

Design of Intelligent Construction Safety Equipment Oriented Towards the Dual Carbon Goals Taking the Intelligent Early-warning Safety Helmet as An Example

Di Zhang, Hao Zhang, Yaxian Zhang, Mingzhang Ji

Faculty of Intelligent Construction, Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China

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Abstract: Based on the dual-carbon goal and the development demand for intelligent construction, we take intelligent early warning safety helmet as the research object, analyzing the relationship between the functional design of facilities and low carbon development, it finds out that what is the key early-warning function requirement for safety helmets under the background of smart building. optimizes the functional structure and technical options based on low-carbon design thinking, and explores the path to apply low-carbon materials and energy saving technologies into equipment functional design. The study provides reference for low-carbon and smart enhancement of safety facilities in intelligent construction.

Keywords: Dual carbon goals; Intelligent construction; Safety equipment design; Intelligent early-warning safety helmets

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1. Introduction

Under the background of dual-carbon goals, it is inevitable to develop towards smart and green construction industry in the field of construction engineering. BIM is one of the important auxiliary tools for intelligent construction. safety equipment needs to coordinate the requirement of intelligence and low carbon development during designing process; Intelligent early-warning safety helmet is the key protection equipment on construction site; however, the current product is mainly oriented towards the function of early warning without considering low carbon factors such as materials used and design of energy consumption. leading to problems of high carbon footprint, high power consumption, lack of functional integration etc. In this article we use this helmet as an object to study how to integrate the function with low-carbon thinking, thus pushing the development of smart construction safety gear to a more green and smart direction.

2. Design requirements for intelligent construction safety equipment under the dual carbon goals

2.1. Functional compatibility requirements for safety equipment in intelligent construction scenarios

The intelligent construction scenes have the characteristics of complex work environment and automatic operation workflow, and sophisticated plant facilities that demand high level flexibility in operation from instrumentation and safety systems to fulfill key plant functions such as advanced surveillance, real time communications, and safety warnings, while being easily integrated into construction equipment and smart project management systems for detecting hazards such as fall from heights in a timely manner, dents, object strikes, and gas leaks. The equipment also must be suited to the particular work requirements of each trade, protecting the user while maintaining ease of use in order not to burden a website's functionality by overcomplicated smartness, ensuring best-fit function-construction context matching. As intelligent construction is completely digital, safety gear should have powerful data gathering, sharing, and processing capacities, and be designed to work well with electronic databases. Information, such as employee location, physical environment, and field condition information—captured from devices need immediate reflection in intelligent control system to support real time site security monitoring.

In addition, due to the work environment on construction sites (open-air, high-altitude operations, dust concentration), it is necessary for smart safety gear to have anti-interference capability and a wear-resistant function.

2.2. Core requirements for low-carbon design of safety equipment under the dual carbon goals

Under the guidance of dual carbon objectives, the low-carbon approach to safety equipment focuses on embedding green, low-carbon concepts across its full life cycle, cutting carbon emissions at each phase, from raw material choice and production to use, upkeep, and end-of-life recovery. At the material stage, emphasis should be placed on selecting low-carbon, eco-friendly, biodegradable, and recyclable materials that replace traditional high-carbon, non-biodegradable feedstocks and lower emissions in the process of manufacture. In the manufacturing process, procedures should be improved by adopting energy-saving and low-emission technologies to cut energy use and decrease pollutant discharge. During operation and maintenance, energy consumption must be minimized to lower the carbon footprint. Low-carbon design also needs the trade-off among light weight, energy saving, and recycle: optimize product structure for less material consumption with maintain protective performance and smart functionalities, thereby minimizing equipment weight and energy consumption during transportation and use ^[1]. Energy-efficient designs focus on intelligent components, employing low-power, energy-efficient chips and sensors together with efficient power systems so as to minimize the energy used for operation of these devices. Recyclable designs include those having modular designs that allow components to be placement, maintenance, and recycling, enhancing resource utilization, reducing waste generation, and achieving low-carbon development across the entire lifecycle.

2.3. Principles for coordinated design of functional intelligence and low-carbonization

Firstly, in order to realize the joint design between function intelligence and low-carbon solution, we should follow the rule of “function first, low-carbon adaptation”, which means that low-carbon design will not affect the basic protection function and intelligence function of the safety device itself. Based on the premise of satisfying the safety demand on site, low-carbon thinking must run through the whole process of functional design. In designing functions such as smart early warning, data transmission, the low carbon characteristic of technological choice and component matching should also be taken into consideration at the same time instead of blindly pursuing intelligentization through using some high energy consumption and high carbon emission technologies and materials, thus reaching an optimal balance point between function and sustainability, collaborative design should also be carried out on the basis of “full-process integration and system optimization”, low-carbon life-cycle management, which includes low-carbon design of the overall function structure, technical scheme, component composition, and shape and structure in the whole process of the safety equipment design; and establish common criteria on the functional-intelligence performance as well as low-carbon level and combine

them together in an integrated rating system instead of focusing solely on function or environment protection.

3. Core functional requirements and low-carbon correlation points of intelligent early-warning safety helmets

3.1. Core functional requirements for the intelligent early-warning safety helmet at construction sites

The core functional framework of the intelligent early-warning safety helmet for construction sites is built upon safety protection as its foundation and centered around intelligent early-warning capabilities, integrating data acquisition and real-time communication functions to form an integrated system encompassing “protection–early-warning–data–communication. The safety protection features must meet fundamental requirements such as impact resistance, puncture resistance, and fall prevention to ensure workers’ head safety. The intelligent early-warning functions include alerts for hazardous environments, operational behavior anomalies, and equipment collisions, utilizing sensors to detect dangerous signals and trigger immediate audio-visual alarms. The data acquisition module collects workers’ location, heart rate, environmental temperature, and humidity data, while the real-time communication feature enables two-way interaction between workers, the platform, and colleagues. The helmet’s functional system also features personalization, interoperability, and adaptability to meet diverse operational needs across various construction scenarios and job types. For specific applications like high-altitude work, underground operations, and welding tasks, the helmet’s warning system must dynamically adjust monitoring parameters and alert thresholds; interoperability requires seamless integration with on-site smart cameras, construction machinery, and safety management platforms to achieve synchronized multi-source detection and rapid response to hazardous signals ^[2].

3.2. The intrinsic connection between helmet functional modules and low-carbon design

Low-carbon design is closely related to the function modules of helmet, such as materials choice module directly determines the carbon emission in the process of helmet making and recycling, is a key component of low-carbon design, and conventional helmet materials such as high-carbon engineering plastic or metal parts have large carbon footprints, whereas the application of low-carbon material greatly decreases total lifecycle emission. Technical selection and components setting for intelligent warning module is directly related with energy saving: higher power sensor, chip will lead more energy consumption when wearing helmet. while the low power component realizes saving energy consumption and low carbon performance. Structural design module can achieve low-carbon at a material level by reducing weight and using less materials. Likewise, the power supply and protection modules are key to low-carbon design, design of the power supply module will have direct effects on energy consumption; traditional lithium battery is not only highly power-consuming, but also causes environmental pollution due to discarded batteries. whereas energy saving solutions such as solar, kinetic self-powering system enable the low carbon operation.

3.3. Optimal approach points for helmet functional design under the low-carbon concept

According to the concept of low-carbon, the priority direction for optimizing the function of helmets is the improvement of materials system towards low carbonization and replacement of conventional high-carbon, difficult to recycle items with environmentally friendly substitutes like bio-based material, recycled plastic, and light-weight carbon fiber, which can be used for helmet shells, helmet linings or housing of smart components. Without loss in materials’ strength and protection capabilities, this strategy lowers CO₂ footprint of manufacturing and facilitates recycling. The materials should be selected to satisfy the functionality, ensuring low carbon material meets the requirement for installation of smart components and protection functions. The low carbon optimization of technical selection and functional structure is an important breakthrough, low power, smart technologies with reduced power consumption (e.g., low power sensors, low power chips, Bluetooth 5.0). Moreover, designing smart early warning system to reduce operating power requirements.

At the same time, with integrated functional design, many smart functions are combined in one module, reducing component numbers and material consumption and energy use; furthermore, the low carbon upgrading of the power supply

system is an important access channel, by developing energy-saving power supplies such as solar-assisted and kinetic self-powering. Coupled by high capacity, low power consumption batteries, the helmet power supply may save energy and reduce carbon emission without increasing dependence on conventional energy supplies.

4. Functional design of an intelligent early-warning safety helmet for achieving the dual carbon goals

4.1. Architectural design of low-carbon intelligent perception and early warning function

The configuration of the low-carbon intelligent perception and early warning system adopts the three-layer structure composed of low-power sensing layer, an energy-efficient communication layer and a light-weighted processing layer". The perception layer uses low power elements like infrared sensors, temperature/humidity sensors and displacement sensors that are spread out on the helmet shell and lining for accurate detection of dangerous environment and operators' status. The sensors run in intermittent mode, going into a sleep mode whenever there's no need of monitoring in order not to consume too much power. Transmission layer relies on the use of low-power Bluetooth and loRa communication technology, which are both suitable for short-range, energy-efficient communication to address the high energy consumption of conventional communications. Lightweight analysis layer includes an ultra-lightweight, energy-efficient microprocessor including hazard warning algorithms capable of performing in real-time, lightweight processing on the perception layer's data, quickly detecting dangerous signals, and sending an alert before the entire dataset is transmitted outside of a platform, thus saving power for transmitting data.

4.2. Module design of the energy-saving intelligent interactive early warning function

The low-power smart interactive alarm system has three basic functions, namely, the visual and auditory alarm function, voice interaction module, and one-touch call module. Each of these modules has power saving design for low-power working in the alert mode. Audio-visual module replaced conventional high power alarm device by low power LED indicator and small size energy efficient buzzer. The LED lights have brightness adaptive adjusting function according to the environmental illumination condition, while the alarms use a hierarchical alarm strategy based on urgency of danger which is also energy efficient and does not delay emergency alerts. Voice interface includes an energy efficient microphone for voice command capability, alarm activation, and communication functions. In case of idle operation, it sleeps to reduce the standby power consumption, while the improved speech recognition algorithm can improve the speed of operation, reduce power consumption on chips ^[3]. One-button dialing function uses a low power wake-up circuit which is activated when it is pressed, paired with a low power communications module to allow immediate distress signal transmission and position reporting on demand.

4.3. Integrated design of lightweight intelligent protection and early warning function

Lightweight intelligent protection and early warning function integration, that is the combination of traditional passive protection and intelligent active warning, through structure optimization and material lightweight, the helmet manages to reduce its weight as well as CO₂ emission, without compromising on its protective properties: in this case, the protective cover has been designed with a two-layered construction consisting of a 'lightweight carbon-fiber-reinforced plastic outer shell' over a 'foam padding inner layer', providing anti-shock function, puncture-proof performance and carbon-free characteristics, and the inner layer is composed of honeycomb structural eco-friendly sponge which can effectively improve the shock absorption capacity under the premise of reducing raw materials consumption, which contributes further to the light-weight concept. The intelligent warning system combines collision detection, fall detection, and high voltage alarm functions in the form of a protective system with sensors and alarm units integrated inside the space between casing and interior cladding, without extra thickness or mass while also realizing an inseparable combination of safety and alarm function.

Meanwhile, the whole structure of the helmet is optimized as a streamline shape for reducing air resistance and

suitable for high altitude operation. Its integrated structural design reduces the number of connection parts, improving structural integrity and minimizing material wastage; as well as optimizing wearing comfort by increasing the helmet's conformity with a better fit and increased ventilation whilst keeping it light for an improved end-user experience.

5. Implementation and assurance of the design for intelligent early-warning safety helmets under the dual carbon goals

5.1. Selection of low-carbon and environmentally friendly materials for helmet functional components

The use of low-carbon environmental materials as a choice in the functional parts of helmets should follow the principle of “performance matching, low-carbon first, economy applicable”, utilizing differential low carbon material based on different function needs. The outer shell of the helmet, as main safety structure is produced out of a carbon fiber-reinforced polylactic acid composite, offering high strength, light weight, and biodegradability—in place of traditional high-carbon ABS engineering plastic materials, greatly reducing carbon dioxide emissions during production. The interior is composed of a biodegradable soy-based memory foam material combined with an air-permeable recycled polyester fiber fabric, ensures best cushioning and breathable property, as well as improved recyclable property of materials. The smart component housing is made from recycled polycarbonate material, provides wear and interference immunity according to the protection requirements of the sensor/chips and has much less carbon emission compared with that of the raw material. The casing for the power module uses light-weighted recycled aluminum alloy, combining thermal conductance and protection function for material recycle.

In terms of key intelligent parts like sensors and chips, it is necessary to select products that are packaged using degradable bio-based materials in order to reduce the difficulty of later recycling; In addition, material choice needs to conform to the low-carbon principle of the supply chain, preferring local low-carbon material suppliers in order to reduce carbon emissions from material transportation, and realizing a low-carbon use of materials across their whole life cycle.

5.2. Integrated application of low-energy technologies in helmet early warning functions

The joint use of these low-level techniques for the development of a helmet-based early warning system must address four main blocks: perception, perception, transmission, analysis and power supply for overall energy efficient and low carbon. In perception stage, low power consumption as it uses MEMS (micro-electro-mechanical system) sensors rather than the conventional high-power sensors with a small form factor, low power utilization, and high accuracy, which satisfy light weight and energy saving of the helmet. Furthermore, sensor sleep technology for intermittent data collection to reduce power consumption in the perception cycle; and low power wireless communications technology in the transmission phase, combining the Bluetooth 5.3 with LoRaWAN for enabling low power data transmission at a short and medium distance range by reducing the amount of energy consumed in transferring the data. Light weight edge computation is used in the analyzing stage, using hazard alert algorithms at a local level (i.e., within the local processor of the helmet) in order to lighten and reduce the energy consumed by data transfer to the Cloud, as well as considering some optimization methods to improve the efficiency of these algorithms; accelerate analysis time, and reduce processor active power^[4].

Whereas kinetic energy generators are integrated into the helmet liner and transform the energy from worker's head motions into electric power. Together with low-power lithium batteries, this system allows the helmet to become a self-powered device as well as an efficient source of electrical power.

5.3. Construction of an evaluation system for helmet design with functional and low-carbon synergy

To construct the performance evaluation index system of functional integration type low carbon design in helmet design based on “functional indices”, “low-carbon indices” and “overall indices”. All the indexes are set with corresponding measurable appraisal standards in order to comprehensively and scientifically appraise the idea for helmets' designs. The

functional indexes include basic ones like protection efficiency, the precision of the early warning capability, timeliness of a response, and ease of use according to nationally accepted or industry standard criteria, such as, protective level based on the national standard “Head Protection: Safety Hats”, but sets some explicit value standards for early warning precision, reaction time in order to guarantee basic functions of safety helmets can satisfy actual needs; low-carbon indexes include material carbon footprint, production energy use, operation energy use, and recycle rate. The material carbon emission quantifies the carbon emissions of component manufacturing process; production energy consumption quantifies the energy use for manufacture; operational energy consumption captures the whole life cycle energy use; and recycling rates assess the recyclability of components, all with well-defined low carbon thresholds.

The overall evaluation index includes the aspects of technical feasibility, economical cost and wearing comfort, balancing between how well the design solution is feasible and applicable in reality. The evaluation method uses 100 points as a score, where functional indicator and low-carbon indicator account for 40 points respectively; the comprehensive index accounts for 20 points. According to the score result, we optimize the design solution to achieve a synergetic optimization between function and low carbon.

6. Epilogue

With the guidance of the dual-carbon goal, taking intelligent early-warning safety helmet as the research object in this paper, systematically studies the function design and low carbon integration of intelligent construction safety facilities, clarifies the design requirements of intelligent construction safety facilities under the background of dual carbon, identifies the inherent relations among the helmet’s core functions and its low-carbon designing principles, and realizes the low-carbon implementation of the three major functions perception based warning, interactive warning, and protective warning. The work also presents an extensive application scheme including materials selection, technological integration and evaluation system. This paper realizes the deep combination of intelligent early-warning ability with low-carbon idea, providing practical and specific ideas to solve the low-carbon and intelligent design problems of intelligent construction safety facilities.

Disclosure statement

The authors declare no conflict of interest.

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