Preliminary version, not for distribution. Contact COMADEM or authors for final version.

Funk P., Olsson E., Bengtsson, M., Xiong, N, (2006), "Case-Based Experience Reuse and Agents for Efficient Health Monitoring, Preventive, and Corrective Actions". In proceedings of the 19th International Congress on Condition Monitoring and Diagnostic Engineering Management, Luleå, Sweden.

CASE-BASED EXPERIENCE REUSE AND AGENTS FOR EFFICIENT HEALTH MONITORING, PREVENTIVE, AND CORRECTIVE ACTIONS

Peter Funk[1], Erik Olsson[1], Marcus Bengtsson[2], and Ning Xiong[1]

[1]Department of Computer Science and Electronics,
Mälardalen University, P.O. Box 883, SE-721 23 Västerås, Sweden,
phone +46 21 10 31 53, fax +46 706 11 91 50

[2]Department of Innovation, Design and Product Development,
Mälardalen University, P.O. Box 325, SE-631 05, Eskilstuna, Sweden,
phone +46 16 15 34 86, fax +46 16 15 36 10
{peter.funk; erik.olsson; marcus.bengtsson; ning.xiong}@mdh.se

ABSTRACT

Experienced staffs acquire their experience during many years of practice, and sometimes also through expensive mistakes. This knowledge is often lost when technicians retire, or if companies need to downsize during periods of reduced sale. When scaling up production, new staff requires training and may repeat similar mistakes. Another issue that may be costly is when monitoring systems repeatedly give false alarms, causing expensive loss of production capacity and resulting in technicians losing trust in the systems and in worst case, switch them off. If monitoring systems could learn from previous experience for both correct and false alarms, the reliability and trust in the monitoring systems would increase. Moreover, connecting alarms to either equipment taking automatic actions or recommend actions based on the current situations and previous experience would be valuable.

An engineer repeating the same task a second time is often able to perform the task in 1/3 of the time it took at the first time. Most corrective and preventive actions for a particular machine type have been carried out before. This past experience holds a large potential for time savings, predictability and reduced risk if an efficient experience transfer can be accomplished. But building large complex support system is not always the ideal way. We propose instead localized intelligent agents, able to either autonomously perform the necessary actions or aid a human in the decision making process by providing the necessary information needed to make an informed and validated decision.

KEYWORDS

Experience Reuse, Decision Support Systems, Condition Monitoring, Intelligent Agents, Case-Based Reasoning

INTRODUCTION

Society has moved from the industrial age to the knowledge age, where information and experience are one of the most valuable resources. This is also becoming increasingly obvious in production industry, how well a production company reuse experience and integrate new knowledge and research results into their production may both be one of the key factors for success as well as a major long term survival factor. Research is rapidly moving forward in the area of condition monitoring and diagnostics (Mba and Rao, 2005) but production companies not following progress in research and integrating research results into their production when results are ripe for commercial deployments take a serious risk. A large part of a company's knowledge and experience is also produced by human mistakes and often costly incidents. When engineers need to make a decision to prevent or correct, they often encounter the information overload problem (Mangina, 2005). Human information overload is also a serious issue, especially when quality of information is difficult to judge, faulty, or missing. Although valuable experience in the same or similar situation may be available from a phone call away, such information is rarely found when needed. Data captured during condition monitoring often hides valuable knowledge. It is increasingly difficult to meet customers demands, requiring increased production flexibility, reliability, and fast delivery times is a major challenge for industry. These requirements make product development and manufacturing increasingly complex.

E-manufacturing (Lee, 2003) is making fast progress and has a huge potential and today already large amounts of monitoring data are available, but these are not often used to its full potential. Methods and techniques from artificial intelligent, such as Case-Based Reasoning and the use of agent based system paradigm offers a number of advantages for these issues. Using Case-Based Reasoning and intelligent agents for the task in finding relevant information, e.g. by identifying similar situations, transfer relevant information and experience, and adapt these cases to the current situation will help this decision process. Agents based solutions may also have knowledge on what the engineers currently are working on and what knowledge they have in order to offer better support and identify relevant documentations, PM's, past cases etc. Agents and Case-Based Reasoning solutions may also reduce costs for technical support. Large companies have reduced their technical support costs with up to 33% by deploying methods and techniques from Artificial Intelligence (Cheetham, 2006).

Using an agent based approach in monitoring and analysis of sensor readings gives a number of advantages in complex monitoring tasks. Handling groups of sensors with a dependency between measurements enabling sensor agents to collaborate and learn from experience, resulting in more reliable performance. Sensors agents may also improve their performance, e.g. recalibrate sensors if needed, or determine if sensors are faulty. Similar sensors may also share experience enabling them to avoid repetition of similar failures or make estimates on their reliability. Uses of standardised agent frameworks have been tested in industrial applications with good results (Pirttioja et al., 2005; McArthur et al., 2005). Well standardised industrial equipment using agent architecture can easily be upgraded and adapted to different reliability and safety requirements. If requirements increase, agents can be added, replaced for better ones, improved by providing agents with more experience or even having multiple agents with the same goal work in parallel (if one agent misses a symptom, the other agent may observe it). Agent may also specialize on different tasks, e.g. one agent may be an expert on oil quality and another agent on bearings, and then both agents may share some sensors or get information from a sensor agent, an agent specialised in pre-processing the sensor data and removing noise and other artefacts. An agent based approach reduces complexity in a complex system and also enables different suppliers of agents. Furthermore, new findings and research results can be integrated into the relevant agents without any redesign or modifications of the condition monitoring system. Agents also have a potential to abstract and (Campos, Prakash, 2006) propose a layered structure: information layer, middleware layer, and interface layer.

We have experimented with a number of different methods and techniques from Artificial Intelligence (AI) with promising preliminary results for health management. In particular two areas of high value are: experience-based diagnosis using AI and condition monitoring and decision support systems using AI. Using intelligent agents for monitoring is an important path to the next generation of monitoring systems (Mangina, 2005). We suggest that the following reasons are valuable properties in an agent based approach for condition monitoring:

1. Agents enable decentralisation of decisions and reduction of complexity.
2. Agents enable localized expertise and experience reuse.
3. Agents enable learning and experience sharing between agents with similar tasks.
4. Agents can be implemented to collaborate with other agents and humans.
5. Agents are able to make informed decisions on what actions to take or when to verify actions or interact with humans.

There are already research prototypes demonstrating the value of agents based monitoring systems in industrial applications, e.g. (Pirttioja et al., 2005). Different research projects use agents for different reasons.

INTELLIGENT AGENTS

In this section we give a brief introduction to agents and also motivate why the agent concept is suitable for the domain of condition monitoring. There are a number of different definitions of agents, but the difference for practical applications are often less important, the definitions are often based on the fact that agent research often is application oriented and having a particular applications in mind may lead to slightly different definitions (Franklin and Graesser, 1997). Russel and Norvig (1995) state that "an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors". A pure reactive system like a thermostat would meet this basic definition, but most definition also includes social skills (communication) and some "intelligent" behaviour, e.g. ability to pro-activeness, learning and predicting. An agent's goals or desires may be to decrease maintenance costs without reducing reliability and life expectancy. Wooldridge and Jennings (Wooldridge and Jennings, 1995) define agents to be computer systems that have properties such as:

- autonomy,
- social abilities, and
- reactivity and pro-activeness

In the context of condition monitoring the agent perceives the environment through one or more sensors (figure 1). Additional information about the environment may also be acquired through communication with other agents or systems (a system may be given an agent wrapper to enable uniform communication). An agent's ability to influence its environment may in the context of condition monitoring be to operate a valve/switch or adjust a process. An action may also be to communicate with some other agents or human, e.g. a technician close by and ask for help to carry out some preventive or corrective needs.

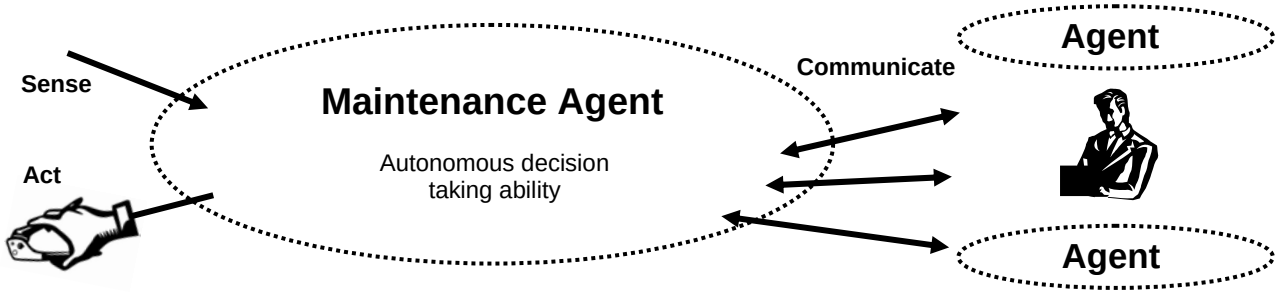

Figure 1. Outline of the Maintenance Agent in its environment.

The application domain autonomy may mean that the agent has the power to shut down some parts of the equipment without consulting an operator first if human response time is not fast enough for the situation. Social ability in this domain may be the ability to communicate with other agents, other computer systems, and humans. Such social ability may include the ability to negotiate, e.g. if some other unit requests the agent to shut down some part immediately, the agent may request information about the reason and suggest a less costly and safer alternative solution to the problem. In the condition monitoring domain reactivity may mean that the agent in an emergency situation shuts down some part the agent is responsible for. To be proactive may be an agent noticing some sensor readings indicating some joints in a robot showing signs of tear and reconfiguration operation routes to reduce further wear on this joint.

The difference between agents and normal computer programs is well captured by Maes (1995) stating "Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed.". Finally Jennings and Wooldridge (2002) state that "an agent is an encapsulated computer system that is situated in some environment, and that is capable of flexible, autonomous action in that environment in order to meet its design objectives", which is a valuable property for a component in a condition monitoring systems. These design objectives may in production industry be to maintain both short term and long term operation and stay within the budget assigned for this task (or negotiate for increased resources).

DESIGNING AND BUILDING AGENT BASED SYSTEMS USING ARTIFICIAL INTELLIGENCE

Important to note is that in order to build an agent based system there are no technological differences compared with building traditional computer systems, the same hardware and computer programming languages can be used. But it is a difference in design where the system is structured in agents and where no central control in the "master process". Complex systems make it very difficult to design and implement a single control process knowing and controlling all. Errors in such a process may have severed consequences. The agent paradigm distributes the complexity to smaller units (agents), experts in what they have responsible for and with these AI techniques they may even improve their performance over time. Another interesting aspect included in agent based systems is that the agent may communicate (via local networks or internet with the necessary encryption) with other agents located in other similar machinery located somewhere else in the world. They may share experience, such as sound or vibration profiles indicating or predicting different faults.

Agents are being implemented with a wide variety of different techniques; both using traditional software engineering methods and techniques such as object oriented programming, and Artificial Intelligent methods and techniques such as Artificial Neural Networks or Case-Based Reasoning. Agent based frameworks enable agents to interact in a standardised and controlled way and agents can easily be added and removed. An agent based framework may also allocate resources in a controlled manner to different agents and discover when agents overstep their given responsibilities.

INTERACTING AGENTS AND AUTONOMOUS DECISIONS MAKING

In this section we give an example of an agent based maintenance system both able to perform corrective maintenance, preventive maintenance, and condition based maintenance (possibly with help of other agents and technicians).

Success and failure is often directly or indirectly connected with the ability to share and communicate each other's experiences. An agent based system may also benefit from communication with other agent based systems. In (Olsson et al., 2004; Bengtsson et al., 2004) an agent based Case-Based Reasoning system determines what condition an industrial equipment is in and determines either autonomously or by interaction with a technician what actions to perform.

The proposed fault diagnosis system uses a hybrid Case-Based Reasoning method using a nearest neighbour approach for a light weight solution of recognizing and diagnosing audible faults on industrial robots. Sensor signals such as sound is recorded and compared with previous recordings, although also currents and other input signals have been explored and works appropriate. Similar cases are then shown to the user with corresponding diagnosis and actions based on previous experience. The system aids engineers in making a correct objective diagnosis of the industrial robot based on earlier classifications of similar sensor signals. The system is able to successfully diagnose faults in an industrial robot based on sound recordings.

The Case-Based fault diagnosis system uses three different steps in its classification process; pre-processing, feature identification, and classification. Sound is obtained from the robot to be diagnosed via a microphone. The sound is recorded to a computer and the recording is taken as input to the pre-processing step. The pre-processing process is responsible for filtering and removal of unwanted noise. It also extracts period information from the sound. In the feature identification process, the system uses a two-pass model, first identifying features and then creating a vector with features. Once the features are identified, the system classifies the feature vector. The classification is based on previously classified measurements (case library). When a new sound has been classified, the new case is added to the case library. The system collects experience through the cases and becomes more competent as additional cases are added to the case library. When a case occurs for the first time, an experienced engineer may identify and repair the fault. In a condition based maintenance scheme, all measurements are recorded before a fault occurred, and contain significant information to identify the fault within a given time frame and suitable maintenance tasks are performed to repair the fault. The difference between corrective and preventive maintenance is small in case-based reasoning when seen from a case-based reasoning implementation point of view (Funk and Jackson, 2005).

In figure 2 the concept of a maintenance agent is given. On the left side the agent observes its environment through one or more sensors. The agent may have some basic domain knowledge about when to bring the findings to the attention of a human and when to shut down a process. The agent also has social skills to communicate its findings. It may also ask for additional information to make a final decision. Knowing its own limitation is also an important property, e.g. if the agent is not confident enough in performing some actions (consequences of the action may be very expensive).

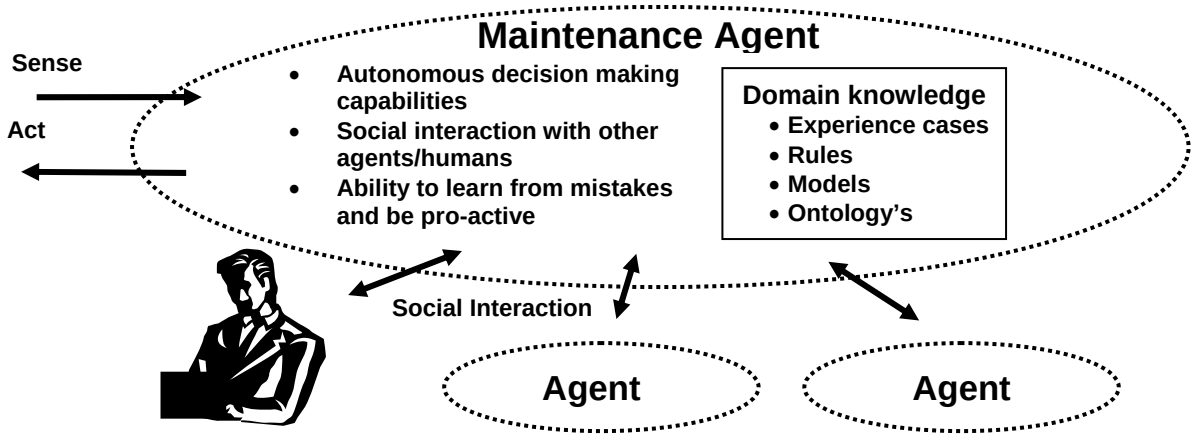

Figure 2. The concept of a Maintenance Agent able to monitor, prevent, and correct.

The domain knowledge (box on the upper right side in figure 2) may be past cases and their outcomes, rules that are known to be valid for the domain and also may be used to adapt a case to the current situation. If it is possible, a model for some parts of the application domain may help in the decision making, e.g. if it is possible to simulate the outcome of a specific action, simulation may help in fine-tuning the final solution (revision step) and combination of Case-Based Reasoning and model based reasoning have been applied in different research projects, e.g. CREEK (Aamodt 2004). The ontology may be valuable in interaction with experts and external sources of information. An example of social interaction may be an agent asking users to confirm some decisions. After a number of times the system may notice that only in some particular situations the user rejects the proposed case. It may also learn that the user sometimes makes the wrong decision, but consequences are limited. If there is no user close by the agent may decide to perform this action autonomously.

In figure 3 an example of an agent using case-based reasoning is shown. The Sensor is pre-processed, compared with the case library based on domain dependent similarity matching; the best matching cases are adapted to the current situation and suggested as solution to a human.

If the system is confident in the suggested solution or if there is no time to wait for a human decision (e.g. an emergency situation with serious consequences if no action is taken immediately), the agent may carry out the suggested solution autonomously. If the solution is successful the new case is added to the case-library representing a new instance of experience. The domain knowledge in figure 2 is used in the matching, adaptation, and also deciding if asking an expert/agent for assistance, or carry out the action autonomously.

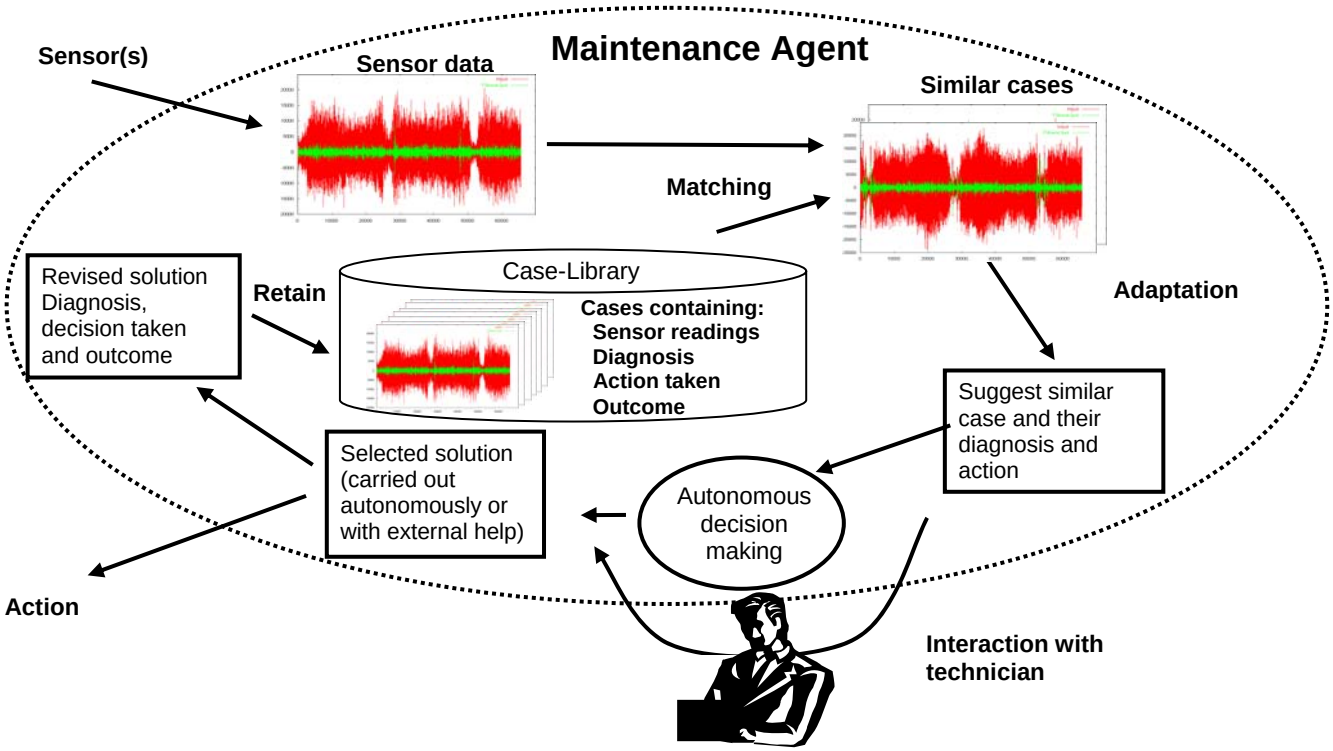

Figure 3. An example of an agent based system using case-based reasoning.

FACTORS AFFECTING DECISIONS BY AGENTS

In an agent based approach a critical issue is the agent's decision whether to take a certain action autonomously or to collaborate with humans (technician/economist) in problem solving. For this decision a number of factors have to be considered. Some of them are domain dependent and also dependent on

the reasoning method applied by the agent, since different methods and techniques enable more or less informed decision making.

Case-Based Reasoning Systems have some desirable properties enabling an informed decision. These systems make reasoning in terms of similarity, confidence and usefulness. These are important for agents as well as humans during a decision making process. The most central measurement in Case-Based Reasoning systems is similarity, i.e., how similar a previous case is to the current situation and also reflecting how well the previous solution can be reused in the current situation. Some adaptation of the solution may be needed. If all the symptoms and conditions are identical between the current situation and the case from the case library, the same solution can be reused without modifications. Otherwise, even if a good matching case is found, other factors may influence the decision and the agent may decide to either doing nothing or applying/adapting a solution case further down the similarity ranking list or apply multiple solutions.

Other factors the agent may take into account to make an informed and final decision are given below. Some of the most central factors in the context of maintenance are (not given in priority order):

1. How similar is the case to the current situation
2. Track record of how successful the case was in the past
3. The confidence in the case and its solution given a current situation
4. The benefit of a case (how efficiently the solution solves the problem)
5. The cost of implementing the solution correctly
6. The consequences/costs, short term/long term if the agent/human is idle by taking no action
7. The consequences/costs if the proposed solution in the case is wrongly deployed

The track record of a case (factor 2) is important since a good matching case may have a less good track record and other statistics appearing against it. The confidence in a case (factor 3) may depend on the nature of the cases in the case library that are similar to the current situation. E.g. if there are many similar cases nearby the same solution, the confidence grows. But if there are surrounding cases with a very different solution, the confidence in the most similar case may be reduced. The benefit of a case (factor 4) may also have a large influence on which case is selected, e.g. one case may have a solution fixing the problem temporarily while other cases offer long term solution. Factor 5-7 are cost and risk related factors. They have a major influence on the selection of the final case and also if an expert should be included in the decision process. These factors should reflect company policy, current economical situation and also laws and regulations. An example would be that a specific well matching case is the best matching case, and there is a high confidence and success rate connected to the case, but the solution in the case increases the risk of hazardous leakage damaging the environment, and environmental regulations may forbid this and may give the company unacceptable negative publicity. It may be argued that some of these factors may be included into the case descriptions and similarity measurement, but since many of them change with time and are complex in themselves, we propose that for monitoring and diagnostic tasks in industry it may be an advantage and lead to reduced complexity if these factors are handled separately in the decision process or decision support process instead of completely integrating them into the Case-Based Reasoning system.

CONCLUSIONS

Artificial Intelligence offers a number of powerful methods and techniques, which offers potential benefits if harnessed properly. The Agent paradigm and agent architecture is one of these. In combination with other methods such as case-based reasoning the potential for building valuable systems for monitoring and maintenance is argued to be large and enable valuable properties, sometimes difficult to

achieve with a traditional software architectures and engineering. This is exemplified with a system that we have implemented in the area of industrial machine diagnostics. The concept of agents bring a number of benefits to maintenance, increased reliability e.g. redundancy, improved decision making, collaborations, reduces complexity, and enables flexible and modular maintenance systems where different suppliers can deliver agents, developed to be experts in a specific tasks. Most of the different parts needed for an agent based maintenance approach have been shown to work in different research projects and case studies. To bring the benefits of agent based maintenance systems to industry the first thing is to spread knowledge and understanding of the agent paradigm and its benefits. Also spreading information on successful research projects where the agent paradigm is used, or where the agent paradigm has been used as a thought concept for ideas, implementation and functionality is important. But industry does not need to wait for an industry standard framework for maintaining agents; thinking in terms of agents already gives a number of advantages in system design and development, and may lead to valuable features and functionality that may not have been thought of without this framework of thoughts.

ACKNOWLEDGEMENT

This work is sponsored by the Swedish Foundation for Strategic Research, ProViking, and is a part of the ExAct and Factory in a Box projects.

REFERENCES

Aamodt A. (2004), “Knowledge-Intensive Case-Based Reasoning in CREEK”, In 7th European Conference on Case-Based Reasoning, editor(s): Funk, González Calero, pp. 1-15. Published by Springer Verlag.

Bengtsson, M. Olsson, E., Funk, P., Jackson M. (2004), “Technical Design of Condition Based Maintenance Systems - A Case Study”. MARCON (Maintenance and Reliability Conference), Knoxville, TN, USA.

Campos J. and Prakash O., (2006), “Agent architecture in condition based maintenance for decision-making”, in press, COMADEM 2006, Luleå, Sweden.

Cheetham, W. (2006), “Case-Based Reasoning for General Electric Appliance Customer Support”, forthcoming paper, contact cheetham@research.ge.com.

Franklin, S. and Graesser, A. (1997), “Is it an agent, or just a program?: A taxonomy for autonomous agents”, Lecture Notes in Computer Science, 1193:21–35.

Funk, P. and Jackson, M. (2005), “Experience Based Diagnostics and Condition Based Maintenance Within Production Systems”. In proceedings of the 18th International Congress and Exhibition on Condition Monitoring and Diagnostic Engineering Management (eds. Mba D. U., Rao R. B. K N.), pp. 105-111, Cranfield, UK.

Lee. J. (2003), “Review E-manufacturing—fundamental, tools, and transformation”, in journal: Robotics and Computer Integrated Manufacturing, pp. 1-7, Published by Elsevier Ltd.

Jennings, N. R. and Wooldridge, M. (2002), “Agent-oriented software engineering, In Jeffrey M. Bradshaw, editor, Handbook of Agent Technology”, AAAI/MIT Press. See: www.ecs.soton.ac.uk/~nrj/download-files/agt-handbook.pdf.

Maes, P. (1995), “Artificial life meets entertainment: Lifelike autonomous agents, Association for Computing Machinery”, Communications of the ACM, Vol. 38, No. 11, pp. 108-115.

Mangina, E. (2005), “Intelligent Agent-Based Monitoring Platform for Applications in Engineering”, International Journal of Computer Science & Applications, Vol. 2, No. 1, pp. 38-48.

Mba D., Rao R. B. K. N. (eds.) (2005), Condition Monitoring and Diagnostic Engineering Management, COMADEM, Proceedings of the 18th International Congress. Cranfield University Press, Cranfield, UK.

McArthur, S. D. J., Booth, C. D., McDonald, J. R., and McFadyen I. T. (2005), “An Agent-Based Anomaly Detection Architecture for Condition Monitoring”, IEEE TRANSACTIONS ON POWER SYSTEMS, Vol. 20, no. 4, pp. 1675-1682.

Olsson, E., Funk, P., and Bengtsson M. (2004), “Fault Diagnosis of Industrial Robots using Acoustic Signals and Case-Based Reasoning”, In 7th European Conference on Case-Based Reasoning, editor(s): Funk, González Calero, Springer, pp. 686-701. Published by Springer Verlag.

Pirttioja, T., Pakonen A., Seilonen, I, Halmel A. and Koskinen K. (2005), “Multi-Agent Based Information Access Services for Condition Monitoring in Process Automation”, 3rd IEEE International Conference on Industrial Informatics (INDIN), pp. 240-245.

Russel, S. and Norvig, P. (1995), Artificial Intelligence A Modern Approach, Prentice Hall International Editions.

Wooldridge, M. and Jennings, N. R. (1995), “Intelligent agents: Theory and practice”, The Knowledge Engineering Review, Vol. 10 No. (2) pp. 115–152.