System Architecture and Key Technologies for the Whole Life Cycle of Smart Road

Zhen Liu1,a, Xingyu Gu1,*b, Yihan Chen1,c, Yizheng Chen1,d

1Department of Road Engineering, School of Transportation, Southeast University, Nanjing, China
a230208344@seu.edu.cn, b* Corresponding author: guxingyu1976@seu.edu.cn, cychchen99@foxmail.com, dyyzseu@163.com

Abstract. Aimed at the "smart individual" of the road, the functional and performance requirements in the process of Planning, Construction, and Maintenance for the whole life cycle of Smart Road is analyzed. Next, BIM, GIS, IoT, Big Data and AI and other advanced information technologies are integrating these technologies into the life-cycle management of smart road in this paper. Therefore, the "three-layer" logical architecture model is conducted. Then, according to the knowledge of Bionics, Smart Road is compared to a smart individual. The critical technologies needed for the SR life cycle system are analyzed based on the key elements required for the growth and development of intelligent individuals. Finally, the implementation scheme and process are analyzed in detail, which provides a reference for future SRs researchers.

1. Introduction
With the continuous development of smart cities and smart buildings, the level of intelligence in the field of transportation infrastructure is gradually improving. Smart Road is based on the evolution of a series of concepts such as Automated Highway Systems [1], Intelligent Vehicle Initiative [2] and Intelligent Transport System [3]. It is a new concept and new form of road in the information age.

The exploration of smart road abroad has been launched for a long time, and it plays an important role in traffic safety, congestion control, and environmental protection. As shown in Fig. 1: The first section of "Europe E4" smart road opened in Sweden, using solar sensors to provide early warning of road icing and traffic jams, reflecting the functions of environmental intelligent perception and self-adaptation. Sweden launched the "eRoad Arlanda" project and built the world's first "charging road" [4]. In the 1970s, the experimental "Drive Wanda Highway" built by the United States in Los Angeles realized the functions of early warning and feedback decision-making of traffic conditions through vehicle positioning and camera acquisition technology [5]. The United Kingdom, Japan, the Netherlands and other countries have also carried out research and practice on smart roads [6]. They use sensor technology, information technology and smart facilities to continuously expand the functional areas of smart roads according to their needs. At present, representative examples include the American "Smart Traveler" project [7], the Japanese "Smart-way" project [8], and the Dutch "Smart In-Car" project [9].
Figure 1: Application and implementation comparison at home and abroad of Smart Roads

Chongqing (for the first time in China) [10], Zhejiang, Changzhou, Yunnan and other provinces have taken the lead in the construction of smart roads in China. With the advancement of the strategy of strengthening the transportation country, the government has successively issued policy documents to support it [11]. In 2018, the "Notice on Accelerating the Promotion of a New Generation of National Traffic Control Network and Smart Highway Pilots" clearly stated that it is necessary to implement big data traffic control networks, collaborative integration of people, vehicles and roads, and digital construction management for several provinces and cities. Preliminary results have been achieved: Daxing Airport's "anti-icing and snow-melting" highway built this year, Jiangsu Middle Road Project and Southeast University jointly developed new technologies for active traffic emergency lane management and control.

At present, countries in the world have not yet defined a clear definition and standard system for smart roads, and only Chongqing City in my country has proposed a framework for the construction of smart roads [12-13]. The construction experience of developed countries shows that the construction of smart roads cannot be separated from the intelligentization of transportation infrastructure, management, decision-making and services. At the same time, the smart road is a huge multi-discipline and multi-technology integration systemic project, and it is still a long way from being completed in the sense of complete functions [14].

From the perspective of highway "intelligent individuals", this paper studies the functional requirements and key technologies of the whole life cycle process of its design, construction, and maintenance. Many advanced information technologies such as BIM, GIS, Internet of Things, big data, cloud computing and artificial intelligence are integrated into the life cycle management of smart highways. A "three-tier" logic is proposed (perception layer→communication layer→decision layer) based on the overall functional and performance requirements of smart highways. Moreover, the five-part subsystem composition and key technologies of the individual are studied by comparing the smart road to a biological individual, which provides a reference for future research on the intelligent road.

2. Design for System Architecture of Smart Road

Through summarizing the construction experience of smart roads at home and abroad, the smart road system studied in this paper aims to meet the basic requirements of durability, safety, reliability and economy. Aiming at the current lack of smart road management for its own construction life cycle, the research is based on advanced the smart road system framework integrated with information technology determines the functions and performance requirements of the smart road in the planning, design, construction, maintenance, operation and maintenance process, and analyzes the logical structure mode of the smart road data information in combination with the processing of data information flow.

2.1. Analysis of functional requirements

Based on the above summary of the practical exploration of representative smart roads at home and abroad, combined with the system integrity characteristics of smart roads, the specific functional requirements of smart roads were analyzed as shown in Table 1.
Table. 1 functional requirements of smart road

| Function modules of Smart Road | Concrete function connotations |
|--------------------------------|--------------------------------|
| Intelligent design and Scheme optimization | Remote sensing image spatial data, spatial analysis based on GIS |
|                                  | Display of detail information based on BIM |
|                                  | Comprehensive scheme and optimization decision with integrate all information |
| Intelligent building and Construction control | Smart materials: self-aware, environmentally adaptive paving materials |
|                                  | Intelligent building: the integrated pavement assembly process |
|                                  | Intelligent construction: intelligent construction machinery and technology |
|                                  | Smart site: Information control platform integrating people, materials and machines |
| Intelligent perception and Sensing monitoring | Intelligent perception: health state detection based on rapid nondestructive testing |
|                                  | wireless sensing: performance detection of wireless self-induction sensing |
|                                  | Multi-source data fusion and transmission |
| Intelligent maintenance and Operation management | Road big data: data management of the whole life cycle |
|                                  | Intelligent maintenance: pavement performance prediction based on data Mining |
|                                  | Intelligent operation: comprehensive analysis based on expert experience and AI |
| Environmental intelligence and Green Power | Photovoltaic corridor system: Solar energy utilization, pavement performance improvement |

2.2. Analysis of performance requirements

The smart road life cycle management system needs to process the perception, analysis and response of the key data information of the highway core system in order to provide managers with an accurate, real-time and intuitive grasp of the road's own conditions. Therefore, the performance requirements of the perspective of system data were described in Fig. 2.
2.3. Logic structure of system

Based on the analysis of the functional requirements and performance requirements of the smart highway system, a three-tier logical architecture model of the smart highway was established as shown in Fig. 3, according to "perception layer → communication layer → decision-making layer".

![Figure 3: Schematic diagram for the whole life cycle of Smart Road](image1)

- **Perception layer**: According to the requirements of system acquisition accuracy, the basic function of "measurable and visible" for smart road was realized by using high-precision positioning equipment, road surface performance and environmental detection sensors, drones, etc., combined with advanced technologies such as three-dimensional laser scanning, remote sensing measurement, ground penetrating radar, and ultrasound, which could conduct the comprehensive perception layer of information.

- **Communication layer**: Based on the perception layer data and combined with the basic information of highway periodic inspection records (planning and design data, performance inspection, maintenance and repair records, etc.), preliminary data files were obtained after multi-source data fusion processing. Then, a smart road database integration platform was built based on big data, blockchain and cloud computing technologies to realize the efficient and safe management, storage and calculation of smart road data.

- **Decision layer**: Based on the data analysis and calculation results of the communication layer, the comprehensive analysis and decision-making system for smart roads is formed [15] by using artificial intelligence decision tree technology and combining the experience of actual field experts.

Based on the three-tier architecture model of system data and combined with the requirements of life cycle management of smart roads, the concept of smart road system was demonstrated based on life cycle management in Figure 4.

![Figure 4: Logical architecture pattern of Smart Road](image2)

3. Research for the key Technologies of Smart Road

Combining the knowledge of "bionics", the smart road is analogous to the "intelligent individual". The growth and development of the intelligent individual is closely related to its own limbs, brain, heart,
nerve, immunity and other important organs or systems [16]. Analyzing the life cycle process of smart road for reference, the basic capabilities and corresponding system key technologies that "smart road individuals" need to possess was listed in Table 2.

Table 2: Individual basic ability of smart road and key technologies of system

| Biological elements | The ability of smart road individuals | Smart road system key technologies |
|---------------------|--------------------------------------|-----------------------------------|
| Brain               | Intelligent design and Scheme optimization | Intelligent design and decision optimization based on BIM, GIS and remote sensing technology |
| Limb muscle         | Intelligent building and Construction control | Intelligent construction and construction control based on IoT and big data |
| Nervous system      | Intelligent perception and Sensing monitoring | Intelligent perception and detection sensing based on omni-directional wireless self-sense |
| Immune protection   | Intelligent maintenance and Operation management | Intelligent maintenance and maintenance management based on big data and artificial intelligence |
| Heart               | Environmental intelligence and Green Power | Intelligent environmental protection and green power based on photovoltaic corridor system |

3.1. Intelligent design and decision optimization based on BIM, GIS and remote sensing technology

Under the background of the Industry 4.0 era, with the gradual development of GIS technology in the direction of 3D modeling, BIM, GIS and the integration technology of the two have gradually been widely used in the field of transportation infrastructure [17-18], and their combination with BIM technology will represent the prospect of the smart road design industry from 2D to 3D. The powerful spatial analysis capabilities of GIS combined with remote sensing image data collection and recognition can obtain high-precision geographic spatial reference maps [19]. Three-dimensional GIS technology can also provide geographic information on a macro scale, provide spatial query and analysis functions for BIM models, and achieve the improvement of design accuracy and decision-making science [20], as shown in Fig. 5. At the same time, the BIM model would also present GIS micro view as an intuitive data information model [21], and the integrated use of the two realizes the scientific and precise design of smart roads, the simulation deduction of schemes, and the optimization of comparison and selection decisions.

3.2. Intelligent construction and construction control based on IoT and big data

The construction of smart roads includes people, material, machine and other aspects, and new concepts such as smart construction sites, smart materials and smart construction have emerged [22]. In the
construction of smart roads, considering the management and control content of human, material, and machinery, and the functional concepts of smart construction sites, smart construction, and smart materials was combined by using advanced technologies such as the Internet of Things, big data, RFID and video analysis. The intelligent construction and construction management and control system was established based on the Internet of Things and big data to realize intelligent and real-time monitoring and management in construction projects in Fig. 6.

![Figure 6: Intelligent control system of smart road construction](image)

**3.3. Intelligent perception and detection sensing based on omni-directional wireless self-sense**

Smart perception and detection sensing are the functional basis of the underlying smart road perception. The sensory system needs to rely on advanced detection technology, sensor technology and data acquisition and fusion processing technology. Its data mainly comes from two parts:

- Road intelligence perception based on rapid nondestructive testing: the road surface condition quality information monitored by rapid nondestructive testing equipment (such as 3D laser scanning [23]) and the road interior quality condition information detected by ground-penetrating radar ultrasonic wave.
- Detection sensor based on omni-directional wireless self-induction: The technical parameters of road periodic quality are detected by embedding new-type wireless self-induction sensors of temperature, humidity, and stress and strain [24].

![Figure 7: Structure form smart road sensing sensor system](image)

**3.4. Intelligent maintenance and maintenance management based on big data and artificial intelligence**

All kinds of information in the whole life cycle of smart road construction need to be combined with big data technology to establish a data information database, and comprehensive analysis based on big
data mining, artificial intelligence, deep learning and other technologies: based on the original performance genes of the road and combined with data mining analysis technology for road foundation Prediction of the development law of facility performance [26], intelligent recognition based on machine learning [27] combined with artificial intelligence decision analysis for road maintenance decision-making and operation and maintenance management, as shown in Fig. 8.

![Figure 8](image)

**Figure 8** Intelligent maintenance and operation based on big data and AI

### 3.5. Intelligent environmental protection and green power based on photovoltaic corridor system

- The photovoltaic corridor system of the smart road was shown in Fig. 9 based on photovoltaic power generation (Photovoltaic power generation) [28], Resonant inductive coupling (Resonant inductive coupling) [29] and Wireless Power Transmission (WPT) cars [30]. The technologically efficient and environmentally friendly energy system assumes the role of the "power heart" of the entire smart road.

![Figure 9](image)

**Figure 9** Schematic diagram of operation mechanism for photovoltaic corridor system of smart road

- The photovoltaic corridor system has the following functions for the construction and improvement of smart roads:
  - Improvement of road performance and driving safety: significantly reduce road temperature, improve temperature load stress, slow down rutting; reduce road drainage design difficulty, reduce water damage; solve winter road area snow, icing, and snow removal problems, and reduce...

![Figure 10](image)

**Figure 10** Comparison of road temperature between ordinary asphalt pavement and photovoltaic system (left - road surface, right - middle)
road material freezing and thawing damage, improve the driving environment, etc. An example of a certain expressway section in Jiangsu Province was shown in Fig. 10. The temperature of the road surface and the middle of the asphalt layer in a year (a set of data is measured every 12 hours) and the temperature of the photovoltaic system are compared. The photovoltaic corridor system can be seen significant improvement in road surface and middle temperature (especially obvious in the high temperature in summer and the highest temperature at 2-4 pm every day).

- Environmental protection and energy utilization: On the one hand, the use of wireless charging cars and solar energy basically eliminates automobile exhaust emissions; on the other hand, the construction of photovoltaic corridors greatly reduces the cost of road maintenance and management [31]. At the same time, the power supply of photovoltaic power generation system mobile phones can be used for vehicles and equipment, road infrastructure and national power grid, which is of great significance to energy conservation and environmental protection.

4. Conclusions and Prospects

Combining the use of domestic and foreign construction experience, advanced information technology and various interdisciplinary knowledge, a whole life cycle-based smart road system architecture was established and the key technologies required for the realization was analyzed in this paper as following:

- The functional requirements and performance requirements of the entire life cycle of the smart road were analyzed. Based on this, a three-tier logical architecture system for the life cycle of the smart road of “perception layer→communication layer→decision-making layer” was proposed, and the specific process of data collection, transmission and decision-making in smart road was established.

- By analogizing to the basic biological elements of bionics, the subsystems and key technologies of the life cycle of the smart road were analyzed, and each subsystem was elaborated to build solutions using various advanced technologies.

- Aimed at the proposed smart road photovoltaic corridor system, taking a section of the highway in Jiangsu Province as an example, the conclusion that the photovoltaic system has played a good role in improving the road temperature environment is deduced based on the monitored and statistical road temperature data.

Based on the road itself, this article discusses the development model of smart roads. In the future, the construction of smart roads would inevitably be embedded in intelligent transportation systems and smart city systems along with more advanced information technology and various interdisciplinary disciplines. This could further enrich the development connotation of transportation, promote the improvement of the service level of the modern transportation system, and promote the intelligent transformation of cities. At the same time, these will also require policies and standards, science and technology, public consciousness in the constant exploration and practice to be finally realized.

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