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The Function of the Embedded Intelligence in the Family Ecological System: The Coexistence and Sustainable Development Research of Sensors and Actuators

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Abstract. Because of the techniques' rapid fusion, mechatronics has already become an inevitable societal tendency in the family environment. This paper mainly studies the microcomputer controlling technique of the embedded system of household appliances, emphatically analyzing the coexistence working mechanism between sensors and actuators. The research purpose is to evaluate these systems' technique mechanism and societal value of the aspect of promoting health, industry innovation and sustainable possibility within the framework of the sustainable development purpose of the United Nations. This study adopted the methods of literature analysis and comparative analysis. The research subjects were the hardcore architectures in contemporary smart household appliances. The research data mainly originated from global academic databases and the technical specifications of related equipment. The study found that the high-precision feedback loop constructed by sensors and actuators in coordination is the foundation for maintaining a healthy indoor environment and optimizing energy consumption. This paper discovered that embedded intelligence is a technological advancement and also a key driving force for achieving sustainable development. Through extending the lifespan of devices and reducing ecological footprints, these integrated systems provide a solid hardware foundation for future sustainable communities.

Keywords: Mechatronics, Embedded Systems, Sustainable Development, Sensors

1. Introduction

Mechatronics is the deep fusion product of Mechanical Engineering, Electronic Technology and Information Science. It has already become the core driving force of the evolution of contemporary intelligent household appliances. The embedded system utilizes microcomputer control technology to efficiently convert the multidimensional environmental signals sensed by sensors into precise actions of actuators. Eventually, it forms the "hardware core" of the smart home ecosystem.

Although the current digital transformation index indicates that the process of enterprise reconfiguration is continuously advancing globally, and digital technology has demonstrated significant enabling value in industrial innovation, there are still research gaps that need to be filled

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regarding how the underlying hardware of household appliances can precisely match the United Nations Sustainable Development Goals through the collaboration of sensors and actuators.

The motivation for this research stems from the excessive emphasis on artificial intelligence software algorithms in the current academic community. It aims to re-examine the fundamental value of the feedback mechanism of the underlying hardware in ensuring public health and optimizing system energy efficiency.

This paper specifically explores the hardware coordination logic based on microcomputer control, as well as the practical paths and potential challenges of this logic in the research framework of health well-being, industrial innovation, and sustainable development.

This research mainly adopts the methods of literature analysis and comparative analysis, and deeply deconstructs the technical architecture and social output of contemporary typical smart household appliances.

The significance of this paper is to provide independent, innovative ideas for the green energy efficiency revolution in the household appliance industry. This paper also provides valuable theoretical support and practical guidance for future researchers in exploring the balance point between technological evolution and social responsibility.

2. The hardware support of the coexistence system of sensors and actuators

The collaborative efficiency of the mechatronic system depends on the quality of individual components, as well as on the seamless coupling between software and hardware. In the embedded architecture, the microcomputer acts as the dynamic decision-making center from perception to response [1,2]. The core lies in converting the analog signals of the physical world into manageable digital logic.

2.1. Precision of the environmental feedback loop

The perception of the environment by modern intelligent household appliances has shifted from simple analog signals to high-resolution digital descriptions. By utilizing digital sensors with up to 32-bit precision, the system can capture minute physical changes (such as 0.01mm edge displacement or extremely low concentrations of gas components). This digital leap is reflected in the increase in bit depth, also resulting in a significant reduction of the inevitable electromagnetic noise interference in traditional analog circuits. By enabling the system to capture components such as trace amounts of cooking oil components or extremely subtle pressure changes.

This precision is achieved through closed-loop control algorithms (such as Proportional-Integral-Derivative) or fuzzy logic control, ensuring that the system can continuously correct execution deviations based on real-time feedback.

At the control level, the introduction of fuzzy logic gives hardware a kind of "perceptual intelligence" similar to that of human experts. Unlike traditional Proportional-Integral-Derivative(PID), which relies on strict mathematical modeling, fuzzy PID can convert natural language logic, such as "temperature is too high" or "response lag," into dynamic adjustment control parameters. This "gain scheduling" mechanism allows microcomputers to optimize the proportional, integral, and derivative terms in real-time during system operation. It also effectively counteracts common hysteresis phenomena in household appliances (such as the residual heat effect of electric heating elements after power-off or the transmission gap of mechanical structures). This deep coupling of hardware and software enhances the robustness of the control system, enabling household appliances to maintain nearly perfect execution trajectories. And when the deep coupling

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of hardware and software faces dynamic and unpredictable, non-modelable household environments, it fundamentally provides precise underlying logic support for sustainable energy efficiency management.

Studies have shown that fuzzy PID control models have better adaptability and shorter adjustment times when dealing with complex and nonlinear environments [3].

2.2. Real-time execution control of physiological comfort

Human-centered hardware control focuses on physical parameters and physiological sensations. By integrating micro-electromechanical system microphones, inertial sensors, and pressure sensors, household appliances and wearable devices can monitor physiological indicators. The physiological indicators are usually the heart rate, respiratory rate, and chewing habits in real time. The microcomputer uses the predicted average voting index as feedback for the air conditioning system. Predicted Mean Vote (PMV) is a thermal comfort scoring system. And the PMV considers temperature, humidity, wind speed, and human metabolic rate comprehensively. The embedded system can predict the comfort level of the user by using the artificial neural network model (ANN). The embedded system works in the current environment and adjusts the actions of the actuators (such as variable-frequency fans or heating elements) automatically. This transformation from "passive response to instructions" to "active prediction of demands" enhances the living experience, reducing unnecessary energy waste through precise control, thereby adjusting the actions of the actuators and maintaining the optimal physiological comfort range dynamically [4].

2.3. Soft and hardware co-design for error reduction

To reduce system complexity, the concurrent development of software and hardware (i.e., "collaborative design") has become an industry standard. This approach emphasizes considering the running efficiency of software algorithms at the hardware selection stage to achieve the optimal balance of performance, cost, and power consumption. For example, in complex sensor fusion scenarios, the algorithm needs to process data from multiple channels simultaneously. Any minor synchronization delay can lead to execution deviations. By integrating specialized processing units (such as lightweight machine learning models) at the chip level, the system can quickly compensate for the nonlinear drift of sensors locally without relying on cloud processing.

This collaboration is not merely the physical stacking of components, but rather a deep integration at the abstract level of the system. As the traditional Moore's Law progresses and slows down, the clear boundaries between hardware and software that once existed are rapidly disappearing. Instead, a full-stack collaborative thinking is taking its place. In this model, developers no longer view hardware as a universal, static platform, but instead customize dedicated instruction sets or heterogeneous computing units based on specific application loads (such as complex smart home logic reasoning). This heterogeneous architecture can intelligently allocate computing loads through software-defined hardware orchestration. Thus, this architecture is achieving millisecond-level real-time decision-making responses while maintaining ultra-low power consumption. The maturity of software-hardware co-verification technology enables systems to complete rigorous reliability assessments in the simulation environment before physical prototype manufacturing. This full lifecycle collaborative logic ensures absolute accuracy in executing instructions. And the logic that has an intact lifecycle can significantly improve the stability and durability of the system in extreme environments. And the methods we can use are reducing computational redundancy and heat loss, demonstrating the resilience of electromechanical integration at the hardware level. It can

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be shown that the software and the hardware need to coexist so that they could diminish the programming errors.

3. Electromechanical integration optimization of sensors and actuators in sustainable development research

Sustainability has evolved from a slogan to a hard requirement in mechanical and electrical design. Through integration optimization, the electromechanical system can achieve long-term operation in resource-constrained environments.

3.1. Enhancing efficiency through microcomputer control strategies

Microcomputer control strategies are crucial for reducing the energy consumption of household appliances throughout their entire lifecycle. By employing dynamic voltage and frequency adjustment technology, the system can optimize the power consumption of the processor in real time based on the task load. In intelligent buildings and Heating, Ventilation and Air Conditioning systems, AI-driven scheduling algorithms can automatically optimize the operating time based on occupancy rates and price fluctuations. As for the household appliances, it can identify peak electricity usage periods. It can be recognized that the household appliances could operate in a way that avoids these periods automatically. And it can also switch to an extremely low-power standby mode when no one is in the room. Additionally, the real-time energy monitoring feature provides users with transparent data insights, enabling them to identify "power vampires" in their homes and thus cultivate more environmentally friendly electricity usage habits. This kind of self-awareness driven by technology is an important force in promoting society towards a low-carbon model. The real-time energy monitoring function can help users identify and cut off the power consumption of "standby vampires" devices, further optimizing household energy efficiency [5]. To sum up, the microcomputer control strategies, especially for the scheduling algorithms and the real-time energy monitoring function, are showing potential abilities in efficiency.

3.2. Modular structure and long-life design of actuators

The "Eco-mechatronics" concept emphasizes the durability and recyclability of products. Through modular design, key mechanical components such as actuators can be easily disassembled and replaced like building blocks. This means that when a motor breaks down, the user only needs to replace the specific module instead of discarding the entire appliance. Thus, it can be significantly reducing the generation of electronic waste. At the same time, the "predictive maintenance" technology based on sensors is becoming a new standard for household appliances. By monitoring the vibration frequency, current fluctuations, and operating temperature of the actuators in real time, the microcomputer can issue a maintenance alert to the user several weeks before a fault occurs [6]. According to the statistics, this preventive intervention can reduce maintenance costs by 40% compared to traditional maintenance methods and increase equipment lifespan by nearly twice. Consequently, the design of modular and "predictive maintenance" is playing essential effect on the running of the actuators.

3.3. Human-centered automation integration in smart cities

At the macro scale, the sensor network of individual household appliances is evolving into a "city nervous system". Smart meters, water meters, and sensor nodes achieve cross-departmental data interconnection through open Application Programming Interfaces, creating a "digital twin" image of the city [7]. This integration optimization improves the efficiency of resource allocation (such as Columbus reducing 15% of emergency response time by using connected vehicle technology). It also ensures that technological development always focuses on improving the quality of life of residents, achieving a true "humanistic intelligent city".

This system generates approximately 2.5 quintillion bytes of real-time data streams every day, covering various dimensions ranging from micro-level household energy efficiency to macro-level traffic fluctuations. The digital twin is no longer a static 3D display model but a dynamic simulation environment with high fidelity. And the digital twin is enabling managers to conduct stress tests for energy scheduling or disaster response before deployment. The behavioral data of household appliances can even be transformed into community-level social care under the deeply integrated ecosystem. For instance, by monitoring the operation patterns of elderly people living alone, the system can intelligently identify falls or sudden health crises and immediately link to medical resources. This shift from a "technology-centered" approach to a "human-centered" one depends on the interoperability of hardware. And at the same time, it also requires the establishment of a strict governance framework to ensure data privacy and digital equity. Therefore, we can learn that it is necessary to locate the human-centered automation integration in the cities.

4. Conclusion

This paper systematically discusses the integrated application of mechatronic systems in household appliances. And it particularly discuss about the core pivotal role played by the microcomputer control system. This research concentrates on analyzing how the software and hardware collaboration between sensors and actuators becomes a key mechanism for promoting the transformation of household life towards intelligence and sustainability under the framework of the United Nations' Sustainable Development Goals.

This paper mainly focuses on the qualitative analysis of the technical architecture and the construction of the theoretical framework. However, it has not yet conducted a detailed quantitative assessment (such as Life Cycle Assessment, LCA) of the environmental impact of specific electronic components throughout their entire production and disposal lifecycle.

Looking ahead, future research should transition toward affective computing, enabling embedded systems to decode human emotional states through non-invasive physiological sensors for proactive, empathetic interaction. Integrating self-healing polymers and modular "eco-mechatronics" design will play an imperative role in supporting a circular economy. Both of them are extending device longevity and curbing electronic waste so that they can achieve it. These interdisciplinary subjects will ultimately narrow the gap between technical precision and human-centric values, ensuring that the next generation of smart homes is both ethically robust and environmentally sustainable.

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