*Journal of Nanotechnology and Innovative Materials*

*Review Article*

# Application of Nanomaterial-Based Smart Sensors in Mechatronic Systems and Biomedical Devices

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Received: 18.02.2026 Accepted: 06.03.2026 Published: 31.03.2026

https://doi.org/10.54414/MDWR6644



**Abstract**

This paper investigates the application of nanomaterial-based smart sensors in mechatronic systems and biomedical devices and examines their advantages compared to conventional sensor technologies. Measurement accuracy and response speed are among the key factors determining the effectiveness of control and monitoring processes in mechatronic systems and biomedical devices. Conventional sensor technologies are characterized by limitations such as low sensitivity, high inertia, and delayed response time. The high surface-to-volume ratio and unique electrical and mechanical properties of nanomaterials enable the mitigation of these limitations. This paper provides a systematic analysis of the working principles, advantages, and application prospects of nanomaterial-based sensors in mechatronic systems and biomedical devices.

**Keywords:** nanomaterials, smart sensors, mechatronic systems, biomedical devices, sensor sensitivity, response time

## 1. Introduction

The widespread application of mechatronic systems in modern industry, automation, and high-tech fields has necessitated the rapid development of sensor technologies. Robotics, automated production lines, aviation and space technologies, intelligent control systems, as well as medical monitoring and diagnostic devices operate based on data received from sensors. The signals obtained from the sensors are directly transmitted to the control, analysis, and monitoring algorithms; their accuracy, sensitivity, stability, and response time have a significant impact on the overall performance of the systems [1], [2], [3].

High-speed data processing, real-time control, and resistance to external influences are considered key requirements in modern mechatronic systems. In biomedical devices, accurate measurement of physiological parameters, detection of weak biological signals, and long-term reliable monitoring are of particular importance. For this reason, the sensors used are required to not only perform the measurement function, but also have high accuracy, low energy consumption, and fast response characteristics [2], [4], [5].

Conventional sensor technologies have been widely used in various industrial and medical applications for many years. However, the limited sensitivity of classical sensors based on macroscopic materials, their relatively long response time, and their sensitivity to external influences somewhat limit their application in modern high-precision systems [3], [4]. Reliable detection of small-scale signals, especially in real-time control systems and biomedical monitoring devices, poses a serious challenge for conventional sensors.

The rapid development of nanoscience and nanotechnology in recent years has led to the formation of nanomaterial-based sensor technologies. Graphene, carbon nanotubes, metal oxide nanostructures, and other nanomaterials have been widely studied in sensor technologies due to their properties such as high surface-to-volume ratio, high electrical conductivity, and small size [6], [7], [8]. The use of nanomaterials allows for increased sensitivity of sensors, reduced response time, and more accurate detection of weak physical and biological signals [8], [9], [10], [11], [12].

Nanomaterial-based sensors are currently considered a promising technology in mechatronic systems, smart robots, wearable electronic devices, implantable medical devices, and biosensor systems [11], [13], [14]. The application of these sensors not only increases the stability of control systems but also improves the quality of medical diagnostics and monitoring processes.

The purpose of this article is to comparatively analyze the main characteristics of nanomaterial-based sensors with conventional sensor technologies, investigate their application possibilities in mechatronic systems and biomedical devices, and analytically evaluate the advantages of nanosensors based on the existing scientific literature. The article comparatively examines key parameters such as sensitivity, response time, stability, and applicability.

## 2. Conventional Sensors

Conventional sensors have long been widely used in mechatronic systems, including biomedical measurement and monitoring devices, to measure physical, mechanical, and chemical parameters. These sensors are usually based on macro-sized materials, and the measurement process mainly occurs within the limited surface area of the sensor. Parameters such as temperature, pressure, force, vibration, and chemical environment are converted into electrical signals and transmitted to control and monitoring systems. However, conventional sensor technologies have a number of fundamental limitations:

- The low sensitivity of the sensors is due to the fact that only a small part of the material actively participates in the measurement process. This leads to the loss of weak physiological signals, especially in biomedical measurements [3], [4], [5]. As a result, measurement errors increase in mechatronic systems and biomedical devices that require high accuracy.
- The long response time of sensors is due to their relatively large size and mass. As a result, additional time is required for thermal, mechanical, and chemical effects to propagate within the material. This causes control delays in real-time mechatronic systems and vital biomedical devices [3].
- Conventional sensors are sensitive to external influences such as high temperature, vibration, and electromagnetic noise. During long-term operation, drift of measurement values, calibration instability, and reduced repeatability of results may be observed [3], [4].

The problems mentioned are particularly acute in biomedical devices, as the variability of the physiological environment, bioelectrical noise, and temperature fluctuations directly affect measurement accuracy [2], [15]. Ultimately, these factors indicate that conventional sensor technologies cannot fully meet the requirements of both modern highly dynamic mechatronic systems and biomedical devices that require high reliability and stability [3], [4].

## 3. Nanomaterial-Based Sensors

Nanomaterial-based sensors encompass modern sensor technologies that use nanometer-sized materials as the measuring element. These sensors enable more accurate and faster measurement of physical, mechanical, chemical, and biological effects in mechatronic systems and biomedical devices [6], [7], [8].

The high surface-to-volume ratio of nanomaterials increases the sensitivity of sensors and allows them to detect smaller changes, including weak biological signals, compared to conventional sensors [7], [8], [9].

The small size and low mass of nanomaterials ensure a reduction in the response time of sensors. This feature creates a significant advantage for mechatronic and biomedical systems operating in real-time [10], [11].

## 4. Application Possibilities in Mechatronic Systems and Biomedical Devices

A comparative analysis based on Table 1 demonstrates that nanomaterial-based sensors exhibit superior properties over conventional sensor technologies in key functional parameters, especially in terms of sensitivity, response time, and measurement stability. This scientifically justifies their promising application possibilities in mechatronic and biomedical systems. Nanomaterial-based sensors increase measurement accuracy, improve dynamic response characteristics, and enhance the stability of real-time control systems [14], [16].

**Table 1.** Comparison of conventional and nanomaterial-based smart sensors.

| Criteria | Conventional Sensors | Nanomaterial-based Smart Sensors |
|---|---|---|
| Size of sensitive element | Macroscale materials | Nanoscale structures |
| Surface-to-volume ratio | Low | High |
| Sensor sensitivity | Limited | Usually high [8], [9] |
| Detection of a weak signal | Limited | More effective detection capability [17], [18], [19] |
| Response time | Relatively long | Usually short [10], [11], [19] |
| Real-time applicability | Limited | More suitable for real-time applications |
| Stability of measurement parameters | Long-term drift may be observed | Relatively high, but requires further research |
| Need for calibration | Frequently required | In some cases, less is required |
| Resistance to external noise/ interference | More sensitive to external influences | Better durability has been observed in certain nanostructures |
| Sensitivity to temperature effects | High | May be lower depending on the material |
| Energy consumption | Relatively high | Usually low |
| Miniaturization capability | Limited | More opportunities are available |
| Use in mechatronic systems | Limited or partially suitable | Promising application opportunities exist [16], [20] |
| Use in biomedical devices | Noise and stability restrictions exist | Shows high potential for biomedical applications [14], [21], [22] |
| Wearable and implantable devices | Limited application capability | Promising for wearable systems [14] |

## 5. Problem Statement

The current limitations of conventional sensors make the problem of creating nanomaterial-based smart sensors and their integration into mechatronic systems, as well as biomedical devices, urgent. Existing sensor technologies cannot fully provide the necessary performance in applications requiring high accuracy and fast response, especially in real-time control and medical monitoring systems.

According to literature data, the sensitivity coefficient of graphene-based relative strain sensors has been shown to be significantly higher than that of conventional metal foil sensors [8], [9]. At the same time, reducing response time to the millisecond level is considered an important advantage for real-time mechatronic systems.

It has been found that nanocomposite elastic structures in pressure sensors based on carbon nanotubes (CNTs) show high sensitivity to small mechanical deformations [10]. This feature is important for biomedical applications, especially arterial pressure and respiratory monitoring.

It has been shown that in gas sensors made based on metal oxide nanomaterials, the interaction of the nanostructured surface with gas molecules is more intense, resulting in an increase in signal amplitude [12], [16], [20].

Faster response time and lower detection limit achieved when nanomaterial-based biosensors are applied to glucose monitoring [17], [18]. These results demonstrate the high efficiency of nanomaterials in detecting weak biological signals.

A summary of the research conducted shows that:

- High surface-to-volume ratio leads to increased sensitivity;
- Small size and low mass reduce reaction time;
- High electrical conductivity allows for clearer signal formation;
- Detection of weak physiological signals in biomedical environments becomes more reliable.

These facts indicate that the application of nanomaterial-based sensors in both mechatronic systems and biomedical devices is scientifically and practically justified.

## 6. Research Methodology

This study was conducted as a conceptual and review study based on a comparative analytical analysis of the existing scientific literature, rather than experimental measurements. The article compares the main characteristics of nanomaterial-based sensors and conventional sensor technologies based on results presented in various scientific sources.

During the research, existing scientific articles, review studies, and theoretical approaches on sensor systems based on graphene, carbon nanotubes, and metal oxide nanostructures were analyzed [8], [23], [24], [25], [26]. The following key parameters were taken into account during the comparison process:

- Sensitivity coefficient (Gauge Factor – GF);
- Reaction time;
- Surface-to-volume ratio;
- Signal-to-noise ratio;
- Energy consumption;
- Application possibilities in biomedical and mechatronic systems.

The results presented in the article are based on an analytical summary of results provided in various scientific sources, rather than on direct laboratory experiments or full mathematical modeling by the authors. For this reason, the assessments conducted are of a preliminary conceptual and analytical nature.

The main goal of the study is to identify the promising properties of nanomaterial-based sensors, demonstrate their comparative advantages over conventional sensor technologies, and identify key directions for future experimental research.

## 7. Comparative Analysis of Sensitivity and Response Time

The assessments presented in this section are based not on the authors' direct experimental measurements but on a comparative analysis of results provided in various scientific sources and a conceptual model approach. During the comparison, literature data on gauge factor (GF), response time, and signal characteristics were analyzed.

According to literature data, the sensitivity coefficient of conventional metal strain sensors usually varies in the range of $GF \approx 2–5$ [3]. It is noted that this indicator is significantly higher in graphene-based nanosensors [8], [9]. In some studies, $GF > 100$ has been observed in graphene-based structures [8], [9].

Sensors based on carbon nanotubes have been shown to record weak mechanical deformations more accurately due to their high surface-to-volume ratio and high electrical conductivity [10]. The small size of nanostructures allows for faster signal formation [11], [19]. The comparative analysis of the main characteristics of conventional and nanomaterial-based sensors is presented in Table 1.

## 8. Initial Comparison of Reaction Time

The comparison of reaction times was conducted based on an analytical analysis of experimental results presented in various scientific studies. According to literature data, the response time of conventional macro-scale sensors usually varies in the range of tenths of a millisecond [3]. In nanomaterial-based sensors, it has been shown that the response time is reduced to a few milliseconds or less due to the small size and low mass [10], [11].

In gas sensors based on metal oxide nanostructures, the high active surface area enhances the interaction with gas molecules and increases the response speed [12], [16]. Carbon nanotubes and graphene-based structures are considered superior for real-time systems because they provide faster signal transmission [8], [10].

Nanomaterial-based biosensors, especially glucose sensors, are characterized by lower detection limits and faster response times [17], [18]. Carbon-based nanostructures and metal oxide nanomaterials enable more efficient detection of biological molecules [24], [26].

These properties indicate that nanomaterial-based sensors have important advantages for real-time mechatronic control and medical monitoring systems.

Figure 1 presents a comparison of the surface-to-volume ratio for bulk materials and nanoscale structures. As can be seen from the figure, increasing the surface area in nanomaterials expands the active measurement zone of the sensor, resulting in increased sensitivity.

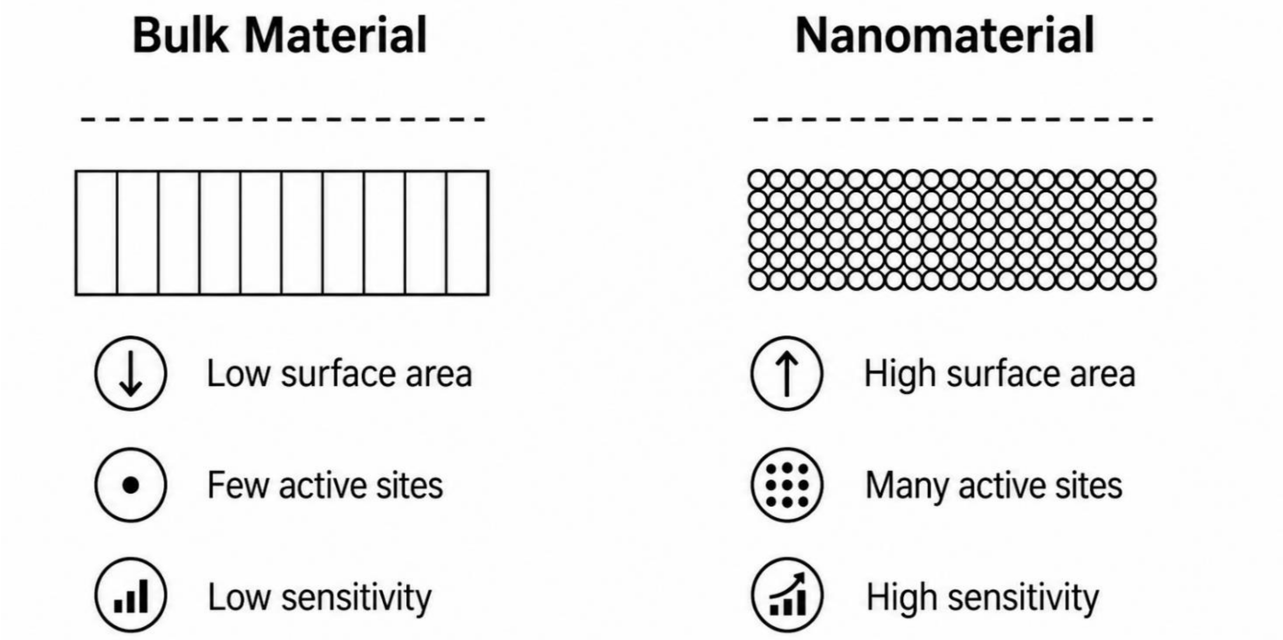


**Figure 1.** Comparative description of surface-to-volume ratio in large-scale and nanoscale materials.

Figure 2 compares the response time of conventional and nanomaterial-based sensors. The comparison shows that nanomaterial-based sensors have a shorter response time, making them more suitable for real-time mechatronic control and medical monitoring systems.

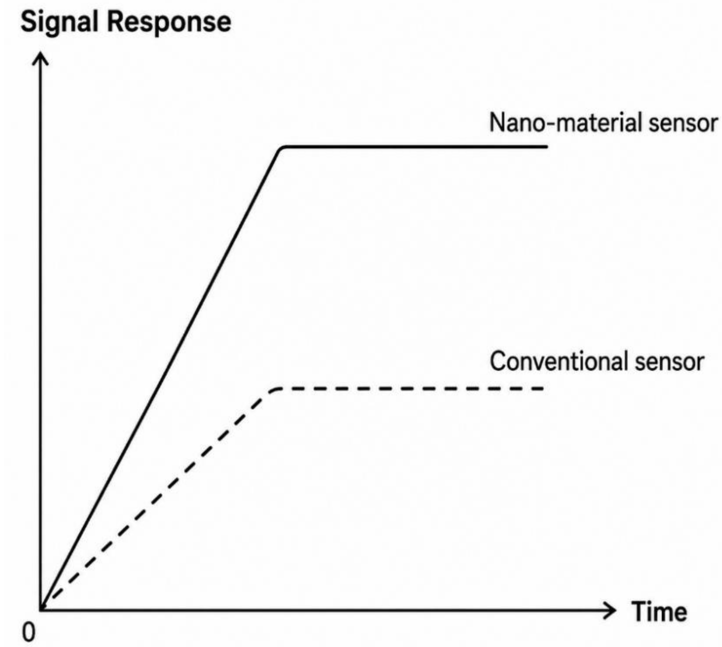


**Figure 2.** Comparison of response time in conventional and nanomaterial-based sensors.

## 9. Key Parameters for Future Experimental Validation

Based on the initial analytical evaluation, the following key measurement parameters were determined:

- Sensitivity coefficient (GF);
- Reaction time (t-response);
- Signal-to-noise ratio (SNR);
- Long-term stability;
- Temperature dependence.

Systematic measurement of these parameters in future experimental studies will allow for a quantitative assessment of the advantages of nanosensors.

However, the long-term stability, noise resistance, calibration processes, and temperature effects of nanomaterial-based sensors require further scientific research, especially for biomedical applications [15], [18].

### 10. Conclusion

The conducted analytical and comparative literature review shows that nanomaterial-based sensors demonstrate more promising properties than conventional sensor technologies in terms of sensitivity, response time, and detection of weak signals. The high surface-to-volume ratio and high electrical conductivity of sensors made especially from graphene, carbon nanotubes, and metal oxide nanostructures expand their measurement capabilities. The research shows that nanomaterial-based sensors have significant potential for improving real-time control processes in mechatronic systems, as well as for more accurate detection of weak physiological signals in biomedical devices [13], [14], [19], [25]. However, since the presented results are mainly based on an analytical summary of the existing scientific literature, the study can still be assessed as being in its conceptual and research phase.

The analysis revealed that issues such as long-term stability, calibration characteristics, temperature effects, and reliability in biological environments require further experimental studies for the practical application of nanomaterial-based sensors [15], [18], [26]. For this reason, it is considered appropriate to continue future research in the direction of conducting experimental measurements, comparative testing of various nanomaterials, and evaluating their application possibilities in real mechatronic systems.

Thus, although the preliminary analytical study conducted shows that nanomaterial-based sensors have high application prospects in mechatronic systems and biomedical devices, additional experimental and applied research is essential for their widespread practical application.

### Author Contributions

Both authors contributed to the conception, preparation, review, and final approval of the manuscript.

### Conflict of Interest

The authors declare no conflicts of interest.

### Funding

This study was not supported by external funding.

### Acknowledgment

The authors express their sincere gratitude to all those who contributed to the completion of this study.

### Abbreviations

Carbon Nanotubes (CNTs), Gauge Factor (GF), Signal-to-Noise Ratio (SNR).

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