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Overview of Applications of the Sensor Technologies for Construction Machinery

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ABSTRACT In recent years, great development in sensor technologies have resulted in substantial progress in the construction efficiency and the degree of automation of construction machinery have made great progress. Applications of the sensor technologies, such as condition monitoring, autonomous construction and the Internet of Things (IoT), have been extensively studied for construction machinery. Firstly, this paper discusses the condition monitoring technology in construction machinery, which mainly involves the monitoring of oil pollution and leakage, vibration monitoring, emission monitoring and whole-system monitoring. Second, regarding autonomous construction technology, this paper conducts analysis and discussion on linear motion, rotary motion, navigation/positioning systems, and visual systems. Third, research on IoT technology in construction machinery is comprehensively discussed, especially in term of life cycle maintenance, construction management and safety management. Finally, higher reliability, the development of smart sensors and big data management of sensor information are described as prospective issues that must be addressed for future construction machinery.

INDEX TERMS Construction equipment, condition based maintenance (CBM), global navigation satellite system (GNSS), building information modelling (BIM), Internet of Things (IoT).

I. INTRODUCTION

Construction machinery is a kind of heavy equipment widely used in construction, mining, transportation, water conservancy, agriculture, national defense [1], [2]. Figure 1 shows a variety of commonly used construction machinery. After more than one hundred years of development, construction machinery has experienced several major technological advances such as power system, transmission system and control system, and its main support technology has gradually matured. However, due to the complex structure, harsh construction environment and large fluctuation of load conditions for construction machinery, there are still some technical problems that need to be studied as follows: 1) more efficient condition monitoring systems, 2) higher autonomous construction technologies and 3) more detailed scene information of the construction fields. In recent years, sensor technologies have been rapidly developed and applied to various types of construction machinery. Sensor technologies have become an important breakthrough to solve the above technical problems.

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However, different from other fields such as industry and automobile, the mechanical structure, power system, transmission system and construction environment of construction machinery are very complex, so the applications of sensor technologies in construction machinery have more strict requirements, even comparable to the military equipment. Therefore, the sensor technologies which have been applied successfully in other fields cannot be transplanted directly to construction machinery, and it usually needs a long time of improvement and testing to determine whether they are suitable for construction machinery. As a result, many of the latest sensor technologies cannot be applied to construction machinery immediately, which makes the sensor technologies for construction machinery seem to be a little behind the trend. Therefore, it is urgent and important to study the applications of sensor technologies for construction machinery.

At present, the application research of sensor technologies for construction machinery mainly focuses on condition

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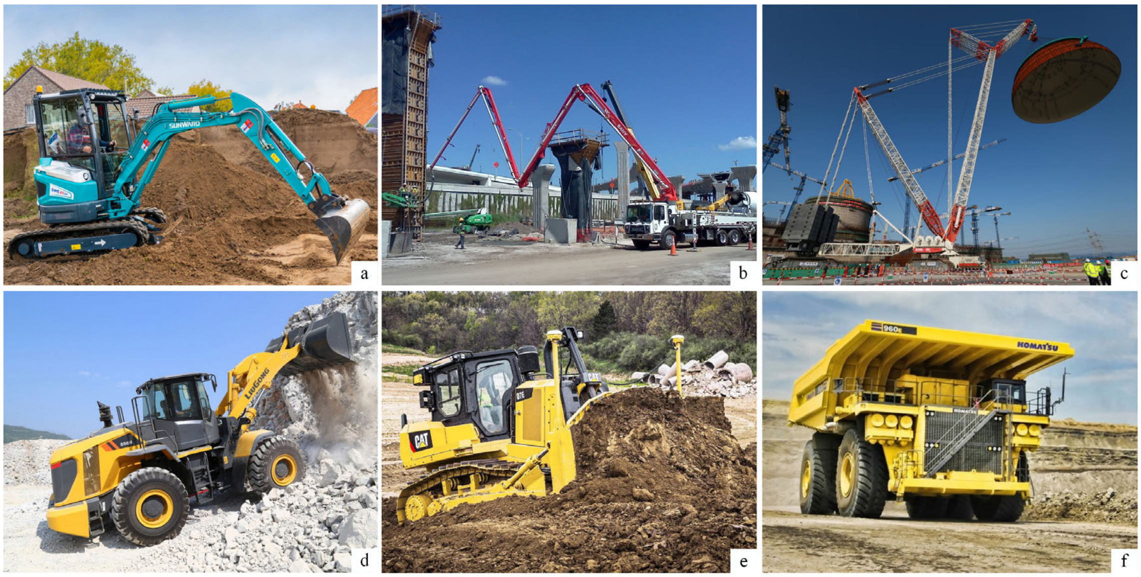


FIGURE 1. Some typical construction machinery: (a) Hydraulic excavator; (b) Truck-mounted concrete pump; (c) Crawler crane; (d) Wheel loader; (e) Bulldozer; (f) Mining truck.

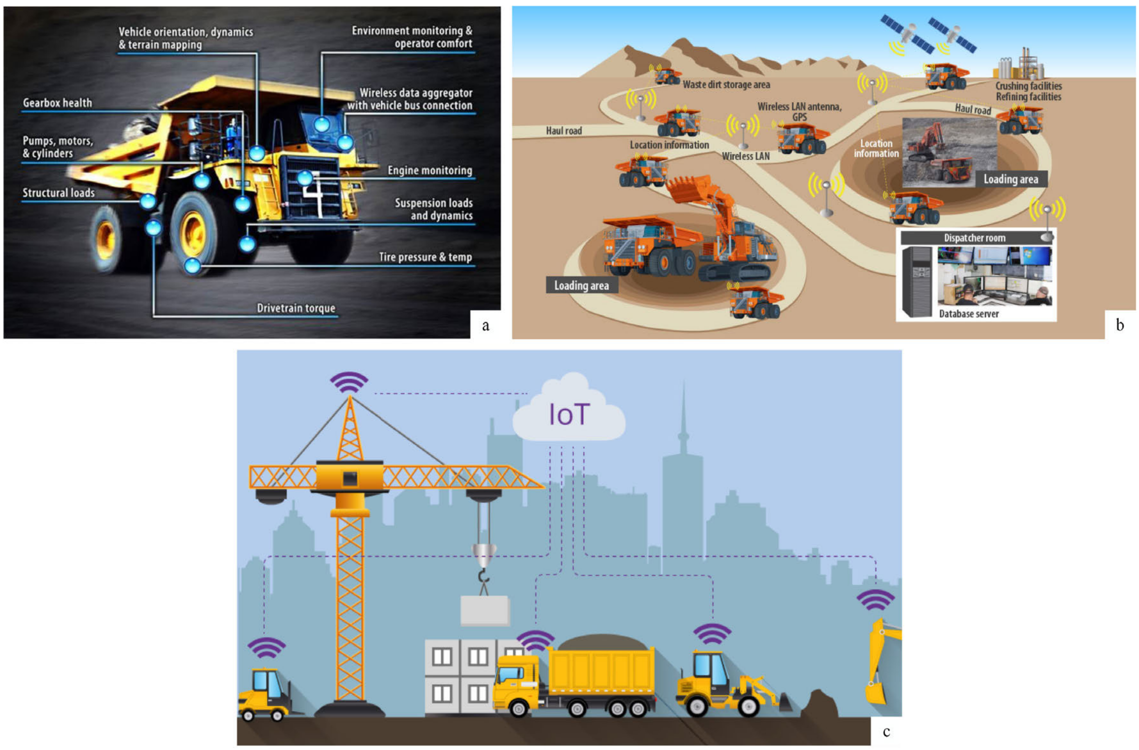


FIGURE 2. The applications of sensor technologies for construction machinery: (a) Condition monitoring [3]; (b) Autonomous construction [4]; (c) IoT [5].

monitoring, autonomous construction and Internet of Things (IoT) [3]–[5], as shown in figure 2. According to the time sequence, sensor technologies were first applied in the field of condition monitoring of construction machinery. Condition monitoring is usually aimed at important parts of construction machinery that are prone to failure. The data of oil contamination, vibration and emission are obtained through the sensor to determine the health condition of construction machinery.

Subsequently, sensor technologies were applied to the autonomous construction of construction machinery. On the one hand, sensors are used to obtain the linear or rotary

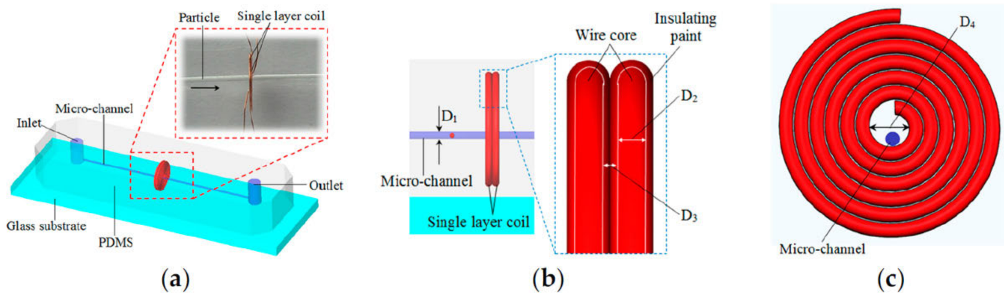


FIGURE 3. Schematic of the on-chip impedance sensor [11]: (a) The overall design; (b) Cross-section of the sensor; (c) A single-layer coil.

motion of the manipulators and actuators. On the other hand, navigation sensors can be used to obtain the position data of each construction machinery in fleet construction.

In recent years, the applications of IoT based sensor technologies for construction machinery have become a research hotspot. The introduction of IoT brings all kinds of data about the life cycle of construction machinery, construction management, worker status, etc.

As mentioned above, sensor technologies play a very important role in the development of construction machinery and will be the technical basis of a new generation of reliable, efficient and intelligent construction machinery. This paper will conduct a comprehensive review on the applications of the sensor technologies for construction machinery from condition monitoring, autonomous construction and IoT. It is expected that this paper can provide important reference for researchers in this field.

II. CONDITION MONITORING

The complex structure of construction machinery leads to various fault sources. In order to predict the occurrence of faults, the condition monitoring systems need to install a variety of sensors to accurately diagnose the health status of construction machinery. Hydraulic transmission systems (HTSs) and internal combustion engines (ICEs) are the most important parts of the construction machinery [6]. Therefore, this section mainly discusses and analyses the monitoring sensor technology related to HTSs and ICEs.

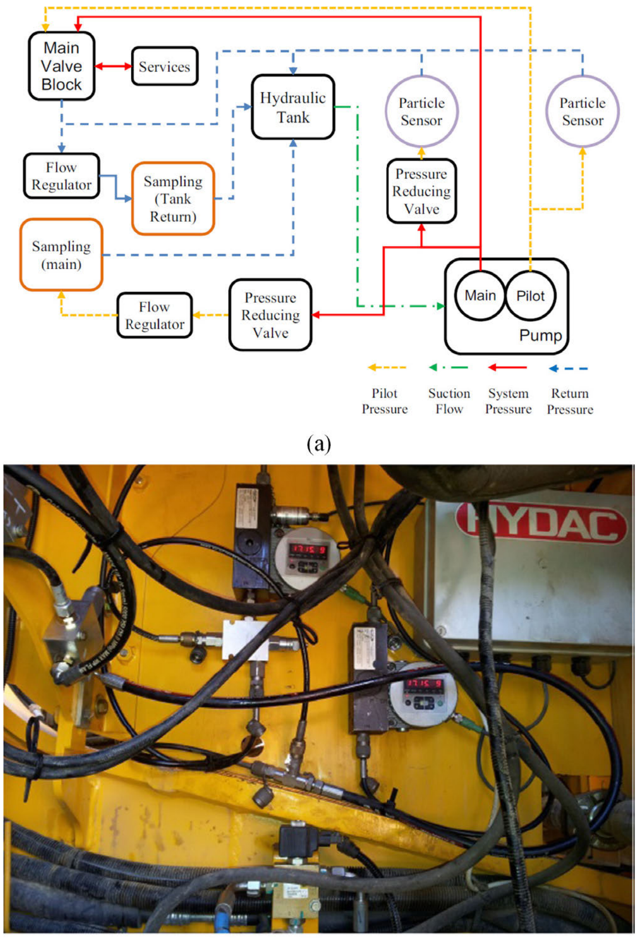
A. OIL CONTAMINATION AND LEAKAGE

Hydraulic or mechanical transmission failures caused by oil contamination are common, and oil contamination is responsible for 70% of the failures in hydraulic systems [7], [8]. When metal parts come into contact with each other, they will release metal particles; when these particles accumulate in the oil, it may lead to failure of hydraulic components [9], [10]. Obviously, wear failure is closely related to hydraulic oil contamination, so the wear conditions of hydraulic components can be indirectly analysed by detecting oil contamination.

In Ref. [11], a novel on-chip impedance sensor for on-line analysis of wear and tear fragments is proposed based on the monitoring of industrial hydraulic transmission systems. In figure 3, the on-chip impedance sensor is depicted as being mainly composed of impedance sensors and linear micro-channels. The impedance sensor consists of two single-layer coils that are glued together, and micro-channels near the inner wall pass through the inner holes of the two coils. Taking into account the sample opacity, flow velocity and working pressure, the sensor integrates lens-less microscopy and stroboscopic lighting. The sensor can be used not only as an inductive sensor to detect ferromagnetic and non-ferromagnetic particles in petroleum but also as a capacitive sensor to detect water droplets and bubbles in petroleum. The results of testing this sensor show it can detect four kinds of particle pollution in hydraulic oil and that it can be used for monitoring and fault diagnosis in hydraulic systems.

Ref. [12] proposes a dynamic data acquisition technique for the HTSs of hydraulic excavators, using a mobile embedded particle contamination sensor to assess whether it is suitable for achieving state-based maintenance, diagnostic and prognostic requirements, as shown in figure 4(a) and (b). It is proposed that the oil pollution monitoring systems should be part of construction machinery design processes. Moreover, the sensor installation locations have an important impact on the real-time performance of data and can also reduce the installation and operation costs. The applicability of mobile inline particle pollution sensors in hydraulic excavators was evaluated by monitoring the oil pollution for 1900 hours. Shi *et al.* [13] introduced a multifunctional sensor for the on-line detection of hydraulic oil contamination. Experiments showed that the sensor could also detect 90 μm water droplets and 170 μm bubbles through capacitance measurement. The sensor can provide real-time information on contaminants in hydraulic oil for the on-line health testing of construction machinery.

Leakage is also a common failure in HTSs [14], and a local tiny leakage is very difficult to diagnose and detect. Similarly, internal leakage in a HTS is usually difficult to detect because it is not easy to install sensors at the leakage site; these leakage can affect the overall efficiency of the system [15]. Ref. [16] developed an in-pipe fibre optic pressure sensor array for hydraulic transient measurement and pipeline leakage detection based on these transients. The sensor array can be plugged into a pipe through an access point and



(a)

(b)

FIGURE 4. An in-line hydraulic oil contamination monitoring system [12]: (a) A simplified diagram of a hydraulic system with particle sensors for a 20-ton hydraulic excavator; (b) Particle sensors installed on a 20-ton hydraulic excavator.

sealed with an o-ring to measure the pressure at multiple locations.

B. VIBRATION MONITORING

Mechanical vibration signal plays an important role in the reliability of HTS [17], [18]. Therefore, using vibration signals to analyse the reliability and faults of hydraulic pumps has important theoretical and practical significance [19]. At present, the main method to perform these analysis is to use sensors to transform vibrations into electrical signals [20].

In order to diagnose faults in hydraulic pumps while working with inaccurate information, Jia *et al.* [21] propose a data-driven fault diagnosis method based on SPIP and HMM. Their experimental platform adopts the NI pxi-8880 sensor system to collect vibration signals from a hydraulic pump with a sampling rating is 10000 Hz and a rotation speed is 2900 RPM. Six hundred vibration signal samples under four working conditions were used to verify the performance of the system. Experiment showed that the method has the ability to diagnose faults in the hydraulic pump in an actual running process.

A vibration monitoring system was developed for a hydraulic pump based on the uniform charge structure fibre Bragg grating (FBG) vibration sensor [22]. FBG vibration sensors are designed based on the intensity of rays to solve the problems of electric vibration sensor for hydraulic pump vibration detection, such as high false alarm rates, ease of interference by electromagnetic devices, and difficulty in realize long-term reliable monitoring. By building a test platform, the design of FBG vibration sensor is tested by using two vibration sources of different frequencies. The results of test data analysis show that the sensor has good response characteristics and can accurately measure the vibration frequency signal.

The full vector spectrum is an effective tool for homologous multi-sensor data fusion in rotary machinery and is particularly suitable for hydraulic components with rotary parts in hydraulic pumps and motors. In Ref. [23], three mutually perpendicular vibration sensors were installed to capture fault information as shown in figure 5(a) and (b). In this way, there was a certain inclination angle between the friction pair and the rotation axis; therefore, the vortex characteristics of the rotor containing information about the pump operational state transmitted not only in the spatial domain but also for the whole shell.

C. EMISSSION MONITORING

Because the construction machinery generally uses high power diesel engines, serious exhaust emissions have been one of their main sources of critique [24], [25]. Emission regulations have become increasingly strict, but measurement methods have been unable to keep up with the regulations, especially with regards to the higher requirements for sensors [26], [27]. At a construction site, dozens or even hundreds of construction machinery engines are turned on at the same time [28], which makes the accurate detection and control of emissions very difficult. To solve the above problems, Ref. [29] first conducted accurate measurements of greenhouse gas emissions by using a ZigBee sensor to configure a wireless network, conduct greenhouse gas emission trading, and measure the greenhouse gas emission of construction machinery within a duty cycle in real time. ZigBee is an emerging network technology and wireless communication standard, that can meet the needs of ubiquitous environment. In this study, vehicle vibration is converted into electric energy to power a ZigBee network sensor. Meanwhile, ZigBee network sensor data can be uploaded and saved to the web, sparing the limited storage space of onboard computers.

D. WHOLE-SYSTEM MONITORING

Construction machinery can be considered a complex nonlinear system that contains a large number of system variables [30]. Whether these variable data can be accurately measured and obtained is related to the correct judgment

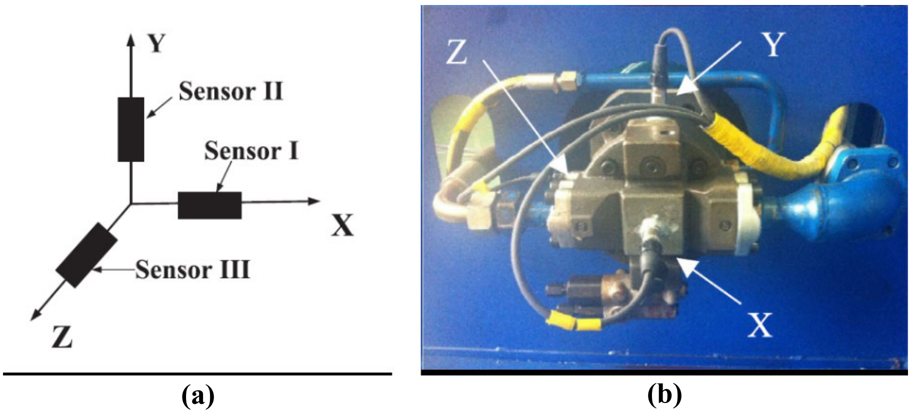


FIGURE 5. **The full vector spectrum with multi-sensor data fusion for hydraulic pumps [23]: (a) Layout of the vibration sensors; (b) A hydraulic pump with the vibration sensors.**

of the state of the construction machinery. Model-based, rules-based and case-based diagnostic methods must be based on adequate and accurate sensor data [31], [32]. Xu *et al.* [33] proposed an ontology-based fault diagnosis method for loaders, which overcomes the difficulty of understanding their complex fault diagnosis knowledge and provides a general method for fault diagnosis of all loaders. Combining ontology and case-based reasoning (CBR), the fault diagnosis is realized effectively and accurately through four steps: feature selection, case retrieval, case matching and case updating. The data acquisition layer is the most important part of this method. A large amount of sensor data is collected every 2 seconds. The collected sensor data are encapsulated in three electronic control units (ECUs), which communicate with each other through a controller area network (CAN) bus. The method was validated by analysing a case study. For the condition-based maintenance (CBM) of underground construction machinery, sensors provide a wealth of data and help workers identify upcoming maintenance needs in advance [34]. Typical measurement variables are vibration, temperature, speeds and pressures, and preliminary data analysis from a load haul dump shows that vibration measurement provides a good basis for the development of CBM systems.

III. AUTONOMOUS CONSTRUCTION

For different construction objects, the installation and measurement requirements of sensors for the working devices and walking mechanisms of construction machinery are very complicated [35], [36]. Motion measurement sensors can measure many variables, such as displacement, velocity, acceleration, tilt angle, rotation, and position [37], [38].

A. LINEAR MOTION

As mentioned earlier, most construction machinery relies on the HTS to drive the working device. Their linear motion is mainly realized by hydraulic cylinders [39], [40]. The large-volume external linear sensor once installed on hydraulic cylinders is not been able to meet the requirements of modern construction machinery, so embedded miniaturized

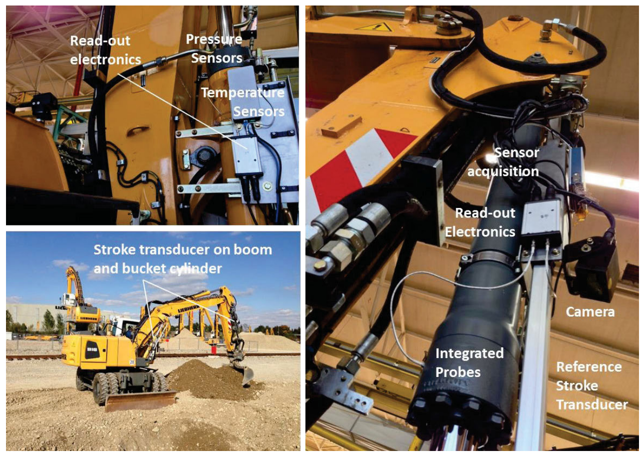


FIGURE 6. **Stroke transducers on the hydraulic excavators [43].**

linear sensors have become popular and widely used replacements [41]–[43]. Linear motion sensors are often used to measure the stroke of the cylinders (called stroke transducer) to drive the manipulator of a hydraulic excavator [43], as shown in figure 6.

The Widman effect, a magnetostrictive effect used in the measurements carried out by displacement sensors, describes the mechanical deformation of a long, thin ferromagnetic bar in a longitudinal external magnetic field [44], [45]. As the current flows through the rod, a concentric magnetic field is created. Usually, a magnetostrictive displacement sensor includes a sensing element (waveguide), sensor electronics, a position-determining permanent magnet, a strain pulse converter system and damping at the waveguide end. Compared with other linear sensing technologies, magnetostrictive technology has become the preferred technology for the high precision applications of hydraulic cylinders [46], [47]. The sensor consists of a stainless-steel tube probe and a short annular permanent magnet mounted in a secondary hole in the piston of the hydraulic cylinder. The most common package design is to insert the sensor electronic shell into the o-ring

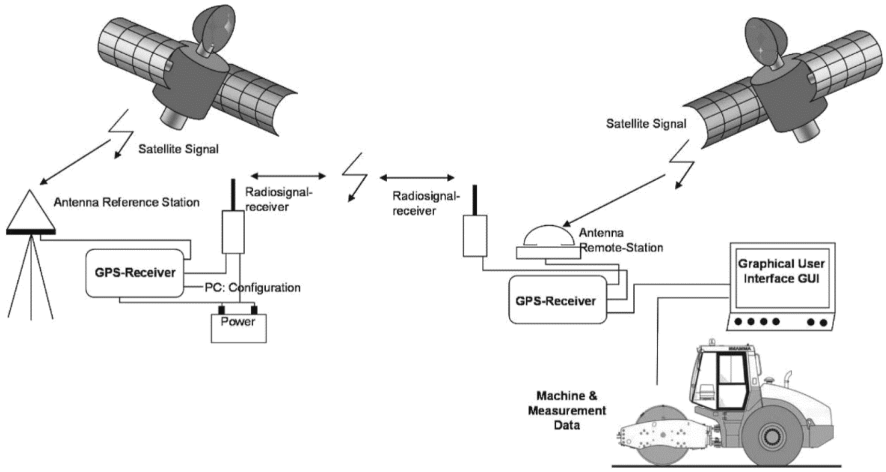


FIGURE 7. Differential GPS application on a single drum roller [64].

end at the back of the cylinder and install the slender probe into the rod hole.

The magnetostrictive sensor can only be used for hydraulic cylinders with piston rods, and their costs are high. The microwave displacement sensor is another high precision linear motion sensor [48]. This sensor element includes an ultrasonic waveguide that is periodically excited by a current pulse. The interaction between the obtained magnetic field and the magnetic field at the marked position produces a mechanical torsional wave propagating backward. This conversion of propagation time provides precise target locations. Research results show that the microwave displacement sensor can meet the requirements of industrial applications in term of precision, robustness, feasibility and cost performance [49].

B. ROTARY MOTION

A rotary motion sensor is mainly used to measure the angle, angular velocity, angular acceleration and other variables of rotary joints used in construction machinery [50], [51]. It is a good choice for measuring the angle of the joint, because it is obtained directly and in real time. A rotary encoder is a high-precision rotary angle sensors that converts a rotation position or quantity into an analogue or digital signal. The rotary encoder can provide high-precision measurement data for rotary motion in construction machinery [52]. There are two main types of rotary encoders: absolute and incremental. The output of the absolute encoder indicates the position of the current axis, making it an angle sensor. The output of the incremental encoder provides information about the axis's motion, usually processed elsewhere as position, speed, and distance.

It is often difficult to measure the rotatory motion directly, because the sensor needs to be installed at the rotation joint, which impacts high requirements on the volume, reliability and installation of the sensor [53], [54]. Therefore, indirect measurement of the rotary angle by measuring the tilt angle has become one of the first choices in the application of sensors for construction machinery [55], [56]. Tilt sensors are actually acceleration sensor that use the principle of inertia to perform their measurements. Tilt sensor can be divided into three kinds of inclination sensors: solid pendulum, liquid pendulum and gas pendulum. From the classification of the tilt sensor, the number of installed axes of the tilt sensor can be divided into two categories: one axle and multiple axle [57], [58]. The most widely used type of dip-sensor is the hydraulic excavator because it can be mounted directly on the boom, stick or bucket. At present, two-dimensional positioning hydraulic excavator technology is adopted to define and control the position of the operating parts of construction machines with two parameters: elevation and slope. In ref [56], the two-dimensional positioning system uses multiple integrated tilt sensors that are fixed to the working parts of the machine.

C. NAVIGATION AND POISTIONING SYSTEM

In modern construction, global navigation satellite system (GNSS) equipment information must be introduced to improve construction automation and precision. It is inevitable that modern construction machinery will ubiquitously obtain positioning information from a GPS [61, 62], Galileo navigation system [61] or Beidou navigation system [62], [63] by positioning sensors to assist construction.

Ref. [64] propose a 3D scheme for a vibration roller based on GPS, as shown in figure 7. The roller is equipped with a GPS satellite signal-receiving sensor and a GPS reference position device at the construction site, which are capable of high-precision positioning. The vibration roller combines the working process of pavement compaction with measurement and control technology to establish the overall process control and monitoring. First, the vibration roller visualizes the road compaction process. By realizing the real-time flow animation of the construction process, the driver can optimize

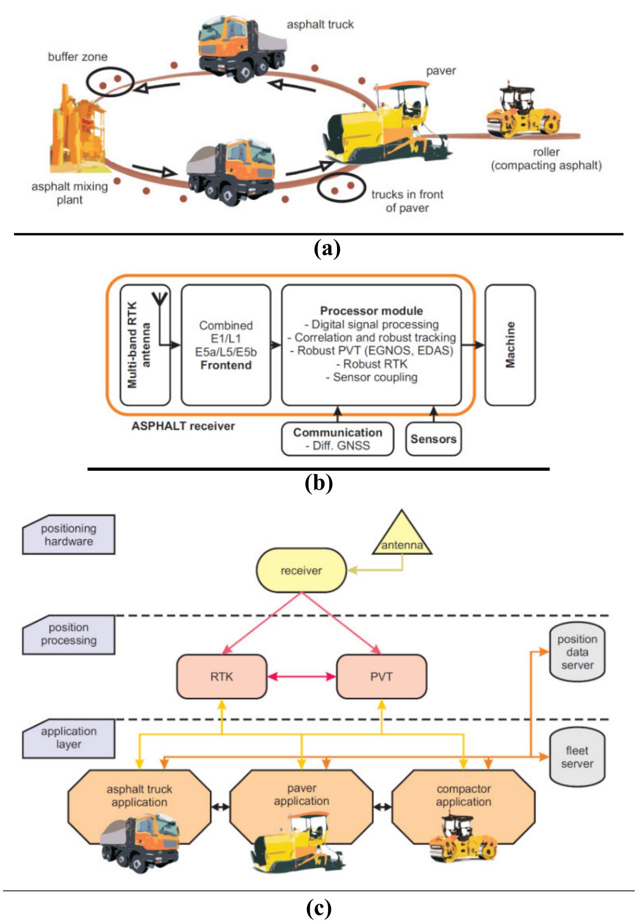


FIGURE 8. Asphalt fleet machines based on the Galileo navigation system [61]: (a) Supply chain for asphalt construction; (b) Block diagram of the receiver; (c) decomposition of the whole system.

the construction tasks performed by the vibration roller in real time. The vibration roller can automatically record construction data (every second), even in the event of power failure; it can also retain historical construction data.

Ref. [61] provides a high-precision positioning service for asphalt fleet machines with the advanced Galileo navigation system. Figure 8(a) shows that the asphalt fleet machines incorporate the asphalt supply chain and the asphalt road paving process, which requires the use of asphalt mixing plants, trucks, pavers, and rollers. The receiver architecture of ASPHALT is based on a 3-frequency approach combining the E1/L1 Galileo/GPS/EGNOS with the E5a/L5 Galileo/GPS and E5b Galileo signals as shown in figure 8(b). Figure 8(c) illustrates how an asphalt fleet machine based on the Galileo navigation system can implements scalable, cost accurate optimization positioning solutions to bring higher performance and allow new monitoring circuits in asphalt construction. Therefore, asphalt paving based on the EGNOS and Galileo system is considered not only practical but also of strategic importance.

Laser sensors are a kind of high-precision positioning and distance measurement sensor [65]. The advantages of laser sensors lie in their low interference, measuring distance source, small error and high stability. Although the GNSS can achieve higher accuracy through RTK, laser sensors can achieve a higher accuracy with the help of auxiliary equipment. In addition, in some cases where GNSS information is not available, such as underground tunnels, laser sensors become one of the best choices for construction positioning [66], [67]. Based on the requirements of unmanned mining of deep, dangerous coal seams, ref. [68] uses laser sensor to achieve high-precision measurements of cantilever tunneling machine postures in unmanned environments. The pose measurement method describes the pose state of the cantilever road-header in the tunnel coordinate system constructed by the laser receiver, which lays a foundation for its remote and precise control. In addition, the autonomous emissions from rotary, planar scanning laser receivers by laser emitters are considered the best way to measure the autonomous posture of cantilever tunneling machines. The simulation results show that in the narrow and long spaces of coal roadways, the accuracy of the laser sensor is lowest in the horizontal direction and highest in the vertical direction.

D. VISUAL SYSTEM

In addition to navigation sensor systems, visual sensor systems is also the premise of unmanned construction machinery [69]. Due to the changeable construction site environment, the visual sensor system is not only responsible for the acquisition of visual data but also must be able to establish a 3D model of the construction environment in real time so as to ensure construction safety and accuracy [69], [70].

Soltani [71] carried out 3D modelling research based on a visual sensing system for the working environment of construction machinery, and combined it with GPS and other positioning data. With computer vision (CV) and a real-time location system (RTLS), the construction site configuration can be completed quickly, as shown in figure 9(a). As shown in figure 9(b), the 3D model can be automatically integrated with different construction site backgrounds, and the training quality can be continuously improved to achieve the auto annotation of synthetic images. Following the above steps, data fusion and excavator parts recognition (figure 9(c)) and skeleton extraction and 3D pose estimation (figure 9(d)) can be realized successively, providing guarantees for autonomous and safe construction. Through the above steps, the 3D position and pose information of the hydraulic excavator can be successfully obtained. The 3D pose information can perform autonomous construction, prevent collision accidents and estimate productivity.

Ref. [72] proposed an autonomous excavator operation solution based on multi-frame target detection. The autonomous excavator solution features rugged cameras overlooking the shovel, cab monitors that provide real-time status updates, and remote monitoring portals. The solution allows the operator to quickly create a decision module that combines a given excavator's perception of its environment with a high-definition map of the surrounding environment to guide the excavator's operations autonomously.

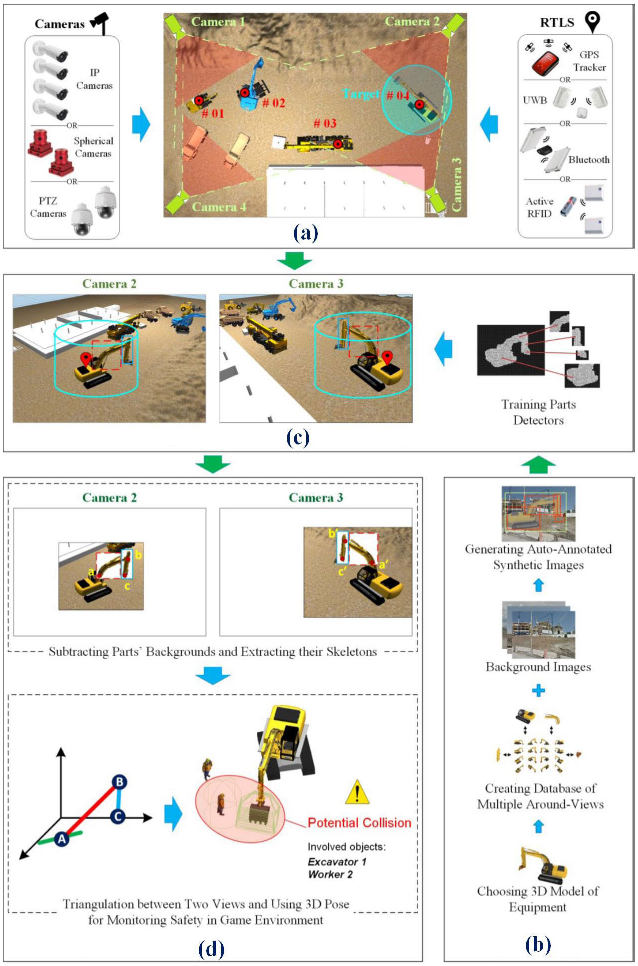


FIGURE 9. The framework of the 3D pose estimation system [71]: (a) Defining the construction site; (b) Auto annotation of synthesis images; (c) Data fusion and excavator parts recognition; (d) Skeleton extraction and 3D pose estimation.

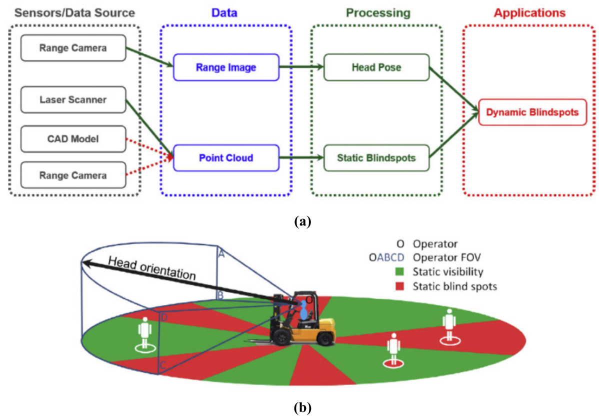


FIGURE 10. Dynamic blind-spot measuring method [73]: (a) Method diagram; (b) System representation.

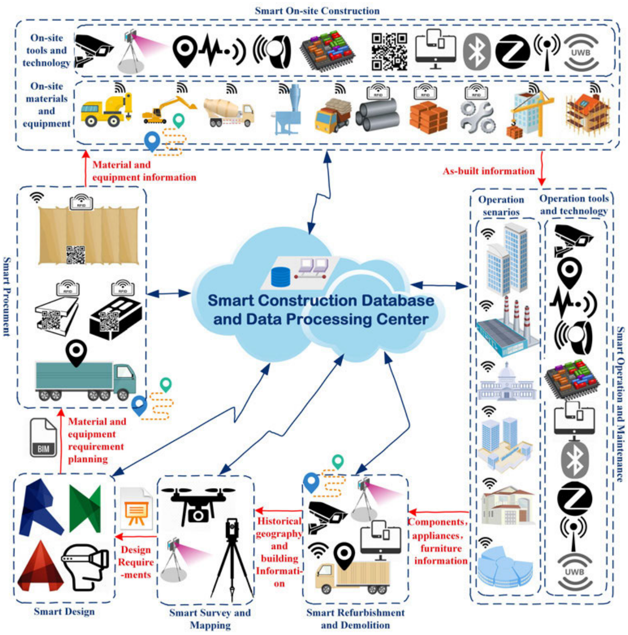


FIGURE 11. Landscape of the closed-loop smart construction [77].

In the assembly of construction machinery, site restrictions and equipment shielding will inevitably result in the creation of blind spots. The use of proximity detection technology can reduce the number of casualties in construction sites caused by human-equipment interactions. Ref. [73] proposed a method to measure the visibility of equipment operators in real time using visual sensors and range-based technology, which is expected to be used to create an intelligent proximity warning system, as shown in figure 10(a) and (b). At the same time, real-time proximity detection can be used as an early warning system to warn vehicle operators of nearby pedestrians. In addition to being a possible proximity warning system, the method can also be used to record proximity incidents. A dynamic blind spot or visibility map is generated from the operator's point of view by using head attitude information and point cloud data from construction equipment.

IV. IoT IN CONSTRUCTION MACHINERY

Sensor network and detection technology are the premise and foundation of internet technology [74], [75]. IoT technology based on a sensor network can sense thermal, mechanical, optical, electrical, acoustic and displacement signals, providing the most original information for the processing, transmission, analysis and feedback of the IoT system [76].

A. LIFECYCLE MANTAINANCE

The importance of lifecycle management and maintenance in ensuring the efficient assembly and maintenance of conruction machinery throughout its life cycle. Ref. [77] proposed a closed-loop lifecycle management system frame based on IoT. The schematic of this frame is shown in figure 11. In this frame, all equipment, materials, components, and workers are aware of the past, present, and future status of the construction system, which facilitates better system operation and visualization and thus better prediction and management. Moreover, different equipment, materials, components, workers, engineers and managers can communicate in real

FIGURE 12. **Future construction management [79].**

time to solve problems and make faster and better decisions. In this way, the construction process can achieve full life cycle management and promote cooperation among different developers, contractors and suppliers. Thus, the different phases of the construction machinery life cycle are linked as a closed loop to collect, store, and process information for automated and intelligent decision-making.

According to Ref. [5], equipment with IoT sensors can help managers decide when to carry out preventive maintenance to optimize performance and avoid failures. For example, sensors can track indicators such as excessive vibrations or temperature fluctuations to determine whether a machine's engine needs to be checked or an air filter needs to be replaced. Then, the IoT system can alert repairmen's smartphones, tablets or computers so they can fix the problem before it causes serious complications. Dong *et al.* [78] uses the safety monitoring and maintenance system of coal mine equipment as an example to establish a predictive maintenance system based on IoT technology. They hope to change the existing maintenance model of coal mine equipment and ensure the safe and efficient operation of mining equipment.

B. CONSTRUCTION MANAGEMENT

The high-precision scheduling and management of construction machinery in the construction process is still a great challenge. However, the introduction of IoT seems to have provided the perfect high-tech solution to this problem. Ref. [79] proposes an IoT based digital skin concept specifically for the future management of construction machinery, construction sites and construction personnel. For today's decentralized and highly dynamic construction supply chain, digital skins will make future construction more powerful and productive, with real-time information retrieval and dissemination, structured and efficient communication, and embedded intelligence as shown in figure 13. Tools and components at the construction site will carry radio frequency identification devices (RFID) tags and will be associated with related workflows to increase productivity. In the building information modelling (BIM) system, the real-time visualization of on-site engineering machinery scheduling will be linked with material consumption, and progress monitoring will be automatically updated in the system, so as to better control the project progress.

Ref. [80] proposed directions for the development of digital mining, and the Internet of things (IoT) is considered one of the key technologies that could provide a connection framework for mining sites. In fact, mining and mine transportation equipment are very expensive and require large investments, but developers seldom pay attention to IoT technology for efficiently planning and managing of the mining process [81]. IoT technology enables managers to have a comprehensive understanding of the mining process and the state of mining machinery, allowing them to make decisions and adjust plans in real time.

C. SAFETY MANAGEMENT

Safety has always been a key concern in construction. Because of the particularities of construction equipment and the construction environment, casualties occur frequently. In particular, great progress in vehicle safety has made research on safety problems in regard to construction machinery increasingly urgent. Different from vehicle safety, there is a higher risk and more types of accidents in relation to construction machinery [73], [82]. Therefore, more relevant sensor information is needed to ensure the effectiveness and reliability of safety monitoring. Kanan *et al.* [83] proposed a safety monitoring solution based on IoT technology to prevent fatalities in construction sites, as shown in figure 13(a) to (c). By applying new design technologies at the architectural, electrical, and system levels, this study proposed two autonomous, energy-efficient, and real-time sensing systems using IoT. Figure 13(a) shows a fatal injury prevention system for a construction truck that helps provide higher safety for construction workers and eliminates rework accidents. The system shown in figure 13(b) is used to automatically alert workers in real time when they are near a predefined hazard area. In figure 13(c), data entering the server through the cellular network can be evaluated by a safety expert.

In the digital skin concept based on IoT technology [79], researchers believe that the smart building sites of the future will actively guard against the risk of accidents. In particular, due to the dynamics and complexity of construction activities and the increasing number of interactions between various objects on site, automatic controls for collision avoidance as well as accident prevention through active identification and risk mitigation will have to be implemented. Figure 14 shows potential safety problems for the working process of construction machinery systems. In this way, automatic safety management system of future construction sites can be designed.

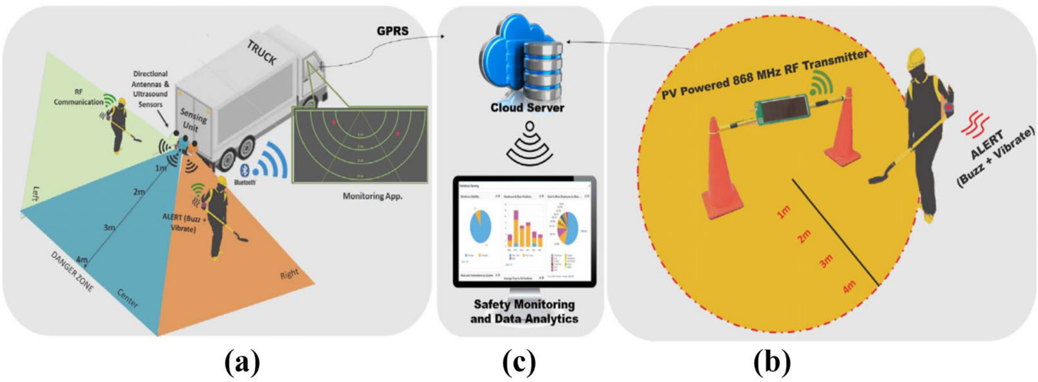


FIGURE 13. An IoT-based autonomous system for worker safety [83]: (a) Backover accidents prevention; (b) Smart alerting for potential hazard avoidance; (c) The Middleware IoT platform.

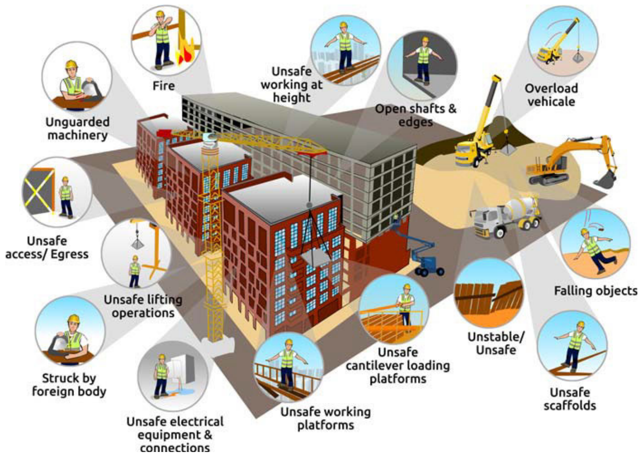


FIGURE 14. The conception of the safety management system for future construction projects [79].

V. CONCLUSIONS AND PROSPECTS

As summarized in the discussion and analysis in the above sections, sensor-based technologies such as condition monitoring, autonomous construction and IoT have been widely studied and applied in construction machinery. Despite the current state of technologies described in the above research, there are still many technical barriers to overcome, which are worthy of further research.

(1) Environmental factors can accelerate sensor failure due to element defects. Due to the severe construction environment of construction machinery, the high reliability of sensors is related not only to the efficient operation of the machinery itself but also to the safety of the construction workers [84]. Therefore, it is necessary to improve the reliability of sensors design and manufacture for application in construction machinery.

(2) Autonomous construction has high requirements for the intellectualization of construction machinery, and correspondingly, high requirements for the intellectualization level of sensors: in other word, smart sensors. In addition, in the future, the number of sensors in construction machinery will likely increase exponentially. It is impossible for controllers and on-board computers to process all sensor data, so the sensors themselves must be more intelligent.

(3) With the integration of various sensor-based technologies into construction machinery, high-frequency sampling periods will generate massive data. The storage and mining of big data becomes a very important link that can realize the deep informatization of construction machinery.

(4) Due to the development level of the construction machinery industry, its sensor technology standard cannot fully meet the requirements of real-time, bandwidth, compatibility and so on. If industry 4.0 standard can be introduced into the applications of sensor technologies for construction machinery, it will bring significant changes to the construction machinery industry [85].

The applications of sensor technologies for construction machinery still have lots potential research directions. It is expected that this review will be an important reference for researchers in this field.

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