Chapter 20
Application of Open Source Hardware to the Development of Autonomous Maintenance Support Systems

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Abstract Autonomous maintenance systems offer organizations the opportunity to embed state of the art maintenance tools and techniques with minimal operator input supported by a range of technologies such as condition monitoring sensors and techniques, intelligent data processing systems and smart prognostic algorithms. Many companies perceive that autonomous maintenance is difficult to achieve due to a lack of understanding of the infrastructure required to support such an approach as this requires an understanding of the fundamental principles of electronic instrumentation, processing and communication techniques, alongside the ability to create and integrate the appropriate software and firmware. Open source hardware has received attention in recent years as it allows a range of users to create sophisticated applications quickly using readily available components and modules. Such platforms are supported by a range of library software designed to further accelerate and simplify the development process. These products have attracted much attention from hobbyists but are now attracting attention in their own right from potential industrial users. However the reliability of these systems in an industrial environment remains a concern. In this chapter the benefits of applying open source technologies to create an autonomous maintenance system will be examined alongside the perceived and actual barriers limiting their uptake. The required enablers to achieve the potential benefits will then be explored leading to a detailed roadmap identifying what needs to be achieved for the significant industrial potential of these devices and systems to be realized.

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20.1 Introduction

Maintenance strategies in industry have evolved as the underlying technologies have developed. Prior to the 1950s, *reactive maintenance* was prevalent which was subsequently replaced by *preventive maintenance*. During the 1960s, *productive maintenance* became more popular. It was, however, in the 1970s that *Total Productive Maintenance (TPM)* emerged as the preferred form of maintenance. Seiichi Nakajima, vice-chairman of the Japanese Institute of Plant Engineers (JIPE), is known as the founder of TPM. TPM is designed to maximize equipment effectiveness and thus improve overall efficiency by establishing a comprehensive productive-maintenance system covering the entire life of the equipment, spanning all equipment-related fields (planning, use, maintenance, etc.) and, with the participation of all employees from top management down to shop-floor workers, to promote productive maintenance through motivation management or voluntary small-group activities [1].

One of the main arms of TPM is Autonomous Maintenance (AM), known as *Jitshu Hozen* in Japanese. The success of TPM is largely dependent on the success of AM. Autonomous Maintenance is a practical application of TPM which aims to promote a culture in which operators feel that they “own” their machines, learn much more about them, and in the process release skilled trades to concentrate on problem diagnosis and equipment improvement projects [2]. AM ascertains the roles and tasks of production operators so they can perform easy daily maintenance activities alongside yet distinct from planned maintenance. In other words, AM is designed to oblige production operators to maintain their own equipment independently without notice or instruction from the maintenance department [3].

20.1.1 The Role of Computers in Autonomous Maintenance

The advent of computers into asset maintenance has brought about major changes in the field in the last two decades AM, as defined by Seiichi Nakajima in the 1970s, placed the emphasis on cleaning, inspection and minor repairs/adjustments by the operator [4]. A part of this AM system was diagnosis and prognosis of the fault using predictive maintenance tools. Initially, the most widely available tool with the operator was his experience on the machine. The practice was to focus more on the social aspect of the issue by motivating the operator to feel ownership of the machine and become familiar with it so that any impending failure could be “sensed” by the operator. With the increase in computing powers and decrease of the cost of data acquisition and analysis, it has become possible to equip the operator with modern tools of condition monitoring sensors and techniques, intelligent data processing systems and smart prognostic algorithms. Condition-based autonomous maintenance methods are being widely used in industry today. Some of these are manually controlled and provide information to the operators through cameras and sensors.

Others are semi-autonomous/fully autonomous in their monitoring process. The more modern maintenance systems are capable of self-monitoring/-healing/-repair.

20.1.2 Low-Cost Embedded Computing Systems

Recent years have seen the introduction of a range of microprocessor platforms and single board computers which are designed to encourage those from non-traditional electronic engineering backgrounds to become familiar with this technology [5, 6]. Such systems are supported by a range of tools to simplify and accelerate the software development process. The simplicity of programming coupled with the low cost of these platforms has made them attractive to a range of users including hobbyists, students and educational establishments. The popularity of such hardware and the evident potential it offers means that industrial users are now seeing a range of potential applications.

The term ‘Open Source Hardware’ refers to circuits and assemblies whose design can be freely modified and used in any setting. The definition proposed by the Open Source foundation is “hardware whose design is made publicly available so that anyone can study, modify, distribute, make and sell the design or hardware based on that design” [7]. The open source hardware movement is supported by a range of licenses that can be applied to the reuse of designs and associated documentation and software etc. It should be noted, however, that most licenses are based around the concept of ‘copyright’ and thus do not extend to the hardware itself or any aspect of its manufacturing [7].

A number of single-board microprocessor platforms are supported by additional modules which can be connected to the processor offering a range of functionalities such as motor control, LCD displays including touch screens and various environmental sensors. Examples of such ranges include Arduino ‘Shields’, which share a common footprint and pin layout allowing easy physical integration with the main processor board for a number of different accessories. These entire devices offer a degree of ‘plug and play’ in their application minimizing the need to develop bespoke printed circuit boards (PCBs) and other interconnecting hardware. The ‘open source’ nature of the Arduino platform in particular has fostered a culture of innovation where a worldwide community of hardware developers have created a diverse range of low cost hardware add-ons including many which are manufactured at low cost in the Far East and marketed worldwide via the World Wide Web (WWW). The quality and extent of the documentation for low cost hardware modules is, however, variable.

The Arduino platform was launched in 2005 and offered a single board platform based initially on the Atmel AVR microcontroller. One of the principal target markets for the Arduino platform was hobbyists—a community in which the platform has been extremely popular. In addition to the official product which is affordable to all, the Arduino hardware is open source in nature meaning low cost 'clones' are also available which has contributed to the popularity of the platform. Since launch, a number of variants have been developed using a range of different processors and with a range of different capabilities.

The primary advantage of the Arduino platform is the ability it offers to users to develop applications without any hardware development, without the need for additional programming hardware. This removes a significant barrier to those wishing to use microprocessor systems but who do not have the time, infrastructure or knowledge to develop the underlying hardware [5].

Following the success of Arduino, a number of similar single-board systems have appeared on the market. The BeagleBoard was launched by Texas Instruments in 2008 and can function as a single-board computer. The Raspberry Pi platform was first launched in 2012 and also functions as a single-board computer. More recently the Arduino movement has released new versions such as the Arduino Yún with similar capabilities.

20.1.3 Embedded Autonomous Maintenance Systems

Low cost embedded systems such as those described above offer a significant opportunity for the development of systems and devices which can be used to support localized, operator led maintenance activities. In this chapter the nature of AM will be investigated. Enabling technologies and concepts will then be explored such as the functionality of the available hardware, its reliability and robustness for the proposed application and the impact of current research areas such as the "Internet of Things" and "Big Data".

20.2 Literature Review

20.2.1 Examples of Autonomous Maintenance

Autonomous Maintenance (AM) is one of the pillars of Total Productive Maintenance (TPM). TPM is a partnership between maintenance and production functions in the organization to improve product quality, reduce waste, reduce manufacturing cost, increase equipment availability, and improve the company's state of maintenance [8]. There is a plenty of work available in literature that deals with benefits of a successful implementation of TPM in the industry [9–14]. Similarly, there is ample research on the barriers to implement a successful TPM program [15, 16]. Ahuja and Khamba [17] summarizes the problems in TPM implementation as cultural resistance to change, partial implementation of TPM, overly optimistic expectations, lack of a well-defined routine for attaining the objectives of implementation (equipment effectiveness), lack of training and education, lack of organizational communication, and implementation of TPM to conform to societal norms rather than for its instrumentality to achieve world class manufacturing [18, 19].

AM has come a long way from what it was described by Nakajima [4]. AM of the modern times can be categorized into two main categories. The first is the "self-monitoring and repair/healing" category. The second focuses upon automating maintenance practices within organizations, with a particular focus upon the use of autonomous robotics to aid, guide or take over current maintenance tasks undertaken by human engineers/workers [20]. The next two paragraphs deal with the literature in these two categories.

Literature in the self-* category deals with the ability of the machines to self-test, self-monitor, self-diagnose, self-heal and self-repair. Important steps are; firstly, to make the machine aware of its current status; secondly, to know how it is expected to behave and thirdly, to arrive at a proper diagnosis by sensing the difference between the two [21–23]. Bell et al. [24] describe three methods to do automated diagnosis; Model based, Bayesian belief network based and case based reasoning. The corrective action in the machine can then take place either through self-healing or self-repair. Self-healing involves the part to heal the damage from inside. This can be done with the help of self-healing materials, software or mechanisms. A detailed survey on this can be read in [25]. Self-repair; on the other hand, means that the system has the ability to partially or fully fix a given fault. This can be done through self-reconfiguration [26]. A single spare module can be designed that is able to replace a host of primary modules in spite of having different structure. Alternatively this concept of self-repair through self- reconfiguration does not necessarily require additional materials; instead performance can be sacrificed to ensure continued functionality utilizing only the currently available resources [24].

Most prominent applications of the second category have been found in maintenance of railways, pipelines, sewerage systems. Turner et al. [27] describe a project in novel sensing, scheduling, and decision-making strategies customized for the automated planning of maintenance activities within the rail industry. Three key areas of research in the project are sensor fusion, planning & scheduling and costing. Dadashi et al. [28], Bye [29] and Dadashi et al. [30] have studied the applications of handheld computers in the rail industry. Robot agent based technologies are considered as an attractive alternative for fully/semi-autonomous pipeline monitoring and inspection. Moreover, robot agent-based technologies free the engineers from the confinement of pipeline inaccessibility, environment hazardousness, and system scalability [31]. In the field of autonomous maintenance of pipelines, Wang et al. [32] developed a novel autonomous in-pipe robot to perform the preventive point repair for long-distance offshore oil pipelines. The autonomous in-pipe robot performs online ultrasonic inspection for pipe wall thickness, and the original inspection data are stored in large capacity hard disk. Through the offline data analysis by the data analysts and the software tool, the pipeline health status is known. If server defects lie there, the in-pipe robot is introduced into the pipeline once more to indicate the defect's location to the maintenance ship. Kim et al. [31] propose a novel Radio Frequency Identification (RFID)-based Autonomous maintenance system for

Pipelines which combines robotic, sensing, and RFID technologies for efficient and accurate inspection, corrective repair, and precise geo-location information. Other works in this field include [33, 34]. Kirkham et al. [35] and Hertzberg and Kirchner [36] describe semi-autonomous inspection robots for sewer pipes. Robots have been of great help in carrying out maintenance where climbing vertical structures is involved. Schmidt and Berns [37] conduct a comprehensive literature review on climbing robots for inspection and maintenance of vertical structures.

20.2.2 Role of Autonomous Maintenance Within TPM

AM is a major constituent of the TPM approach. AM simply implies that the inspection be incorporated with production when possible, thus allowing people to inspect their own work and learn from their mistakes. This also reduces the number of communication links across departmental boundaries. The fewer the variances that are imported from the place where they arise, the fewer the levels of supervision and control that are required [38]. AM is one of the eight pillars of TPM that aims at developing operator ownership. The operator performs day-to-day tasks to be able to develop skills and in turn mastery of the equipment [39]. As operators are trained, they begin to inspect and maintain the equipment and perform basic maintenance tasks. This allocation of maintenance tasks to production operators frees up, provides more time or something similar up time for maintenance personnel to perform long-term improvement efforts and plan maintenance interventions [40]. Nakajima [4] presented a framework for a four phase implementation of an AM and Planned Maintenance approach. Mckone and Weiss [40] later included a fifth phase in the framework. These five stages and the steps taken as part of the AM approach are enumerated in Table 20.1.

The first phase of the plan deals with attaining control over the machine by eliminating the sources of problem. In the second phase, operators are trained to carry out general inspection of the machine and follow the standards set in phase 1. Phase 3 is related to carrying out autonomous inspection based on preventive

Table 20.1 AM in the five phases of TPM development [40]

	Phase 1 Reduce life span variability	Phase 2 Lengthen average life span	Phase 3 Estimate life span	Phase 4 Predict life span	Phase 5 Design life span
Autonomous maintenance steps	1: Basic cleaning 2: Eliminate source of problem 3: Set standards	4: General inspection of equipment	5: Autonomous inspection	6: Maintenance of quality 7: Autonomous maintenance	8: Process improvement and design team 9: Implement in all support areas

maintenance schedules. In phase 4, predictive maintenance tools such as condition monitoring are available that help carry out high quality maintenance. In phase 5, design teams made up of engineers, maintenance workers, and operators prepare equipment so that cleaning and inspection standards are established and personnel are trained to produce effectively upon roll-out. Phase 5 decisions also consider other non-maintenance systems, such as spare parts, raw materials, and production scheduling that impact the equipment productivity and quality [40].

There have been major advancements in the field of autonomous monitoring and maintenance of the machines. Sensor networks have witnessed a rapid growth due to the development of inexpensive sensing devices and communication technologies and are used for several applications such as agriculture, military, health care, and pipeline monitoring [31]. The use of robotics has also increased in the recent years. The application of robots can be restricted to being non-autonomous being guided by the humans for navigation to the fault and conduct of inspection through the robot by the operator [41]. These non-autonomous robots (e.g., remote-controlled) are equipped with cameras, sensors, and master-slave controlled manipulators [42]. The robots are termed as semi-autonomous where the navigation part is carried out autonomously but the decision making and repairing is done by the humans [43]. The autonomous robots have the capability to carry out navigation, inspection and repair.

AM implied that the operator is skilled and trained to autonomously undertake inspection and repair of his machine. AM has evolved to mean that the machine itself is able to monitor and repair faults in it. Researchers are looking for methods of self-monitoring, self-testing and self-diagnosis of faults by the machines.

20.2.3 Barriers to Autonomous Maintenance

While the benefits of Autonomous Maintenance are clear, there are certain barriers in implementing a truly AM system capable of carrying out the required actions. These barriers are listed below.

- **Non-modularity of the design of the assets**: AM demands high level of modularity in the assets. It helps in diagnosis, fault isolation and disassembly. The damaged or in need of service components can be maintained or repaired after disassembly at a later date at separate and more ideal facilities. Incorporating such an ideal of modularization into design could be an alternative route to building ever more complex autonomous robots [20]. Modularity will also help in incorporating redundancy of parts by having spare modules that are of same type as the degenerate module; or have single spare module that has the capability to replace any defective module [24].

- **Embedding of sensors in the existing assets**: Majority of the AM tasks involve some level of monitoring by the sensors. In case an AM plan has to be implemented in existing assets, it is a challenge to embed these sensors without adversely impacting the asset itself. It implies that in certain cases, there may be a need to re-design the asset itself. Other option would be to invest more on robotic monitoring systems that are external to the asset.
- **Adapting to non-deterministic environment**: Maintenance is a non-deterministic activity. The situation and environment of the maintenance activity is likely to change; and at an unknown rate. These varying scenarios present a vast number of possible decisions for the AM system to make. The AM system needs to have cognitive ability and intelligence to pick the most optimal decision.
- **Diagnosis**: Diagnosis of the fault has traditionally been the most difficult step in maintenance. The same is true even in the case of AM systems. The machines are getting complex and hence there are a vast number of possible system states. There are further challenges of not having adequate confidence in the diagnosis. An additional step is required in which the diagnosis must be confirmed, to avoid undesirable events such as ‘good’ components being unnecessarily removed or routed around [24].
- **Financial barrier**: Any new technology will find practical application in the industry if there are cost benefits of doing it. The investments in modern AM systems are large; larger than the possible returns of reduced maintenance and downtimes. Due to this reason, the application is limited to most critical systems and places where it is hazardous for the human beings to operate. This is the possible reason why the research is focussed more on AM of vertical structures and underwater pipelines. Low cost systems discussed in this chapter attempt at breaking this barrier and making AM more cost effective.
- **Social barriers**: All organizations are sociotechnical systems. Organizational objectives are best met not by the optimization of the technical system and the adaptation of social system into it, but by the joint optimization of the technical and the social aspects [38]. Sociotechnical theory has at its core the notion that the design and performance of new systems can be improved, and indeed can only work satisfactorily, if the ‘social’ and the ‘technical’ are brought together and treated as interdependent aspects of a work system [44]. AM may have evolved technically over the years, but the social implications in successfully implementing it in an industry have not changed. The workers may see it as a means to cut down jobs. There are extra skills required by the operators to operate semi-autonomous robots. This in turn implies greater investments in training. The top management may be committed to implement such a program, but it must have the patience to implement it in stages. The success and the lessons learnt in a stage should be utilised to fuel the subsequent stages of implementation.
- **Need of a multi-disciplinary workforce**: There is a need to have a multi-disciplinary workforce; particularly in the decision making echelon that has the knowledge of engineering, computing, analytics, automation, design and

production. This may be difficult in certain industries. It also results in increasing the costs of hiring and retaining a potentially more qualified workforce.

- **High risk of disruptions**: There is a high-risk associated with new technology and system implementation. The implementation of an AM system "may negatively impact operations while personnel are achieving competency or fail to operate as originally intended" [45].

20.3 Role of Low Cost Embedded Systems in Facilitating Autonomous Maintenance

Low cost embedded microprocessor based platforms offer the potential to develop solutions which address many of these barriers. Low cost platforms and the rapid system development they offer have the potential to de-risk the development of localized condition monitoring systems which can be readily adapted to operate on a range of assets. This means that condition monitoring systems which adapt to non-modularity can easily be developed to suit particular 'bespoke' equipment and systems. Furthermore sensor systems can be designed more flexibly to address impacts on the normal operation of the asset.

The computational power of platforms such as Raspberry Pi, Arduino and BeagleBoard mean that a considerable level of intelligence can be embedded at the level of a particular asset. Historically, condition monitoring systems often relied on centralized processing, rule setting and data storage to handle the data from many assets thus decoupling the operator from the process and undermining the principles of AM. This can now be avoided through the use of localized processing and storage. Furthermore, the connectivity offered by such platforms means that the benefits of interconnection are not lost meaning that centralized monitoring can still take place alongside operator led processes.

The accessibility of such platforms means that condition monitoring can become truly integrated within the AM and TPM methodologies rather than being something practiced by specialist technicians. Any machine operator will have the ability to understand, develop and enhance the condition monitoring platform with minimal training if the appropriate development tools and aids are in place.

20.3.1 Integration Between Localized and Centralized Systems

Big Data has been identified by the scholars as "the next big thing in innovation" [46] and the "new paradigm of knowledge assets" [47]. Wu et al. [48] describes Big Data characteristics through HACE theorem; large-volume and Heterogeneous, Autonomous source with distributed and decentralized control, and seeks to explore Complex and Evolving relationships among data. High dimensionality of this big data helps in predicting the future by establishing relationships between variables. Autonomous data sources with distributed and decentralized controls are a main characteristic of Big Data applications. Being autonomous, each data source is able to generate and collect information without involving (or relying on) any centralized control [48]. The real world relationships amongst the variables are complex and evolving. Large sample size of the data helps in understanding this complex relationship by firstly, exploring the hidden structures of each subpopulation of the data, which is traditionally not feasible and might even be treated as 'outliers' when the sample size is small; and secondly, by extracting important common features across many subpopulations even when there are large individual variations [49]. Big Data Analytics (BDA) has helped organizations and systems to analyze large volume of high dimension data from a large sample size collected by autonomous decentralized sensors. BDA has the capability to predict the future course of events by establishing trends in otherwise unrelated variables.

AM involves collection of data by autonomous sensors placed on the machines. There are other sources of data which reside in the ERP systems, process control systems, smart devices etc. The employees and customers are adding to this ever increasing data deluge through social media. The data need not always be numerical data. Keywords being used in the reviews, tweets, logbooks, inspection sheets, job cards and other such sources can be picked up to derive meanings. This data needs to be analysed along with data from several such sources distributed across the globe to discover hidden relationships that can help in predicting the future events like equipment failure. Big data and predictive analytics can also help by providing operation warnings and automatic interventions. Predictive analytics software use fast algorithms scalable to massive data with high dimensionality to detect subtle variances for each piece of equipment, which often warn of impending problems that might have gone unnoticed otherwise.

The machines have traditionally been fitted with sensors that transmit data through proprietary communication protocols to proprietary control interfaces that are generally located within the premises of the organization. With emergence of Internet of Things (IoT), these sensors can now communicate using the standard internet protocols, using open standards, making the data available to a wide range of users on the internet. The cost of computing as well as the cost of the sensors is decreasing rapidly. This has increased the potential to embed the machines with more sophisticated sensors and processors. As these sensors are now connected through standard internet protocols, the volume of data has increased that can lead to real-time analysis.

20.3.2 *Enablers Required for Realization of Low Cost Autonomous Maintenance Support*

In order for Low Cost Hardware Platforms to be effectively and optimally applied to the support of AM, the following barriers and issues must be addressed:

- **Reliability and Resilience**. One of the major issues affecting low cost "off the shelf" hardware is the fact the design of these devices is often heavily focused on non-industrial applications. A number of reliability related issues exist for these platforms and devices:
    - The reduction in size of the devices involved means that there is a greater risk of transient faults affecting the reliability of the system [50].
    - Such devices are often developed with a minimal level of protection against various stresses such thermal conditions, electrical transients and electrostatic discharge (ESD). While there are well-proven techniques to mitigate against these issues in high risk situations such as the use of protection diodes, shielding, protective grounding and transient protection devices [51], these are often overlooked in low cost applications.
    - Electronic systems are often incorrectly assumed to be immune to aging process due to the absence of moving parts. While wear rates are potentially lower, several studies, e.g. Knight et al. [52] have indicated that faults can occur—even in low power systems such as electronic systems in automotive environments. Thus systems operating in a manufacturing context are likely to be equally susceptible to age related degradation processes.
- **Cost**. A further enabler for the industrial use of off the shelf microprocessor systems for AM applications lies in the cost. While the 'core' platforms themselves are often low-cost, the required additional hardware should be minimized since this is often where costs can accumulate. This can make the selection of platform critical since an incorrect choice e.g. of a platform with no intrinsic communications capabilities can be rapidly undermined by the need to add hardware to achieve wider integration. Other additional hardware which may add cost in condition monitoring applications include signal processing and conditioning systems involved in integrating with sensors and other data sources. A fundamental trade-off thus exists between having a platform that is intrinsically flexible enough to benefit from mass production and one which is not so heavily featured as to drive up cost.
- **Development Support**. One of the key factors in the success of the Arduino platform is the common and easily accessible development environment which is offered and which is based on widely used programming languages such as Java, C and C ++. Such platforms by their very nature do not provide support for application specific functionality since these are likely to be underutilized. While additional software libraries exist to perform many such functions, these are often lacking in the degree of verification required for industrial users to have confidence in them.

20.4 Roadmap for Achieving Low Cost Autonomous Maintenance Support

If autonomous maintenance is to be successfully supported by off the shelf hardware with the minimum level of additional development, the following research outcomes need to be achieved:

- **Identification of core functionality to ensure efficient production and minimum additional hardware**. Ensuring the correct balance is struck between versatility and simplicity of a platform will be a critical consideration in the design of an open-source computing platform that is suitable for supporting AM and localized condition monitoring. A key issue will be the choice of microprocessor or microcontroller. Thus analyzing the needs implied by the potential applications will be critical in this process.
- **Identification of key reliability issues in electronic systems/industrial environments**. Once the core functionality and key devices have been selected a robust yet affordable platform will need to be generated taking full advantage of established approaches to designing robust electronic systems. This will require research into the environmental conditions that might be reasonably expected in the desired application, as well as detailed prototyping, testing and evaluation to demonstrate the reliability of the hardware.
- **Identification of core software development support systems**. This will require consideration of the existing skills and knowledge of the operators and an understanding of how they may wish to configure and use such systems to support their role in autonomous maintenance. Systems and approaches to support rapid development and reconfiguration are thus required while maintaining the ability for advanced users to fully exploit the capabilities of the platform.
- **Identification of core technical knowledge and skills required for machinery operators to actively engage in AM**. It is likely to that some upskilling will be required but this should focus on how the platform can support AM rather than on the technical details of the platform. Thus abstracting the details of the implementation and developing a platform that encourages enhancement of operator skills is a key objective.

20.5 Conclusions

Reliability and efficiency of equipment is a key factor in productivity for many manufacturing and engineering operations. While approaches such as TPM are well established, their role within an asset management approach continues to evolve in the light of continuous developments in supporting technologies.

Off the shelf embedded platforms offer considerable potential for further evolving the role of operators in maintaining their own assets. In order to fully maximize this potential the technology needs to be carefully developed to ensure that it is robust, reliable, easy to develop and apply and of commercial benefit. Furthermore, and perhaps more importantly, it must be seen and perceived to possess these attributes by those at all levels within organizations with responsibility of maintenance, from senior management down to operators, if widespread uptake is to be achieved.

References

1. Tsuchiya S (1992) Quality maintenance: zero defects through equipment management. Productivity Press, Cambridge, MA
2. Willmott P (1994) Total quality with teeth. TQM Mag 6(4):48–50
3. Min CS, Ahmad R, Kamaruddin S, Azid IA (2011) Development of autonomous maintenance implementation framework for semiconductor industries. Int J Ind Syst Eng 9(3):268–297
4. Nakajima S (1988) TPM development program. Productivity Press, Cambridge, UK
5. Severance C (2014) Massimo Banzi: building Arduino. Computer 47(1):11–12. doi:10.1109/MC.2014.19
6. Hill L, Steven C (2013) Using a low cost open source hardware development platform in teaching young students programming skills. In: Proceedings of the 14th annual ACM SIGITE conference on information technology education, pp 63–68. doi:10.1145/2512276.2512289
7. English A (2015) Open Source Hardware—an iGEM Guide. University of Cambridge. http://2015.igem.org/wiki/images/d/db/CamJIC-Practices-Guide.pdf
8. Rhyne DM (1990) Total plant performance advantages through total productive maintenance. Conference proceedings APICS, Birmingham, pp 683–686
9. Windle WM (1993) TPM: more alphabet soup or a useful plant improvement concept? Plant Eng 47(2):62–63
10. Chowdhury C (1995) NITIE and HINDALCO give a new dimension to TPM. Udyog Pragati 22(1):5–11
11. Ireland F, Dale BG (2001) A study of total productive maintenance implementation. J Qual Maint Eng 7(3):183–191
12. Chan FTS, Lau HCW, Ip RWL, Chan HK, Kong S (2005) Implementation of total productive maintenance: a case study. Int J Prod Econ 95:71–94
13. Sharma KR, Kumar D, Kumar P (2006) Manufacturing excellence through TPM implementation: a practical analysis. Ind Manag Data Syst 106:256–280
14. Ahuja IPS, Khamba JS (2007) An evaluation of TPM implementation initiatives in an Indian manufacturing enterprise. J Qual Maint Eng 13(4):338–352
15. Attri R, Grover S, Dev N, Kumar D (2013) Analysis of barriers of total productive maintenance (TPM). Int J Syst Assur Eng Manag 4(4):365–377
16. Poduval PS, Pramod VR, Raj VPJ (2013) Barriers in TPM implementation in industries. Int J Sci Technol Res 2(5)
17. Ahuja IPS, Khamba JS (2008) Total productive maintenance: literature review and directions. Int J Qual Reliab Manag 25(7):709–756
18. Crawford KM, Blackstone JH Jr, Cox JF (1988) A study of JIT implementation and operating problems. Int J Prod Res 26(9):1561–1568
19. Becker SW (1993) TQM does work: ten reasons why misguided efforts fail. Manag Rev 82(5):30–34

20. Farnsworth M, Bell C, Khan S, Tomiyama T (2014) Autonomous maintenance for through-life engineering. Through-Life Eng Serv 395–419
21. Frei R (2010) Self-organisation in evolvable assembly systems. PhD thesis, Department of Electrical Engineering, Faculty of Science and Technology, Universidade Nova de Lisboa, Portugal
22. Visinsky ML, Cavallaro JR, Walker ID (1994) Robotic fault detection and fault tolerance: a survey. Reliab Eng Syst Saf 46(2):139–158
23. Laddaga R (1997) Self-adaptive software. Technical report 98–12, DARPA BAA
24. Bell C, McWilliam R, Purvis A, Tiwari A (2013) Concepts of self-repairing systems. Meas Control 46(6):176–179
25. Frei R, McWilliam R, Derrick B, Purvis A, Tiwari A, Di Marzo SG (2013) Self-healing and self-repairing technologies. Int J Adv Manuf Technol 69:1033–1061
26. Stoy K, Christensen D, Brandt D (2010) Self-reconfigurable robots: an introduction. MIT Press, Cambridge
27. Turner CJ, Tiwari A, Starr A, Durazo-Cardenas I, Blacktop K (2015) An intelligent framework and prototype for autonomous maintenance planning in the rail industry. In: Proceedings of the first international conference on vehicle technology and intelligent control systems, Lisbon, Portugal
28. Dadashi Y, Wilson JR, Sharples S, Clarke T (2008) Applications of handheld computers for the rail industry. In: Bust PD (ed) Proceedings of the international conference on contemporary ergonomics (CE2008), Nottingham, UK. CRC Press
29. Bye R (2013) Designing mobile user experiences: disruptive innovation in railway asset information. In: Dadashi N et al (eds) Rail human factors: supporting reliability, safety and cost reduction, Leiden. CRC Press
30. Dadashi Y, Sharples S, Wilson JR, Clarke T (2012) Investigating presentation of rail specific spatial information on handheld computer screens. Pers Ubiquitous Comput 16(8)
31. Kim JH, Sharma G, Boudriga N, Iyengar SS, Prabakar N (2015) Autonomous pipeline monitoring and maintenance system: a RFID-based approach. EURASIP J Wirel Commun Netw 2015:262
32. Wang Z, Cao Q, Luan N, Zhang L (2010) Development of an autonomous in-pipe robot for offshore pipeline maintenance. Ind Robot: Int J 37(2):177–184
33. Henrique VS, Morooka CK, Guilherme IR, Tiago CF, Mendes JP (2005) Leak detection in petroleum pipelines using a fuzzy system. J Petrol Sci Eng 49(3/4):223–238
34. Feng J, Zhang HG (2005) Diagnosis and localization of pipeline leak based on fuzzy decision-making method. Acta Automatica Sinica 31(3):484–490
35. Kirkham R, Kearney P, Rogers K, Mashford J (2000) PIRAT—a system for quantitative sewer pipe assessment. Int J Robot Res 19(11):1033–1053
36. Hertzberg J, Kirchner F (1996) Landmark-based autonomous navigation in sewerage pipes. In: Proceedings of the first Euromicro workshop on advanced mobile robot, pp 68–73
37. Schmidt D, Berns K (2013) Climbing robots for maintenance and inspections of vertical structures—a survey of design aspects and technologies. Robot Auton Syst 61:1288–1305
38. Cherns A (1976) The principles of sociotechnical designs. Hum Rel 29(8):783–792
39. Parikh Y, Mahamuni P (2015) Total productive maintenance: need and framework. Int J Innov Res Adv Eng 2(2):126–130
40. Mckone KE, Weiss EN (1998) TPM: planned and autonomous maintenance: bridging the gap between practice and research. Prod Oper Manag 7(4):335–351
41. Parker LE, Draper JV (1998) Robotics applications in maintenance and repair. Handbook of industrial robotics, 2nd edn
42. Akrout H, Anson D, Bianchini G, Neveur A, Trinel C, Farnsworth M, Tomiyama T (2013) Maintenance task classification: towards automated robotic maintenance for industry. In: 2nd international through-life engineering services conference, Procedia CIRP, vol 11, pp 367–372

43. Dobie G, Spencer A, Burnham K, Pierce GS, Worden K, Galbraith W, Hayward G (2011) Simulation of ultrasonic lamb wave generation, propagation and detection for a reconfigurable air coupled scanner. Ultrasonics 51:258–269
44. Clegg CW (2000) Sociotechnical principles for system design. Appl Ergon 31:463–477
45. O'Donovan P, Leahy K, Bruton K, O'Sullivan DTJ (2015) An industrial big data pipeline for data-driven analytics maintenance applications in large-scale smart manufacturing facilities. J Big Data 2:25
46. Gobble MM (2013) Big data: the next big thing in innovation. Res Technol Manag 56(1): 64–66
47. Hagstrom M (2012) High-performance analytics fuels innovation and inclusive growth: use big data, hyperconnectivity and speed to intelligence to get true value in the digital economy. J Adv Anal 2:3–4
48. Wu L, Yuan L-Y, You J-H (2015) Survey of large-scale data management systems for big data applications. J Comput Sci Technol 30(1):163–183
49. Fan J, Han F, Liu H (2014) Challenges of big data analysis. Natl Sci Rev 1:293–314
50. Gracia-Morán J, Baraza Calvo JC, Gil Tomás DA, Saiz-Adalid L, Gil P (2014) Effects of intermittent faults on the reliability of a reduced instruction set computing (RISC) microprocessor. IEEE Trans Reliab 63(1):144–153. doi:10.1109/TR.2014.2299711
51. Department of Defense (1998) Electronic reliability design handbook
52. Knight I, Eaton A, Whitehead D (2001) Reliability of electronically controlled systems on vehicles. Transport Research Laboratory (TRL) Report