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The Future of Maintenance

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9.1 Introduction

In this book, a number of perspectives on predictive and proactive maintenance have been presented that were developed during the course of EU/ECSEL project MANTIS in the years 2015–2018. At the start of the project, a number of developments heralded things to come: The Big Data and data science revolution, internet of things (IoT), advances in machine learning, improvements in wireless connectivity, sensor technologies and available computing power. At the level of software, cloud computing, software services, semantic interoperability and multi-tiered architectures all displayed a fast-moving field. This final chapter takes a step back and presents some views towards the future. Whether one deals with PM on a manufacturing process or a fleet of machines, in logistics or construction, the potential gains from improving the maintenance policies can be substantial. With a daily yield of 30% of a particular production process, an improvement of only 3 percentage points due to improved maintenance policies constitutes an improvement of 10% on the status quo. In maintenance services for customers of a leased fleet of machines, the statistical analysis of customer usage patterns allows a company to design services, adapted to the wear & tear patterns that are typical for different customer groups and provide economically attractive solutions (e.g., 'bronze, silver and gold' maintenance service levels). With this in mind, it is surprising that maintenance is sometimes considered as a liability. In the biological world, the praying mantis will clean its body and sensors, autonomously. For cyber-physical systems of the near future, one would hope that at least part of such behaviors is controlled on the basis of intrinsic feedback loops. This should ideally be realized in a cost-effective manner, i.e., with minimal human intervention at all levels of control, ranging from analytics to decision making, corrective interventions and preventive actions at the physical level. Only an integrated design of primary and secondary system functions of cyber-physical system will lead to efficient and resilient systems. When NASA rovers were sent to Mars, it quickly became clear that in spite of the impressive technological advances, a 'minor' aspect was overlooked: Dust was accumulating on the solar panels, the camera lenses and the color-calibration disk for true-color adjustments [KinchMarsDust, 2007]. Unlike its biological counterparts on earth, e.g., insects, the Mars rover did not have actuators, neither for cleaning its essential photovoltaic energy-harvesting system, nor its sensors (Figure 9.1).

Today, companies will need to decide what their basic policy is with regards to maintenance, a.k.a. that secondary but nevertheless essential process in working systems. Production tools and consumer products are increasingly designed on the basis of appearance and perceived simplicity. According to this philosophy, large components are often replaced as a whole and no attempt is made at maintenance 'below the hood'. It is questionable whether this is sustainable in the long term, due to limited global resources. As an example, take a large data center. If the storage and server units are purchased and installed at one concentrated point in time, the sub systems will statistically fail after a few years and the total quality of service is jeopardized. Users of that data center will expect a reliable operation without interruptions. Should the company aim at a gross replacement of large groups

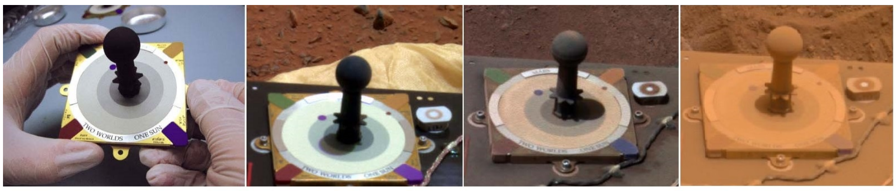

Figure 9.1 Unexpected dust accumulation on the color calibrator of a Mars rover. Without actuators for autonomous self maintenance, only the wind can help out [KinchMarsDust, 2007].

of racks at the end of their life cycle, coincident with a long off-line period? Should one, alternatively, aim at gradual replacement of servers at the level of blade-server modules? Or should the investment be aimed at a solid frame architecture offering uninterrupted operations? The latter approach would entail a continuous robotic replacement of small disk units in a manner that is similar to a biological metabolic process, with an input buffer of spare disks and an output stream of defunct units. Is there a cost-effective combination of these different approaches? In order to make rational choices concerning the level of granularity and in order to learn effective operating policies as a company, the quantitative approach to maintenance as sketched out in this book is essential. In the remainder of the chapter, we will focus on the following provocative questions:

- Is it cybernetic or is it human?
- Real-time communication in maintenance?
- How to determine granularity in space and time?
- Open or closed maintainability?
- Insourcing or outsourcing?
- Explicit modeling or data-driven pragmatics?
- How to apply Virtual Reality and Augmented Reality?
- Service robotics for maintenance?

9.2 Is it Cybernetic or Is it Human?

From the experiences in the project, it is clear that current practice is still lagging today's maintenance control capabilities. Although the amount of logged data can be quite impressive in the use cases, it is clear that the exploitation of the available information is limited. Maintenance-related decision processes are slow. They often require human-to-human interaction concerning the selection of relevant data from legacy data bases, sometimes with a complicated access-clearance procedure. As a result of preliminary analyses, usually more data are needed, requiring ever more human-to-human communication and negotiation. This predicament is exacerbated if the analytics is not performed by in-house data scientists but by external companies providing analytics services. The necessary data will usually exist, somewhere in a huge storage repository. However, even after it has been collected there will be a labor-intensive process of data cleaning, normalization and repackaging before it can be used by traditional statistics or modern machine learning off-the-shelf tools. In this process, additional human-to-human communication is needed ranging from database administrators to operators on the shop floor in order to actually understand the data and the underlying physical processes. In order to really close the maintenance-oriented feedback loop of a CPS, a number of steps need to be made:

- A transition needs to be realized, from isolated ad-hoc problem analysis to continuous measurement processes and effective control policies, at a pace that fits the underlying process and is economically viable;
- The connection between the target process itself and the analytics modules needs to be an information highway in itself, not an improvised ad-hoc connection. Standardisation is therefore a necessity at all levels, from network I/O to semantic interoperability. The Explanator concept for adding specific signal metadata to a .csv spreadsheet column (Chapter 3) is just one example of the additional scaffolding that is necessary;
- The standardized data can be easily presented to in-house and external analytics consultants, allowing for selecting the best predictions or policy suggestions from several opinions or perspectives. If the packaging of analytics results is also standardized, even the selection process of finding the best solution can be automated.

Closing this feedback loop into a fully autonomous cyber-physical system is not desirable at this stage, but a substantial reduction in human labor and an improvement in the quality of the decisions can be expected as a result of following these suggestions.

9.3 Real-time Communication in Maintenance?

An effective condition maintenance procedure requires the acquisition of dozens of signals, some of which are related with the normal operation of the system, while other are very specific to the maintenance requirements. Some of these acquisitions are performed at very high rates (e.g., with an interval of 10 ms). Achieving these timing requirements in low-performance wireless networks like Zigbee or Bluetooth is a challenge that has to be faced when designing any maintenance-based processing system. Additionally, if we have several sources with the same requirements, the networks supporting them might be occupied close to their operating limit. Condition-based maintenance will in some cases also require true real-time detection of physical problems. This can be the case, for example, in cars, trains or industrial manufacturing machines. In such cases, malfunctions have to be detected within a tightly limited time frame in order either to avoid the problem, or put the system into a safe state. For different types of malfunctions, a characteristic limited deadline for reporting must be specified. Possible solutions to achieve these capabilities concern the use of multi-core computing platforms together with real-time operating systems that are also tightly integrated with the analysis tools. While finding an adequate real-time operating system can be an easy task, adapting and connecting data-analysis tools is still a challenge that needs to be addressed, both in relation to parallelization and to the technical details of the integration with such a real-time operating system. The work performed during the MANTIS project allowed the identification of two main challenges for future research: i) The realization of maintenance-related real-time communication capabilities, and ii) attaining real-time guarantees for (close to) real-time data analysis at the level of analytics.

9.4 How to Determine Granularity in Space and Time?

Large, disruptive transformations in a system architecture are expensive, risky and time consuming. On the contrary, a system that is designed for maintenance and maintenance-related processes will allow for incremental improvements that do not disturb ongoing processes. Going back to the example of the data centers: If it holds a maintenance criterion such as 'duration of a disk hot swap should not take more than 2 minutes', this requirement may have a domino effect on the temporal granularity of other interventions. If other maintenance operations have a duration in the same order of magnitude, the total process is much easier to manage. In the current practice of data centers, users will often not even notice that maintenance on RAID disk systems is going on. In addition to the granularity in time, the scale of replaced system components ('just a disk' versus 'a complete rack') plays a role too. It is possible to design good systems with maintainability in mind, thus avoiding operating costs that can be foreseen and prevented. This can be realized by choosing the proper granularity for component replacement.

9.5 Open or Closed Maintainability?

Depending on the application area, maintenance in manufacturing or maintenance of consumer products, there will be different company goals. The increased digitization has allowed some companies to create customer 'lock-in' by means of specialized electronic tools for maintenance diagnostics. Sometimes there are contracts where a user is allowed to operate, but not maintain a particular product. Currently a countermovement is emerging in the United States under the 'Right to Repair Act' in several states, for automobiles and agricultural equipment.

Rather than pursuing a conflict model, companies can create goodwill and customer involvement in maintenance issues by the proper use of big data on wear & tear for different usage patterns and by offering customized maintenance services for individual users. In this manner, predictive maintenance is beneficial for both parties and companies keep a strong position thanks to their information advantage.

9.6 Insourcing or Outsourcing?

The increased availability of analytics consultants with a statistical or machine learning background poses new dilemmas for companies. In recent years, there was a trend to outsource a number of activities and ICT services to external companies. It is debatable whether maintenance-related information processing is 'just ICT'. The involved knowledge is highly sensitive and is the intellectual property of a particular company. Decisions will have to be made concerning the employment of external parties because maintenance-related topics are directly connected to the reputation of a product and the profit model that is in action. Evidently, legal mechanisms can be applied to mitigate the risk of allowing third parties access to a core process. On the other hand, predictive maintenance is so knowledge intensive and tightly coupled to the center of a company's activities that outsourcing should be avoided in some cases. Replacing a body part with an extraneous replacement may be acceptable in some areas, but would we outsource the brain, too? The amount of knowledge that needs to be shared with external analytics partners is usually also detailed and still requires substantial time investments, by both parties. Whereas the company sees an opportunity for success with limited loss of time, the analytics company expects to find low-hanging fruit: Both expectations are overly optimistic. There is no free lunch: Modern machine learning only works with enough high-quality data from the problem owner. At the same time, companies may have worked for decades on a particular maintenance problem such that it may be very difficult for newcomers to improve existing results.

9.7 Explicit Modeling or Data-driven Pragmatics?

The project unrolled in a period where there are tremendous advances in artificial intelligence and machine learning. Almost every month there was a breakthrough in *deep learning*, considering hard, nonlinear problems, such as the game of Go. Although most advances have been made in the area of image processing, or problems where a 2D array of cells is given at the input, there are also advances in time-series processing using recurrent neural networks, such as the LSTMs. On the other end of the spectrum are the traditional modeling approaches, such as hidden-Markov models or regression statistics for modeling aspects of maintenance processes. In the traditional approach, modeling from *interpretable models* (white box modeling) is used to obtain a detailed insight in complex processes and the underlying causalities. In the relevant communities there is considerable mutual scepticism, not so say animosity, concerning ‘the other’ (black box modeling) approach. The easy answer would be to say that time will tell. However, it is already becoming clear in what direction future developments may go. The new machine-learning tools allow to discuss regarding the existence of a particular I/O mapping with sufficient accuracy and reliability. From that point on, it depends on the actual goal of the analytics exercise. If a prediction with an acceptable error margin is at stake, it may not always be necessary – for a company – to understand all minute details and causes of this particular I/O relationship. Human-based analysis is costly and the traditional explicit-modeling approach is not always perfect, either. On the other hand, if a thorough understanding of an important and costly maintenance issue is needed, the investment in human-based research may be warranted. The new wave of machine learning has taught us at least one powerful lesson: Each model (including the handcrafted ones) can be viewed as just a stochastic sample from a universe $\mathcal{H}$ of possible model designs [Valiant, 1984]. There may exist several alternative models with similar accuracies and reliabilities: “All models are wrong, but some of them are more useful than others”. The challenge for a company then is to make effective use of these available variants for a particular problem. After all, the ultimate goal may be the economic yield, not the scientific understanding, per se.

9.8 How to Apply Virtual Reality and Augmented Reality?

Current industry is one of the key domains where virtual, augmented and mixed reality can create a huge added value.

The most commonly known applications of Virtual Reality (VR) in condition monitoring and maintenance are training, actual maintenance, remote maintenance/condition monitoring and maintenance assembly. Virtual Reality generates a computerized environment of the real system to be used in the previously mentioned aspects (see Figure 9.2).

VR could, for example, help the maintainer identify where exactly the problem is, from a whole system down to single component level, in a virtualized system so that the maintainer can reduce the asset's downtime.

Maintenance training has been used in several applications including aircrafts, automobiles, power plants and other process industry applications. In actual maintenance, VR has been used mostly in aircraft maintenance applications like military fighter planes because of the complexity of the maintenance process. Some other examples of remote maintenance applications for process industry and rotating machinery can also be found.

Figure 9.2 Virtual Reality system for maintenance.

Augmented reality (AR) is a blend between VR and actual reality. AR applications contain basically the same repertoire than general VR solutions. AR allows for maintenance training, actual maintenance, service based mobile maintenance tools, remote maintenance, maintenance assembly and e-maintenance solutions. Some applications contain even simple diagnostics and utilization of the user's speech.

Maintenance training has been used in similar applications as in VR. Current maintenance covers solutions like aeroplanes, armoured military vehicles and different industrial solutions. Remote maintenance solutions are targeted mainly for small and medium size enterprises. Some examples can be found from service based mobile maintenance tools and e-maintenance solutions. More sophisticated solutions utilize even simple diagnostics and the user's speech to make decisions.

9.9 Service Robotics for Maintenance?

Rapid developments are taking place not just in the area of machine learning. Robot technology is also advancing at a fast pace. There is a diversification of the application areas. Whereas in the eighties and nineties the focus was on statically located robot arms with strong force, high speed and accuracy, today's robots span a wider spectrum of implementations. Convenience of programming, man-machine collaboration and improved sensing are needed in the work place. In the Robocup@Home benchmark competition, the participants only hear a day in advance what the actual testing scenario will be (given a number of constraints on the robot design, in advance). Standardisation on the basis of ROS (Robot Operating System), and the Python programming ecosystem, have allowed fast prototyping. In light of these recent developments, it is amazing to see that current industrial robotics is still mechatronics based, very accurate but difficult and expensive to program. However, if one observes human operator activities along a production line, it is clear that part of this work also lends itself to possible robotisation. Evidently, the replacement of complex modules and tools in a manufacturing production line will still be a job for human operators. On the other hand, some tasks are repetetive and menial, involving visual or other types of inspection on known places along a production line, such as the occasional removal of dirt and providing oil in locations where friction starts to become a problem. The mean time between failure can be fairly short, for complicated production lines, while the human-based corrective actions sometimes are surprisingly trivial: A push here, a removal of a small obstruction, or simply cleaning an area with compressed air. Current robotics technology is well able to fulfill at least a part of these tasks, notably on a '24/7' basis. This prevents the buildup of large problems as a consequence of accumulated small problems. Under conditions of variable operating conditions, it would be too expensive to install dedicated hardware to solve a wide variety of the aforementioned problems. On the contrary, the solutions provided by service robotics are not hardware but behavior based, i.e., relying on trainable software. If service robots will be employed in a manufacturing setting, this will change but not obliterate the necessity of human interventions. Operators will become the robot trainers, providing the robots with a library of corrective behaviors for different problem locations along a production line. An important advantage is that such pragmatic knowledge is then shared among the members of a team of maintenance robots. The presence of such robots also provides an incentive for making the maintenance-related knowledge more explicit within the company. Interesting new research topics will evolve at the level of dynamic tool use by robots, using standard clip-on tools. An image emerges of large cyber-physical facilities with mobile maintenance robots supporting static production robots and maintaining active legacy production machines of a different era that are not yet at their end-of-life state from an economical point of view.

9.10 How will the Maintenance Practices Change

Most of the maintenance strategies that are followed today to some extent have existed for a long time e.g., the first edition of Maintenance Engineering Handbook was printed in 1957 [Higgings, 1987], the first edition of Moubray's Reliablity-centred Maintenance [Moubray, 2007] was published in 1991, Jardine & Tsang came up with Maintenance, Replacement, and Reliability [Jardine, 2006], Theory and Applications in 2006, Crespo's The Maintenance Management Framework [Crespo, 2007] was published in 2007, and E-maintenance came out in 2010 [Holmberg, 2010]. Also, the key standards have existed for a long time. In spite of the existence of these theories and methods, the everyday maintenance practices vary a lot. The so called corrective maintenance is still used to a great extent although it has been proven to be in many cases costly and ineffective. The main reasons for this situation are the lack of data that would help to understand the need for maintenance, and the lack of ways to define what would be the best practice from financial point of view.

The book in hand discusses widely the first aspect i.e., how to get data and how to turn that data into meaningful information about the current state of the machine i.e., is maintenance needed and when should that action be taken when considered from technical point of view. It is clearly shown what the Cyber-Physical Systems are capable of and how they can help in the definition of the condition of machinery and thus basically enable Condition-Based Maintenance i.e., enable maintenance based on need and not e.g., calendar. The dramatic reduction of cost of sensors and the dramatic development of processing power and wireless communication are the key elements in enabling IoT 4.0 and thus Maintenance 4.0 [Jantunen, 2018].

The second aspect i.e., the lack of ways to define what would be the best practices is not covered quite to the same extent. However, the increase of reliable data will enable the full use of the maintenance strategies named in the beginning of this section. For example Reliability-centred Maintenance (RCM) has been considered very hard to use due to the enormous manual work in collecting meaningful data. Even when the studies have been made in cases where it has been considered financially justified, the results have been criticized or at least doubted due the number of assumptions that have been made and the limitations in the amount of the data. Now this will change dramatically as the data will be available and, assuming it is managed in proper ways as discussed in chapter 3 of this book, and the basis for following the above described strategies exists. In fact it can be claimed that the most dramatic change will take place when the above described data will be used by Computerized Maintenance Management Systems (CMMS) to answer the what if question i.e., make comparisons between choices on strategic level and on practical level. The point is that collected data make it possible to run numerous scenarios comparing the financial results of different kind of approaches, e.g., conservative maintenance where maintenance actions are carried out early in order to guarantee high availability or more risky approach where maintenance actions are carried out closer to the end of the life of the components. In theory this means that in the future maintenance policies can be based purely on financial issues and not feelings, opinions, and partial information.

In a futuristic scenario, the maintenance can be automatic and without human intervention, managed by the CMMS that manages work orders and spare parts and at the same time, much of the practical work is actually carried out by robots as described earlier in this chapter. The reality today is that we are very far from the above described scenario. Today manufacturing companies are very keen on developing maintenance service businesses for the equipment they have sold. The main idea behind this is that it is realized that providing maintenance services to customers can stabilize the business against the variation of sales that are varying depending on local and world economy. Another scenario for manufacturing companies is that they would sell not the production machinery but the capability to produce at certain level. Even though there was a boom in providing maintenance services, quite a lot of work is needed in order to reach the scenario described above. Unfortunately, today the level from where the manufacturing companies start their development for the development of maintenance services varies a lot. Consequently, it can be expected that there will be great success stories when the development will follow efficient maintenance strategies, but there is also the risk that someone might have too high hopes regarding how quick and easy the development can be.

9.11 Conclusion

The evolution from human-paced, ad-hoc, intuition-based maintenance to integrated, quantitative and autonomous maintenance in cyber-physical systems will still require considerable effort in the coming years. The MANTIS project is an important step in this direction, which could not have been realized by a single organization.

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