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What Is a Sensor? A Discussion Paper

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Abstract

Sensors are among the most widely used tools created by humans, appearing virtually everywhere in our daily lives. They help us interact more effectively with our surroundings, especially as our natural senses alone can no longer fully meet modern demands. Sensors are also indispensable components of contemporary equipment and machinery. This is largely because most of today's machines operate in closed loops; every action is monitored and adjusted in real time, and this control is made possible by sensors. The information a sensor provides cannot be independently verified in the moment except by other sensors. This is why people often say: No machine can perform better than its sensors. This leads to a fundamental question: Do we truly understand what this extremely important thing called a "sensor" is? We would confidently say yes—we know what a sensor is. But if we ask whether we can define a sensor in a clear and widely accepted manner, the answer becomes less certain. Looking around, we find a variety of different sensor definitions. Matters grow even more complicated when we consider specifications, terminology, and classifications. Even something as basic as the function of a sensor is frequently misunderstood. In short, the term "sensor" lacks precision in its meaning. In this article, we present the current situation regarding sensor terminology and definitions. Our aim is to encourage discussion rather than impose a particular understanding or viewpoint. The article is organized into four sections: 1) the "Sensor Definitions" section; the "Properties of Sensors: Practical Language Use" section; 3) the "Classification of Sensors" section; and 4) the "Can Sensors Be Smart?" section.



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Sensor Definitions

The vast number of sensors manufactured and used today, along with the wide variety of sensor principles and types, has led to the term "sensor" being applied in many different ways. To date, there is still no generally accepted definition of what a sensor actually is. As a result, the term "sensor" is commonly used to refer to quite different things, including the following:

- sensor elements that convert a nonelectrical quantity into an electrical signal
- devices containing primary electronics located close to the sensing element

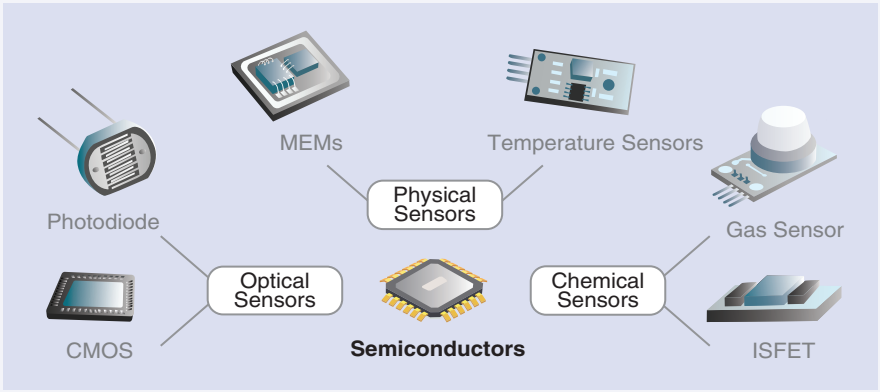
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- devices that provide a standardized analog electrical output (e.g., 4–20 mA), which still hold a considerable share of the market.

In addition, terms such as detector, transducer, pickup, probe, and meter are often used alongside "sensor," though they typically have more limited or domain-specific meanings (e.g., IR detectors).



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Sensors have existed since ancient times, although they were not called sensors back then. For example, Philon of Byzantium (ca. 260–200 BC) built a device that indicated how air expands or contracts with changes in temperature [1].

The term "sensor" originates from the Latin *sentire*, meaning "to perceive," "to feel," or "to sense." The corresponding Latin noun sensor would have meant "one who perceives" or "one who feels." In its modern technological sense, the word sensor began to appear in English in the early 20th century, around the 1930s, although identifying the exact publication, author, or date of its first use is difficult. It is generally assumed that the term entered use gradually, coined to describe something that "senses" physical phenomena, such as temperature, pressure, light, or motion, as technology and automation advanced. In short: etymology: Latin sentire ("to perceive, feel") → modern sensor ("something that perceives or reacts").

The modern development of sensors began in the 19th century with the discovery of the thermoelectric effect and its use in thermocouples by Thomas Seebeck (1821) [2] as well as the discovery of the photoelectric effect by Heinrich Hertz (1887) [3]. The discovery of the piezoresistive effect in semiconductors in 1954 by Charles S. Smith [4] marked a major advance in sensor technology, particularly in the development of miniaturized semiconductor sensors. On the one hand, this breakthrough made it possible to exploit the exceptional mechanical and electrical properties of semiconductors, especially silicon. On the other hand, it enabled the use of microelectronic manufacturing processes for the mass production of sensors.

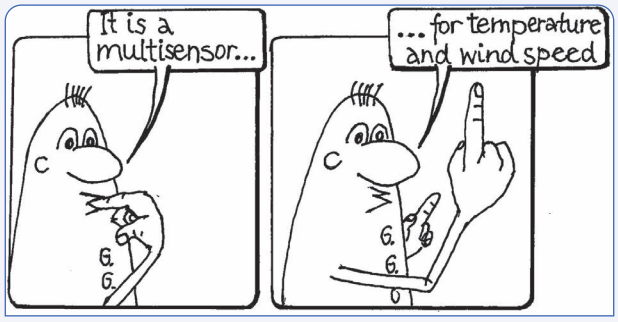
With the emergence of Industry 4.0, artificial intelligence, and the Internet of Things, sensors have become increasingly powerful, capable of collecting and analyzing data in real time to support decision-making and control automated processes. The exact number of sensors produced worldwide each year is not publicly available due to the vast diversity of sensor types and the proprietary nature of industrial data. Nevertheless, estimates suggest that several tens of billions of sensors are manufactured annually. Furthermore, a study by the Association for Sensors and Measurement (AMA) [5], the world's largest network of key industries in sensor and measurement technology, indicates that the annual production of sensors doubles approximately every five years [6], [7].

When discussing definitions of the term "sensor," it is useful to briefly consider what modern disciplines, such as logic, epistemology, linguistics, and terminology theory, tell us about how definitions are constructed. In essence, two steps are required to define any concept as follows:

1) The object to be defined must be assigned to a group of similar objects to which it most appropriately belongs.
2) A unique characteristic or property must be identified that distinguishes the object from all others within that group.

With this in mind, let us examine several commonly cited definitions of "sensor," summarized in Table 1. For clarity, the defining group and the unique distinguishing property in each definition are highlighted in bold.

At first glance, it becomes apparent that the preferred group for sensors in these definitions is "devices." A device is generally understood as a man-made object—an extremely broad category. This breadth can sometimes lead to confusion. In many application areas, a sensor is intuitively assumed to be a compact, small, single-piece object. In other fields, however, sensors are regarded as distributed systems—such as radars or certain optical sensors—that incorporate spatially separated emitters and receivers.



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Table 1 A selection of definitions of what a sensor is, showing the range of the term "sensor."

Source	A Sensor Is ...	Reference
Wikipedia	"... **device** that receives and **responds** to a signal or stimulus. The stimulus is the quantity, property, or condition that is sensed and converted into electrical signal." "... **device, module, machine, or subsystem** that **detects** events or changes in its environment and sends the information to other electronics, frequently a computer processor." (broadest definition)	[8]
JCGM	"... **element** of a measuring system that is **directly affected** by a phenomenon, body, or substance carrying a quantity to be measured."	[9]
Merriam-Webster Dictionary	"... **device** that **responds** to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control)."	[10]
Oxford English Dictionary	"... **device** that **detects** or measures a physical property and records, indicates, or otherwise responds to it."	[11]
Cambridge Dictionary	"... **device** that is used to **record** that something is present or that there are changes in something."	[12]
IUPAC	Chemical sensor "... **device** that **transforms** chemical information, ranging from the concentration of a specific sample component to total composition analysis, into an analytically useful signal."	[13]
	Physical sensor "... **device** that **provides information** about a physical property of the system."	
IEEE	"... **component providing a useful output** in response to a physical, chemical, or biological phenomenon."	[14]
	"... **transducer** that **converts** a physical, biological, or chemical parameter into an electrical signal."	[15]
AMA	"... man-made **device** to **acquire information** on a process or an object that picks up a stimulus and transmits information about the stimulus picked up."	[16]

JCGM: Joint Committee for Guides in Metrology; IUPAC: International Union of Pure and Applied Chemistry. Note: The defining group and the unique distinguishing property in each definition are highlighted in bold.

A second source of confusion concerns the unique properties attributed to sensors in Table 1. These include detects, responds, acquires, provides information, transforms, and records—terms that are clearly not synonymous. One might argue that a sensor can have more than one characteristic property, but this risks introducing ambiguity. Moreover, devices that "detect" are typically referred to as detectors, not sensors. Detectors usually have two output states indicating the presence or absence of something or whether a process is occurring. In contrast, the output of a sensor is generally far more informative.

The other properties, acquire, provide information, transform, and record, are not characteristic of sensors themselves. A sensor generates an output signal that is related to a physical stimulus. A signal, by definition, is a physical carrier of information. Extracting that information requires signal processing capabilities, which are typical of other devices—but not of sensors in the strict sense.

Next, we provide information about the origin and conceptual background of the definitions listed in Table 1, along with our own perspective on their practical relevance as follows:

- Wikipedia's definition illustrates the broad range of terminological interpretations of the term "sensor" by presenting both a narrower and a broader definition.
- The *International Vocabulary of Metrology (VIM)*, published by the Joint Committee for Guides in Metrology, aims to establish a unified language and consistent terminology in metrology. However, the definition provided there offers limited guidance for understanding or practically applying the concept of sensors within the sensor community.
- The two IEEE standards cited primarily address smart transducer interfaces for sensors and actuators rather than sensors themselves. This is the reason for the differences between the two definitions.
- The definition by the International Union of Pure and Applied Chemistry (IUPAC) is the result of extensive discussions within its Commission on General Aspects of Analytical Chemistry, under the Analytical Chemistry Division. It focuses specifically on chemical

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sensors as components of chemical analysis systems rather than on conventional physical sensors.

- The AMA road map "Sensor Trends 2030" provides the most recent definition among those listed. It stems from discussions among experts from both academia and industry. The underlying premise of this definition is that sensors are devices that "mine information." Following this logic, the term "sensor" is not used in the conventional sense of a device that merely responds to a stimulus and outputs a signal but rather as a device that picks up a stimulus and transmits information about it. Nevertheless, this raises the question of whether sensors always provide information or whether, in some cases, they simply generate a basic output signal without performing any signal processing that would directly enable decision making.

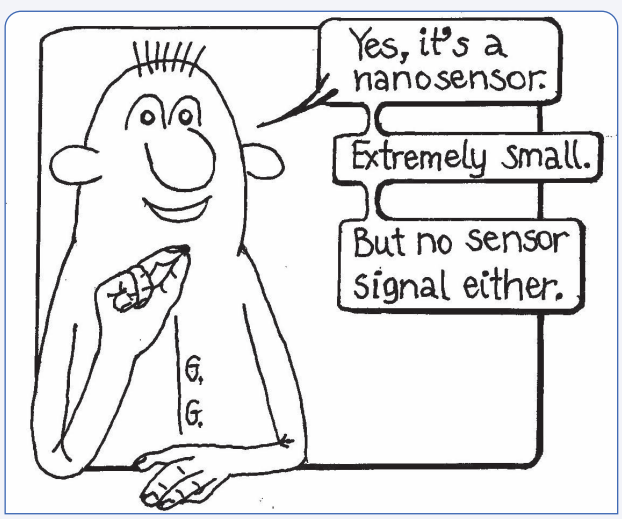
Properties of Sensors: Practical Language Use

Sensors are used individually or as a part/element of more complex systems, such as measurement instruments and servo systems, where the measurand or the controlled parameter is a nonelectrical quantity that first needs to be converted into an electrical signal before the information is extracted and processed. Here, the term "input transducer" is also used as a synonym for a sensor. To find a most useful and generally acceptable definition for sensors, we will first formulate characteristic features that are significant in practical usage by users, developers, and manufacturers of sensors and highlight certain terminology misunderstandings.

- An interesting misunderstanding emerges when sensors are used as part of a measurement instrument. In this case, it is sometimes assumed that the sensor is "measuring," which, of course, is not correct. Sensing and measuring are different functions. For clarity, let us look at the definition for measurement, as defined in the *International Vocabulary of Metrology (VIM)* [9]: "A process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity." In other words, *measurement is a process during which an unknown quantity is compared with a reference quantity of the same kind, and a value is assigned to the unknown quantity with associated uncertainty interval (error) and a probability with which the real value is in the uncertainty interval.* Obviously, sensors cannot do this complex operation.
- A sensor can deliver multiple output signals corresponding to several selected measurands when active. Such sensors are generally referred to as "multisensors" or "sensor combos." There are also so-called "functional multisensors," which can react to different stimuli when their mode of operation is changed. Examples of such functional multisensors reacting to temperature or magnetic field and to temperature or light intensity are reported in [17] and [18]. The term "sensor array" is commonly used for spatially distributed multisensors. The term "sensor" is also used as a short form for multisensors and sensor arrays.
- Most sensors provide electronic signals as output data, but there are also other sensors, such as those used in glass or bimetal thermometers (actually temperature sensors), which present visual data.
- Typically, a sensor is no larger than the size of a hand. Terms such as "miniaturized sensor," "micro sensor," or even "nano sensor" are commonly used to describe significantly smaller sensors. Larger measuring devices are often referred to as measuring devices, measuring instruments, or even measuring systems, although some sensors can be quite large.
- In general, a sensor is understood to be artificially manufactured, i.e., something man-made, a device.
- The objective of using sensors is to obtain useful information that provides an answer to a specific question (e.g., what is the air pressure?) or enables a meaningful decision to be made (e.g., is high blood pressure present, and is treatment necessary?). Initially, the sensors themselves provide only an output signal corresponding to the measured quantity. These data can then be interpreted by either humans or other technical devices. This allows decisions to be made as to whether agreed, prescribed, or expected conditions are met, in particular, whether specified tolerances are adhered to (what is referred to as testing).

Based on the previous statements on the general understanding of what a sensor is, the following conclusions can be drawn:

- A sensor is something man-made, i.e., a device.
- A sensor responds to a stimulus called in some applications "the measured variable" or "measurand."
- The output signal is usually electrical in nature but can also be nonelectrical.



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In our opinion, this leads to a simple general definition of a sensor:

> A sensor is a device that responds to a stimulus (measurand) and produces a useful signal related to it.

We are aware that a simple definition cannot provide a complete synopsis of something. None of the definitions in Table 1 does this for sensors. The role of the definitions is to give the essence of our understanding of the object of interest. The definition should also provide a distinction between the defined object and everything else.

Classification of Sensors

The enormous variety of sensing principles, applications, and production technologies often leads to confusion when attempting to group sensors into different categories. Additional confusion may arise when classifications are made without a clear classification parameter linked to an essential property or characteristic of the sensor. Since sensors are characterized by multiple parameters, each classification should be based on a single parameter that does not overlap with others. In this section, we first discuss the most important parameters that support meaningful classifications. We then apply this information to present the most commonly used sensor classification schemes.

One of the most important characteristics of a sensor is the stimulus or quantity to which it responds. In [19] and [20], six signal domains are identified: magnetic, chemical, radiant, mechanical, thermal, and electrical. The stimulus of a sensor belongs to one of these domains. This domain can serve as a general classification parameter, giving categories such as magnetic sensors, chemical sensors, and so on. Each domain contains many phenomena or conditions that produce signals of interest—such as temperature, pressure, displacement, acceleration, force, light intensity, or heat—leading to more specific sensor names: temperature sensor, pressure sensor, force sensor, etc.

Another important characteristic is how sensors behave in electrical circuits. Modern sensors deliver electrical output signals when connected to an electronic circuit or an instrument capable of sensing or measuring electrical quantities, such as a voltmeter. The electronic circuit serves two functions: 1) to establish the required operating mode of the sensor and 2) to read the sensor's output signal. This effectively makes the sensor part of the electronic circuit. Based on this parameter, sensors can be classified as resistive, inductive, capacitive, current, voltage, frequency, or charge sensors. Importantly, the same sensor may be operated in different modes, resulting in different interpretations of its role within the electrical circuit—for example, as a voltage source (voltage sensor) or a current source (current sensor) or as an inductance (inductive sensor) or a capacitance (capacitive sensor).

A further classification parameter relates to the output signal and whether the sensor generates an electrical signal (voltage, current, charge, or power) without the use of external electrical power or requires external power in the form of bias voltage or current [21]. The first group is referred to as *generating sensors*, while the second group consists of *modulating sensors*. A photodiode is an example of a generating sensor; it converts light intensity directly into current, voltage, or power, depending on the mode of operation. A photoresistor exemplifies a modulating sensor; it is a resistor whose value changes when exposed to light. Resistors, inductors, and capacitors are not electrical signals but electronic components. To sense resistance, for instance, a voltage is applied, and the resulting current is measured (or vice versa). Thus, converting a nonelectrical stimulus into an electrical signal with resistive sensors requires two conversions: stimulus-to-resistance and resistance-to–electrical signal. This creates ambiguity regarding where sensor operation ends and where sensor signal processing begins. If we classify a sensor as "resistive," its output should strictly be resistance; what follows belongs to signal processing in the electrical domain.

However, some argue that the sensor's electronic interface should be considered part of the sensor. If this view is taken, the output signal of one and the same physical sensor can vary considerably depending on the signal conversions performed by the attached electronics. This assumption is supported by the fact that some sensors can be integrated on the same CMOS die together with their signal processing circuits. This raises an important question: If the output of a resistive sensor plus its integrated electronics is a current, voltage, frequency, or charge signal, should this still be called a "resistive" sensor? We return to this question in the next section, "Can Sensors Be Smart?".

Another classification parameter is the physical or biochemical phenomenon that enables the sensor's function. The sensor's reaction to a stimulus can be understood as an energy conversion from one domain to another. These energy domains coincide with the previously mentioned signal domains: magnetic, chemical, radiant, mechanical, thermal, and electrical [19]. For example, when the piezoelectric effect is used, the energy of the electrical output signal is obtained directly from the mechanical energy of the measurand. No auxiliary power sources are required. This is the operating principle of generating sensors and reflects the fundamental physical law of energy conservation; energy can be neither created nor destroyed, only converted. In optical sensors such as photodiodes and photoresistors, the internal photoeffect is used; in both cases, the radiation energy of light is converted into electrical energy. The difference lies in the fact that photodiodes convert this energy into

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an electrical signal that can be read directly by electronic circuits, whereas photoresistors require additional electrical energy to convert absorbed radiation into a measurable electrical signal.

Sensors may also be classified by production technology and packaging. Both characteristics are strongly tied to the application domain for which the sensors are conceived, designed, and manufactured. Table 2 summarizes the most commonly used classification criteria discussed previously, along with representative examples. Table 3 lists several application areas of sensors.

Sensors span an exceptionally wide range of applications—from the automotive sector, where prices may be only a few cents, to medical technology, where prices are higher, and to process measurement technology, where sensors can cost several thousand dollars. The corresponding requirements differ dramatically across these fields and strongly influence their respective development trends. In process measurement technology, for example, in addition to low measurement uncertainty and increasing reliability, there is a pressing demand to reduce maintenance costs through improved fault detection, diagnostics, and increasingly, reconfiguration capabilities. In this domain, maintenance expenses—such as those resulting from plant downtime—are often significantly higher than the cost of purchasing new sensors.

Table 2 Classification of sensors.

No.	Criterion	Examples		
1	Kind of stimulus, what is sensed?	Pressure, temperature, heat, level	Flow, radiation, acoustic, magnetic field	Concentration of chemical/biological species
2	Output signal (electrical interpretation)	Resistive, capacitive, inductive	Voltage, current, frequency	Power
3	Applied physical/biochemical phenomenon	Piezoelectric effect, piezoresistive effect, Hall effect, photoelectric effect, Seebeck and Peltier effect	Energy absorption in a gas due to the amount-of-substance concentration	Severinghaus principle, protein-based receptors
4	Transduction principle (energy conversion)	Generating/reversible (without energy supply)	Modulating/parametric (with energy supply)	
5	Production technology	MEMS based	IC based	Standard macro production
6	Packaging	IC chip, chiplet	System on chip, sensor module	Standard housing
7	Application field	See Table 3		

Table 3 Application areas of sensors.

Fields	Applications
Process instrumentation	Process and analysis measurement technology in chemistry, metallurgy, the food industry, power plant engineering, mining, and pharmaceuticals
Production measurement technology	Use in mechanical engineering, production, and assembly lines
Automotive sector	Use in passenger cars
Transportation	Vehicle manufacturing, rail vehicles, the aircraft industry, and shipbuilding
Building technology	Use in heating, air conditioning, elevators, and fire protection technology
Environmental measurement technology	Air, water, exhaust gas, and wastewater monitoring
Consumer sector	Use in smartphones, computers, consumer electronics, photographic equipment, and toys
Medical and laboratory technology	Use in analysis, diagnosis, monitoring, and therapy technology
Precision measurement technology; metrology	Diagnostic and testing technology in industry; transfer of units of measurement

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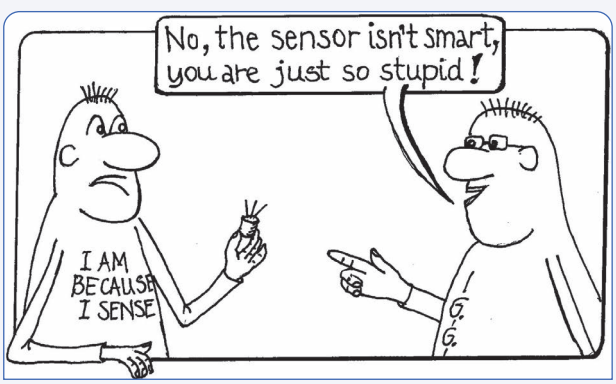
> The concept of the "smart sensor" emerged in the early 1980s, when microprocessors began to be embedded into sensors for local signal processing.

Can Sensors Be Smart?

In everyday verbal and written communication, we often "borrow" words and expressions from one domain and apply them in another, sometimes with similar and sometimes with entirely different meanings. We do this to be more expressive, impressive, or distinctive. This practice also appears in commerce, especially in advertising, where language is used strategically to attract attention and achieve a competitive edge. A familiar example is the term "hot dog." Today, most people recognize it as a popular street food, although the literal meaning is entirely different; the expression originated in American slang in the 1890s and was inspired by "dachshund sausages."

This tendency can also be observed in science, technology, and industry. For instance, we frequently refer to "industrial revolutions," although strictly speaking, revolutions in their primary meaning do not occur in industry, nor would they be desirable. A revolution is a social phenomenon involving abrupt changes to the social order, often accompanied by destruction and human suffering, before a new order emerges—one that is not necessarily better than the old.

Unfortunately, similar terminological ambiguities exist in the field of sensors. It is not possible here to offer a complete overview of the phenomenon or a comprehensive analysis. Instead, we focus on one widely "imported" term and its impact on communication and mutual understanding in the sensor domain: the term "smart."



The concept of the "smart sensor" emerged in the early 1980s, when microprocessors began to be embedded into sensors for local signal processing. Since then, numerous interpretations of "*smartness*" have been proposed, often creating confusion rather than clarity. The adjective *smart* originates from the Old English *smeart* or *smeortan*, meaning "*to be sharp or quick*" [22]. It originally referred to sharp pain or quickness, eventually extending to mental acuity. Importantly, *smart* refers to a quality, not a quantity.

This creates two problems. First, qualities cannot be measured and therefore cannot be used reliably for comparison. As a result, attempts to explain sensors' smartness typically link it to specific measurable properties intended to distinguish "smart sensors" from "conventional" sensors. Second, many of the properties associated with smart sensors do not relate to the sensor function itself (reacting to a stimulus and producing a signal) but rather to the processing of the sensor's output signal [23], [24]. A popular definition describes a smart sensor as a "system-in-package combining a sensor with dedicated electronics" [25], [26], [27]. However, this definition focuses on packaging rather than performance.

Essentially, the adjective *smart* suggests a sensor plus something extra. It also implies enhanced or superior performance and thus becomes synonymous, in many contexts, with terms like *good* or *advanced*. Such use may be helpful for marketing purposes but is less beneficial for precise communication and mutual understanding within the sensor community.

This raises the question: Should the adjective *smart* be removed entirely from sensor terminology? Or should we agree on a new and quantifiable meaning of *smart* when applied to sensors? Alternatively, should we revisit the definition of a sensor itself and attempt to identify the intrinsic properties or behaviors that impart intelligence to its performance [28]?

Let us explore the last option. A useful approach is to define an ideal sensor under the assumption that the ideal sensor is also the "smartest" sensor. In the following, we list some properties of such an idealized sensor:

- It reacts to only one stimulus—the one of interest—ensuring immunity to external disturbances.

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- It adapts to changing operating conditions.
- It survives harsh environments without degradation of performance.
- It adjusts its performance to any required set of specifications (resolution, sensitivity, range, stability, etc.).
- It imposes no constraints on the performance, form, shape, or packaging of the system to which it belongs.

A sensor possessing these idealized characteristics would resemble living organisms that adapt, survive, and thrive under changing conditions—a hallmark of natural intelligence. In this case, there would be no need to introduce an additional meaning for the adjective *smart* when referring to sensors.

Conclusion

In this article, we addressed several important aspects of sensor terminology and definitions, without claiming completeness. We hope that this contribution stimulates further discussion. Any feedback on this topic will be greatly appreciated.

Acknowledgment

This article is based on a discussion during a special session initiated by Stoyan Nihtianov at the IEEE Sensors Conference in Kobe, Japan, 20 October 2024. The text is edited by ChatGPT for improving structure, grammar, clarity, and flow, while preserving meaning and arguments.



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