CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2020

1st Conference on Production Systems and Logistics

An Upgradable Cyber-Physical System Enabling Smart Maintenance of UV Lamps in Industrial Applications

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Abstract

The supply of customer-specific products is leading to the increasing technical complexity of machines and plants in the manufacturing process. In order to ensure the availability of the machines and plants, maintenance is considered as an essential key. The application of cyber-physical systems enables the complexity to be mastered by improving the availability of information, implementing predictive maintenance strategies and the provision of all relevant information in real-time. The present research project deals with the development of a cost-effective and retrofittable smart maintenance system for the application of ultraviolet (UV) lamps. UV lamps are used in a variety of applications such as curing of materials and water disinfection, where UV lamps are still used instead of UV LED due to their higher effectiveness. The smart maintenance system enables continuous condition monitoring of the UV lamp through the integration of sensors. The data obtained are compared with data from existing lifetime models of UV lamps to provide information about the remaining useful lifetime of the UV lamp. This ensures needs-based maintenance measures and more efficient use of UV lamps. Furthermore, it is important to have accurate information on the remaining useful lifetime of a UV lamp, as the unplanned breakdown of a UV lamp can have far-reaching consequences. The key element is the functional model of the envisioned cyber-physical system, describing the dependencies between the sensors and actuator, the condition monitoring system as well as the IoT platform. Based on the requirements developed and the functional model, the necessary hardware and software are selected. Finally, the system is developed and retrofitted to a simulated curing process of a 3D printer to validate its functional capability. The developed system leads to improved information availability of the condition of UV lamps, predictive maintenance measures and context-related provision of information.

Keywords

Smart Maintenance; Cyber-physical System; Smart Factory; UV lamps

1. Introduction and motivation

UV lamps are used in a wide range of applications of machines and equipment. One application area comprises disinfection and sterilization processes such as water treatment. Here, UV lamps are a safe and environmentally friendly solution. Another application area of UV lamps is in the hardening of polymers in coating equipment or 3D printers. Traditional UV lamps provide a broad light spectrum and high energy, and even though a short lifetime compared to LED-based UV lamps, these are still required in the mentioned application areas. From an economic perspective, the UV lamps are often a big cost driver in the operational cost of machines and equipment. Unplanned failure of an UV lamp in a machine or equipment can have far-reaching consequences, resulting in high failure cost. Here, objectives of maintenance are to safeguard a high safety, availability, reliability and value preservation at a minimum cost [1]. The value-adding potential of maintenance, therefore, results from the three to five times higher follow-up costs avoided as a result of inadequate or neglected maintenance [2]. Preventive, condition-based and predictive maintenance strategies avoid unplanned breakdowns. So far, there are only a limited number of established methods to monitor and predict the condition of components in machines and equipment, such as vibration analysis, ultrasonic analysis, oil analysis or the analyses of electrical parameters [3]. However, for a large number of critical components, there is still no established method for condition monitoring which is the foundation of predictive maintenance strategies. In particular, there is no method described in the literature for the upgradable condition monitoring of UV lamps, although UV lamps are used in a wide range of industrial applications and have often a leading role in the respective processes. For this reason, approaches must be found to improve the maintenance of UV lamps. UV lamps are often part of machines and equipment and do not have an individualised or extra condition monitoring system. This motivates the following main requirements for the system to be developed:

- simple adaption of the system to the intended application for upgrading existing machines and equipment;
- using reliable low-cost components in order to be also affordable in developing countries;
- improving the availability of information about the condition of the UV lamp;
- enabling predictive maintenance strategies.

One possibility to address the differing objectives and challenges is to apply information and communication technologies and use the approach of cyber-physical systems (CPS) [4] [5]. CPS can be applied on basically all applications in various areas of the factory, such as development, production planning or maintenance. A value-adding network including a factory formed by CPS is then called a Smart Factory, for which several concepts already exist [6] [7] [8]. Smart maintenance in this context is defined as "learning-oriented, self-regulated, intelligent maintenance to maximise the technical and economic effectiveness of maintenance measures through the use of digital applications, taking into consideration the respective existing production system" [9]. This paper presents an upgradeable low-cost CPS focused on the purposes of maintenance and is in this paper referred as a smart maintenance system. The goal of this smart maintenance system is to improve the maintenance of UV lamps in machines and equipment.

2. Related work

For the development of the envisioned smart maintenance system approaches and architectures of existing smart maintenance systems, as well as the lifetime estimation of UV lamps, are considered.

2.1 Smart maintenance systems

In both literature and in the market there are several existing approaches for smart maintenance systems. The basis of a smart maintenance system is a planning system that manages maintenance objects, schedules, and controls maintenance tasks. In addition, other functions can also be integrated with the planning system, such as spare parts and ordering, maintenance controlling or maintenance personnel management. The IT system thus supports the maintenance staff in the planning and execution of maintenance activities. The overall goal of such smart maintenance systems is to dynamically adapt the maintenance strategy based on the current condition and remaining lifetime of components and machines as well as planning information such as the production plan or the shift calendar of maintenance workers. Therefore, a smart maintenance system integrates modules for maintenance management and planning, condition monitoring, deterioration and remaining useful lifetime calculation [2] [10] [11]. On a technical side, the so-called Industrial Internet of Things (IoT) architectures can be used as a foundation. One example is the IoT reference architecture by Guth et al. [12]. Also, there are mostly domain agnostic commercial solutions such as the ActiveCockpit of Bosch Rexroth AG available in the market already [13]. Commercially available systems in the market for maintenance are made either for a specific solution, for instance as bearing monitoring such as ABB ability [14] or I-care [15]. Oher solution covering only a part of a smart maintenance system such as a condition monitoring system or platforms for predictive maintenance such as ABB ability, General Electric Predix [16] or Mathworks [17]. Further solutions are based on traditional computerized maintenance management systems for planning.

2.2 Influencing factors of the lifetime of UV lamps

In the literature, there are only a few rough lifetime models of UV lamps by manufacturers. Typically, a UV lamp with mercury spectrum has a lifetime of 1500 hours specified by the manufacturer. The emitted UV radiation of a UV lamp decreases with increasing operating time due to physical effects. As soon as 75 % of the initial UV intensity is measured, the useful lifetime is exhausted. The lamp can still be operated, but it can no longer be used for curing. Also, the lifetime of the UV lamp is stated under the premise that a maximum of three starts per day are permitted. Each additional switching on and off of the UV lamp leads to a reduction of the lifetime by 0.5 hours. Furthermore, UV lamps have to be cooled, because the glass temperature is about 600 °C – 900 °C and from temperatures above 1000 °C the quartz softens and the UV lamp inflates or bends. For optimum cooling, an air volume of 100 m^3/h applies per kW UV lamp output. In addition, the resulting hot air cushions are aspirated above the UV lamp [18] [19]. In highly accelerating lifetime tests with discharge lamps, the vibration experienced by the lamp needs to be considered, as vibration has an influence on the lifetime [20]. In summary, it can be said, that the burning time, which is the time the lamp is being switched on, is the key factor leading to wear – through further factors which reduce the lifetime of a UV lamp are switching on and off, increased temperature and vibrations during operation.

3. Concept

The main idea in order to improve the maintenance of UV lamps as critical and costly components in machines and equipment is to use the approach of a cyber-physical system. Here, the key element is the functional model, describing functions and the relations between the different modules (Figure 1). Main modules of the smart maintenance system for UV lamps are the condition monitoring system and the smart maintenance planning system presented in the following sections.

3.1 Condition monitoring system

Sensors and actuators build the foundation of each data-driven application. In this case, as relevant measures for estimating the remaining useful lifetime of a UV lamp the temperature, acceleration and UV intensity, as well as the electrical power consumption, have been identified. The corresponding sensors are connected to the signal processing of the condition monitoring system. The measurements are carried out automatically and at defined time intervals. An actuator is provided as optional, in order to control the UV lamp directly. In the present case, the device forms the condition monitoring system and aims to monitor the condition of the UV lamp and can intervene if required by the actuator. All functions for the acquisition, processing and storing of the collected data is performed locally on-site, with the goal to reduce the data to prediction relevant information. Also, the device acts as a connection component to facilitate the connection of different sensors with the smart maintenance planning module. Driver software integrated on the device allows

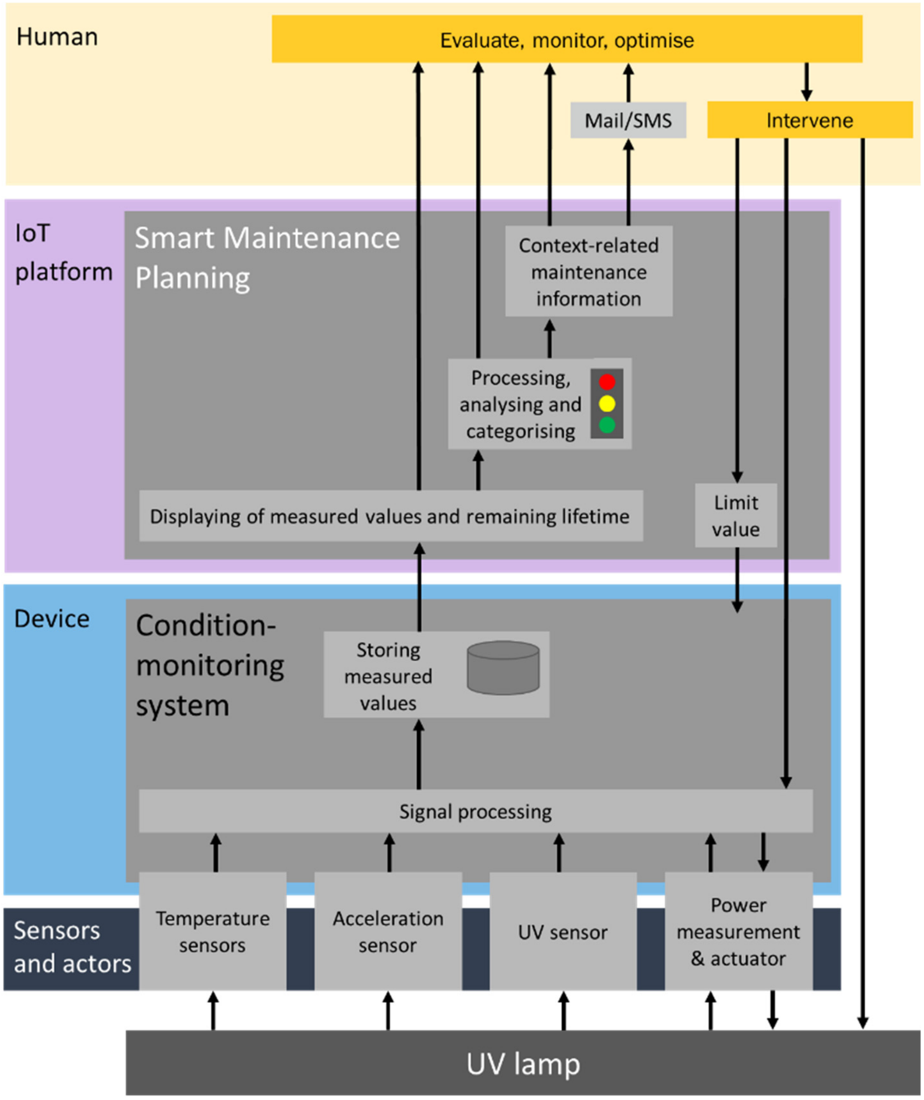

Figure 1: Functional model of the smart maintenance system for UV lamps, own representation based on [2] and [10]

uniform access to the different sensors. The device has communication standards like I2C, Onewire, IP, Ethernet, WiFi, Zigbee or a transport protocol like HTTP or MQTT and has a compatible payload format, which means that no further gateway is needed for communication to other IT Systems. The measured values are temporarily stored for a short time on the device and then sent to the IoT platform via a transport protocol.

3.2 Smart maintenance planning

The main functions of the smart maintenance planning module are an analysis and categorisation of information received from the condition monitoring system as well as a determination of a remaining useful lifetime of the UV lamps. Further functions are related to context-related maintenance information provision and visualisation of the communication with the human planner or supervisors. The smart maintenance planning module is implemented on an IoT platform, which can run as a local or cloud-based solution. The IoT platform receives the protocol with all measured values sent by the device, adds a timestamp and stores it in a database. The individual measured values of the sensors are clearly displayed in diagrams in the dashboard of the IoT platform. The live values are presented here, but historical values can also be viewed. Furthermore, the remaining useful lifetime of the UV lamp is calculated as well as on and off switching operations. As a result, the maintenance staff can get an overview of the live status of the UV lamp and at the same time have access to important information about the UV lamp, both for the currently running process as well as about past processes.

The maintenance technician has a decisive role in maintenance. It is therefore suggested that context-based maintenance measures are used. In this case, the specific place in the user manual where the UV lamp replacement is described is mentioned. The maintenance staff is informed by their preferred output medium such as a computer, a tablet or a smartphone, which maintenance measures he should carry out in order to preserve or restore the operating condition of the UV lamp.The stated information is automatically sent by SMS or email with a PDF attachment to the maintenance staff. The maintenance staff can now access all relevant information from a mobile device and perform the suggested maintenance measure based on this. He can intervene in the UV lamp in different ways. For the actuator, power measurement values can be defined from which the UV lamp can be switched off. The UV lamp can also be switched off and on directly via the actuator.

4. Implementation

Based on the requirements and the functional model, the hardware and software are selected and implemented. The selection criteria for the hardware and software components are a low cost, wide availability and preferably open source. Based on these premises for the implementation of the smart maintenance system the following components have been selected:

- Sensors and Actuators:
  - Adafruit MCP980 temperature sensor
  - Adafruit MMA845 accelerometer
  - Adafruit VEML6075 UV sensor
  - HomeMatic radio switching actuator with power measurement
- Condition monitoring system:
  - Raspberry Pi 3 Model B
  - HomeMatic radio gateway
- Smart maintenance planning module:
  - Cloud-based Losant IoT Platform

The smart maintenance system monitors the influencing factors for the lifetime of UV lamps. For this purpose, the burning time, the number of the switch-on and switch-off operations per day, the temperature in the direct vicinity to the UV lamp as well as the vibration that the UV lamp experiences is captured with the mentioned sensors. Furthermore, the relative UV intensity of the UV lamp is determined since the UV intensity influences the process result of the present UV application. For the implementation, the measurands are temperature, acceleration, relative UV intensity as well as power-related maesurands measurands such as current and voltage. The measured values are categorised into an acceptable, critical and rejected range on the basis of prescribed limit values in order to preserve the operating condition of the UV lamp and adhere to the required process factors.

The starting point for the calculation of the lifetime is the useful lifetime of 600 hours specified by the manufacturer. In addition, the existing lifetime model is integrated into the calculation. The model describes additional wear of the UV lamp of half an hour per further start of the UV lamp, which is performed for the fourth time or higher within 24 hours. A function is generated to compute the remaining useful lifetime that uses the measured current and a timestamp to determine the burning time as well as the switch-on and switch-off operations within 24 hours. Subsequently, the remaining lifetime is analysed and categorised. As an example, the acceptance range is defined from 600 to 50 hours of remaining useful lifetime. The critical range is stated between 50 and ten hours. The dashboard shows the message that the critical remaining lifetime has been reached. It also states that the stock of replacement lamps must be checked and ordered as required. This ensures that a replacement lamp is available when the remaining useful lifetime is over, and no unplanned machine downtime occurs. In addition, emails and SMSes will be sent to the maintenance staff with the above information. The email could also be sent directly to the spare parts supplier who provides a new UV lamp. The rejection range is accordingly from ten hours to the end of the useful lifetime. A red highlighted alarm message appears that the remaining useful life is reached.

The visualisation of the measured and categorised values are displayed in a dashboard. The Losant IoT platform is used for this purpose. An individual function for each temperature sensor categorises the values into an accepted, critical and rejected range. In the dashboard, accepted values are highlighted in green background and no further information is required. Values in the critical range are highlighted in a yellow background, and a warning message appears. In addition, the specific sensor location where the criticality occurred is displayed. Also, the values of the acceleration sensor are given in a diagram in the dashboard. The acceleration is given in x-, y- and z-axes and is expressed in the unit m/s^2. The values are stored, and it is checked afterwards how significant the influence of vibration is on the lifetime of the UV lamp. Also, for analysis purposes, the power measurement captures the values such as voltage, current, effective power, frequency and energy consumption. All values are displayed separately in a diagram. The values of the UV intensity in the UVA and UVB spectrum are also visualised in a diagram. The dashboard features live and historical values. The initial values of the UV intensity in the UVA and UVB spectrum measured with the UV sensor are used as the reference values. All following measured values in the UVA and UVB spectrum are set in relation to the defined initial values. The acceptance range is defined as 80 % to 100 % of the initial UV intensity which corresponds to a remaining buffer of 20 % until insufficient UV intensity is reached. The critical range is therefore from 75 % to 80 % of the initial UV intensity.

In a second step, an email and SMS is sent to the maintenance staff informing them where measured values have been exceeding the critical range. As soon as a value is measured in the critical range, the dashboard highlights in yellow or red and an alarm message pops up with additional recommendations e.g. that the system must be switched off immediately. The message sent by SMS and email also contains an attachment with a report and suggested maintenance measures. In this report not only measurement values and the maintenance object is stored, but also the relevant section in the user manual is named to provide the appropriate maintenance measure for the present case. In this way, search times for required information are reduced through improved user guidance, as context-related maintenance measures are suggested to the maintenance staff.

5. Validation of the smart maintenance system

The developed smart maintenance system is validated on a system, which simulates the application of a UV lamp in an additive manufacturing process (see Figure 2). The validation process is carried out according to a defined test cycle, which is based on three different factors. The printing mode can be set to high-speed or high-quality mode. The size of a simulated printed object is preset to either 50 mm or 100 mm, which is stimulated by the linear working spindle. The complexity of an object to be printed is determined as low or high, which leads to a simulated printing time twice as long with a high complexity. A combination of the three factors results in a total of eight different printing settings. The performed validation reveals that the functional capability of the smart maintenance system is achieved. All previously defined requirements for smart maintenance are fulfilled. The system is able to provide information about the condition and the remaining useful lifetime of the UV lamp by using an existing lifetime model. As soon as measured values are in critical or rejected ranges, measures are initiated to preserve the operating condition of a UV lamp such as the provision of context-related information. For the application of the smart maintenance system for other UV lamps, the influencing factors of the components to be investigated are already known. The lifetime can be determined on the basis of the existing lifetime model and adapted to the lifetime specified by the UV lamp manufacturer.

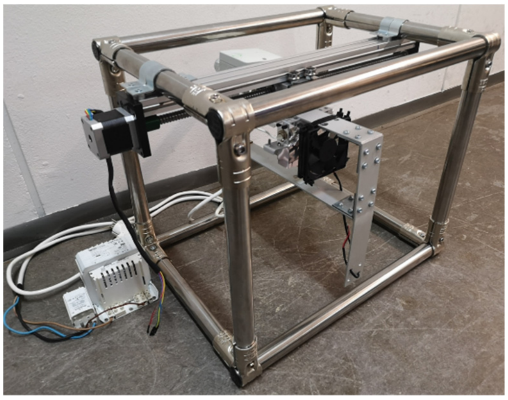

Figure 2: Setup of the printing process simulation system

The required sensors are retrofitted to the printing process simulation system (see Figure 3).

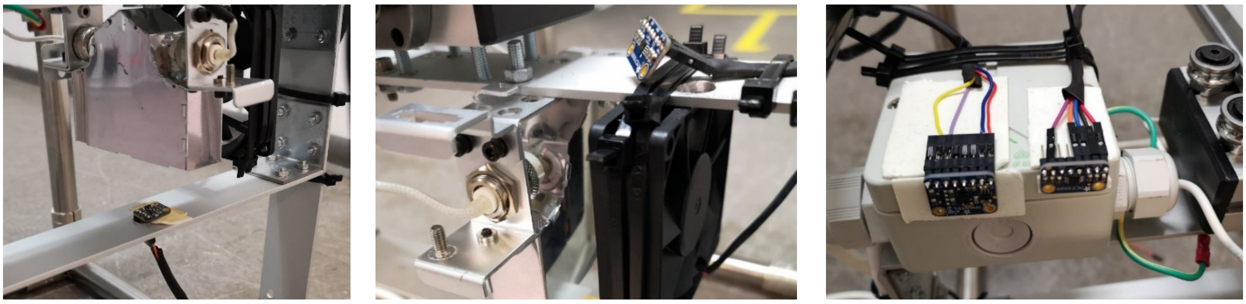

Figure 3: UV sensor under the UV lamp with reflector unit, temperature sensor next to the UV lamp, acceleration and temperature sensor in the upper part of the printing chamber (from left to right)

If a lifetime model of the UV lamp applied is available, this model can be used as a basis. Furthermore, the factor which has an influence on the process result of the application must be known. For an application with a certainly required UV intensity, a reference value must first be defined. The reference measurement is carried out with the UV sensor at the same distance to the UV lamp as the sensor is integrated within the later application. The defined reference value is set in relation to the values determined during the operation of the application. Subsequently, the respective limit values for the application have to be determined, such as the required UV intensity or external temperature.

6. Conclusion and outlook

This paper presented the concept and implementation of an upgradable low-cost CPS, to enable smart maintenance of UV lamps in machines. Further research is needed to provide more accurate predictions about the remaining useful lifetime of the UV lamp. Also, with regard to the influence of vibration on the UV lamp, further testing needs to be done. The approach of the statistical design of experiments serves as the basis for the creation of a more accurate lifetime model. More specifically the developed additive manufacturing process simulation system can be used for the execution of further experiments. The statistical experiments have to be carried out to obtain the precise wear of the UV lamp depending on the load which is derived from the size and complexity of the objects to be printed as well as the printing mode setting. The objective is to develop a model that calculates the remaining useful lifetime taking into account the experienced, current and expected load of the UV lamp. The experienced load reflects the wear caused by the prints already performed, whereas the current load is the live wear during the printing process. The expected load represents the wear of the UV lamp, which is predicted due to the characteristics of the object to be printed and the printing mode settings. In addition, the expected load on the wear of the UV lamp of the following objects to be printed can be considered. In this way, the objects to be printed can be individually evaluated according to their expected load on the wear of the UV lamp and the objects can be selected or prioritised depending on whether the remaining lifetime is still sufficient.

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Biography

Max Böhm (*1994) studies Digital Industrial Management and Engineering (M.Sc. and M.Eng.) at Reutlingen University and Stellenbosch University (2018 - today). He has done his bachelor's degree in Industrial Engineering – Service Management (B.Sc.) at Furtwangen University (2013 - 2018).

Prof. Dr-Ing Dominik Lucke (*1980) is a professor at the ESB for production technology, automation and digitization of production and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart in the department „Sustainable Production and Quality". He studied mechanical engineering from 2001 - 2007 and finished his doctorate in 2013 at the University of Stuttgart. From 09/2007 - 09/2017 he worked at the Institute of Industrial Manufacturing and Management IFF of the University of Stuttgart as well as at the Fraunhofer IPA in the topics digital factory, smart factory, factory planning and maintenance management. His focus topics are apart from the development of industry 4.0 applications, the optimization of maintenance.

Konrad von Leipzig (*1958) is a senior lecturer at the Stellenbosch University and director of the Institute for Industrial Engineering. He studied Industrial Engineering (M.Eng.) at the Stellenbosch University from 1991 – 1993. From 1986 – 1990 he completed his Bachelor of Commerce at the University of South Africa. He studied Industrial Engineering (B.Eng.) at the Stellenbosch University from 1978 – 1981. His focus topics include the application of smart technologies in a developing and skills-scarce environment.