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Received 25 January 2023
Revised 22 May 2023
Accepted 31 August 2023

A computer vision approach to improve maintenance automation for thermal power plants lubrication systems

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Abstract

Purpose – Lubricating oil leakage is a common issue in thermal power plant operation sites, requiring prompt equipment maintenance. The real-time detection of leakage occurrences could avoid disruptive consequences caused by the lack of timely maintenance. Currently, inspection operations are mostly carried out manually, resulting in time-consuming processes prone to health and safety hazards. To overcome such issues, this paper proposes a machine vision-based inspection system aimed at automating the oil leakage detection for improving the maintenance procedures.

Design/methodology/approach – The approach aims at developing a novel modular-structured automatic inspection system. The image acquisition module collects digital images along a predefined inspection path using a dual-light (i.e. ultraviolet and blue light) illumination system, deploying the fluorescence of the lubricating oil while suppressing unwanted background noise. The image processing module is designed to detect the oil leakage within the digital images minimizing detection errors. A case study is reported to validate the industrial suitability of the proposed inspection system.

Findings – On-site experimental results demonstrate the capabilities to complete the automatic inspection procedures of the tested industrial equipment by achieving an oil leakage detection accuracy up to 99.13%.

Practical implications – The proposed inspection system can be adopted in industrial context to detect lubricant leakage ensuring the equipment and the operators safety.

Originality/value – The proposed inspection system adopts a computer vision approach, which deploys the combination of two separate sources of light, to boost the detection capabilities, enabling the application for a variety of particularly hard-to-inspect industrial contexts.

Keywords Automation, Corrective maintenance, Detection, Inspection, System health monitoring

Paper type Research paper

This work was partially supported by the 2020 Li Ka Shing Foundation Cross-Disciplinary Research under Grant 2020LKSFG06D, the Research and application of defect image intelligent recognition system of Haimen Power Plant of Huaneng Power International Co. Ltd., China, (HM-19KA03005) and the research and modeling of economic operation efficiency of steam-driven induced draft fan under variable working conditions of Huaneng Shantou Haimen Power Generation Co.Ltd., China (HZ-19ZC03-020).

Journal of Quality in Maintenance Engineering
Vol. 29 No. 5, 2023
pp. 120-137
Emerald Publishing Limited
1355-2511
DOI 10.1108/JQME-01-2023-0007

1. Introduction

Thermal power plants (TPPs) represent an important asset of the current energy infrastructure with particular reference to developing countries (Fausing *et al.*, 2020). According to the statistical bulletin on National Economic and Social Development in 2020 released by the National Bureau of Statistics of China, the country's electricity generation capacity in 2020 was 7,779.06 billion kWh, of which, the thermal power generation capacity was 5,330.25 billion kWh, accounting for 68.52% of the national electricity generation capacity (National Bureau of Statistics of China, 2021). In India, the major portion of total captive power comes from TPPs from coal, oil, natural gas, etc., of which coal-fired units contribute 41% of global electricity (Chandrasekharan *et al.*, 2014). TPPs are industrial plants that use coal, oil and natural gas as fuel to produce electricity. In modern TPPs the core equipment are boilers, steam turbines and generators. The basic requirements of TPPs operations are to ensure safety, economy and power quality (Raza and Hameed, 2022). From an operational perspective, modern TPPs consist in very complex industrial integrated systems, characterized by extensive pipework (Bao *et al.*, 2022) requiring continuous improvement in all aspects of their operations, including maintenance, in order to ensure competitive operational performance (Singh and Gurtu, 2022). Therefore, accurate and timely detection of anomalies is essential for the safe and economic operation of complex TPP environments (He *et al.*, 2022).

In TPPs, the lubrication system supplies lubricating oil for auxiliary equipment to reduce the friction in the rotating mechanical parts of the equipment. Most common lubricants are oil and grease, in reducing equipment wear at the same time also play the role of sealing, cooling, clean, anticorrosion (Sarkar, 2017). The basic purpose of a lubricant is to reduce friction and wear between two surfaces moving relative to one another. In most cases, a lubricant also dissipates heat, prevents rust corrosion, acts as a seal to outside contaminants and flushes contaminants away from bearing surfaces (Nowak *et al.*, 2019). However, the equipment utilized for oil transportation for a long time is exposed to various degradation mechanisms such as corrosion, cracking, fatigue, erosion, etc. These problems are likely to lead to the occurrence of oil spills (Rachman and Ratnayake, 2019). Lubrication system failures during the production process will lead to insufficient lubricant supply, with consequent accelerated equipment wear, oil leakage, overheating and ultimately affect the boiler operation (Sarkar, 2017). Leakage of lubricating oil is an important source of pollution. These oils biodegrade relatively poorly in soil and water and degradation products and wear debris may adversely affect agricultural areas, forests, harbors and parks (Nowak *et al.*, 2019). The chemical composition of lubricating oil has a potential chronic toxicity, with negative impact on animals and humans (Mangas *et al.*, 2014). Additional safety concerns involve lubricating oil low ignition point, that, along with the operating temperature of the equipment could result in accidental combustion (Tao, 2016). Such considerations highlight a strong need of pipeline maintenance operations, to ensure the safety of the pipeline, its related equipment and the overall plant.

In this context, an effective maintenance plan is the essential approach to lubricating system failure risk prevention (Yang, 2004). Maintenance is classified into three types: improvement maintenance (IM), preventive maintenance (PM) and corrective maintenance (CM) (Divya *et al.*, 2022). IM aims at optimizing maintenance in the design stage, while PM seeks to predict failure to ensure the normal operation of equipment, and CM involves timely maintenance operations after failure. In engineering practice, IM and PM cannot completely eliminate all failures therefore CM is still widely used in actual production environments (Wang *et al.*, 2014). As a maintenance method to find the cause of the failure from the fault phenomenon, CM plays a very effective role in the maintenance and improvement after the failure. As in TPPs, image recognition technology be used as a CM tool to monitor liquid leakage pipelines and provide timely corrections and optimizations (Bao *et al.*, 2022).

Due to the large number of pipes in TPP with close spatial arrangement and highly variable lighting conditions, computer vision is usually used as the main enabling technology for maintenance automation. Literature review show interesting contributions in the use of ultraviolet (UV) fluorescence for monitoring purposes. Simeone, Woolley *et al.* utilized UV fluorescence to monitor clean-in-place industrial cleaning processes for a variety of food fouling (Simeone *et al.*, 2018; Woolley *et al.*, 2018). A. A. Ionin *et al.* used ultraviolet filaments to detect thin oil films on water surface and investigated the possibility of using ultraviolet laser pulses as a spectrometric method for detecting oil and oil surface films (Ionin *et al.*, 2016). Sharikova *et al.* developed an ultraviolet laser-induced fluorescence system for real-time monitoring of mineral content in tap water (Sharikova and Killinger, 2008). Kavanagh *et al.* utilized fluorescence to detect oil-bearing wastewater produced by bitumen extraction (Kavanagh *et al.*, 2009). Contributions on oil detection on water surfaces using UV-based techniques can be found in (Chase *et al.*, 2010; Sun *et al.*, 2011; Son *et al.*, 2011) for various types of process waters. As regards power equipment components, Zhang Jing *et al.* designed and developed a portable oil leak detection device for high-voltage power equipment based on ultraviolet fluorescence effect (Liu *et al.*, 2019). Xu-Xu Li *et al.* studied the composition and fluorescence characteristics of oil in industrial equipment and proposed a method to detect oil leakage by using the fluorescence characteristics (Li *et al.*, 2022). Dong Baoguo proposed a color-characterization-based oil detection method for oil leakage in transformer equipment, by analyzing the Hue-Saturation color histogram from digital images (2013). Yan Haijun *et al.* proposed a method for detecting oil leakage in pipes by determining the extent of the oil leakage by judging the approximation between an image taken in real time and a UV image taken previously without an oil leakage (Yan *et al.*, 2019). Zhou Ju proposed to use UV intensity control to obtain real-time oil leakage information in the monitored target area, and this method was applied to monitor oil leakage on the target surface (Ju, 2019).

An extensive survey at Huaneng thermal power plant facilities, Shantou, China, aimed at characterizing the lubrication system pipework for maintenance automation purposes.

Such survey shows a large number of equipment and pipework to be inspected have a complex and close space arrangement, making image acquisition particularly challenging; The lighting conditions in the factory workshop is highly variable in terms of light color and intensity, resulting in a hard image acquisition process. Oil leakage from lubricating systems appear as irregularly shaped semi-transparent effusions on various types of surfaces resulting technically difficult to identify for most image-based technologies. At present, most of the lubricating oil leakage inspection is manually carried out by operators, resulting in a low efficiency, time-consuming procedure with possible safety concerns. Despite an evident potential in terms of accuracy an safety, automatic maintenance techniques are not fully deployed in such complex environment (Lu *et al.*, 2020).

The literature review on oil leakage detection techniques and the survey carried out in a real plant environment, highlighted a number of research and technological gaps for automatic maintenance systems development and implementation. In this respect, the method of detecting oil droplets in water (Ionin *et al.*, 2016; Sharikova and Killinger, 2008) is not suitable for the detection of oil leakage in power transformers, due to the following limitations: (1) The detection accuracy will decrease with the decrease of circulating water purity; (2) Need a lot of manual detection; (3) Serious waste of circulating water; (4) Complex equipment installation and a high number of detection points; (5) High system cost (Chen, 2010). A general limitation of any machine vision-based oil leakage detection system consists in the complex environment to be inspected. Variable lighting conditions and the distributed presence of pieces of equipment represent a technological challenge for digital imaging-based inspection (Lu *et al.*, 2017). In addition, the UV imaging can be badly affected by the reflective characteristics of auxiliary items, such as plastic tags, rubber tubes, plastic straps and other plastic products which can produce image noise under a UV light source. Overall, due to the complexity of the actual environment (see Figure 1) and the limitations of the state-of-the-art methods, the existing oil leakage methods cannot be directly used in TPPs environments for maintenance automation purposes.

To overcome the above-mentioned issues, this paper proposes a novel real-time inspection system using an automated guided vehicle (AGV), a dual light source illumination and a tailored image processing algorithm. The AGV moves along a pre-defined inspection path to acquire digital images in correspondence of a number of preset inspection points. The dual light source allows for a reduction of image background noise while providing a proper illumination intensity throughout the inspection process. The image processing algorithm ensures a suitable inspection accuracy. Such inspection system aims at boosting the automation of maintenance operations in terms of equipment inspection with reference to lubricating oil leakage detection in TPPs. The application can include the possibility of a continuous and real-time automated inspection, allowing for a prompt maintenance of the production environment.

The remainder of this paper provides a definition of the inspection system requirements in section 2 in terms of expected performance, AGV hardware, lighting system and image acquisition. Section 3 provides for a detailed description of the inspection system modules. Section 4 reports an experimental verification of the proposed system with an industrial case study within Huaneng TTP to verify the inspection capabilities. The experimental results are presented and discussed in section 5 demonstrating the effectiveness of the proposed inspection system for oil leakage detection purposes. Concluding remarks and research outlook are reported in section 6.

2. Inspection system requirements

As regards the detection sensitivity, the system should be able to detect oil leakages as small as 100 cm^2. At the same time, the whole system equipment meets the following communication performance requirements: image data transmission should be guaranteed within the whole factory facility resilient to interference and obstacles (e.g. factory walls). The system data storage capacity should allow saving and handling at least 18 months of data. Finally, concerning the industrial suitability, the detection accuracy should be higher than 90%.

2.1 Lighting system

In any visual inspection operation, the light source plays a crucial role. The design of light source has a significant impact on the success of the entire inspection system (Simeone *et al.*,

Figure 1. TPP complex environment: (a) front pump; (b) oil station

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2018). Besides, lighting technology also plays an important role in defining the image quality in machine vision scopes (Benxing and Wang, 2019; Guo *et al.*, 2017). The choice of the light source directly affects the features of the acquired images and the complexity of subsequent image processing algorithms (Simeone *et al.*, 2018). Suitable light source is beneficial to collect characteristic image information and optimize the machine vision system. Furthermore, a suitable angle of light source can highlight image features while suppressing unwanted interference features.

The color of lubricating oils can range from transparent to opaque. The color is based on the raw material, its viscosity, method and degree of treatment during refining and the amount and types of additives included (Fitch, n.d).

Oil-based lubricants fluoresce when exposed to UV light within a certain wavelength range (Gong *et al.*, 2017), for example, the fluorescence of lubrication and light diesel oil is the most significant within the range 270–400 nm (Chen and Li, 2017). Fluorescence refers to the cold luminescence phenomenon of photoluminescence (Roda *et al.*, 2016). When ultraviolet rays irradiate on the lubricating oil and the oil absorbs the energy of UV light, electrons are excited to transit from the low energy level to a high energy level, therefore, the energy level transitions occur, and fluorescence is generated (Beard *et al.*, 2019). Considering the lubricant oil characteristics adopted in TPPs applications, a suitable UV light source needs to have a wavelength range of 300 nm–450 nm, which covers not only the invisible light but also part of visible light.

When the UV light source is used to illuminate the area to be inspected, a blue-white fluorescence occurs on the oil leakage surface, as shown in Figure 2. This kind of light source, within a poorly illuminated indoor context, allows to highlight the oil leakage for a facilitated detection.

Due to the complexity and diversity of the areas to be inspected, there could be the risk of having various types of image noise and artifacts caused by UV light source.

In this context, various elements of the equipment, by their very nature, can appear as fluorescent under the action of UV light. Figure 3 shows a variety of such cases, ranging from polymeric wires (a) appearing as bright-yellow, to metal tags (b) appearing as bright-cyan and polymeric pipes appearing as white, rubber bands (c) appearing as bright-white. Such undesired fluorescence phenomenon is likely to produce false positive in the detection phase.

In an actual industrial floor, the UV fluorescence intensity could result too weak due to the presence of natural and artificial ambient lights, making the oil detection task more difficult. To reduce the influence of ambient light and the visible light component of the UV light

Figure 2.
Oil leakage under various sources of light: (a) visible light; (b) UV light

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source, and to provide enough light intensity, the proposed inspection system is endowed with a dual light source illumination unit.

Like previously stated, the wavelength range of the UV light source is in the 300–450 nm range and then as can be seen in the spectrogram shown in Figure 4, blue is the color of the highest frequencies of visible light after the violet spectrum. For this reason, and in order to cover a larger portion of the UV/near UV/visible light without interfering with the ambient light, a blue light was chosen as additional illumination source oil leakage detection purposes. Figure 5 shows the effect of the blue light when used to irradiate the industrial equipment. In such case the oil leakage is not highlighted by any fluorescence phenomenon, however, due to

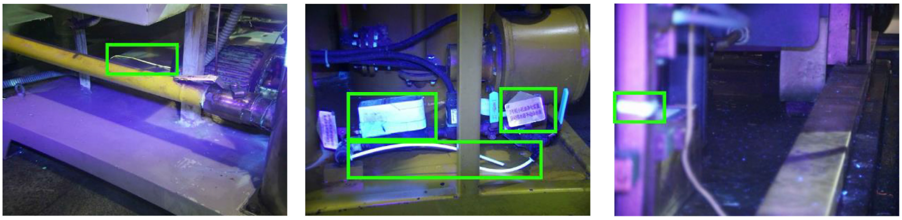
(a) (b) (c)

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Figure 3. Image artifacts by undesired fluorescence, (a) plastic wires, (b) shell, pipes and tag, (c) band

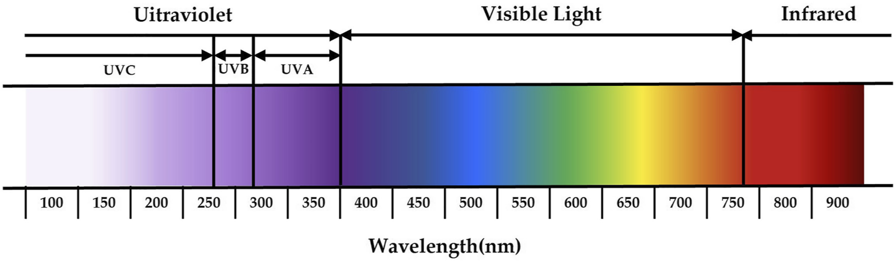

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Figure 4. Light spectrum diagram


(a) (b)

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Figure 5. The illumination effect of a blue light source on an oil leakage. (a) Natural light; (b) blue-light

visible blue light irradiation, the entire area to be detected glows blue, allowing for a more effective image processing.

2.2 AGV hardware design

Figure 6(a) shows the image acquisition unit, consisting in an AGV, the dual light source and a digital camera, including the AGV motion control unit and data transmission unit via Wireless Area Network (WAN).

An image acquisition script is designed and implemented to turn on the ultraviolet light source to illuminate the target area, trigger the camera to acquire an UV image, then turn off the UV light source, turn on the blue light source to illuminate the target area, and eventually acquire the blue light image. Such procedure is designed to overcome any image registration issue. The images acquired in this way are then stored and processed to detect any oil leakage in the area of interest within the field of view. A full view of the AGV on-field is shown in Figure 6(b).

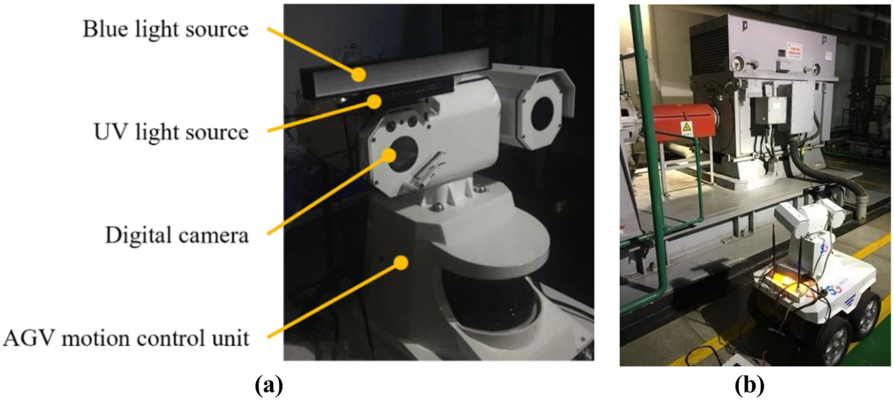
3. Inspection system architecture

The inspection system proposed in this paper has a modular structure as illustrated in the flow-chart reported in Figure 7. The modules are namely the image acquisition module, the image processing module and the operation module. A detailed description of the various modules is reported in the following subsections.

3.1 Image acquisition module

This module allows for the digital image acquisition. In this context, the maintenance team identifies the equipment hot spots, i.e. those areas which are likely to be affected by oil leakages. Every inspection point can have one or more object of interests, i.e. inspection targets. In this case the camera should capture an adequate number of images to cover the entire area of interest.

The central unit activates the AGV and initializes the predetermined inspection path. Employing radar navigation technology, which utilizes radio waves (frequency range 3,400–3,500 MHz) for signal transmission and reception, the AGV is guided towards a predefined inspection point. The radar system measures the round-trip time of the reflected signals



(a)
(b)

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Figure 6.
AGV. (a) AGV and image acquisition unit; (b) full view of AGV on-field

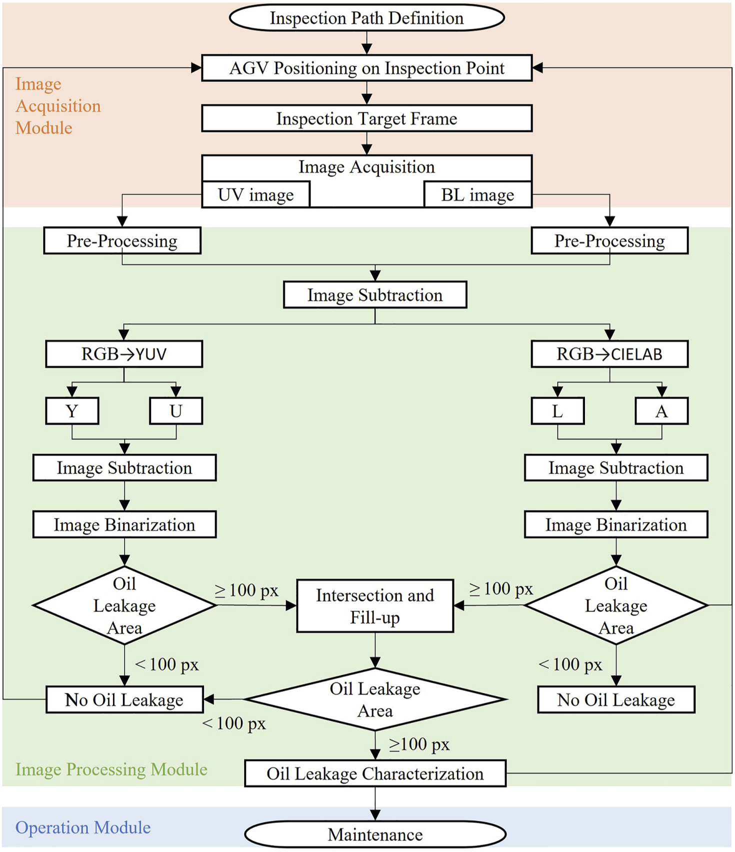

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Figure 7. Inspection system overall flowchart

bouncing off objects in the surrounding environment. By analyzing these reflected signals, the radar system accurately determines crucial parameters such as range, direction and speed of the objects, facilitating precise positioning and navigation of the AGV (Jonasson *et al.*, 2021). By measuring the signal on the path, the position deviation between the vehicle itself and the target tracking path is obtained, to control the vehicle to carry out acceleration, deceleration, turning, stop. The AGV operates in fully autonomous mode, following a pre-programmed route for ordinary maintenance inspections. Nonetheless, in the event of anomalies or exceptional maintenance requirements, the maintenance team has the option to manually control the AGV to address the specific needs.

Once reached an inspection point, the image acquisition system acquires the required number of digital images and transmits the images to the computer through a local WAN for image processing. The AGV-powered image acquisition module is completely automated. In this respect, the inspection areas, inspection points and inspection target are pre-defined, and the relevant instructions are fed to the AGV to programmatically acquire the required images. While the computer performs the image processing procedure in background, it sends instructions to the AGV through the WAN to resume the movement along the inspection path in accordance with the radar navigation.

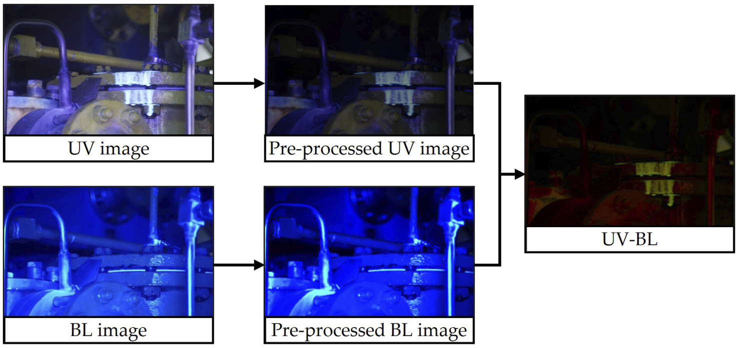
The above-mentioned procedure is then repeated until all the image acquisition on inspection targets are completed. The AGV then returns to the starting point following the inspection path backwards according to the radar navigation.

3.2 Image processing module

The image processing module implements a tailored procedure aimed at detecting any presence of oil leakage in the images acquired by the previous module. A flow chart of the inspection system is shown in Figure 7 and reported in detail in the next sub-sections. The image processing module was implemented using the QT development framework, specifically with the QT5.13 library and the Qt Creator 4.9.1 development environment. In this context, the algorithms utilized within the image processing module were developed using Halcon 12.0 on a Windows operating system. These algorithms were subsequently encapsulated into a dynamic link library (DLL) to enable seamless integration and usage within the whole inspection system. By utilizing the combination of these technologies, the image processing module achieves efficient and robust image processing capabilities, enhancing its overall functionality and performance.

3.2.1 Image pre-processing and subtraction. Whilst the inspection system hardware has been designed to facilitate the image acquisition and processing, the real-time image acquisition process could be potentially disturbed by various sources of noise, resulting in low quality images to be processed likely affecting the detection capabilities. In this context, an image pre-processing procedure is designed and embedded in the image processing module to enhance the entire or local features of the image (Munadi *et al.*, 2020; Tian *et al.*, 2017). Specifically, the image pre-processing is aimed at highlighting the oil fluorescence characteristics for a more reliable assessment, which is still subject to the equipment sensitivity. The pre-processing operations can involve brightness and contrast adjustment, filtering, etc (Kuang *et al.*, 2016; Sule *et al.*, 2020).

In this paper, due to the equipment and material involved, the light conditions and the hardware characteristics, the pre-processing procedure is limited to a contrast adjustment by a multiplication factor set to Mult = 0.006 (the grey scale adaptation factor) for the UV light images. As regards the blue light image the contrast is adjusted by a multiplication factor of Mult = 0.002. As shown in Figure 8, the pre-processing procedure is applied to minimize the background noise.



Note(s): Preprocessing and image subtraction
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Figure 8.
UV and BL image processing steps

Following the flowchart reported in Figure 7, the two pre-processed images, namely UV and BL images are subject to an image subtraction procedure. By subtracting the BL image from the UV image, the background intensity noise can be reduced, and the oil leakage area can be enhanced (Nakashima *et al.*, 2009). The image subtraction is obtained by subtracting the pixel values of the corresponding coordinates of the UV pre-processed image and the BL pre-processed image:

$$D(x, y) = |I_{uv}(x, y) - I_b(x, y)| \tag{1}$$

Where $D(x, y)$ refers to the result of the image subtraction process; $I_{uv}(x, y)$ is the UV pre-processed image, and $I_b(x, y)$ is the BL pre-processed image.

This procedure emphasizes the difference between the two images, removing most of the background (visible in both images) and highlighted the leakage (visible in the UV light only) with a basic operation, easy to implement with a very short computation time. At the same time, not only the oil leakage area is preserved, but also the area of reflection and interference noise of the equipment is weakened, as shown in Figure 8. However, there are still some reflections in the image after subtraction, which need further processing.

3.2.2 YUV color space image processing. The RGB channel image is converted to YUV color space YUV is a color space that includes three channels: The "Y" channel indicates brightness, the "U" channel and the "V" channel are used to describe the image color and saturation, with "U" being the blue projection and "V" being the red projection (Gonzalez and Woods, 2007).

Figure 9 indicates that Y and U channels show a clearer oil leakage region, while still showing some background content. In order to remove the unwanted background and to isolate the oil leakage region, an image subtraction is performed by subtracting U from Y. The resulting image is then binarized and the size of the potential oil leakage area is computed. If such area is less than 100 pixels, the output result is "no oil leakage"; if it is greater than or equal to 100 pixels, further image processing steps are required. The procedure is reported in Figure 9 for a sample set of images.

3.2.3 CIELAB color space image processing. Additional information for the oil leakage characterization is obtained by converting the RGB image to a CIELAB color space image. CIELAB is a color system consisting of three channels, channel L representing brightness, channel A representing the green to red color range, and channel B representing the blue to yellow color range (Ly *et al.*, 2020).

Then, L channel image is subtracted from A channel image to obtain the potential oil leakage, and the resulting image is then binarized. The process is illustrated in Figure 10, and

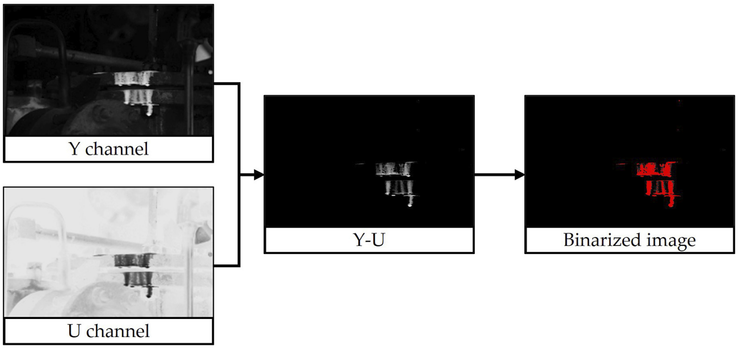

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Figure 9. YUV image processing procedure

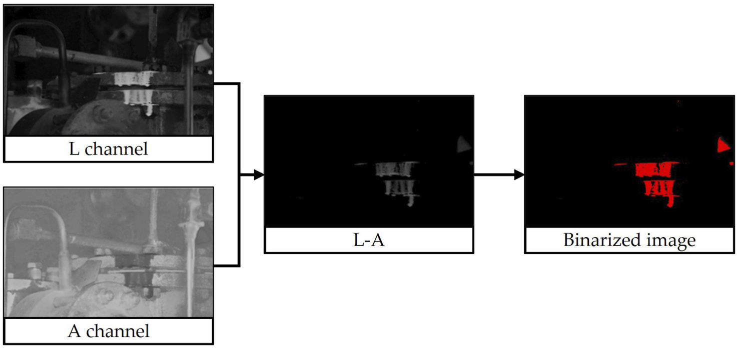

Figure 10. CIELAB image processing procedure

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it can be seen in this case, the potential oil leakage area is larger than the one obtained with the RGB to YUV transformation mentioned in the previous section, while possibly including some noise. Also in this case the binarization results has an acceptance threshold of 100 pixels.

3.2.4 Image intersection and fill-up. The two potential oil leakage areas (1 and 2) are subject to an image intersection procedure to improve the accuracy of the oil leakage detection, as shown in Figure 11.

Calculating this intersected area, if the area is less than 100 pixels, the output result is directly "no oil leakage". If the area is greater than 100 pixels, then the holes and gaps of the image will be filled to make it close to the shape and size of the actual oil effusion area. Finally output the detection result, as shown in Figure 11. A final fill-up operation of the binarized image is carried out for visualization purposes.

3.3 Operation module

When an oil leakage is detected, the system displays a warning message on the operator interface, indicating the leak entity and the location corresponding to the specific inspection target.

The operation module has strict requirements regarding the environment in which it operates. As soon as the environment of the TPP is temporarily changed for the operation of

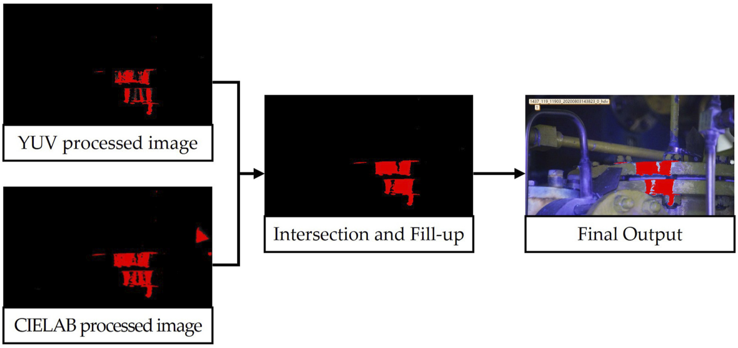

Figure 11. Intersection and fill-up image processing steps

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the equipment, then the positioning system of the AGV must be changed in time to make the appropriate adjustments, always ensuring that the position information obtained by the operator module corresponds to the actual situation on site.

This is what will enable the maintenance team to take efficient and timely action to perform a direct diagnosis in the area of the oil leakage and carry out the appropriate maintenance operations based on the piece of the equipment where the leakage occurs.

4. Case study

To demonstrate the effectiveness of the proposed inspection system, a case study is reported considering a real power plant facility, the Huaneng plant located in Shantou, China. In this context, two oil stations, namely Oil Station A and Oil Station B were chosen for the experimental activities. The oil station consists of one oil tank, two oil filters, thermal energy storage tank, instrument panel, oil cooler and auxiliary pipework. The base under the oil station is considered as a part of the equipment to be inspected, as shown in Figure 12. The main function of the oil station is to enable the flow of the lubricating oil through other machine components.

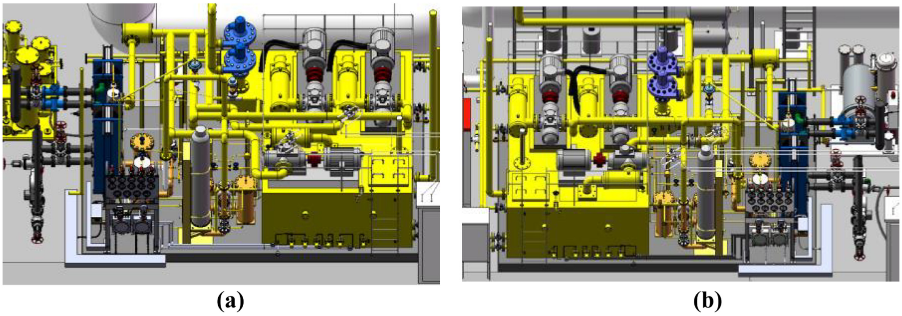
The lubricating oil utilized in the plant is a Total Energies No. 32 engine oil, which is highly transparent with a light-yellow tint in visible light, resulting particularly difficult to detect by the human eye considering the ambient light conditions.

The experimental setup includes an OPT-DPA6024-2 UV light source with a wavelength range of 300–450 nm. LED stripe light source (P-BL2-147-28-B) with a wavelength range of 465–475 nm. The light source controller is equipped with a 256-level brightness control, which can be adjusted manually or via software.

The image acquisition module utilizes a DS-2ZMN3008 © CMOS camera with 3 million pixels resolution (2048 × 1,536), horizontal field of view angle 57.2–3.5° (wide-angle-telescope), 12× digital zoom, aperture F1.6-F4.4, horizontal view 58.9–2.11° (wide-angle - viewing distance), close-up range 10–1500 mm (wide-angle - viewing distance). The image acquisition system is mounted on an AGV supplied by Huaneng Power Plant. The AGV size is 738 ×592 × 864 mm, and the weight is about 80 kg. The AGV has a four-wheel drive, with a top speed of 1.5 m/s, using radar navigation with 8 h battery autonomy.

A series of experimental tests has been designed and realized to validate the detection capabilities of the inspection system in terms image processing effectiveness and detection accuracy.

The testing area for the experimental validation of the methodology proposed in this paper is represented in Figure 13. 13 inspection points have been identified within the testing area. In this context, the AGV moves along a predefined inspection path covering the 13



(a) (b)

Source(s): Figure created by authors

Figure 12. Huaneng Haimen power plant: (a) oil station A; (b) oil station B

inspection points distributed over the two oil stations, as illustrated in Figure 13. Each inspection point corresponds to a specific AGV positioning location which is designed to provide for a clear view of the inspection point itself, minimizing cluttering and shading.

Figure 14 illustrates the experimental procedure. A number of artificially simulated oil leakages were randomly placed along the 13 inspection points throughout the testing area (see Figure 13).

It is important to note that an inspection point could contain more than one inspection targets, as illustrated in Figure 15(a)-(c), possibly requiring the acquisition of more images to

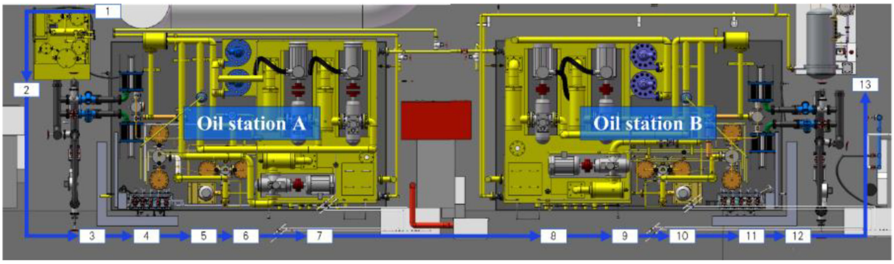


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Figure 13.
The inspection path around the two inspection areas

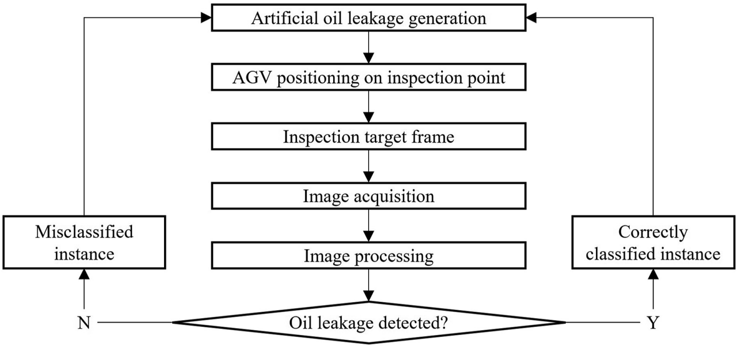

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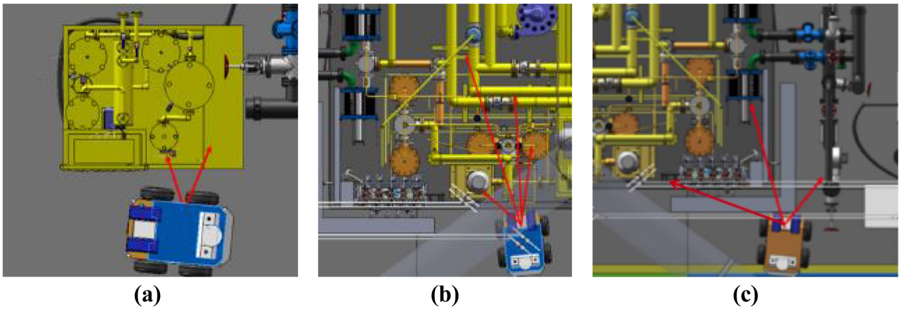
Figure 14.
Flowchart of the experimental process



Source(s): Figure created by authors

Figure 15.
Multiple inspection targets for each inspection points. (a) Point #2; (b) point #6; (c) point #12

fully cover the whole inspection point. Specifically, a total of 23 inspection targets are considered in this paper, distributed over the 13 inspection points, as shown in Figure 13.

Experimental samples of oil leakage have been applied in correspondence of each inspection target manually, dropping a fixed amount of oil (30g) from a height of 10 cm. In this way each inspection target is characterized by an artificial oil leakage with a surface of roughly 100 cm2. Such value is to be considered as the lower threshold for detection purposes, as required by the industrial partner.

The AGV moves along the inspection path and reaches an inspection point. Here the system performs the image acquisition and processing algorithm described in section 3. As mentioned above, the number of inspection targets at each inspection point is not necessarily only 1, so the AGV needs to position the camera to cover each inspection target, then it moves to the next inspection point.

In the experimental programme performed for this research work, each inspection target has been tested 20 times by changing the location of the artificial oil leakage within the same inspection target area. In this way a total number of 460 tests were carried out.

The inspection task in these experimental tests consists in a classification problem in correspondence of each inspection target. If the system correctly detects the oil leakage the test result is recorded as correct classification. Alternatively, if the system fails to detect the oil leakage, the test result is recorded as misclassification.

5. Results and discussion

Out of 460 experimental tests, only 4 cases of misclassification were found, yielding to an overall accuracy rate of 99.13% and an error rate of 0.87%. Table 1 reports the experimental tests results for each inspection area, inspection points and inspection targets in terms of misclassified instances.

It is important to stress how the experimental fine-tuning of both lighting system and image processing parameters allowed to successfully eliminate all the false positives instances of encountered during the whole experimental campaign.

The overall classification performance appears to be highly suitable for industrial applications. As concerns the misclassifications, the following considerations can be made. For the inspection targets 2a and 13a, the main reason for the misclassified instances was the reflection of some extraneous light source on the inspection point, due to random circumstances, altering the provided illumination and over-exposing the digital images. The oil leakage in the misclassified instance at inspection target 6c was only partially included within the inspection target field of view resulting poorly illuminated by the light system therefore producing less fluorescence. A similar situation can be defined for the misclassified instance at inspection target 12c. Here, the artificial oil leakage was applied in an area for which the field of view was partially occluded by dense pipework, resulting in the presence of an obstacle between the camera and the oil leakage to be detected. Such issue suggests, for the next research stage, an improved design of the camera setup and inspection path definition, including the possibility of field of view remote adjustment.

6. Conclusions

In view of the environmental complexity of the area to be inspected, a novel automatic inspection system endowed with an AGV, a double light source and a specific image processing algorithm, was developed in this paper to aid the maintenance automation by performing oil leakage inspection on TPP equipment.

The experimental results show that this inspection system is highly stable, accurate and shows good applicability. From an image processing perspective, the proposed system

Table 1.
Experimental results

Inspection Area	Inspection point		Inspection target	Misclassified instances
Oil station A	#1	1a	Ground below the control valve	0
	#2	2a	Ground below the support column of the oil cooler pipe	1
		2b	Oil cooler side	0
	#3	3a	Oil cooler A base	0
	#4	4a	Oil filter A base	1
	#5	5a	Oil filter B topside	0
	#6	6a	Base of Oil filter A	1
		6b	Ground below the energy storage tank	0
		6c	Top of the pipe	0
		6d	Side of the pipe	0
	#7	7a	Roadside of the fuel tank	0
		7b	Base of the fuel tank	0
		7c	Top of oil filter A	0
Oil station B	#8	8a	Fuel tank side	0
		8b	Fuel tank base	0
		8c	Oil filter B topside	0
	#9	9a	Ground below the energy storage tank	0
	#10	10a	Oil filter A topside	0
	#11	11a	Dashboard base	0
		11b	Ground below the control valve	0
	#12	12a	Ground below the support column of the oil cooler pipe	0
		12b	Oil cooler A	0
		12c	Oil cooler A base	1
	#13	13a	Ground below the pipe support column near the backup purification station	1
TOTAL			23	4

Source(s): Table created by authors

effectively identifies the oil leakages and significantly reduces the negative effects of background noise, such as reflections from transparent rubber hoses and plastic equipment casings and plastic belts, typical of TPP equipment environment. Furthermore, the inspection system takes full account of the diversity and complexity of scenes within power plants and provides a real-time determination of oil leakage with significant advantages in terms of identification and maintenance support.

In this respect, the manual maintenance scenario requires 6–7 operators to likely spend more than 4 h a day in the workshop to manually inspect and record oil leakages in various parts of the equipment without interruption. With the correct configuration and implementation of the proposed inspection system, a single AGV can be utilized to inspect the whole factory for 12 rounds every day, guaranteeing better detection performances compared to the human, saving time, resources and reducing the related safety risks. During manual inspection operations, the detection accuracy usually reaches no more than 70–80%, while the accuracy of this inspection system can reach up to 99.13%. As concerns the operator safety, the manual inspection procedures required operators to hold the UV flashlight to each point being in this way exposed to long-term irreversible damages to human skin such as inflammation, cancer and other diseases. Near ultraviolet light with a wavelength of 290–400 nm can cause damage to the human eyes, which is one of the pathogenic factors of senile cataract. Therefore, the automated maintenance inspection system has a clear potential to improve the operators' working conditions.

Further research is required to improve the system capabilities specifically: (1) adaptability to ambient light intensity in the inspection area. In this respect, both hardware and software should be able to perform an adaptive calibration to dynamically compensate the illumination conditions. (2) At present, the automatic maintenance mainly consists in the automation of inspection procedures, while the maintenance operations themselves are still carried out manually based on a visual diagnosis carried out by the operators. The next research steps are aimed at providing an automatic oil leakage diagnosis by performing a root cause analysis and potentially endow the AGV with a mechanical arm to carry out the daily maintenance of wiping, cleaning, lubricating and adjusting the equipment of the TPP, so as to maintain and protect the performance and technical status of the equipment.

References

Baoguo, D. (2013), "Detection of transformer oil leakage based on image processing", *Electric Power Construction*, Vol. 11, pp. 121-124.

Bao, N., Fan, Y., Ye, Z. and Simeone, A. (2022), "A machine vision—based pipe leakage detection system for automated power plant maintenance", *Sensors*, Vol. 22 No. 4, p. 1588.

Beard, E.J., Sivaraman, G., Vázquez-Mayagoitia, Á., Vishwanath, V. and Cole, J.C. (2019), "Comparative dataset of experimental and computational attributes of UV/vis absorption spectra", *Scientific Data*, Vol. 6 No. 1, 307.

Benxing, G. and Wang, G. (2019), "Underwater image recovery using structured light", *IEEE Access IEEE*, Vol. 7, pp. 77183-77189.

Chandrasekharan, S., Panda, R.C. and Swaminathan, B.N. (2014), "Modeling, identification, and control of coal-fired thermal power plants", *Reviews in Chemical Engineering*, Vol. 30 No. 2, pp. 217-232.

Chase, C.R., Lyra, G. and Green, M. (2010), "Real time monitoring-the key to effective oil spill prevention and response", *Proceedings of the Rio Oil and Gas Expo and Conference*, Rio de Janerio, pp. 1-10.

Chen, M. (2010), "Design and implementation of online oil leakage checking system", *Journal of Fujian University Technology*, Vol. 8 No. 3, pp. 284-288.

Chen, P. and Li, Y. (2017), "Signal processing of oil detection in port area based on UV-induced fluorescence", *ICCSS 2017-2017 International Conference on Information, Cybernetics and Computational Social Systems*, No. 1, pp. 32-35.

Divya, D., Marath, B. and Santosh Kumar, M.B. (2022), "Review of fault detection techniques for predictive maintenance", *Journal of Quality in Maintenance Engineering*, Vol. 29 No. 2, pp. 420-441.

Fausing Olesen, J. and Shaker, H.R. (2020), "Predictive maintenance for pump systems and thermal power plants: state-of-the-art review, trends and challenges", *Sensors*, Vol. 20 No. 8, 2425.

Fitch, J. (n.d.), "Understanding oil color", Machinery Lubrication, available at: https://www.machinerylubrication.com/Read/29651/use-zone-inspections

Gong, X., Tian, H., Sun, Y., Li, J. (2017), "Research on fuel-dilution monitoring of engine lubricant by UV fluorescence", *2016 5th International Conference on Energy and Environmental Protection*, Vol. 37 No. 12, pp. 3758-3762.

Gonzalez, R.C. and Woods, R.E. (2007), *Digital Image Processing*, 3rd ed., Prentice-Hall, Inc up, ©2006 Pearson, Saddle River, NJ, 976.

Guo, X., Li, Y. and Ling, H. (2017), "LIME: low-light image enhancement via illumination map estimation", *IEEE Transactions on Image Processing*, Vol. 26 No. 2, pp. 982-993.

He, K., Wang, T., Zhang, F. and Jin, X. (2022), "Anomaly detection and early warning via a novel multiblock-based method with applications to thermal power plants", *Measurement*, Vol. 193 February, 110979.

Ionin, A.A., Mokrousova, D.V., Seleznev, L.V., Sinitsyn, D.V. and Sunchugasheva, E.S. (2016), "Detection of thin oil films on the water surface with the help of UV filaments", *Atmospheric and Oceanic Optics*, Vol. 29 No. 4, pp. 339-341.

Jonasson Et, Ramos Pinto, L. and Vale, A. (2021), "Comparison of three key remote sensing technologies for mobile robot localization in nuclear facilities", *Fusion Engineering and Design*, Vol. 172, 112691.

Ju, Z. (2019), "A method, system and device for detecting oil leakage", CN110044559A.

Kavanagh, R.J., Burnison, B.K., Frank, R.A., Solomon, K.R. and Van Der Kraak, G. (2009), "Detecting oil sands process-affected waters in the Alberta oil sands region using synchronous fluorescence spectroscopy", *Chemosphere Elsevier Ltd*, Vol. 76 No. 1, pp. 120-126.

Kuang, H., Chen, L., Gu, F., Chen, J., Chan, L. and Yan, H. (2016), "Combining region-of-interest extraction and image enhancement for nighttime vehicle detection", *IEEE Intelligent Systems*, Vol. 31 No. 3, pp. 57-65.

Li, X.-X., Zhang, W.-H., Liu, X.-J., Yang, X.-M. and Ma, X.-M. (2022), "Small amounts of transformer oil leakage fluorescence detection using image processing", *IEEE 5th International Electrical and Energy Conference,* CIEEC, IEEE.

Liu, Y., Ma, X., Li, Y., Tie, Y., Zhang, Y. and Gao, J. (2019), "Water pipeline leakage detection based on machine learning and wireless sensor networks", *Sensors (Switzerland)*, Vol. 19 No. 23, 5086.

Lu, L., Ichimura, S., Moriyama, T., Yamagishi, A. and Rokunohe, T. (2017), "A system to detect small amounts of oil leakage with oil visualization for transformers using fluorescence recognition", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 24 No. 2, pp. 1249-1255.

Lu, H., Iseley, T., Behbahani, S. and Fu, L. (2020), "Leakage detection techniques for oil and gas pipelines: state-of-the-art", *Tunnelling and Underground Space Technology*, Vol. 98 September 2019, 103249.

Ly, B.C.K., Dyer, E.B., Feig, J.L., Chien, A.L. and Del Bino, S. (2020), "Research techniques made simple: cutaneous colorimetry: a reliable technique for objective skin color measurement", *Journal of Investigative Dermatology*, Vol. 140 No. 1, p. 3-12.e1.

Mangas, I., Sogorb, M.A. and Vilanova, E. (2014), "Lubricating oils", in *Encyclopedia of Toxicology*, Third Edit, Elsevier, Vol. 3, pp. 670-676.

Munadi, K., Muchtar, K., Maulina, N. and Pradhan, B. (2020), "Image enhancement for tuberculosis detection using deep learning", *IEEE Access*, Vol. 8, pp. 217897-217907.

Nakashima, T., Nakajima, H. and Matoba, O. (2009), "Oil leakage detection system for plant inspection", *Japanese Journal of Applied Physics*, Vol. 48 No. 9, 09LD05.

National Bureau of Statistics of China (2021), "Statistical communiqué of the people's Republic of China on the 2020 national economic and social development".

Nowak, P., Kucharska, K. and Kamiński, M. (2019), "Ecological and health effects of lubricant oils emitted into the environment", *International Journal of Environmental Research and Public Health*, Vol. 16 No. 16, 3002.

Rachman, A. and Ratnayake, R.M.C. (2019), "Corrosion loop development of oil and gas piping system based on machine learning and group technology method", *J Qual Maint Eng*, Vol. 26 No. 3, pp. 349-368.

Raza, S.A. and Hameed, A. (2022), "Models for maintenance planning and scheduling – a citation-based literature review and content analysis", *Journal of Quality in Maintenance Engineering*, Vol. 28 No. 4, pp. 873-914.

Roda, A., Cui, H. and Lu, C. (2016), "Highlights of analytical chemical luminescence and cataluminescence", *Analytical and Bioanalytical Chemistry*, Vol. 408 No. 30, pp. 8727-8729.

Sarkar, D.K. (2017), "Flushing of lube oil piping system", in *Thermal Power Plant*, Elsevier, pp. 131-156.

Sharikova, A.V. and Killinger, D.K. (2008), "Lif detection of trace species in water using different UV laser wavelengths", in *Spectral Sensing Research for Water Monitoring Applications and Frontier Science and Technology for Chemical*, Biological and Radiological Defense, Vol. 17, pp. 61-67.

Simeone, A., Deng, B., Watson, N. and Woolley, E. (2018), "Enhanced clean-in-place monitoring using ultraviolet induced fluorescence and neural networks", *Sensors*, Vol. 18 No. 11, p. 3742.

Singh, R.K. and Gurtu, A. (2022), "Prioritizing success factors for implementing total productive maintenance (TPM)", *Journal of Quality in Maintenance Engineering*, Vol. 28 No. 4, pp. 810-830.

Son, K., Choi, Y. and Park, J.W. (2011), "Oil leakage monitoring system by using image processing", *2011 11th International Conference on Control, Automation and Systems*, pp. 355-356.

Sule, O.O., Viriri, S. and Abayomi, A. (2020), "Effects of image enhancement techniques on cNns based algorithms for segmentation of blood vessels: a review", *2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD)*, Vol. 2 No. 1.

Sun, Z.Q., Zhao, Y.S., Yan, G.Q. and Li, S.P. (2011), "Study on the hyperspectral polarized reflection characteristics of oil slicks on sea surfaces", *Chinese Science Bulletin*, Vol. 56 No. 15, pp. 1596-1602.

Tao, C. (2016), "Common fault features and causes of steam turbine lubricating oil system", *China High Technical Enterprises*, Vol. 30, pp. 77-78.

Tian, Q., Xie, G., Wang, Y., Zhang, Y. (2017), "Pedestrian detection based on laplace operator image enhancement algorithm and faster R-CNN. Proc -", *2018 11th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics, CISP-BMEI 2018 2019. CISP-BMEI 2018* 2019.

Wang, Y., Deng, C., Wu, J., Wang, Y. and Xiong, Y. (2014), "A corrective maintenance scheme for engineering equipment", *Engineering Failure Analysis*, Vol. 36, pp. 269-283.

Woolley, E., Wanjeri, A. and Simeone, A. (2018), "Enhancement of clean-in-place procedures in powder production using ultraviolet-induced fluorescence", *Procedia CIRP*, Vol. 78, pp. 364-369.

Yan H., Lai D., Zhang Y. and Zhang, L. (2019), "Oil-immersed casing leakage detection system and method based on intelligent patrol platform", CN110346093A.

Yang, S.K. (2004), "A condition-based preventive maintenance arrangement for thermal power plants", *Electric Power Systems Research*, Vol. 72 No. 1, pp. 49-62.

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