts the possible machine failures in advance. The latter allows one to perform preventive maintenance on the machine to avoid machine failures. Smart sensors periodically monitor the condition of the machine by analyzing the data obtained from the sensing element. An on-board microprocessor, which analyzes the data, makes decisions as to when to take corrective action to avoid machine or plant failure. In a more advanced scenario, the sensor sends information to a robot about the possible failure of a machine so that the robot immediately attends the machine to rectify the fault. Prognosis is not restricted to plant level and shop floor, but can be extended to products, and their subassemblies and components. If a smart sensor is implanted in a component, the sensor warns the product user about possible failure so that any danger or damage can be averted. The application of sensor networks in assembly operations to detect faults is addressed by Khan and Ceglarek[6].

Smart sensors can be deployed in various locations in a product, machine, or plant. Combining information from various sensors and enabling updates to situational descriptions on timely manner are essential for a sensor network to perform efficiently. A smart sensor network collects real-time data and makes it accessible by personnel, who can monitor, and predict any failures in a machine or plant and detect defects in a product. Large scale smart sensor networks can be deployed in hostile physical environments such as remote geographic regions, toxic industrial environments, and large integrated factories[7]. Smart sensor networks spread across a geographically distant locations will permit remote monitoring and tracking of machines, and products. Consider the following scenario presented by Estrin *et al.*[7]; each part produced in a factory has a tag attached to it. Smart sensors embedded in floors, ceilings, and walls of the factory or office complex, track the location history of each part. The smart sensor network can automatically locate items, report on those needing servicing, analyze long-term correlations between workflow and wear, report unexpected large-scale movements of parts, and eliminate manual scanning (those based on bar-codes) of parts in inventory.

2.2 Condition based monitoring

Condition based monitoring is the performance of periodic or continuous measurements on parameters which are believed to indicate the condition of a component, subassembly or system and analysis of measurements to assess the item's current condition and possible future deterioration trends[8,9]. Condition based monitoring relies on advanced technologies such as (a) vibration measurement and analysis, (b) infrared thermography, (c) oil analysis and tribology, (d) ultrasonics, and (e) motor current analysis to determine equipment condition and potentially predict failures[10]. Condition based monitoring relies on the sensing and processing of the parameters by single or multiple sensors[11].

A smart sensor network enhances the reliability of plant condition monitoring by eliminating bottle-neck failures. The network does not break down if a single sensor in the network malfunctions. The work load of the malfunctioning sensor is shared among other functioning sensors. The condition monitoring sensors often fail when the plant enters a critical state. The data generated increases tremendously as the components are overloaded, vibration levels increase and threshold alarms are triggered. It becomes difficult to process the data that is truly critical when overwhelmed by the data that is unimportant. With smart sensors, the data can be classified according to its criticality to avoid unnecessary data processing during a critical stage of the plant[5]. Traditional sensors collect data at periodic intervals to predict machine breakdowns. If the sensor fails to capture critical information when the machine condition is deteriorating, it will lead to the eventual machine breakdown. In contrast, smart sensors can collect data more frequently, eliminate unnecessary data, and collect data when machine is in a critical state and send information to the maintenance personnel only when the machine needs maintenance[5].

2.3 Product quality monitoring

Monitoring the quality of products is essential to satisfy customer demands. Bad quality products result in customer dissatisfaction and bring losses to the firm manufacturing the products. Product quality monitoring can be performed using various techniques: (a) inspection by human inspector (b) machine vision systems, (c) inspection by laser beams, and (d) optical gauging systems, to name a few.

With a smart sensor network in place, quality control of parts will become less time consuming. Any defect in a part can be detected in its infancy; in this case the part is either scrapped or an immediate corrective action is taken to rectify the defect. Product quality and throughput rate can be greatly improved if smart sensors are used. In turn the work in process (WIP) level in the factory will be reduced because there will be no blocking and starvation of stations and no buffer overflows.

3. MODELING OF S²IM SYSTEM

Current manufacturing systems are controlled by centralized servers which receive information from sensors deployed in various locations in the shop floor. The information thus obtained is processed by the servers to make decisions based on the current operating conditions of machines. The decision making is restricted to the centralized servers, which makes it difficult to take quick decisions in emergency situations because the raw sensor data may overwhelm the network channels. It is thus required to have decentralized decision making capability in the manufacturing systems. With the advent of smart sensors this decentralized information processing will become a reality. A manufacturing system that is embedded with smart sensor network will realize the dream of a decentralized network. To study the performance of such a system, one must build its model that captures the behavior of the system.

A formal model of a manufacturing system is defined as "an unambiguous, complete, verifiable, and consistent specification of a manufacturing cell [or a system] in an implementation-independent language with precisely defined syntax and semantics" [1]. There are mainly four types of modeling approaches for manufacturing systems: (a) discrete event simulation, (b) finite state automata, (c) petri-nets, and (d) multi-agents. In this paper, a multi-agent approach is adopted to model a smart sensor integrated manufacturing system, because the features of agents lend themselves to precisely capture the behavior of a smart sensor network.

3.1 Multi-agent system

An agent is a system component that is capable of perceiving and acting at a certain level, communicating with other agents, and striving to meet certain goals[12,13]. In manufacturing systems agents are used to represent physical entities

such as workers, cells, products, tools, machines, or abstract entities such as product demand, scheduling systems, and manufacturing planning[14].

The features of an agent and a multi-agent model that compare with those of smart sensors are tabulated below.

Smart sensor network	Multi-agent model
A smart sensor consists of a sensing element and a microprocessor that enables it to make independent decisions.	An agent is capable of perceiving, acting, and making independent decisions.
Smart sensors in a network can communicate with one another.	Agents in a system can communicate among themselves.
Smart sensors are capable of choosing the correct observation when multiple and conflicting observations are sensed.	An agent has the ability to identify and resolve conflicts with other agents in the multi-agent system.
Smart sensors in a network can make collective decisions, and set common goals for the entire network.	Agents in a system can make collective decisions, and set goals that are common for all agents in the system.
A group of smart sensors can self-organize themselves to form an effective network.	Agents can also self-organize in a system to function effectively.

In addition agents have the following features[15]:
- An agent can be either autonomous or controlled by humans or other agents.
- An agent has the ability to respond quickly to unanticipated events.
- An agent can predict the future events, actions and its effects.
- An agent is capable of operating for prolonged periods of time while unattended.
- An agent has the ability to accommodate changing user needs and working environments and deal with heterogeneous agents and information resources.

A group of agents that communicate with one another and collaborate together to perform certain tasks is called a multi-agent model. The multi-agent model has an architecture that links the agents. The following are the features of multi-agent models for manufacturing systems:
- An agent can adapt its behavior according to the performance of other agents in achieving common goals.
- Agents can maintain and interpret knowledge about states, events, other agents and the environment.

The multi-agent manufacturing models require fewer changes when an entity is added or removed from the manufacturing system. Failure of any agent in the model will not freeze the system from functioning.

3.2 Proposed multi-agent model for S²IM system

Agent-based systems have been applied in various areas of manufacturing such as manufacturing planning and scheduling, materials handling, and supply chain management[16]. Shen and Norrie[16] have identified the application areas in manufacturing for the multi-agent models: (a) enterprise integration and supply chain management, (b) manufacturing planning, scheduling and control, and (c) holonic manufacturing systems. Simulation models built to study the issues in these areas of manufacturing might or might not have considered the use of sensors as part of the model. If at all sensors were part of the models, they probably considered traditional sensors. The existing manufacturing systems in practice use smart sensors in a limited domain, restricted to a single machine or at the most in a manufacturing cell. There is a definite need to develop and study models of manufacturing systems integrated with smart sensors.

The proposed multi-agent model architecture for a S²IM system is presented in figure 1. The architecture includes agents at the production unit, production system, and production planning levels. The levels above production planning such as design and development, and management are not included in the model to restrict the scope of the study to manageable limits. Agents at each level can communicate with agents at the same level and with specific agents in the preceding and/or succeeding level. Each agent at the production system and production planning levels is a multi-agent model, whereas the agents at the production unit level are the basic entities of multi-agent models in production system level. So the architecture of S²IM system is a network of many multi-agent models that interact among themselves. The S²IM system architecture is a complex network of agents with many interactions taking place simultaneously.
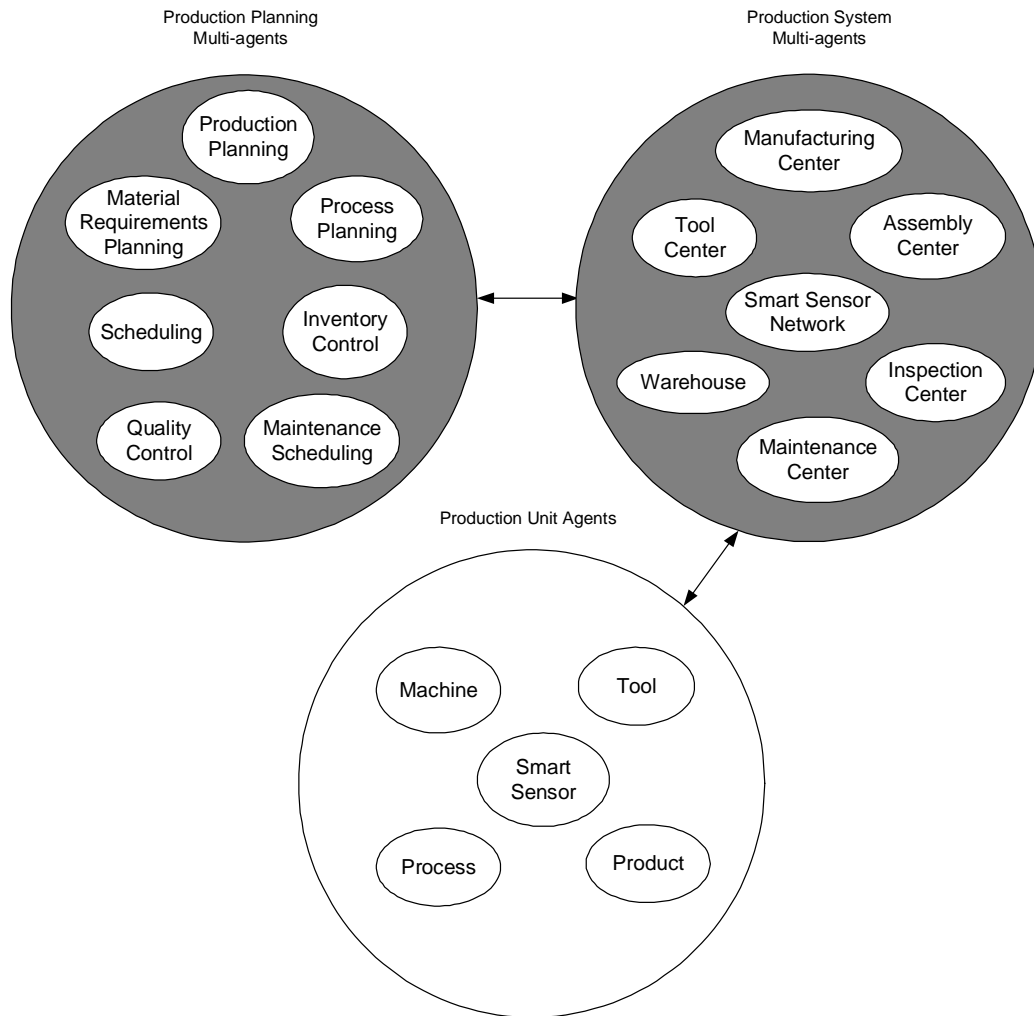
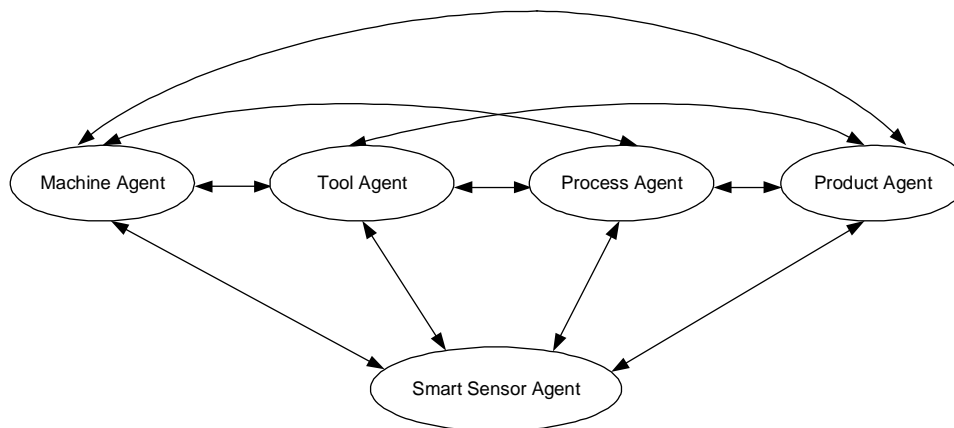Figure 1: Architecture of a multi-agent model for S^{2}IM system

Figure 2: Interaction among production unit agents

The function and characteristics of each agent at the production unit level is described below:

Machine Agent: All machines and material handling equipment are modeled as machine agents. Such an agent performs a set of operations on components that arrive in a queue. Some of its attributes are: (a) machine identification number, (b) machine failure rate (the mean time between machine failures), (c) machine life (the total span of time a machine can run before it fails), (d) machine life remaining (the span of time remaining before a machine break down can occur), (e) machine nominal production (number of components the machine has successfully processed so far), and (f) mean processing time of a particular processing operation. The agent has the knowledge that the smart sensor agent is monitoring the critical machine components.

Tool Agent: Any tool used by the machine to machine the component is modeled as a tool agent. Some attributes of this agent are: (a) tool identification number, (b) tool failure rate, (c) tool life (the total span of time a tool can be used before it fails), (d) tool life remaining (the span of time remaining before a tool can fail), and (e) tool wear (the amount of wear the tool has undergone). This agent has the knowledge that the smart sensor agent is monitoring the tool and the process being performed on the part.

Process Agent: Any processing operation that is performed on a component is modeled as a process agent. Some of its attributes are: (a) process number (the process identification number), (b) process parameters (a list of current process parameter values), and (c) tolerance bands for process parameters (the upper and limit of each process parameter). It has the knowledge that smart sensor agent is monitoring the process parameters.

Product Agent: The components, subassemblies and finished products are modeled as product agents. Some of the attributes of a product agent are: (a) product identification number (unique number to identify the product), (b) product location (the current location of the part in the manufacturing system), (c) product quality (an attribute that represents the product quality, for example, surface finish), and (d) processing time so far (the total time elapsed from the moment the product arrived at the first workstation). This agent has the knowledge that smart sensor agent is monitoring the quality of the product.

Smart Sensor Agent: A smart sensor agent has an amalgam of characteristics of a smart sensor and an agent[17,18]. Smart sensors for monitoring machine condition, process parameters, and product quality are each modeled as a smart sensor agent. Some of the attributes they have are: (a) sensor identification number (unique number to identify a smart sensor), (b) sensor characteristics (sensor characteristics such as sensitivity, dynamic range, precision, resolution, accuracy, linearity, etc.), (c) sensor output (displays the sensor measurement of the phenomenon that the sensor is monitoring), and (d) sensor tasks (list of actions the sensor performs). A smart sensor agent captures smart sensor's intelligence by storing the smart sensor's knowledge in the agent's knowledge base in the form of rules.

Interaction among the agents at the production unit level (see figure 2) occurs in the following circumstances,
1. Tool is setup or it requires maintenance: here the machine and tool agents interact.
2. Process is initiated and completed on a part: here the machine and process agents interact.
3. Process parameters are beyond tolerance limits: here the machine and process agents, tool and process agents, process and smart sensor agents interact.
4. Quality of work being performed on the part is deteriorating: here the machine and product agents, tool and product agents, process and product agents, product and smart sensor agents interact.

Each agent (machine, tool, process, product, smart sensor) has its own objectives. Sometimes these objectives are in tune with each other's and sometimes they are conflicting. Each agent at the shop floor level has the following objectives:
Machine Agent: (a) to minimize the mean time between failures, (b) to work under optimal machine working conditions, (c) to perform machining operation on the component precisely, and (d) to monitor machine working conditions.
Tool Agent: (a) to minimize tool failure rate, (b) to work in conditions that maximize tool life, (c) to perform machining operation on the component precisely, and (d) to monitor tool operating conditions and wear.
Process Agent: (a) to monitor the process parameters and (b) to report any variations in the process parameters.
Product Agent: (a) to monitor the product quality and (b) to monitor the component location until it leaves the manufacturing system.
Smart Sensor Agent: (a) to monitor the machine working conditions, (b) to monitor the process parameters, (c) to monitor the product quality, and (d) to monitor the tool operating conditions and wear.

4. EXPECTED BEHAVIOR OF THE PROPOSED MODEL FOR A S^2IM SYSTEM

The smart sensor network in a manufacturing system will bridge the gap between various departments (manufacturing center, scheduling, production planning, etc.) that are involved in manufacturing a product. There will be an increased level of interaction between these departments in decision making. Thus, a department has to consult departments that are directly or indirectly affected by it to arrive at a decision.

Consider the effect of a smart sensor network on a manufacturing center (see figure 1) and how it impacts the process planning and scheduling departments. Assume the manufacturing center layout to be the product layout (machines are arranged in the sequence of operations to be performed on a job). In such a manufacturing center, the smart sensor network (a) minimizes the frequency of unexpected breakdown of machines, (b) increases the uptime efficiency of the machines, (c) increases the mean time between machine failures, and (d) satisfies the demand for items and ensures that no backorders occur. Interaction between the manufacturing center and process planning department occurs when a possible breakdown predicted by a smart sensor requires one to seek an alternative process plan. The process planning department must therefore anticipate such dynamic problems and build alternative process plans in advance. In situations like these the manufacturing center and the scheduling department get to interact with each other.

The effect of smart sensor network in a maintenance center (see figure 1) is seen when (a) smart sensors monitoring machines or machine tools raise an alarm when they are on the verge of becoming nonfunctional and the decision of performing preventive maintenance is to be made, (b) the maintenance center should be able to perform maintenance in a short notice, i.e., the maintenance schedule (prepared by the maintenance scheduling department) must accommodate untimely and unanticipated alarms of smart sensors, and (c) in some cases of machine and tool maintenance, the damaged part needs to be replaced, in which case the request for a new part is sent to the resource planning department.

In a warehouse (see figure 1) a smart sensor network aids in (a) determining inventory levels, (b) tracking items in the warehouse, (c) quick retrieval of items from the warehouse, and (d) identifying obsolete items, i.e., items whose shelf life expires in the warehouse. Depending on the inventory levels the smart sensors send this information to the material requirements planning department, purchasing department and/or directly to the vendor who supplies the material.

5. CONCLUSIONS AND FUTURE WORK

Traditional sensors with no in built signal processing capabilities may jam the sensor network channels with information. This may increase the communication time between sensors in the network. On the other hand smart sensors overcome the drawbacks of traditional sensors by performing the information processing locally. Multi-agent models can aptly model the behavior of smart sensor networks in a manufacturing system. A multi-agent model for a S^2IM system is proposed to highlight the effects of smart sensor networks in a manufacturing system. The agent characteristics and expected behavior of the multi-agent model are outlined.

In future work, a simulation model of the multi-agent model for a S^2IM system will be implemented. The simulation model will be used to study the improvements in productivity of a machine, machine uptime efficiency, and product quality. The effect of a smart sensor network on different types of manufacturing system layout will be investigated. Efforts to effectively capture the behavior of smart sensors and smart sensor agents will be pursued. Effort will be made to integrate smart sensor networks with wireless ad hoc networks.

REFERENCES

1. I. Castillo and J. S. Smith, "Formal Modeling Methodologies for Control of Manufacturing Cells: Survey and Comparison," *Journal of Manufacturing Systems*, vol. 21, pp. 40-57, 2002.
2. E. T. Powner and F. Yalcinkaya, "Intelligent sensors: structure and system," *Sensor Review*, vol. 15, pp. 31-35, 1995.

3.   S. J. Prosser and E. D. D. Schmidt, "Smart Sensors for Industrial Applications," *Sensor Review*, vol. 17, pp. 217-222, 1997.

4.   P. G. Ranky, "Smart Sensors," *Sensor Review*, vol. 22, pp. 312-318, 2002

5.   P. Jacob, "Ideas for the exploitation of distributed intelligence in condition monitoring systems," *www.eng.man.ac.uk/Mech/Merg/RESEARCH/fieldbus.htm*, 1994.

6.   A. Khan and D. Ceglarek, "Sensor Optimization for Fault Diagnosis in Multi-Fixture Assembly Systems with Distributed Sensing," *Journal of Manufacturing Science and Engineering*, vol. 122, pp. 215-226, 2000.

7.   D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," *Proceedings of the Fifth Annual International Conference on Mobile Computing and Networks*, 1999.

8.   A. Davies, *Management guide to condition monitoring in manufacturing*. London: Institution of Industrial Engineers, 1990.

9.   D. T. Pham and E. Oztemel, *Intelligent Quality Systems*: Springer, 1996.

10.   S. Dunn, "Condition Monitoring in the 21st Century," *www.plant-maintenance.com/articles/ ConMon21stcentury.shtml*.

11.   W. Hu, A. G. Starr, Z.Zhou, and A. Y. T. Leung, "A systematic approach to integrated fault diagnosis of flexible manufacturing systems," *International Journal of Machine Tools and Manufacture*, vol. 40, pp. 1587-1602, 2000.

12.   K. S. Barber and J. Kim, "Toward flexible and fault tolerant intelligent manufacturing: Sensible agents in shop-floor control," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 14, pp. 337-354, 2000.

13.   J. Ferber, *Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence*: Addison-Wesley, 1999.

14.   B. Qiao and J. Zhu, "Agent-Based Intelligent Manufacturing System for the 21st Century," *http://www.shaping-the-future.de/pages/abstracts/abstract_152.htm*.

15.   W. Shen, D. H. Norrie, and J.-P. A. Barthes, "Multi-Agent Systems for Concurrent Intelligent Design and Manufacturing," *Taylor & Francis*, 2001.

16.   W. Shen and D. H. Norrie, "Agent-Based Systems for Intelligent Manufacturing: A State-of-the-Art Survey," *Knowledge and Information Systems*, vol. 1, pp. 129-156, 1999.

17.   G. O. Allgood and W. W. Manges, "Sensor Agents—When Engineering Emulates Human Behavior," *Sensors*, vol. 18, 2001.

18.   A. C. Knoll, "Distributed contract networks of sensor agents with adaptive reconfiguration: modelling, simulation, implementation and experiments," *Journal of The Franklin Institute*, vol. 338, pp. 669-705, 2001.