Sensors and Materials, Vol. 38, No. 4 (2026) 2245–2254
MYU Tokyo

S & M 4434

Sensing Technologies and Hardware Requirements for Health and Safety Monitoring of Pets Using IoT Microchips: Fuzzy Analytic Hierarchy Process-based Evaluation

Qi Wang,[1,2] Hsin-Hung Lin,[2,3,4*] Hwee-Ling Siek,[2] and Wang Siyuan[2]

[1]Academy of Fine Arts, Yanbian University, Yanji 133002, China
[2]Department Institute of Creative Arts and Design, UCSI University, Kuala Lumpur 56000, Malaysia
[3]Department of Creative Product Design, Asia University, 500, Lioufeng Rd., Wufeng, Taichung 41354, Taiwan
[4]Meizhouwan Vocational Technology College, Wutang, Putian 0594-7692626, China

(Received January 29, 2026; accepted April 13, 2026)

Keywords: fuzzy AHP, NFC-enabled IoT, health management, sensor-integrated microchip, pet care system

As pet care systems evolve from simple identification tags into sophisticated IoT-enabled networks, current near-field communication (NFC) microchip-based pet care systems face challenges related to interoperability, limited sensing capabilities, and fragmented data management. Therefore, for improving the pet care system, the technical requirements and functional design criteria were examined for a sensor-integrated, NFC-enabled IoT pet microchip application in this study. Using the fuzzy analytic hierarchy process, 32 experts from veterinary medicine, IoT engineering, and user experience design evaluated a three-level hierarchy comprising 6 criteria and 24 subcriteria. The results reveal that health management is the most significant dimension [a weight (w) of 0.1724], followed by identification and registration (w = 0.1690), underscoring a shift from basic tracking to active medical monitoring. At the subcriteria level, controlled medical information sharing showed the highest global weight (w = 0.0465), highlighting the need for owner-authorized secure data exchange. Other important factors include NFC scanning reliability (w = 0.0455), data accuracy and traceability (w = 0.0455), and smartphone operating system/device compatibility (w = 0.0452). The results provide a reference for sensor technology development and propose the integration of biometric sensing, high-stability antenna arrays, and hardware-based encryption modules. An actionable roadmap can be established for developing integrated, trust-centered ecosystems for sustainable smart pet care.

1. Introduction

Smart pet care systems have rapidly evolved, progressing from simple identification tags to sophisticated IoT-enabled networks. These systems extend beyond basic identification to encompass health record management, vaccination reminders, emergency contact maintenance,

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[*] Corresponding author: e-mail: hhlin@asia.edu.tw

https://doi.org/10.18494/SAM6267

and lost-pet reporting. Despite these advances, insufficient interoperability and poorly designed user interfaces continue to limit the effectiveness of near-field communication (NFC)-enabled microchip systems. To realize the potential of IoT-based pet management, critical functions such as health record integration, privacy protection, sensing reliability, and material stability must be addressed.

IoT networks have been increasingly adopted to improve animal identification efficiency and strengthen owner accountability. Within these networks, NFC technology has emerged as a widely used solution, enabling convenient short-range data access through smartphones for identity verification and mobile data retrieval.(1) However, the widespread use of current microchips and devices remains constrained by limited sensing capabilities and material requirements. To advance their utility, microchips must incorporate dynamic physiological monitoring functions, such as subcutaneous temperature measurement and heart rate detection, which depend on reliable sensor design and biocompatible materials.(2)

The effectiveness of microchips relies on accurate registration records and efficient post-scan communication workflows. Evidence shows that microchipped pets often fail to return home owing to incomplete or inaccurate registration data, highlighting the need for improved sensing reliability and workflow integration.(3,4) Developing biocompatible encapsulation materials and optimized sensor-to-tissue interfaces is essential to prevent signal attenuation caused by biological fluids.(5) Beyond sensing reliability, data fragmentation across microchip registries, veterinary databases, shelter systems, and governmental platforms creates silos that hinder update consistency and workflow continuity. Such fragmentation leads to challenges in health information systems, where inconsistent standards and integration difficulties impede effective data exchange.(6)

As NFC adoption expands, cybersecurity risks, including unauthorized reading, relay attacks, and data leakage, have become pressing concerns. Therefore, NFC-based applications require systematic risk assessment and security-aware design to safeguard sensitive biometric data collected by embedded sensors.(7) From a user experience perspective, lengthy registration processes and poorly designed interfaces reduce user acceptance, underscoring the importance of streamlined workflows and intuitive interaction design.

To overcome these challenges, prioritizing sensor functionality and material requirements is required. Next-generation biosensors that integrate NFC technology with advanced physiological monitoring must ensure secure data transmission, reliable sensing, and biocompatibility. In this study, we examine sensor technologies and material innovations for the development of IoT-enabled pet management systems to address such needs. Using a fuzzy analytic hierarchy process (AHP),(8) we assessed the technical requirements for sensors and materials for the design of systems that achieve sensing accuracy, biocompatibility, and hardware-integrated health monitoring.(9) The results of this study provide a basis for advancing sensor technology and material science in the context of smart pet care, contributing to more effective, secure, and integrated management solutions.

2. Methodology

We established an evaluation framework to prioritize design criteria and functional requirements for an NFC-enabled IoT pet microchip application. To address the inherent subjectivity and ambiguity in expert judgments, fuzzy AHP was adopted for multi-criteria decision-making. The research procedure comprised ten steps, categorized into the following four phases.

1. Problem definition and criteria extraction: Gaps in current passive radio frequency identification (RFID)/NFC systems are identified, such as fragmented data management and limited physiological sensing, and key criteria are extracted through a comprehensive literature review.
2. Hierarchical model construction: The decision problem is decomposed into a three-level hierarchy of goal, criteria, and subcriteria.
3. Pairwise evaluation by experts: Thirty-two experts across veterinary medicine, IoT engineering, and user experience design perform linguistic comparisons.
4. Fuzzy computation and prioritization: Fuzzy logic operations are performed to determine normalized weights and generate an actionable technology roadmap.

The decision model was structured into three levels for the analysis of technical performance and user-centric requirements (Table 1).

Table 1
Criteria and subcriteria of decision model constructed in this study.

Criteria	Subcriteria
Identification and registration (C1)	NFC scanning reliability (compatibility across devices, angle, and distance) (S1)
	Registration efficiency (simple steps and low error rate) (S2)
	Data accuracy and traceability (chip ID–owner–pet linkage integrity) (S3)
	Offline access to essential identity information (S4)
Health management (C2)	Completeness of vaccination and medical records (S5)
	Reminder and notification functions (vaccination, medication, check-ups) (S6)
	Controlled medical information sharing (owner-authorized access for veterinarians) (S7)
	Multi-pet profile management (support for households with multiple pets) (S8)
Safety and emergency response (C3)	Lost-pet reporting workflow efficiency (scan → report → contact process) (S9)
	Emergency contact accessibility (quick display, one-tap calling) (S10)
	Anti-theft / misuse prevention (protection against unauthorized data changes) (S11)
	Collaboration support (integration with shelters, volunteers, and community support) (S12)
Security and privacy (C4)	Authorization control (role-based access: owner/vet/third party) (S13)
	Data minimization (limiting exposed personal data during NFC scanning) (S14)
	Data encryption and secure transmission (S15)
	Logging and auditability (tracking reading/modification activities) (S16)
Usability and user experience (C5)	Ease of use and learnability (intuitive operation and low cognitive load) (S17)
	Readability of emergency information display (clarity under urgent conditions) (S18)
	Multi-language and accessibility support (font size, icons, language options) (S19)
	Error tolerance and guidance (clear instructions for failed scans/missing data) (S20)
System and interoperability (C6)	Smartphone operating system (OS)/device compatibility (iOS/Android and NFC standards) (S21)
	Standardized data format and system integration readiness (S22)
	Cloud synchronization reliability (backup and recovery capability) (S23)
	Maintainability and scalability (modularity and long-term expansion) (S24)

1. Level 1 (goal): Design criteria and functional requirements are prioritized for a sensor-integrated NFC-enabled IoT pet microchip application.
2. Level 2 (criteria): Six fundamental dimensions (C1–C6) represent the system domains.
    - C1 (identification and registration): Accuracy of digital identity and registration workflows
    - C2 (health management): Integration of physiological sensing (e.g., thermal and biometric data)
    - C3 (safety and emergency response): Efficiency of lost-pet recovery and emergency accessibility
    - C4 (security and privacy): On-chip encryption and secure data transmission protocols
    - C5 (usability and user experience): Interface intuitiveness and interaction design
    - C6 (system interoperability): Compatibility with biocompatible materials and cross-platform data standards
3. Level 3 (subcriteria): Twenty-four measurable factors (S1–S24) in six criteria are identified to establish a prioritization roadmap.

While AHP requires precise numerical inputs, fuzzy AHP employs triangular fuzzy numbers (TFNs) to capture the uncertainty inherent in human perception. In the method, linguistic variables are mapped to TFNs, which represent the lower bound, modal value, and upper bound. This mapping allows expert opinions expressed during pairwise comparisons to be represented in a way that reflects their inherent imprecision. The determination process for fuzzy AHP weights involves the following mathematical steps to transform expert assessments into normalized crisp weights:(9)

Step 1: Definition of TFNs

Each linguistic judgment is converted into a TFN, represented as $\tilde{M} = (l, m, u)$, where l, m, and u respectively represent the lower, modal, and upper bounds of the relative importance of one criterion over another. The membership function $\mu_{\tilde{M}}(x)$ is defined as

$$\mu_{\tilde{M}}(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m \le x \le u \\ 0. & \text{otherwise} \end{cases} \tag{1}$$

Step 2: Calculation of fuzzy synthetic extent

For each criterion i, the fuzzy synthetic extent value (S_i) is calculated by summing the fuzzy values in each row of the comparison matrix and normalizing them against the sum of the entire matrix.

$$s_i = \sum_{j=1}^{n} \tilde{M}_{i,j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{M}_{i,j} \right]^{-1} \tag{2}$$

Step 3: Comparing fuzzy synthetic extents

To determine the weight of one criterion over another, we calculate the degree of possibility that $S_i \geq S_j$. This is defined as Eq. 3, which expresses the likelihood that S_i is greater than or equal to S_j.

$$V\left(S_i \geq S_j\right) = \begin{cases} 1, & \text{if } m_i \leq x \leq m_j \\ \dfrac{l_j - u_j}{\left(m_i - u_j\right) - \left(m_j - l_j\right)}, & \text{if } l_j \leq u_j \leq m_j \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Step 4: Calculation of weight vector and normalization

The degree of possibility for a fuzzy number S_i to be greater than all other k fuzzy numbers is calculated to find the initial weight $d'(A_i)$.

$$d'\left(A_i\right) = MIN\, V\left(S_i \geq S_j\right) \text{ for } k = 1,\ 2,\ \cdots,\ n;\ \ k \neq i \tag{4}$$

The final weight vector $W' = [d(A_1), d(A_2), \ldots, d(A_n)]$ is obtained by normalizing the weight values so that their sum equals 1.

$$W_i = \frac{d'\left(A_i\right)}{\sum_{i=1}^{n} d'\left(A_i\right)} \tag{5}$$

Here, A_i stands for the ith criterion.

The assessment of 32 experts was integrated to calculate the fuzzy weights using fuzzy geometric mean and the center-of-area defuzzification method. To ensure logical rigor, the consistency of expert evaluations was verified by converting the fuzzy matrices into crisp forms and calculating the consistency ratio. Matrices with a consistency ratio below 0.10 were retained, guaranteeing the reliability of the final priority rankings. To ensure the relevance and technical support, a purposive sampling strategy was used to recruit 32 experts. The experts' experiences include veterinary medicine and animal healthcare (nine experts) with over 10 years of experience in companion animal practice, animal management, and shelter operations (seven experts, directors of animal shelters and municipal animal control officers), and user interface and experience designers (eight experts) with expertise in mobile health applications and IoT interfaces. The average professional experience of the participants exceeded 12 years, ensuring that the pairwise comparisons were based on deep domain-specific knowledge. By balancing technical feasibility (engineering), clinical utility (veterinary), and operational reality (shelter and IT design), the experts' experiences formed a foundation for the fuzzy AHP weight estimation.

3. Results

The weights of criteria for the NFC-enabled IoT pet care system are summarized in Table 2. Health management emerged as the most significant dimension (w = 0.1724), indicating that experts viewed medical and vaccination-oriented services as the most important factor for practical adoption. This finding suggests that the pet care system must transcend basic identification to actively support digital health record continuity and veterinary clinical interactions. Identification and registration presented the second priority (w = 0.1690), implying that hardware-software reliability and accurate identity linkage remain foundational to system trust. Usability and user experience, and system and interoperability showed identical weights (w = 0.1681), underscoring the necessity of intuitive workflows and cross-platform stability to sustain usage. While security and privacy remained a critical concern (w = 0.1644), safety and emergency response received the lowest relative weight (w = 0.1579). This implies that emergency functionalities are important for robust identification and accessible data architectures.

The ranking of the weights of the 24 subcriteria provides information on the functional prioritization of sensors and devices (Table 3). The distribution reveals five important factors: trusted medical exchange, identification reliability, platform robustness, accessibility, and data security. Controlled medical information sharing ranked highest (w = 0.0465), underscoring the importance of owner-authorized access mechanisms that enable secure data transfer between pet owners and veterinarians. NFC scanning reliability and data accuracy and traceability showed w = 0.0455, confirming that signal stability and data integrity form the technical backbone of the system. Smartphone operating system and device compatibility, and the ease of use and learnability (w = 0.0452) highlight the necessity of maintaining low cognitive load across heterogeneous mobile ecosystems. Cloud synchronization, secure transmission, and multi-language support ($w \approx 0.0443$) indicate that long-term viability depends on balancing accessibility with infrastructure security. Overall, the balanced weight distribution suggests that the application must be developed as an integrated ecosystem rather than a discrete identification tool.

The results of the fuzzy AHP analysis show the design requirements of an NFC-enabled IoT pet microchip. Health management and identification reliability are the most critical for the widespread adoption and construction of a trustworthy pet care system, in which functional completeness in medical tracking is matched by platform interoperability and rigorous security protocols.

Table 2
Weights of criteria.

Criteria	Weight	Rank
Health management	0.1724	1
Identification and registration	0.1690	2
Usability and user experience	0.1681	3
System and interoperability	0.1681	3
Security and privacy	0.1644	5
Safety and emergency response	0.1579	6

Table 3
Weights of subcriteria.

Subcriteria	Criteria	Weight	Ranking
Controlled medical information sharing (S7)	C2	0.2699	1
NFC scanning reliability (S1)	C1	0.2692	2
Data accuracy and traceability (S3)	C1	0.2692	2
Smartphone OS/device compatibility (S21)	C6	0.2689	4
Ease of use and learnability (S17)	C5	0.2689	4
Multi-language and accessibility support (S19)	C5	0.2636	6
Data encryption and secure transmission (S15)	C4	0.2695	6
Cloud synchronization reliability (S23)	C6	0.2636	6
Collaboration support (S12)	C3	0.2806	6
Completeness of vaccination/medical records (S5)	C2	0.2571	6
Multi-pet profile management (S8)	C2	0.2502	11
Data minimization (S14)	C4	0.2453	12
Readability of emergency information display (S18)	C5	0.2389	12
Standardized data format and integration readiness (S22)	C6	0.2389	12
Authorization control (S13)	C4	0.2444	13
Registration efficiency (S2)	C1	0.2308	17
Offline access to essential identity information (S4)	C1	0.2308	17
Reminder and notification functions (S6)	C2	0.2226	19
Lost-pet reporting workflow efficiency (S9)	C3	0.2432	19
Anti-theft / misuse prevention (S11)	C3	0.2432	21
Error tolerance and guidance (S20)	C5	0.2285	21
Maintainability and scalability (S24)	C6	0.2285	21
Logging and auditability (S16)	C4	0.2171	24
Emergency contact accessibility (S10)	C3	0.2329	24

4. Discussion

The results of the fuzzy AHP analysis indicate the necessity of the hardware specifications of pet care systems. Current passive identification technologies are insufficient to meet the evolving demands of health management (C2) and controlled medical information sharing. Consequently, the transition from simple RFID to sensor-integrated NFC systems is mandatory. Therefore, the following hardware components are required in new pet care systems:

1. Sensor-integrated NFC microchips
   NFC microchips must be integrated with biometric sensors, such as thermistors for real-time temperature monitoring and biosensors for physiological data acquisition.(10)
2. High-stability antenna arrays
   To ensure NFC scanning reliability (S1), the antenna must be designed to support multi-angle and distance-agnostic coupling to ensure stable signal performance across various animal tissue densities.(11)
3. Encrypted storage modules
   To ensure data encryption and secure transmission (S15), on-chip secure elements or hardware-based encryption modules are necessary to protect controlled medical information sharing (S7) from unauthorized access.

The proposed hardware components enable advancements over existing pet identification systems, as detailed in Table 4.

Table 4
Technical specifications and functional capabilities: conventional RFID and proposed NFC-enabled IoT pet care systems.

Feature	Conventional RFID system	Proposed NFC-enabled IoT system
Operating frequency	Low frequency (125 or 134.2 kHz)	High frequency (13.56 MHz, NFC)
Data interaction	Read-only/basic ID	Read-write/active sensing
Interoperability	Requires specialized scanners	Universal smartphone OS compatibility (S21)
Sensing capability	Nonexistent	Integrated physiological monitoring (C2)
Data architecture	Isolated local database	Cloud synchronization reliability (S23)

While present systems focus primarily on identification and registration (C1), they often fail in usability and user experience (C5) owing to the requirement for proprietary hardware. By adopting NFC standards, the proposed system leverages the existing smartphone infrastructure, reducing the cognitive load and improving the ease of use and learnability (S17) for pet owners.(12) The results of this study contribute to the advancement of sensor technology by transitioning the microchip from a static data carrier to an active health-informatics node. Data accuracy, traceability (S3), and minimization (S14) require a security-by-design framework in veterinary medicine, which has historically lagged behind human healthcare in terms of data protection protocols. The integrated health-service layer proposed facilitates professional veterinary workflows by enabling the completeness of vaccination/medical records (S5). This integration ensures that sensor data are not merely collected but are actionable and accessible for smartphone OS/device compatibility (S21). In addition, collaboration and support (S12) with other platforms must be prioritized to connect shelters, volunteers, and veterinarians into a unified recovery and care system.(13)

The weights and their ranking obtained in this study guide developers and stakeholders for further development of pet care systems and their necessary components.(14) A reliability-centered foundation must be established by ensuring robust NFC scanning reliability (S1) and high-integrity data accuracy and traceability (S3), supported by intuitive error tolerance and guidance (S20) to reduce user friction during emergencies. An integrated health-service layer should incorporate the completeness of vaccination/medical records alongside (S5) controlled medical information sharing (S7), facilitating professional veterinary workflows while maintaining compliance with data protection principles.

Platform interoperability and continuity must be achieved through smartphone OS/device compatibility (S21) and cloud synchronization reliability (S23), ensuring data persistence across diverse hardware environments and enabling future stakeholder integration. Security-by-design principles must be introduced, with data encryption and secure transmission (S15) and data minimization (S14) implemented as default protocols to protect sensitive user and pet data during scanning and exchange. Finally, inclusive and collaborative workflows must be established by integrating multi-language and accessibility support (S19) and collaboration support (S12) to enhance social impact and optimize lost-pet recovery efficiency (S9).

5. Conclusions

The technical and functional requirements for an NFC-enabled IoT pet care application were examined by a rigorous fuzzy AHP analysis. As a result, health management (w = 0.1724) and identification and registration (w = 0.1690) are important factors for expert-validated system design. The ranking of subcriteria indicates that controlled medical information sharing (w = 0.0465) and NFC scanning reliability (w = 0.0455) are also important for adoption and system reliability. By identifying the conceptual and technical advancement of the pet microchip, a pet care system can be advanced from a static data carrier to an active health-informatics node. By integrating biometric sensors for physiological monitoring, such as thermistors and biosensors, the pet care system can address the historical limitations of passive RFID technology. The system can also present high-stability, multi-angle antenna arrays to ensure scanning reliability and on-chip secure elements for data encryption. The results of this study guide developers to develop a security-by-design framework that prioritizes data minimization and encryption, while ensuring smartphone OS compatibility and cloud synchronization. The results also provide a reference for an integrated pet care system that ensures efficient veterinary clinical workflows, hardware reliability, and user-centric interaction design.

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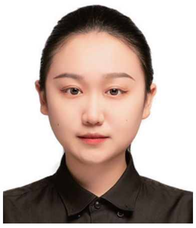
About the Authors



Qi Wang is a Ph.D. candidate at the Institute of Creative Arts and Design, University College Sedaya International, Kuala Lumpur, Malaysia. Her research interests include user interface design and interaction-oriented visual design, with an emphasis on interface aesthetics, visual hierarchy, information presentation, and user-centered digital design. (qiqiwang960203@gmail.com)

Hsin-Hung Lin is a professor in the Department of Creative Product Design at Asia University, Taichung, Taiwan and in the Institute of Creative Arts and Design, University College Sedaya International. His major research interests include the application of fuzzy set theory on product design, concurrent engineering in product design, computer-aided design, the application of the neural network and gray theory in product design, color planning for product design, heat transfer analysis, and the application of reverse engineering in product design. (hhlin@asia.edu.tw)

Hwee-Ling Siek is an associate professor based at the De Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia, where she serves as Deputy Director and Head of Research in the faculty. She engages in multidisciplinary research on cultural design, product design, sustainability, computer-aided design, and creative heritage practices. She is committed to contributing to the growth of both academic and creative communities through collaborative and practice-led approaches. (siekhl@ucsiuniversity.edu.my)

Wang Siyuan is a Ph.D. candidate at the Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia. His primary research areas include fashion design, aesthetic studies, and cultural and creative product design. He focuses on visual hierarchy, information presentation, and the integration of aesthetic and functional considerations in digital and smart product design. (wangsiyuan0614@gmail.com)