Chapter 10

Uncertainty-Resilient Signal Processing in Smart Textiles Using Fuzzy Logic

Ajoy Kanti Das
https://orcid.org/0000-0002-9326-1677
Tripura University, India

Nandini Gupta
https://orcid.org/0009-0000-5450-9783
Bir Bikram Memorial College, India

Takaaki Fujita
https://orcid.org/0009-0007-1509-2728
Independent Researcher, Japan

ABSTRACT

Smart textiles are increasingly embedded with sensors, actuators, and communication modules to enable intelligent interaction with users and environments. However, signal acquisition in textile-based electronics is inherently uncertain due to variability in fabric conductivity, body movements, environmental factors (humidity, temperature), and sensor noise. Classical signal processing methods often fail to handle such imprecision effectively. This chapter introduces a fuzzy logic-based framework for uncertainty-resilient signal processing in smart textiles. We present the mathematical structures of fuzzy sets, fuzzy soft computing, and fuzzy inference systems (FIS), emphasizing their applications in wearable sensing. The framework integrates multi-criteria fuzzy decision-making, adaptive fuzzy filtering, and fuzzy-

DOI: 10.4018/979-8-3373-4287-0.ch010

based classification models for robust signal interpretation. Finally, we discuss future research directions in merging fuzzy systems with machine learning and quantum-inspired models for next-generation wearable intelligence.

INTRODUCTION

Smart textiles are emerging as intelligent systems that can sense, process, and respond to environmental and physiological signals. However, data from wearable sensors are often imprecise, noisy, and uncertain. To handle such complexity, fuzzy logic has been widely adopted as a mathematical tool for modeling uncertainty, enabling robust decision-making in dynamic environments. This review highlights the key developments in fuzzy logic and its extensions relevant to signal processing in smart textiles.

The concept of fuzzy sets introduced by Zadeh (1965) laid the foundation for modeling vagueness in real-world systems. Later, Zadeh (1983) emphasized its role in expert systems for managing uncertainty. Mendel (2000) further extended this line of thought to signal processing, demonstrating how fuzzy systems can handle uncertain and imprecise signals—an idea that directly supports wearable sensor integration in smart textiles.

Recent works highlight the evolution of fuzzy systems into type-2 fuzzy logic and hybrid models to better capture uncertainty. Moreno et al. (2020) proposed an interval type-2 fuzzy model with justifiable uncertainty, improving interpretability and model reliability. Similarly, Beke and Kumbasar (2023) introduced a composite learning framework for interval type-2 fuzzy logic systems, showing enhanced accuracy in regression and uncertainty modeling. Meng et al. (2023) and Zhao et al. (2024) advanced fuzzy reasoning for robust control, particularly in cyber-physical systems, which parallels the challenges of textile-based sensing under variable conditions.

Fuzzy decision-making models have been applied in diverse fields where uncertainty is unavoidable. Chen et al. (2020) integrated rough-fuzzy approaches for supply chain management under uncertain conditions. Mirza et al. (2025) applied fuzzy Z-numbers with Bonferroni operators in textile engineering, demonstrating their utility in multi-criteria decision-making—a relevant framework for textile-based system optimization. Similar strategies are evident in energy management (Mohamed et al., 2021; Baz et al., 2024), environmental engineering (Bressane et al., 2024), and agriculture (Erdoğdu et al., 2025), showing the versatility of fuzzy frameworks in uncertainty-driven domains.

To improve adaptability, soft sets and their extensions have been proposed (Molodtsov, 1999; Maji et al., 2001). These models have been expanded into fuzzy