

Review

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Review

A Comprehensive Review of Sensor Technologies and Signal Processing Solutions for Low-Power IoT Systems with Mini Computing Devices

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Abstract: This paper provides a comprehensive overview of sensors commonly used in low-cost, low-power systems, focusing on key concepts such as IoT, Big Data, and smart sensor technologies. It defines the evolving roles of sensors, emphasizing their characteristics, technological advancements, and the transition toward 'smart sensors' with integrated processing capabilities. The article also explores the increasing significance of mini computing devices in educational environments. These devices offer cost-effective and energy-efficient solutions for system monitoring, prototype validation, and real-world application development. By interfacing with wireless sensor networks and IoT systems, mini-computers enable students and researchers to design, test, and deploy sensor-based systems with minimal resource requirements. Furthermore, the paper discusses the use of signal processing techniques to enhance data acquisition and measurement accuracy, making these systems more reliable and suitable for various educational and research applications. This research aims to equip future engineers with the knowledge and tools to integrate cutting-edge sensor networks, IoT, and Big Data technologies into scalable, real-world solutions.

Keywords: mini computing devices; signal processing; low-power systems; IoT (Internet of Things); sensors; measurement solutions; big data; smart sensors; educational technology; affordable instrumentation

1. Introduction

In recent years, the extensive use of IoT and Big Data has been incorporated into the education of young scientists, [1]. The first term is derived from the ever-increasing number of devices that are connected to a large interconnected network of computing devices, [2]. The second derives from the data that are increasing in our everyday lives and applications making them so "big" that there needs to be a specific term to categorize, them [3]. The term big is used in terms of volume, velocity, and variety (the 3 Vs), [4], which is closely tight to their processing which is performed using deep learning techniques or Artificial Intelligence.

One of the most basic ways of understanding and finding all this information is the so-called intelligent sensors (smart sensors), [5]. As such, the future of these technology domains are

interconnected with the main issue being that the processing power of testing new and existing methods on these areas is becoming exponential. For example, the new trend of chatbot machines using AIS such as Generative adversarial networks, (GAN) which is one of the hottest trends and widely used applications of AI has been heavily criticized for the processing of both training the data used and the time and electricity it requires to answer even the simplest of questions, [6]. As such, there needs to be a computing device that will be able to be used in schools and research facilities as a rapid prototype solution or as a training tool for the students to be educated and learn about these new technologies [7–9]. These devices, if focused in all of the areas mentioned above must be both low power and low cost so either students/young scientists, [10], or hobby enthusiasts on a budget, [11], can and will be able to use them at school or research facilities will be able to easily buy/replace them and maintain them at the lowest cost possible, [12–14]. To find this threshold between pricing and computing capabilities, several solutions are being discovered annually, [15,16]. Some examples include new minicomputers that can connect to external computing devices and support even big and resource-intensive applications like computer vision, [17,18]. The main issue and what this article will study and present are not microcontrollers i.e. devices that receive a signal and base some code/process provide a single output but smarter devices that also incorporate some sort of feedback and memory for the programmers/electrical engineers, [19].

As such, regardless of the needs or an application, the first step for a researchers on a budget to get accustomed to these technologies is to have small in size and low in cost devices that will be able to support these applications (not necessarily at a scale), [20–22]. This article aims to showcase the existing mini-computing devices in the industry regarding how to program small to medium-sized applications and suggest low-cost and low-power solutions mainly focusing on educational purposes applications. Specifically, the outline of this article is that we first briefly review what a sensor is, its properties, and its characteristics. Then, we showcase why we use them and what are the most known categories of them, then we expand on the existing solutions where mini computing devices can be used to connect, use and host these sensors and provide more detailed comparison tables of computing devices that incorporate all the necessary skills for development. In this paper, the pricing of sensors or mini computing devices is not included as it is highly dependable on the area but, it is noted that the range of these devices and their respective capabilities are similar in terms of processing power.

2. Problem Formulation

2.1. Defining Sensory Devices

A sensor is generally defined as a device that is used to measure or detect a physical quantity and produces a measurable output. The first use of sensors was when they appeared alongside living beings and specifically in our everyday instruments and tools. Specifically, the human eyes and ears are typical examples where the initially one may consider what sensing is. As such, one can define sensing via the previous example where, the former detects part of the spectrum of electromagnetic radiation and the latter detects sound, i.e. pressure waves. Over time, man has noticed the lack of measuring instruments for solving everyday practical problems, such as measuring length, weight, or volume, [23,24]. Then as time progressed, these observations and various practical reasons in our everyday lives created the need to measure more accurately than just sensing these physical quantities.

2.2. Defining Sensory Devices Generations and Advancements

Since the beginning of sensor development, the term "smart sensor" has appeared for a variety of devices. This term refers to devices that fully or partially integrate an information processing unit. It is worth pointing out that this embeddedness is necessary either in the form of a data processing system, or in the form of memory feedback, an automatic calibration or compensation process, or even noise cancellation, otherwise the sensor will not be considered 'smart' or 'intelligent', [25–27].

The first generation of 'intelligent' sensors are devices that are usually connected to electronic signal processing and amplification circuitry, [26,28]. The second generation consists of sensors that are remotely located from their installation site and are connected to a section of analog electronic circuitry to adjust and modulate their desired operation, [29,30]. The third generation contains a powerful sensor component usually connected with a signal determination module and is composed of integrated circuits and/or passive components existing in the same implementation part (module). The conversion of the analog to digital signal (A/D conversion) in the converter and the microprocessor are external elements of the sensor composition and structure, [31–33]. Fourth-generation smart sensors are a product of regulation circuits combined with an identical monolithic or hybrid integrated circuit. More specifically, in this phase, the transducer and digital processing circuits communicate with discrete elements and are, as in the previous generation, external elements of the sensor composition and signal conditioning circuits. The generated output is bidirectionally interfaced to the microprocessor which provides the possibility of automatic control of the operation, [34–36].

Finally, in fifth-generation sensors, the converter of the analog to digital signal is located in a similar monolithic or hybrid integrated circuit where the signal conditioner is placed. It is worth mentioning that, depending on the design, a number of these sensors can have as an output a digital signal with the possibility of simultaneous and continuous communication with the microcontroller and the corresponding modern computer system. To achieve this function during their communication, a host system via a communication bus or wired network is used, [37,38]. The main advantages of this generation is the existence of multiple signals from different sensors, the automatic detection of the level of properties such as temperature, humidity, and other environmental factors that can disturb a measurement, the automatic correction of the main errors that occur during the operation of the predetermined life span of the components and, in general, the integration of large-scale integrated systems (VLSI), [39].

2.3. Defining Sensory Devices Properties

For choosing the appropriate instrument for a specific application, it is important to know the characteristics of a sensor device. This is reflected by its performance and behavior during measurements. Some of the most important aspects to take under consideration for technical instruments and consist of the following characteristics and properties:

1. *Accuracy*: measuring how close is the measurement of the sensory device to the actual value of the property that is being measured. As such, high accuracy is translated to minimal error and reliable and accurate results for varying conditions, [40].
2. *Tolerance*: measures and defines the acceptable range of deviation from a specified value of the values and conditions the sensor can withstand without failing or producing incorrect readings, [41].
3. *Linearity*: refers to the degree to which the sensor's output is directly proportional to the input across its entire range. As such, high linearity provides consistent and predictable measurements whereas it may introduce errors and noise to the final data interpretation, [42,43].
4. *Distinctness*: refers to a sensor's ability to differentiate the values between small changes in the measured parameter. As such, sensors with high distinctness can detect fine variations in the input signal.
5. *Repeatability*: refers to the ability of a sensor to provide the same measurement results under the same conditions over multiple trials thus ensuring reliability and consistent performance, [44].
6. *Sensitivity*: refers to the sensor's ability to detect small changes in an input parameter. As such, a sensor with high sensitivity provides minimal variations thus ensuring long-term minoring of crucial environmental and operational changes and conditions, [45].

2.4. Most Known and Widely Used Types of Sensors

This section offers a comprehensive overview of various sensor types commonly used in measurement and control applications. We will explore sensors designed to measure temperature, optics, electrical resistivity, thermistors, pressure, rubber, capacitance, level, humidity, speed, distance, and force/weight. These sensors are vital across numerous industries, including manufacturing, automation, environmental monitoring, and scientific research.

2.4.1. Sensors for Measuring Temperature

Temperature is defined as the physical quantity that determines the equilibrium of a system in terms of its thermal characteristics. The basic discovery for measuring this quantity was the thermometer, which nowadays consists mainly of electronic components and is divided into two categories:

1. *Contact thermometers*: they can produce the desired reading by coming into contact with the system whose temperature is being measured, i.e. by measuring their temperature. In this category, the accuracy of the measurement depends to a large extent on the extent to which thermal equilibrium has been established between the thermometer and the system, [46]
2. *Remote thermometers*: they can give the desired indication of the thermal radiation of the system and indirectly calculate the temperature, since physical contact between the thermometer and the system to be measured is not considered necessary, [47].

The type of sensor to be used to obtain the required measurement depends on several factors, such as the range of variation of the temperature to be measured, the required accuracy, and the fidelity of the environment in which the sensor is placed. Mechanical or other stresses are often a problem and accordingly, the difficulty or ease of measurement is strongly related to the temperature value, the medium in which we want to determine the temperature, and the overall topology of the problem, [48,49]. Some common examples of contact sensors are fiber optic sensors, [50,51], resistors (platinum/nickel), [52–54], thermistors, [55,56], thermocouples, [57,58], cryogenic sensors, [59,60], and integrated thermometers, [61,62].

2.4.2. Sensors for Optics

Fiber optic sensors involve devices that are connected to various parameters using thin optical fibers as the only means of stimulating and reading the sensing element, [63,64]. These fibers are the same as those used in telecommunication devices, [64,65]. For example, when measuring the temperature in the windings of a high-voltage power transformer, the voltage can reach high values of up to 500[kV], so the use of sensors communicating with metallic conductors is impossible for safety reasons, making this type of sensor necessary. Optical fibers have various characteristics, the variation of which can be exploited by the engineer to produce the necessary sensory instruments required for a problem, [66–68]. Such characteristics are micro-bindings, [69], interferometric phenomena, [70,71], changes in refractive index, [72] polarization changes, [73,74], wavelength variations, [75,76], the diffractive barriers, [77], occurrence of the Sagnac effect (detection of rotational motion), [78,79].

2.4.3. Sensors for Electrical Resistivity

The measurement of electrical resistance can lead, under the right conditions, to a fairly accurate calculation and determination of temperature. It should be pointed out here that, according to the literature, resistors and thermometers can be made from a wide range of materials, but the required function between electrical resistivity and temperature is not the same for all classes of materials, [80,81]. This is the reason why for the measurement of temperature, nickel, platinum, and copper are mostly used.

Platinum Resistance Thermometers (PRT) are widely used as contact sensors as most of their variants can be used for temperature measurements with an accuracy of a few [mK]. The same sensor can be used in different temperature ranges without any hysteresis effects. Its characteristics remain

very stable even after many cycles of use and are characterized by low cost and high accuracy. For their activation and operation, it is necessary to have an external excitation, which can be either current or voltage, to find the required quantity by finding their electrical resistance after a predetermined calibration procedure, [82,83].

In modern times, thin-film sensors have been established, these are electronic devices from which the wire sensors are composed of a helical very thin platinum wire placed inside the interior of a ceramic tube. In this way, protection and support of the device is achieved and the overall cost of construction and maintenance of a system is reduced, [84,85]. In particular, wire sensors are in the majority of cases particularly costly compared to thin film sensors due to the purity of the metal.

To ensure the correct operation of the above devices and to avoid wear due to high thermal stresses and other environmental factors that contribute both to the destruction of the equipment and to a reduction in the accuracy of the measurement, the three-wire technique is often used, [86,87]. In particular, the operating principle is the following: suppose three conductors, of which conductors A and B are of identical length and their resistances are at opposite ends of the bridge (cross-connection).

2.4.4. Thermistor Sensors

One of the breakthroughs in terms of smart sensors has been thermistors. More specifically, they are made of semiconducting materials, usually metal oxides, [88]. The specific conductivity of a semiconductor is given by the relation :

$$\sigma = e * (n * p_e + p * p_h)$$

where e is the charge of the electron,

n, p are the concentrations of electron and hole carriers

p_e, p_h are the electron and hole mobilities

At this point it is emphasized that the temperature coefficient of thermistors is generally negative and despite the existence of thermistors with a positive temperature coefficient its use cases are not widespread, [89]. The variation of the temperature coefficient has a large variation which may even reach an order of magnitude of one percent per °C. This fact allows them to detect very small temperature changes that could not be detected by a platinum resistor or thermocouple.

Based on thermistors and the need to further analyze the data they generate, integrated temperature sensors on semiconductors such as microprocessors were created, [90,91]. Their characteristics are the linearity of the output signal, their small size, low cost, extremely high order of accuracy, and limited operating range (from -40 to +120 °C) as long as they are satisfactorily calibrated.

Smart sensors are usually defined as remote sensors that produce their readings without being in physical contact with the system, usually by detecting the thermal radiation emitted by all available bodies with a temperature above absolute zero. As a result, in the majority of applications, this thermal radiation is detected in the infrared region of the electromagnetic spectrum, [92,93]. Their advantages are manifold as the temperatures recorded are very high and in many cases exceed the physical limits of the contact sensor materials. In addition, the difficult step of finding and designing the optimum location for sensor installation is omitted. Also, wear and tear on the sensor is significantly reduced as it does not require the kind of stress that contact sensors are subjected to and also covers cases where wired contact would be impossible.

2.4.5. Sensors for Measuring Pressure

This category includes sensors that exist to measure the force exerted on a surface, which has the direct consequence that its unit of measurement is N·m², [94]. The pressure to be measured may be the product of liquids or gases and consists of an energy detection mechanism (Newton) and their conversion into electrical signals. The main types of these sensors are: elastic pressure sensors, [95], piezoelectric pressure sensors, [96], and capacitive pressure sensors, [97].

2.4.6. Rubber Pressure Sensors

As their name indicates, this category includes sensors whose one or more parts can be subjected to temporary changes (deformation, bending) of their dimensions, [98]. These sensors are usually found in Bourdon tube pressure measurements where the operation is based on a calibrated needle placed on a surface, [99]. In the event of pressure, it moves and the tube to which it is connected deviates from its initial point and this force is measured. Due to the displacement of the needle, the above procedure is often used for distance measurement using displacement sensors. Displacement refers to the change in position of the object by some distance or angle where if it schematically depicts a straight line, it is defined as linear. Similarly, if the reference point is rotation about a given axis of rotation it is defined as angular, [100].

2.4.7. Capacitive Pressure Sensors

In this category of sensors, the diaphragm is placed between two armature elements in each of which a capacitor is formed. The two existing capacitors are then connected to a bridge which is in equilibrium for zero pressure. The occurrence of an electrical signal disturbs the equilibrium and therefore changes the capacitance which contributes to the calculation of the necessary elements. The main negative aspect of these devices is that they are prone to errors in the presence of oscillations or temperature extremes. The basic structure of the measurement bridge and their structure lies in their operation which is determined by the circuitry of the capacitors and the signal to be applied to them respectively, [101–103].

2.4.8. Level Pressure Sensors

Level sensors are defined as sensors whose main purpose is to control a process and are commonly found in industrial applications. In particular, they are intended to determine the maximum and minimum level in a specific and well-defined area of action for the triggering of an actuator. If no moving parts are required in the structures concerned, they can also be converted into point-level sensors, for example, to measure capacitance or for the manufacture of lasers, infrared beams, or photocells, [104,105].

2.4.9. Sensors for Measuring Humidity

The parameter of humidity is one of the most important variables in the design and study of many elements. In particular, humidity and temperature are the main factors to be taken into account to eliminate or even find and counteract corrosion of sensors and measurements. As far as measurement is concerned, this consists of air molecules and chemical reactions which are highly variable in the respective external environment, [106,107].

2.4.10. Sensors for Measuring Speed

In several applications, especially in terms of controlling a machine or its correct operation, it is necessary to monitor data on the flow of a process. The maintenance of airflow, for example, either for proper ventilation or to prevent overheating of a generator and heating and ventilation systems in general, is based entirely on sensors for measuring the speed of air and, in some applications, of liquids. Velocity in these measurements is defined as the distance traveled per unit of time and is expressed in meters per second, [108–110].

2.4.11. Sensors for Measuring Distance

In this category, there are different implementations to achieve the same measurement depending on the objective, available budget, and desired accuracy. The first one is the sonar-type sensors where the detection and the return of values are done using a parabolic curve in space, which covers a distance proportional to the power of the sensor. This method is preferred when it is necessary to cover a large distance between the sensor and the wall, [111,112]. Due to the mode of its

operation, the measurements usually generate a lot of noise. The second is for range sensors where, the sensor is placed at a fixed point (usually pressed) based on a fixed radius, which passes through a certain space. This beam, in the majority of cases, is light amplification by forced emission of radiation (laser) or infrared rays (infrared), [113].

2.4.12. Force-Weight Sensors

The function of weight sensors is that of the so-called S-type load cell. Essentially, it is a transducer that converts a load, in this case, a force, applied (i.e. weight) into an electrical signal, [114,115]. The installation of such sensors is particularly difficult and special attention must be paid to sensitivity, accuracy, and calibration. The operation of S-type sensors is based on the principle of the Wheatstone Bridge. In particular, the principle of operation of the bridge is to apply a potential difference to one pair of ends and measure the voltage difference. In the equilibrium state of the bridge, when no load is applied, this voltage difference is approximately equal to zero, [116,117].

2.4.13. Concise Outline of Sensor Types

The most useful and extensively used sensor types are presented in Table 1 and Table 2 below:

Table 1. A detailed analysis of the most known and used low-cost and low-power computing devices in the industry.

Sensor Type	References	Reference Number
Temperature Sensors	Gazis et al. (2023), Zhao & Bergmann (2023), Mnati et al. (2021)	[108,109,111]
Contact Thermometers	Mnati et al. (2021), Zhao & Bergmann (2023)	[110,111]
Remote Thermometers	Li et al. (2021), Huang et al. (2019)	[112,113]
Optic Sensors	Udd & Spillman (2024), Venketeswaran et al. (2022)	[120,122]
Electrical Resistivity Sensors	Claggett et al. (2022), Kilinc & Erkovan (2023)	[130,131]
Thermistor Sensors	Bodic et al. (2023), Liu et al. (2024)	[137,138]
Pressure Sensors	Mishra et al. (2021), Lu et al. (2020)	[140,141]
Humidity Sensors	Farahani et al. (2014), Sajid et al. (2022)	[148,149]
Speed Sensors	Javaid et al. (2021), El-Sheimy & Youssef (2020)	[150,151]
Distance Sensors	Zhmud et al. (2018), Ye et al. (2020)	[160,162]

Force -Weight Sensors	Russel et al. (2016), Zhang et al. (2021)	[172,173]
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Table 2. A concise analysis of the most known and used low-cost and low-power computing devices in the industry is presented in Table 2.

Sensor Type	References	Reference Number
Temperature Sensors	Mnati et al. (2021), Zhao & Bergmann (2023)	[110,111]
Fiber Optic Sensors	Udd & Spillman (2024), Huang et al. (2023)	[120,122]
Pressure Sensors	Mishra et al. (2021), Lu et al. (2020)	[140,141]
Humidity Sensors	Sajid et al. (2022), Farahani et al. (2014)	[148,149]

3. Comparison of Mini Computing Solutions

After considering many well-known industry options such as Onion Omega2+, [118], ASUS Tinker Board, [119], and Le Potato, [120], Raspberry Pis were chosen to suggest for their balance of storage, speed, processor capabilities, community support, and cost-effectiveness, [121–123], [124]. Moreover, Omega2+ devices are less expensive and can be suggested to be used in several case studies but lacked processing power, whereas an interesting solution is the Tinker Board which lacked extensive community support for sensors and documentation. Similarly, from the mini computing devices studied, Le Potato, despite superior CPU and GPU performance, also suffered from limited community support. Given that our model of study is focused on educational purposes thus it is not resource-intensive, Raspberry Pis, a solution that is not overly engineered is in most cases suggested and preferred. All mini-computers mentioned support SD and WiFi, ensuring connectivity and the ability to store local measurements cost-effectively on an SD card and transmit data remotely. A comparative analysis of these devices is provided in Table 3.

Table 3. A comparison analysis of the most known and used low-cost and low-power computing devices in the industry.

Device	CPU Model	RAM	RAM Technology	Speed	Power
Raspberry Pi 4 Model B	Quad-core Arm Cortex-A72	1.5GHz 1-8GB	LPDDR4	1.5 GHz	5V 3A
Raspberry Pi 3 Model B	Quad Core Broadcom BCM2837	1.2GHz 1GB	LPDDR2	1.2 GHz	5V 2.5A

Onion Omega2+	580 MHz MIPS		128M B	DDR2	580 MHz	3.3V 0.18A
ASUS Tinker Board S	Quad-core RK3288-CG.W	1.8 GHz	2GB	LPDDR3	1.8 GHz	5V 1.6A
Nvidia Jetson Nano	Quad-core Cortex-A57	ARM	4GB	LPDDR4	921 MHz	5V 2A

4. Conclusions

The current century is often characterized as the "information century," but to harness the vast amounts of information available, it is essential to understand, process, and apply data effectively to relevant problems. This article began by outlining the aim of providing young scientists, researches and technical hobbyists with detailed information on how to use sensory devices. We analytically defined what a sensor is, its unique characteristics, and the evolution of sensors, from simple measurement devices to smart sensors. We also elaborated on various types of sensors, emphasizing their unique capabilities and features.

The technical novelty of this article lies in presenting several core components and providing a concise literature review on a vast amount of different sensory devices and mini-computers used to develop early rapid prototypes. These prototypes can serve as a method to validate the ground truth of complex and expensive computing devices and in our case to be used as a low-power and low-cost devices to serve educational puproses. In line with Moore’s Law [125,126] and more recently Hwang’s Law [127], we predict that the capabilities of these devices will continue to increase while their costs remain manageable, given their performance potential.

This article offers readers the ability to define different types of sensors, and by studying Table 1 and Table 2, they can better understand the initial steps of creating a top-down approach for their intended systems. As a result, future scientists can use this article as a reference for selecting sensors and identifying the most suitable types of sensors and mini-computers for their systems. While Raspberry Pi is often considered the go-to solution in many cases, it is evident from the data and the tables of this manuscript that other options should also be considered based on the specific applications of each project. Lastly, as for future use cases and studies, it should be really interesting to provide a more detailed comparison between these low-cost and low-power devices and other even in lower costs devices such as chrome books or ChromeOS flex using devices, [128,129].

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