4

Monitoring of Critical Assets

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Sensors used in the MANTIS project must be able to measure the physical phenomenon relevant for the assets' condition. Examples of this include temperature, light intensity, pressure, fluid flow, velocity, and force among others. Anyhow, it is not a trivial problem for a given installation, where an adequate measurement solution must be chosen or developed in order to accurately and robustly acquire data about the physical process related to each MANTIS use cases [Jantunen et al., 2017].

Another relevant matter is the cost of the monitoring solution. Industry is always aiming for cost savings and a better market positioning. Therefore, new technological solutions such as WSNs have become a strategic asset in this context, increasing the interest of the industrial companies. This type of sensor networks is used to share information with the purpose of increasing productivity, gathering data for developing future technological improvements and/or detecting/predicting maintenance issues. Moreover, even when a single sensor is considered instead of a WSN, the use of wireless communications provides flexibility, installation ease, weight reduction, which makes them suitable for many applications, conditions and situations.

Industrial environments usually have hostile site conditions, both for the sensors themselves and for the wireless communication systems, and a section is devoted to the analysis of the issues and the solutions raising in these environments.

Finally, a section is focused on the intelligent functions that can be offered by CPS, both to preprocess collected data and to support the CPS itself.

4.1 The Industrial Environment

There are situations in which the integration of sensing devices and their associated processing systems within the framework of a hostile environment pose challenges that have to be overcome. Viable solutions must take into account different factors related to the factory and to the environment where the monitoring process takes place. Examples of such situations are described below.

4.1.1 Extreme High/Low Temperatures (Ovens, Turbines, Refrigeration Chambers etc.)

Silicon based conventional electronic devices fail to perform within specifications when subject to external temperatures over 150°C, as conventional CMOS substrates are not designed to withstand such high temperatures, and the same applies to batteries. Regarding plastic materials like cable covers made of polyethylene, they can suffer severe damage, exposing conductive parts, which increases the risk of short circuits or malfunctioning in general.

Opposite to this, temperatures below zero can drain batteries faster, and short circuits can also appear due to ice and frost formations between conductive parts of the circuits. Any amplifying device used in the sensor can suffer from increased gain due to cold temperatures. In addition to this, any cabling deployed between sensing devices and data processing units can break the thermal insulation of the premises. Finally, a wide temperature span can induce thermic stress in the sensing components, and substrates withstanding extremely high and low temperatures (generally of a ceramic type) must be considered.

4.1.2 High Pressure Environments (Pneumatic/Hydraulic Systems, Oil Conductions, Tires etc.)

Sensors or devices inside structures subject to high hydraulic and pneumatic pressure can suffer structural damage, as they are subject to mechanical stress. Furthermore, not only the sensing device is subject to mechanical stress, but the containment vessel itself is subject to pressure, and thus can have its structural integrity compromised, for example if cables are allowed to get outside the housing. Fluids or air used in the industrial process could also escape from sealing O-rings. In the case of tire pressure sensors, for example, small volume, lightweight devices are necessary, as they are introduced on a rubber frame that could be torn if a sharp metallic piece impacted into the tire fabric.

4.1.3 Nuclear Radiation (Reactors or Close and Near-By Areas)

Radiation is a direct threat not only for human individuals, but also for electronic systems (e.g., memory contents can be changed when subject to radiation). In these case, only rad-hard devices that are manufactured to withstand the impact of these high energy particles can be used for the development of intelligent sensors, or sensors with electronic circuitry. Additional elements like cabling coming out of the radiation zone can imply a direct biological hazard to humans, as containment sealing is not guaranteed and the components involved become radioactive wastes. All of these increase the development, deployment and operative costs. Additionally, the replacement of complex and bulky equipment and cabling can become a difficult, costly and time consuming task. If the adopted approach looks for a wireless solution, it is necessary to bear in mind that the containment walls of such premises are usually made of thick reinforced concrete, which means high signal loss, requiring additional amplification for thru-wall communications.

4.1.4 Abrasive or Poisonous Environments

This situation can be similar to the extreme temperature case. Corrosive liquids and gases can degrade plastic covers and generate short circuits in the sensor circuit. The metallic parts and electronic components themselves are also subject to corrosion, compromising sensor performance. Like in the previous situations, an appropriate cabling scheme will usually increase costs.

4.1.5 Presence of Explosive Substances or Gases

It is obvious that in the case of potentially explosive environments, it is of utmost importance the control upon the electric signals that are present on the premise where the sensing process is to be carried out. Electric fields due to excessively high signaling voltages in cables in a flammable gas environment, or current and voltage surges and spikes (due to thunder strikes) travelling down the cables can ignite the explosive substances, if these locations are physically hardwired to the exterior.

4.1.6 Rotating or Moving Parts

The inherent dynamical nature of certain systems (rotors, assembly chains, clutches) persuades the system out of using cables, for obvious reasons, unless additional elements like electric brushes are added. In addition to this, in situations where high rpm regimes are attained (e.g., turbines or motors), the inertial mass, shape and even the orientation of the inserted sensor structure have to be considered carefully beforehand and in direct relation to the particular application for which they are to be used. The reason for this is not only to obtain a reliable and accurate measurement from the sensor, but also not to compromise the structural integrity and performance of the component or part that is being measured (e.g., sensors or parts of sensors impacting on the frame structure, damaging it).

4.2 Industrial Sensor Characteristics

Sensors used in advanced maintenance operations can be classified into three main categories, based on how they are acquired. The first category is the *off-the-shelf sensors*, which are the most commonly employed in the industry, are mass-produced, are cheaper when bought, and target the most common environmental data, which are temperature, acceleration, light, force, audio, humidity and proximity according to [Beigl et al., 2004].

Specialized kinds of sensors make up the category of the *custom sensors*, can be found in specific applications, and are usually not mass produced, their structure presents a high degree of customization, and they retrieve very specific environmental data. Among the plethora of the custom sensors, there are sensors capable of performing crack detection, torque measurement, analyse wear of material and retrieve oil status. All of these environmental data are more complex to detect and can be collected using different approaches. For example, crack detection through non-destructive methods can be performed using different techniques like radiography, ultrasonic, penetrating liquid, and magnetic particle inspection.

The last category is the *soft sensors* (also called virtual sensors), which is a technology used to distil more effective and accurate information out of collected data. Soft sensors make use of readings collected either by a sensor network, or from a single sensor. The soft sensors operate based on data analyses and advanced modelling techniques in order to provide new data related to the physical processes. Data are combined from multiple sources (e.g., temperature, humidity, CO_2) and process models are applied to compute new outputs, based on not only current sensor values, but also on its time series.

Many work have already surveyed off-the-shelf sensors, such as [Beigl et al., 2004], and they will not be further described in here. The rest of this section considers selected topics regarding custom sensors and soft sensors. In particular, PWS is considered, followed by MEMS sensors, and soft sensor computational trust.

4.2.1 Passive Wireless Sensors

Often, a hostile environment comprises several of the aforementioned characteristics. Plus, it is usually difficult to have regular access to the physical location of the sensor, for example for battery replacement or system reset after latching. For each and every sensing case in a hostile environment, sensor performance must be guaranteed under all circumstances. It is advisable thus to make use of a physical working principle, implemented in a simplified architecture, built from durable and robust components to reduce the risk of errors or malfunctions. In addition to this, a reduced consumption or, equivalently, the capability to operate in a passive way is desirable also to minimize maintenance service. This not only reduces costs, but also the probability of errors committed by human operators. On this regard, PWS devices come out as an appropriate and affordable solution that can overcome many of the difficulties that the hostile environments pose, due to their simple working principle and robustness, which is highlighted by their definition itself:

- **Passive:** No need for batteries or power supplies. Energization of the sensing structure relies on the impinging EM field power. Several solutions for this energy harvesting principle are available, like inductively or capacitively coupled antennas or rectennas for DC voltage generation;

- **Wireless:** No cables are needed to convey information from one communication device to the other. All exchanges are carried out via electromagnetic waves. Only antennas are needed for this purpose, decreasing in size as the involved frequencies are located at higher bands.

Surface acoustic wave (SAW) devices or bulk acoustic wave (BAW) devices are feasible options for the implementation of PWS in case there is a need for measuring a temperature in a given location, due to their inherent robust properties and simple operation. The working principles of a SAW device is first reviewed, as BAW's operation is similar to that of SAW's, and then 3 examples of PWS temperature measurement systems are described.

SAW devices for temperature measurement

A SAW device, represented in Figure 4.1, is a small element that consists of a piezoelectric crystal substrate with a metallic pattern printed on its surface in a hairpin-like form, with an input port and an output port. An electric signal applied to this substrate generates a mechanical wave propagating in the surface of the structure (BAW devices operate in a similar fashion, but generating a wave propagating in the bulk of the substrate, rather than in the surface). In a reciprocal way, a mechanical wave moving on the surface can generate an electrical signal that can be captured across the terminals of a metallic port that has been deposited on the piezoelectric substrate. The equivalent circuit of such a component can be approximated by a combination of resistance, inductance and capacitance, thus showing a resonant behavior. As the resonance frequency value depends on the physical properties of the piezoelectric crystal (with these properties varying with temperature) this very resonance frequency of a SAW device can be used as an indicator of the temperature of the environment on which the SAW device is embedded.

It is possible to add antennas to the described device, make an EM wave impinge upon it and then analyze the frequency of the reradiated wave. If the frequency of the "interrogating" wave lies close to the resonance of the SAW element, energy will be stored in the device in the form of an acoustic wave, and for a given frequency bandwidth centered at the resonant frequency. The majority of this stored energy will be contained in this resonant frequency, and when the excitation signal ceases, the device will progressively radiate back the stored energy (as this will convert from a mechanical wave to

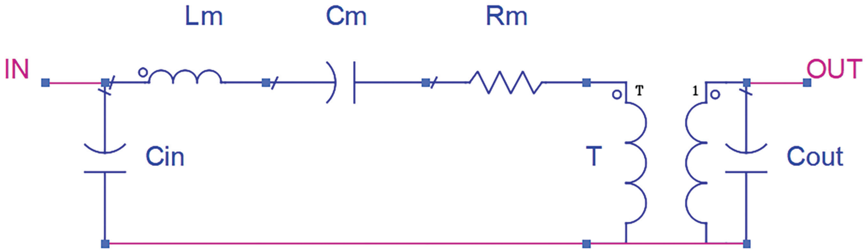


Figure 4.1 SAW device's RLC equivalent circuit.

an electric signal at the antenna terminals, for reasons explained above). An analysis of this received "response" will provide an estimation of the temperature of the SAW device, as the maximum amplitude of the received signal's spectrum will give the value of the resonance frequency. On this regard, the implementation of a group of intelligent functions (mainly signal processing algorithms like filtering and transform calculations, to be explained in this chapter) is necessary in the edge server of the sensing system.

As can be deduced from the explanation above, also represented in Figure 4.2, such a scheme allows for the measurement of temperature in a wireless fashion, allowing for a simple remote temperature sensing method. Nonetheless, in the case of measurements to be carried out in high temperature environments (such as turbines and ovens) the sensing SAW devices that provide the readings need to be designed to withstand such hostile conditions, so that these extreme temperatures do not compromise the device's performance and, hence, the temperature estimation. Different

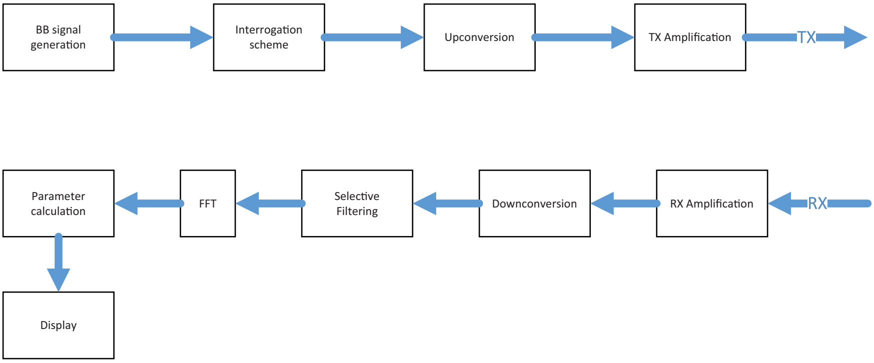


Figure 4.2 Signal processing scheme.

manufacturers providing high-temp SAW devices have been identified [Wisen-tech; Syntonics; SAW].

PWS temperature measurement examples

Environetix has built a dedicated PWS sensor network for hostile environments, and has applied it to helicopter motor monitoring. They have also developed high temperature PWS devices for measurements in rotating parts. These sensors have been tested in JetCat turbine engine. A second example can be found at Wireless Sensor Technologies LLC. This company has developed a temperature measuring system for turbine blades, based on SAW sensors. The sensors were designed to operate in hot sections of gas turbines and the research project was sponsored by the U.S Air Force, Navy and the Department of Energy of the United States [Environetix].

On the framework of the MANTIS collaborative project, a research group at the MGEP (Mondragon Goi Eskola Politeknikoa, Arrasate-Mondragón, Spain) has developed a system for temperature measurement, based on the concepts explained above. The objective consisted on the measurement and monitoring of the temperatures at the surfaces of heating resistances inside a concrete-block curation oven. The mentioned resistance surface temperatures can range from some 20°C up to well in excess of 200°C at the hottest curation process steps. It is known that the properties of the cured blocks correlate with the curation temperature, which, at the same time, is related to the surface temperatures on the surfaces of the heating resistances. Thus, it is of paramount importance to collect a measurement as close to the real surface temperature as possible in order to carry out a real time manufacturing process monitoring. Several issues have to be considered in this case for a correct temperature sensing:

- *Wireless operation.* The high temperatures present inside the oven preclude the use of cables with plastic covers, which can rapidly degrade after few thermal cycles;
- *Passive sensor implementation.* The necessary capability to withstand high temperatures renders commercial electronics, batteries and plastic battery holders, if not unusable, at least not recommendable;
- *Accurate surface temperature measurement.* The sensing element has to be in close contact with the surface under measurement via a low thermal resistivity path. For this reason, if the sensing device is located at a certain distance from the heat source, the sensing structure has to be small in size to avoid heat dispersion in the path between the hot surface and the sensing element (by thermal radiation to the air or by thermal diffusion to other components).

The size constraint is fulfilled by the use of a COTS SAW resonator component (SAW Components GmbH) with a QFN encapsulation. Designed to work from −50°C up to 275°C in the ISM 343 MHz band, it allows for a temperature sensitivity of 15 KHz/°C. Two sensor prototypes have been constructed for this purpose, and they can be seen in Figures 4.3 and 4.4.

The sensor on Figure 4.3 consists of a SAW device with two metallic arms (conforming a dipole) soldered together in a low cost FR-4 substrate. This low cost material does not, of course, withstand high temperature. As a dipole, it cannot be laid in metallic surfaces, as it would preclude the EM energy radiation and absorption from and towards the sensor, but has been used nonetheless as a proof of concept and for validation purposes.

The device in Figure 4.4 is a prototype of the planned temperature sensor for the heating resistances. It consists of a small metallic surface (FR-4 substrate) on which the SAW device is soldered in the upright position. A single metallic arm (monopole) is soldered to one of the terminals of the resonator, the other being soldered to the flat metallic surface (ground) that will mimic the remaining arm of a dipole to sustain the resonance in the SAW device. In the final implementation, the SAW device was soldered vertically to a thin sheet of copper, and the vertical monopole arm included a supporting structure consisting of an additional metallic arm to ground to convert the short circuit at the ground level to an open circuit in the monopole end, thus leaving the monopole's electrical behavior unchanged. Before placing the sensor upon the heating resistor, the bottom part of the copper sheet got covered with thermal grease to keep the thermal resistance from the hot surface to the SAW device to a minimum value. Tests proved that the SAW device is in perfect thermal equilibrium with the surface under measurement,

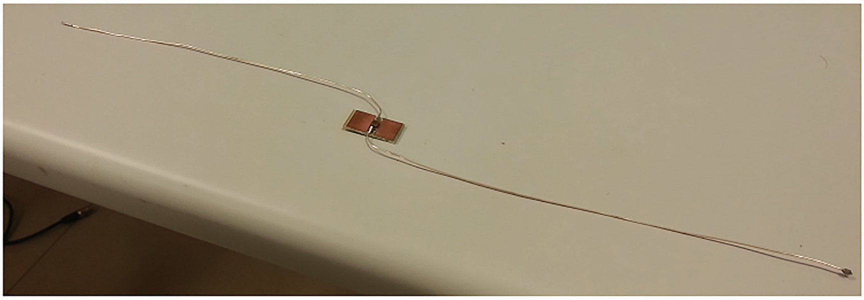


Figure 4.3 First prototype of a SAW sensor.

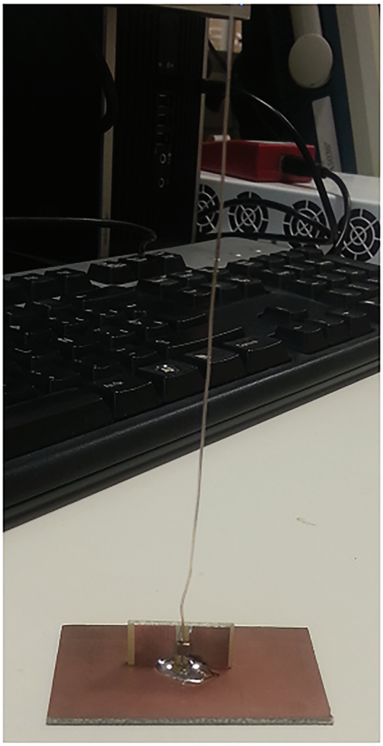


Figure 4.4 Second prototype of a SAW sensor.

and resonant frequency value readings provide an accurate estimation for the temperature of the heating resistance surface.

An external system has been devised to first interrogate and then frequency-analyze the response from the temperature sensor. This system, based on a Software Defined Radio (SDR) architecture, implements the interrogation and response processing systems in a Nutaq's ZeptoSDR© unit [NutaQ]. The hardware solution is visible in Figure 4.5, and it provides the designer with the digital signal processing capabilities of a reconfigurable logic device like an FPGA and the high frequency operation possibilities offered by an incorporated RF front-end mezzanine card.

Two quasi-Yagi antennas were designed and simulated in-house, and they provide enough gain, directivity and required linear polarization to adequately interrogate the sensor and listen to its response. Figure 4.6 shows a graphic user interface (GUI) that has been developed in Matlab©.

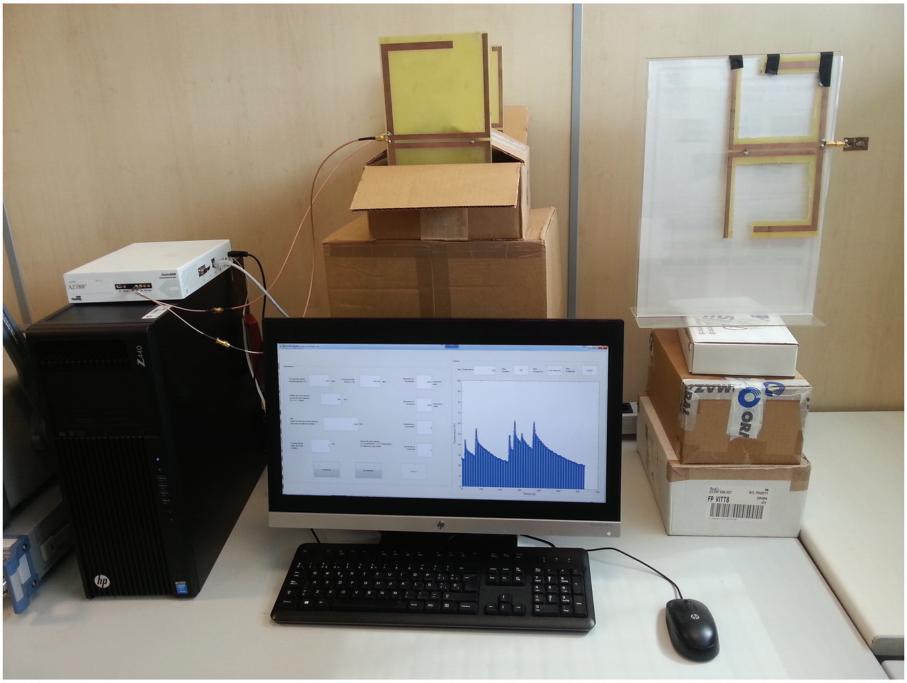
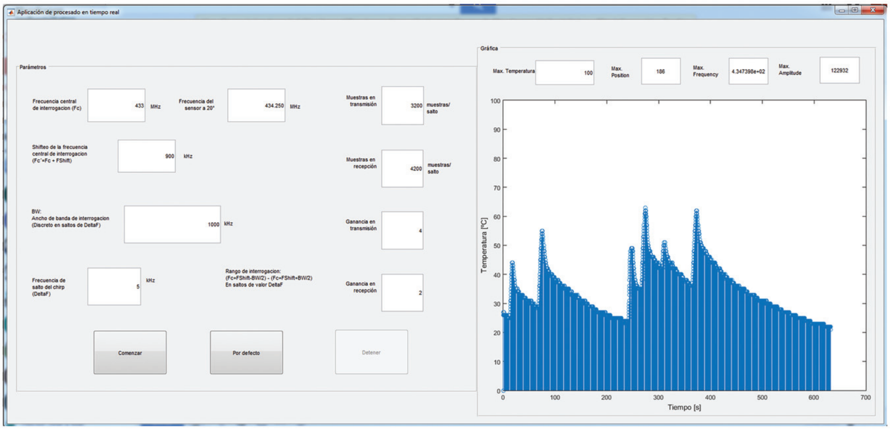


Figure 4.5 Standalone SDR platform, antennas and sensor.



Aplicación de procesado en tiempo real

Parámetros

Frecuencia central de interrogacion (Fc): 433 MHz

Frecuencia del sensor a 20°: 434.250 MHz

Muestras en transmisión: 3200 muestras/salto

Shifteo de la frecuencia central de interrogacion (Fc'=Fc + FShift): 900 kHz

Muestras en recepción: 4200 muestras/salto

BW: Ancho de banda de interrogacion (Discreto en saltos de DeltaF): 1000 kHz

Ganancia en transmisión: 4

Frecuencia de salto del chirp (DeltaF): 5 kHz

Rango de interrogacion: (Fc+FShift-BW/2) - (Fc+FShift+BW/2) En saltos de valor DeltaF

Ganancia en recepción: 2

Gráfica

Max. Temperatura: 100

Max. Position: 186

Max. Frequency: 4.347398e+02

Max. Amplitude: 122932

Figure 4.6 Developed GUI showing real time temperature measurements.

This GUI communicates via Ethernet to the SDR unit, and extracts the temperature measurement to show it in an appropriate manner. A graph shows the temperature variation in real time. Data can also be stored in binary files for further data analysis. It is worth noting the flexibility that such a system architecture offers, as the parameters of the interrogating signal can be accommodated to those of the sensor in use. Thus, as long as the SAW devices used for sensing fall inside the operative frequency band of the ZeptoSDR unit (300MHZ – 3GHz), all that is needed to carry out the temperature estimation is an appropriate set of transmitting and receiving antennas.

4.2.2 Low-Cost Sensor Solution Research

New sensor technologies like Micro Electro Mechanical System (MEMS) sensors and printed sensors are becoming more popular nowadays. The MEMS sensors take advantage of manufacturing processes that are used commonly with the family of integrated circuits called semiconductor manufacturing processes. The used semiconductor manufacturing methods include for example wet etching, dry etching, molding and plating [Angell et al., 1983]. With the semiconductor manufacturing processes it is possible to build many kinds of sensors cost-effectively, and get the price down for the single sensor. Wide variety of MEMS sensors can be acquired commercially, including, but not limited to, accelerometers, gyroscopes, temperature sensors and pressure sensors. The MEMS commonly integrate also capabilities other than just sensing to the same package such as amplification, pre-processing and analogue-to-digital conversion by combining micromechanics and microelectronics. One advantage of MEMS is their small size and lightness in weight. MEMS structures can be really tiny.

Selection of printed sensors is not as wide as with MEMS sensors but the variety is increasing by the day. For example, currently at least temperature sensors, pressure sensors, gas sensors, strain gauges, parts of accelerometer sensors and moisture sensors can be found as printed sensors. Chansin [2014] from IDTechEx divides the printed sensors into 9 categories, and Figure 4.7 shows the ten year market forecast for the printed sensors divided into these categories. Printed sensors are made using common printing methods and equipment. Conductor, semiconductor, dielectric and/or insulator inks are printed on surfaces, leading to flexible and really low-cost sensors. Altogether manufacturing processes have improved in sensor production, decreasing the price of sensors. Table 4.1 shows multiple examples of different low-cost sensors with their prices.

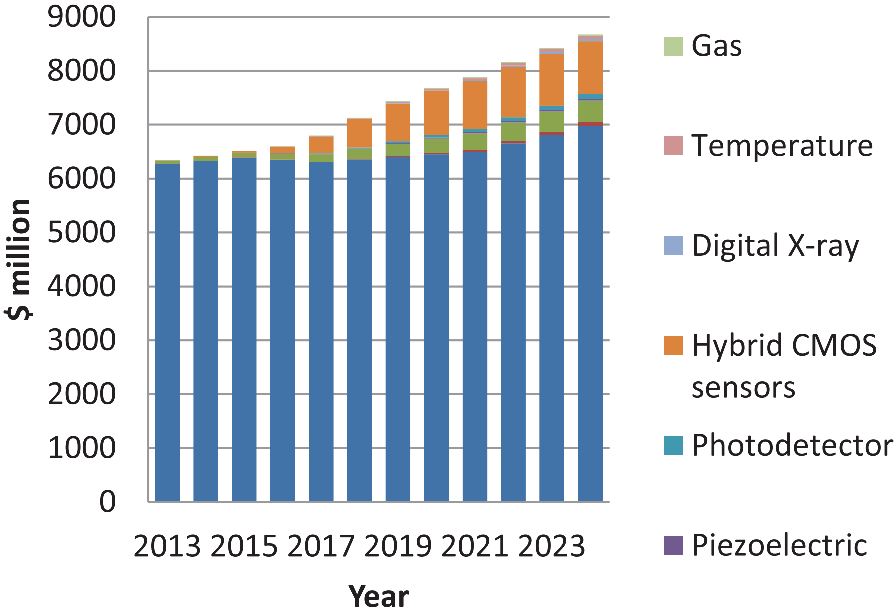


Figure 4.7 Ten year market forecast for printed sensors made in 2014 (in $ million) [Chansin, 2014].

4.2.3 Soft Sensor Computational Trust

This intelligent soft sensor focuses on the interpretation of the errors that occur during the production process in terms of frequency and severity of the different errors in the shaver production plant described in Section 7.1.

In the shaver production plant, tooling quality is one of the factors affecting product (shaver cap) quality. Tooling quality drops as the number of products generated increases and due to problems like a (series of) short circuit(s). When the production monitoring system observes such a problem, it raises an error. There is a list of error codes in the system resulting from different measurements. There is an order of importance among the errors that are considered relevant for tool damage. Increasing number and frequency of errors in a time interval is also considered critical for tooling quality. Operators can stop the process and change the tool due to raised errors and due to finding visible distortions in products upon examination. The changed tool is inspected: if it is faulty it is discarded, otherwise it is added back to the stock.

Table 4.1 Low-cost sensors [Junnola, 2017]

Manufacturer	Model	Type	Sensor Type	Price
Rohm Semiconductor	KXTJ3-1057	MEMS	Accelerometer	0,49 €
STMicroelectronics	LIS2HH12TR	MEMS	Accelerometer	0,49 €
TE Connectivity	1007158-1	Printed Sensor; Piezofilm	Accelerometer	3,40 €
Allegro MicroSystems, LLC	LLC ACS711EEXLT-31AB-T	Integrated Circuit	Current Transducer	0,56 €
Melexis Technologies NV	MLX91209LVA-CAA-000-CR	Integrated Circuit	Current Transducer	1,63 €
Bosch Sensortec	BMP280	MEMS	Pressure Sensor	1,17 €
EPCOS (TDK)	B58601H8000A35	MEMS	Pressure Sensor	1,17 €
Microchip Technology	MTCH101T-I/OT	Integrated Circuit	Proximity Sensor	0,36 €
Semtech Corporation	SX9300IULTRT	Integrated Circuit	Proximity Sensor	0,73 €
NXP	LM75BDP	Integrated Circuit	Temperature Sensor	0,22 €
Texas Instruments	LMT88DCKR	Integrated Circuit	Temperature Sensor	0,17 €

There is room for improvement in this process. Firstly, there can be inconsistencies among operators in interpreting the errors. Moreover, as the shift changes, operators tend to look into the errors raised in their shift time only. A model is presented in the following. It uses error data and the expert knowledge about the relative order of importance among error codes as input and raises a flag when the errors imply a critical tool condition. This soft sensor combines insight coming from different errors and provides some sort of data fusion.

The dataset under consideration consists of *process data* that were collected for several months (162 days) for one of the machines in the shaver production plant and *maintenance logs* serving as the ground truth for why a tool was changed.

A record in the process data contains several process parameters that were measured in the making of a single product, including the time of the production, error code (see Figure 4.8), the ID of the tool used, the numbers of products produced with this tool since it was last replaced and since the first time this tool was ever used. During normal operation the error code parameter contains a 0, otherwise it contains a specific error code corresponding to a certain error type.

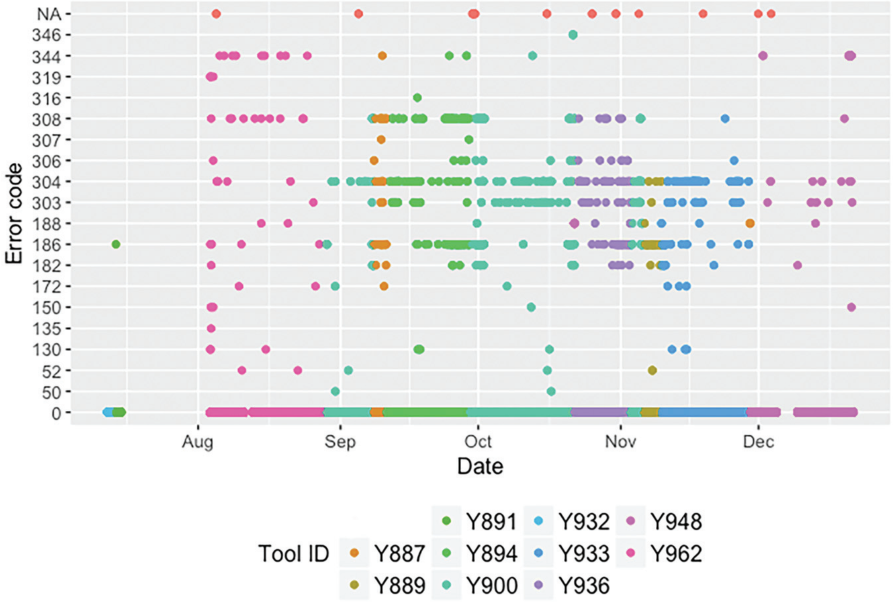


Figure 4.8 Error codes over time, colored based on the tool IDs.

A record in the maintenance log contains the time of the tool change, the number of products produced with that tool at the time of the change, and a note written by the operator indicating the reason why the tool was sent for maintenance.

For tooling quality, not all error signals are considered equally relevant. The codes that operators take into account in practice are 50, 150, 52, 186, 182 and 188. According to the production experts, in a scale of 1 to 5 (5 meaning the most and 1 meaning the least critical), their importance levels are 5, 4, 2, 2, 1 and 1, respectively. This grading can be described by the function:

$$g : X = \{50, 150, 52, 186, 182, 188\} \rightarrow \{1, 2, 3, 4, 5\}$$

$$g(e) = \begin{cases} 5 & e = 50, \\ 4 & e = 150 \\ 2 & e \in \{52, 186\} \\ 1 & e \in \{182, 188\} \end{cases} \tag{4.1}$$

Theoretical background:

Trust is "*the degree of justifiable belief a trustor has that, in a given context, a trustee will live up to a given set of statements about its behavior*" [Bui et al., 2014]. Computational trust aims to quantify the subjective probability (a trust value in [0,1]) that a *trustor* A attributes to the truth of a *trust statement* P that has the following form: "The trustee T satisfies a predicate $\wp$ within context c in the time period δ". In a trust statement, time and context are usually not given explicitly.

The inputs to compute the trust value $tv_{P,i}$ are: positive evidence $p^A_{P,i}$, negative evidence $n^A_{P,i}$, prior trust a^A and the weight of prior trust W^A (see Equation 4.2). Positive evidence and negative evidence are cumulative, and updated after each observation *i* via update rules. These rules capture the anticipated behavior of a trust curve. The weight W^A determines how fast the effect of prior trust decays.

$$tv^A_{P,i} = \frac{p^A_{P,i} + a^A W^A}{p^A_{P,i} + n^A_{P,i} + W^A} \tag{4.2}$$

This is a Bayesian trust model. For further information about Bayesian trust models, see [Jøsang, 2016; Ries, 2009].

Application:

The trust framework was applied to the afore-mentioned production plant dataset. The goal is to make the operators' job easier in a way that reduces inconsistencies across different operators and shifts. Computing trust based alerts can support stability across different operators. Moreover, computed trust will not be impacted by shift changes of people. After each observation, the updated trust value can be compared to a threshold. When the computed trust is below the threshold, the operator can be notified. The trust statement of interest is: "The tooling is in good state for production." The trustee (T) refers to "the tool", and $\wp$ refers to "…is in good state for production". Domain knowledge is inserted into the trust computation through the error importance levels and the design of the update rules given next.

An update rule is implemented by means of the constants $\eta, \gamma, \zeta, \psi \in (0, 1)$, which are chosen to decay the evidence over time. The constants are used together with e_i, which is the error code at observation *i*, and are used to implement the set of formulas in Equation 4.3.

$$
\begin{aligned}
P^{A}_{P,i} &= \begin{cases} \zeta \cdot p^{A}_{P,i-1} & e_i \in X \\ \psi \cdot p^{A}_{P,i-1} + 1 & otherwise \end{cases} \\
n^{A}_{P,i} &= \begin{cases} \eta \cdot p^{A}_{P,i-1} + g(e_i) & e_i \in X \\ \gamma \cdot p^{A}_{P,i-1} & otherwise \end{cases}
\end{aligned}
\tag{4.3}
$$

After each time the tool is replaced, the positive and negative evidences are reset back to zero, implying that the trust value is reset back to the prior trust value (see Equation 4.2). In case the error code is in X, the positive evidence is expected to decay quickly. Also, each time error code is not in X, the negative evidence should decay, but slowly. The following coefficients were chosen to make this possible: $\gamma = .99$, $\eta = .999$, $\zeta = .4$, $\psi = .999$. The prior trust $a^A$is set to .95 and W^A is set to 10.

Figure 4.9 shows the behavior of trust over a shorter interval. The tool was changed three times (on November 3 at 03:24, November 6 at 03:36, and November 9 at 20:53) in that interval and, according to maintenance logs, the reason was error code 186 two of the times, and distortions found upon visual inspection once. There is a small interval with relatively low trust values, on

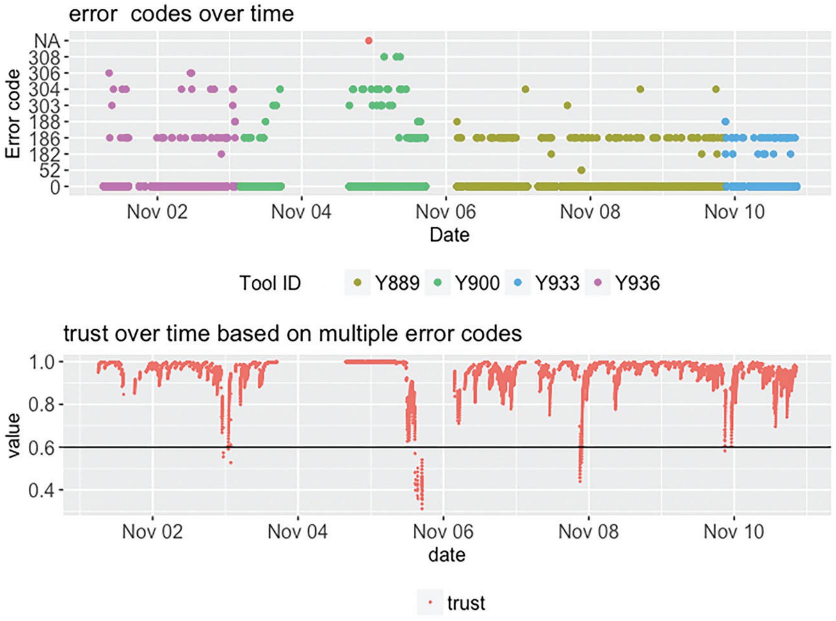


Figure 4.9 Error codes over time, and corresponding trust values.

November 7 around 21 pm. At that time, there is an accumulation of error codes 186 and 52, but the operator chose to take no action.

A set of 13 instances were inspected, where the tool was changed to see if the computed trust was low in the 50 minutes leading to that change. According to the maintenance log, 8 changes were due to errors. Among these for 6 of them the trust was also relatively low. In the remaining 2, despite the operators note that the change was due to errors, these errors were not concentrated in a small enough time interval around a tool change, hence they did not result in low trust. Among the 5 changes that were due to other reasons (due to the preventive maintenance schedule, due to visible distortion in products or other) in two cases, there was also some accumulation of error codes prior to change, hence trust was also low.

Some errors imply deteriorating tool condition, which should result in a tool change. The proposed approach was evaluated by comparing the times of low trust in the tooling being in a good state with the operator notes in the maintenance logs. Mostly, tool changes due to error codes coincide with time intervals with low trust value. There are cases where accumulation of errors did not result in a tool change, or tool changes were due to errors when in fact there were not so many errors. The trust computation shows that there are inconsistencies of operators about how and when the error signals result in a tool change. Supporting operators with the proposed trust framework can anticipate the need for tool changes, improving the timely maintenance of tools and reducing the number of faulty products.

4.3 Bandwidth Optimization for Maintenance

Condition monitoring approaches require sensors in order to gather information about the different components and elements that take part in the performance of the machine. This information may be used locally for estimating the state of the components, but has to ultimately be conveyed from sensors to edge servers or processing centres for data analysis, but bandwidth is, in most cases, a limited resource. Roughly speaking, the bandwidth occupied by a signal can be related to the highest relevant frequency component that conforms the signal waveform. Thus, if one is to reach the maximum data throughput that the channel can offer, a natural choice would consist on trying to reduce the time duration of the waveform for the individual piece of information. This way, more and more information is packed in a given time duration and throughput increases. But as waveform change rate increases, so does the required bandwidth. Fast changing signals occupy a wider bandwidth, and less spectrum-demanding signals have to vary in a slower fashion. With this scheme in mind, it is needed to think of approaches that address the bandwidth optimization issue in an appropriate way. Three such approaches are described below.

4.3.1 Reduced Data Amount and Key Process Indicators (KPI)

One way for decreasing the necessary bandwidth is the reduction in the amount of exchanged data. This way, less spectrum is utilized for the required data throughput and both systems, sensor and edge server, can be of a simpler nature, at least with regards to data processing capabilities. This may lead to a reduced system cost and complexity, but with the drawback of compromised accuracy and reliability of the obtained measurements, as important pieces of information may have to be discarded for transmission. A much better approach could be the reduction of the amount of data by discarding the undesired data and sending only key indicators of the condition of the machines by means of KPIs, which are fundamental for the design and maintenance phase of a machine, as they allow identifying faults, their underlying causes, and any effect that can propagate to other systems. Usually, the monitored machines or parts are comprised of components that are related with each other, so that the deviation of a component from its normal performance causes additional, measurable effects in other components. KPIs are extracted from qualitative models of devices under observation, taking advantage of measurements and estimated magnitudes and parameters. For this purpose, the most meaningful magnitudes of the machines are analysed, highlighting the performance of the system as shown below and described for example in [Mehdi et al., 2015]. See Figure 4.10 for a graphical representation of the process.

On a first stage, all the raw data collected from installed sensors is preprocessed in order to obtain appropriate signals of the measured magnitudes for their later analysis. On the second stage, the preprocessed data is processed through data analytic tools made available by software sensors. At this stage, the condition monitoring of the machines is performed, extracting magnitudes and parameters of interest. At this point, these magnitudes and parameters themselves could be used as KPIs, as they monitor directly the condition of the analysed machine. On the final stage of the data analysis, a high level abstraction data reduction is still possible, by combining the most relevant magnitudes and parameters extracted from the previous stage. These KPIs may not have a straightforward physical interpretation, but they show

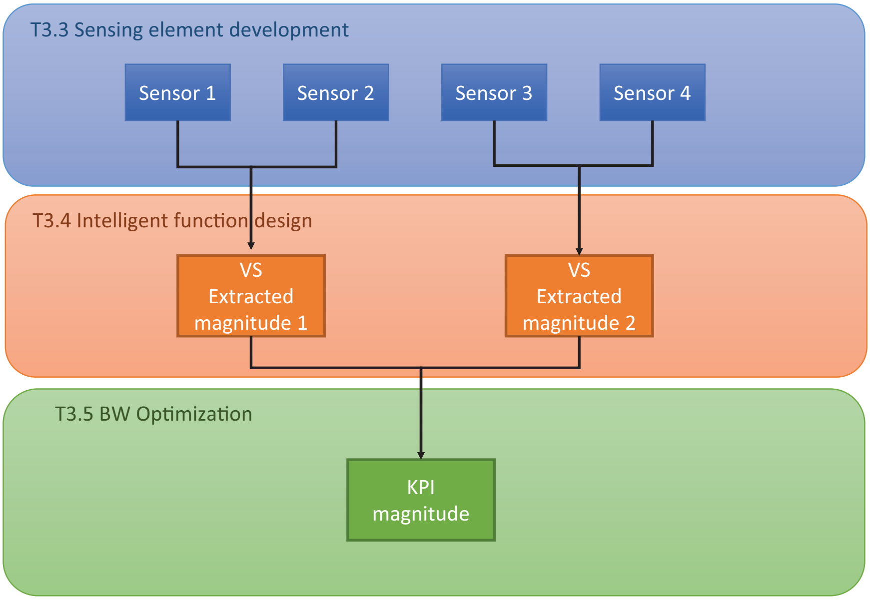


Figure 4.10 BW optimisation by KPI extraction.

the working condition at which the machine is. In this way, KPIs can be used to effectively reduce the amount of data that will be exchanged with the main processing and decision centre, optimising the use of bandwidth.

4.3.2 Advanced Modulation Schemes

In the previous approach, a decrease in the quantity of transmitted data was used for the reduction of the required transmission spectrum bandwidth. Second scheme focuses on the time percentage on which the physical medium is occupied for data exchange, so that alternative sensors can communicate in different time slots.

Communication is performed by the transmission over the wireless of wired medium of a *symbol*, which is the minimal entity that can represent some digital data to be sent. The bandwidth optimization technique is based on the concept of modulation, which is the way that data bits are associated to the symbols.

The bandwidth optimization can be addressed from a frequency, phase or amplitude point of view, or by a combination of them, by means of applying different modulations to the signal used to carry over the data. In fact, while the most obvious signal modulation is able to send a single bit with each signal, for example by encoding a 1 with the presence of a wireless wave and a 0 with its absence, it is possible to use a richer alphabet of symbols to encode the data, and this way send more than one bit at a time. On this regard, an N-fold increase in the number of the allowed discrete symbols used for the modulation allows to send a larger ($\log N$) number of bits at the same time while occupying a single symbol duration, i.e., by means of one symbol. More information on modulation schemes and related subjects can be found in [Proakis, 1995; Oppenheim and Willsky, 1997; Haykin, 1994; Proakis, 1995].

It is worth mentioning that the increase in the data transmission rate achieved by means of such modulation processes comes at the expense of more complex sensor and data processing systems, involving electronics related to modulating and demodulating processes, adding protocol complexity to the signal processing methods and thus increasing the total development and deployment cost. On this regard, despite commercial transceivers are readily available in the market and render the development of such systems from scratch unnecessary, their protocols are generally proprietary and restricted to work at certain limited frequency bands (such as ISM). In addition to this, the power supply requirement of such electronically advanced sensors has to be considered before opting for a complex modulation scheme, as in several measurement systems, low power consumption is an important constraint.

4.3.3 EM Wave Polarization Diversity

The third approach for the bandwidth optimization arises from the fact that antennas respond differently to electromagnetic fields whose spatial field distributions show diverging field orientations. This phenomenon is known as **polarization** [Mehdi et al., 2015] and implies that, for antennas that lie in a given plane, such as the ones represented in Figure 4.11, maximum EM wave power reception occurs for the plane parallel to that of the antenna. On the contrary, a minimum fraction (ideally zero) of the incoming EM field power is captured by the antenna if the relative angle between incoming field and antenna approaches 90 degrees. With this behaviour in mind, it is possible to think of an arrangement of a couple of antennas, orthogonal to each other and both making use of the same transmission frequency value. As long as the data receiving part of the system deploys a pair of also relatively perpendicular antennas (with spatial orientations respectively

Figure 4.11 Linearly polarized quasi – Yagi antennas: Maximum alignment (left) and maximum misalignment (right).

parallel to those of the transmitting antennas), an effective doubling of the data transmission rate is at hand, at the expense of doubled antenna and cabling deployment cost. Nonetheless, present antennas fabricated in printed circuit form (integrating the associated electronic circuitry) can achieve the desired goal at a reduced cost. Finally, it is of importance to consider situations in which the spatial orientation of the antennas changes with time (e.g., Rotating or translating frames for the sensors and/or data receiving equipment). In those cases, it is necessary to ensure that the relative orientation of the transmitting and receiving antennas does not change, as the aforementioned dynamic displacement could lead to a situation in which transmitting sensor antennas are spatially paired with a wrong receiving antenna, and thus different sensor information would not be received and processed by the appropriate system. Several classical texts on antennas [Balanis, 1982; Krauss and Marhefka, 2002; Stutzman and Thiele, 2013] can be consulted for a more in depth knowledge on the subject.

4.4 Wireless Communication in Challenging Environments

New technological solutions such as WSNs have become a strategic asset in industrial context. This type of sensor networks are used to share information with the purpose of increasing productivity, gathering data for developing future technological improvements or detecting/predicting maintenance issues. Besides, the use of wireless communications provides flexibility, installation ease, weight reduction, etc. which makes them suitable for many applications, conditions and situations.

Industrial environments usually have hostile site conditions, both for the sensors (dust, oil, heat, corrosive products, vibrations, etc.) and for the wireless communication systems (interferences, metallic environments, etc.). These conditions must be considered before and during the design and development process of a WSN as they could make an impact on the resultant performance. Besides, there are also requirements such as synchronization, low power consumption or data security that can constrain the design process of the wireless sensors to be deployed within an application.

In this section different possible networking solutions are analyzed in order to describe a design methodology to be followed when a wireless sensor solution has to be deployed within a specific challenging environment. The design methodology aims to gather as many technological alternatives and communication solutions as possible.

4.4.1 Design Methodology Basis

The proposed design methodology is targeted at wireless networks in industrial scenarios, and it is organized as follows:

- *Requirements and challenges identification.* This task consists in the network requirements definition according to the specifications and needs of the industrial application, to investigate the constraints and limitations of the resulting network;
- *Characterization of the medium.* This is an essential step during the development of the communication system, as well as the available bandwidth measurements. This provides information about the main parameters that can negatively affect the wireless signal propagation inside the factory. Moreover, mathematical representation of the environment or wireless channel can be obtained;
- *Interference detection.* It is mandatory to know about the presence of other possible users of the spectrum in the area where the network is located. Interference level information would provide a view on the minimum requirements for the device under design, especially to develop a system robust enough to handle and maintain the communication in a specific interference level;

- *Power and energy saving aspects.* Wireless devices usually are battery powered devices, and consequently they have a limited autonomy level. Therefore, low power and energy cost aspects have to be taken into account before and during the network design and development in order to extend the network lifetime;
- *Development of the device.* Considering all the information gathered from the previous tasks, it is time to select, design and develop the components, the topology and the PHY and MAC layers required by the wireless communication system. There are many examples proposed in the literature, so the adequate alternative should be chosen and modified depending on needs and the requirements determined in the previous steps;
- *Validation.* Once the network is designed and deployed, it is necessary to carry out its validation. As a first step, performance tests using a channel emulator are highly valuable, since this type of device enables the designer to test different propagation parameters and effects in a lab environment, testing if the designed system is reliable enough for the industrial site it is destined to;
- *Performance tests.* As a last step, it is necessary to make performance tests in the target location to know whether the network fulfils the specified initial design requirements or not.

4.4.2 Requirement and Challenge Identification

This step collects the requirements and challenges that can be found in a project related to wireless communication systems.

The industrial environment has always been a very demanding scenario for technology, especially for wireless communications. There are usually elements such as metallic surfaces, electro-magnetic interferences, rotating or moving elements, vibrations, etc. that influence directly or indirectly the wireless devices or the electromagnetic waves used for communication.

The large metal surfaces that are usually located in industrial environments distort the wireless signal, which leads to reflections, scattering and diffraction. The metal surfaces can make the signal travel via different paths, which then suffers from multipath interference.

Moreover, in industrial spaces there is also massive electromagnetic noise. Noise is usually caused by hardware thermal effects, other wireless networks or industrial machinery which can alter the correct behavior of the network at the industrial site. Figure 4.12 shows some processes and devices which cause interference in industrial environments.

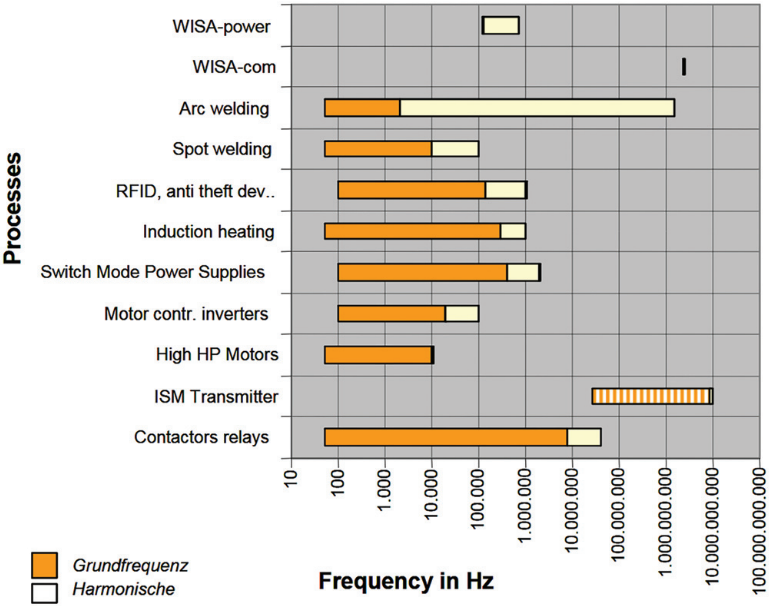


Figure 4.12 Interferences from different processes and devices in industry.

Sometimes it is possible to used wired technologies to protect communication from these problems, but many scenarios do not allow for cables and must use wireless nodes. For example, machines can have rotating or moving parts such as rotors, assembly chains or clutches.

4.4.3 Channel Measurement

The main objective of the channel measurement task is to reduce the effort involved in the selection of the most suitable PHY and MAC layers during the following steps of the methodology as well as to obtain detailed information about the specific industrial environment. This reduces the time and effort required for the development, while maximizing the performance of the resulting network.

Most of channel characterization techniques are based on stimulus-response measurements. The channel is excited with a predefined and known signal and it is received on the other side of the communication. Then, the differences between the acquired and emitted signals are observed to determine the characteristics of the channel. As a result, a mathematical model for the channel is obtained. This model is to be used both in the PHY and MAC selection and as well in the validation process, for example while using a channel emulator.

The most important statistical parameters within a channel model are the following:

Multipath characterization – The multipath effect causes signal amplitude variations because of the arrival of the waves from different paths. Signals usually suffer similar attenuations but different phase modification, which leads to constructive or destructive interference in the receiver. The characterization of this effect may be useful to place the antennas and avoid destructive interferences. To compensate the effect of multipath, the equalization technique is commonly employed. Furthermore, other solutions such as directional antennas provoke less multipath signal components and consequently less fading and delay spread.

Coherence bandwidth measurement – This is a statistical measurement of the range of frequencies over which the channel can be considered “flat”, which is the frequency interval over which two frequencies of a signal are likely to experience comparable or correlated amplitude fading.

The obtained results help in the further selection of the PHY and MAC layers of the communication system to be deployed: wide-band/narrow-band, techniques to mitigate fading (diversity, equalization, OFDM, MIMO), techniques to mitigate interference, etc.

3D modelling – Simulation algorithms based on the ray tracing method-of-images enhanced by double refraction modelling can be used to identify the correct placement of the receiver and transmitter antennas. The algorithm takes as input a 3D model provided as a list of triangulated surfaces and a list of convex edges, outputs a signal loss value in dB for each surface in the receptor plane. An example is represented in Figure 4.13, where the colour scale is from 0 dB loss (black) to 100 dB (white).

4.4.4 Interference Detection and Characterization

The current use of the wireless spectrum by the nearby elements or devices has an influence in the design of a wireless network, so interference measurement and interference modeling is useful to characterize wireless behaviour in a specific environment. Therefore, it is essential to study the primary users of the desired frequencies in order to avoid possible interferences and poor network performance.

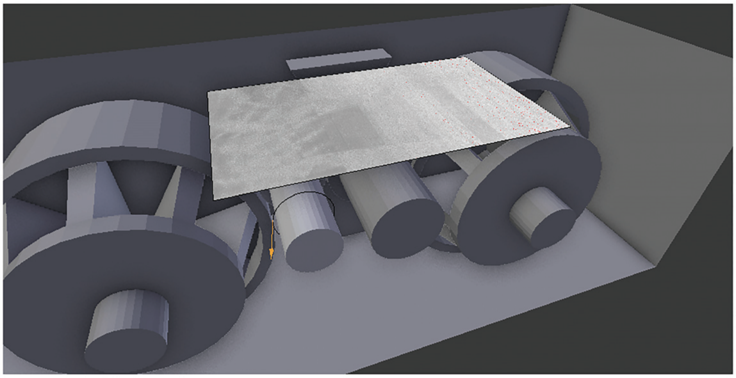


Figure 4.13 Example of a 3D model.

The main causes of external interference are the electric interference and other RF wireless networks. Furthermore, these interfering signals might have been transmitted maliciously by a jammer. RF interference can be a very serious threat especially for low power wireless networks.

Interference may be also caused by industrial machinery, such as motorized devices or computers. Electrical motors and relays are one of the most interfering elements, especially during the switching instants. In addition, other types of high-voltage devices can also be an interference source due to defective insulation.

To solve RF interference problems, the most common alternatives involve eliminating the source of the interference, or modifying the transmission frequency. However, this is not always possible, so researchers are developing new mechanisms to behave dynamically in case of RF interference presence.

4.4.5 PHY Design/Selection and Implementation

The PHY layer is the first and lowest layer of the OSI model, and consequently it has a considerable impact on the final operation and performance of the network. Therefore, the physical layer should be carefully designed/selected to satisfy the requirements defined during the first step of the methodology.

Most standards address PHY and MAC layers together, hence a decision regarding the PHY layer has an impact regarding which MAC layers can be used in the system.

4.4.5.1 Single/multi carrier

The first aspect a designer should decide is whether the physical layer is a single carrier or multicarrier based physical layer. In single carrier based physical layers, just one carrier is used to carry all the information. They are simpler than multicarrier based alternatives and are a better fit for low consumption but low performance solutions.

On the other hand, multicarrier based physical layers are designed to operate with multiple carrier signals at different frequencies to send the data. This approach has got performance advantages and is more robust against narrow-band and multipath interference. On the other hand, the main limitation of multicarrier physical layers is the difficulty to synchronize the carriers correctly. Besides they require more bandwidth and the PHY layer's complexity has a direct impact on power consumption.

4.4.5.2 High performance/low power

This is a dual view with respect to the previous section. An engineer should also take into account the difficulties that may appear to achieve the desired performance with low power consumption. For example, multi carrier modulations are more complex and they are more demanding on the energy. However, they provide a higher data rate and a high robustness against interference comparing to single carrier modulations. Therefore, the data rate and the results from the interference detection step must be taken into account in this decision.

4.4.6 MAC Design/Selection and Implementation

The MAC sublayer is part of the Data Link Layer of the OSI model and there are many alternatives to design or select a MAC layer for the wireless communication system to be developed.

Many aspects can be discussed within the selection/development of a MAC layer: low power consumption, synchronization and real-time features, cognitive features, security, reliability, etc. Moreover, the selected MAC layer must be compatible with the PHY layer chosen in the previous step.

4.4.6.1 Real-time/deterministic MACs

There are many mechanisms to access the medium for wireless technologies, though the techniques can be classified into two major groups. On the one hand, there are channel partitioning based Media Access Control mechanisms where the channel is divided into several parts so that several nodes can access the channel in a multiple manner. In this way, nodes can only communicate on their assigned division. The main advantage of channel partitioning is the ease to organize the communications between nodes, but this alternative is not suited for sporadic and bursty communications. On the other hand, random access based MACs can be also divided depending on contention capacities, such as in the case of ALOHA or CSMA.

The MAC layer has to be chosen depending on the requirements of the application as well as the characteristics of the environment. To ensure determinism and real-time communications, partitioning based media access should be used. The random access based MACs do not ensure transmissions bounded in time because they can allow the presence of collisions among the nodes in the network. However, the partitioning based MACs are more complex due to the fact that they require coordination among the different nodes in the network.

4.4.6.2 Low-power MACs

Apart from the most common options and standards, there are many Low Power MACs for WSNs in the literature. The studied MACs can be divided into the following three categories: asynchronous, synchronous and multichannel.

The asynchronous MACs are aimed for networks whose nodes have different active/sleep schemes. The nodes of this type of networks are asleep most of the time and they wake up to just communicate occasionally. The fact that each node has its own scheme requires communication establishment process with long communication preambles in order to make the receiver detect the transmitter node. Therefore asynchronous MACs can result in an adequate alternative for low traffic networks. The main drawbacks of asynchronous MACs are the low spectral efficiency and channel inhibition due to long preamble as well as poor or none time synchronization, which is usually required by many industrial applications.

The synchronous protocols are thought to obtain instantaneous wake up between the nodes and, on the contrary of asynchronous MACs, the devices of the network have a predefined behaviour. Only predefined transmitter and receiver access the channel at a determined moment, while the other devices remain asleep or just listen to the channel until their communication time. The energy consumption is usually a main issue for synchronous MACs, thus their techniques try to avoid the principal energy wastes: collisions, overhead and overhearing. Synchronization can result in delay reduction and throughput improvement, although it requires an additional overhead to the communication to send information related to the clocks and synchronization.

This requires the implementation of algorithms to manage the temporal aspects of the network.

Multichannel MACs are used to enable parallel transmissions by using different channels for the communication between groups of nodes. The tendency is to combine TDMA and FDMA in order to achieve a higher communication rate and consequently a better overall network performance. Therefore, the nodes must be able to handle frequency changes over time, which usually require more expensive technologies.

4.4.6.3 High level protocols for error mitigation

Communication in a challenging environment has to cope with problems in the communication process, which can take the form of errors in the transmitted data, fluctuating bandwidth, and intermittent connections. Current approaches to cope with the hurdle can be divided into two families:

- *Message caching*: this set of approaches is based on caching the messages to be exchanged. The message is kept in the cache and the communication process is repeated until the recipient is reached. Most of these techniques are based on brokers that act as intermediaries in the communication process. These techniques help only with errors on the channel from the broker to the receiver, and do not support communication from sender to the broker. The Advanced Message Queuing Protocol (AMQP), the Message Queuing Telemetry Transport (MQTT), the Java Message Service (JMS), the Data Distribution System (DDS) and the Open Platform Communications Unified Architecture (OPC-UA) are some of the most common implementations;
- *Cognitive communication*: it is based on the use of context information to drive the mechanisms of communication protocols. Context information is exchanged over the application layers, and it is used to drive the lower layers in order to mitigate the noisy and congested spectrum bands, for example by controlling which wireless frequencies are used over time, yielding reliable and high capacity links for wireless communication.

4.4.7 System Validation

The main objective of system validation is to measure the performance of the designed wireless communication system and verify if it fulfils the requirements identified in the first steps of the design process. This validation

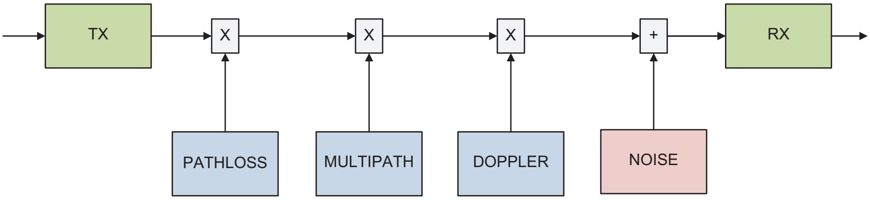


Figure 4.14 Channel emulator scheme.

can be done using instrumentation such as channel emulators or/and via tests in the target location.

4.4.7.1 Channel emulation

Channel emulators enable to reproduce controlled and programmable channel conditions so that product performance can be evaluated in realistic conditions before product release or delivery. Information obtained from the channel measurement step is used in this emulation process, such as parameters on Pathloss, Multipath, Doppler or Noise.

This is shown for example in Figure 4.14, which depicts the insertion of these effects during the emulation of the channel.

The validation by channel emulation can provide useful information about the networks behaviour or performance. The main drawback of wireless channel emulators is the limited support for a high number of devices.

4.4.7.2 Performance tests

Once the communication system has been installed in the target location, the initial design requirements satisfaction needs to be verified. These are the main topics to be taken into account:

- *Channel selection*: Depending on the wireless spectrum used, and especially in 2.4 GHz frequency bands, it is important to select the best channel to avoid interferences;
- *Coverage verification*: For each wireless device installed, it is needed to know how much signal power is arriving to the installation point. Using this information, usually some range or ranges can be defined:

signal > -x	→ Good coverage
-x > signal > -y	→ Normal coverage
-y > signal	→ Poor coverage

After these verifications, some corrective measures could be needed. Some examples could be to move the sensor to a new spot, to use an antenna extender or to add a repeater to improve the coverage area;

- Regarding the topology, it is recommended that every sensor should have at least two good neighbours (with good coverage) to ensure that if any problem occurs with one link, the communication is guaranteed by routing over other links;
- *Packet reception verification*. Once the coverage checking process is completed and eventual problems described in previous paragraphs are solved, it is necessary to ensure that data is transmitted continuously and without losses that could show any kind of coverage problems. Ideally, the test period should have enough time to cover at least: all possible climate conditions (rain, sun, etc.), day and night and several days operating in normal environmental condition with all equipment and staff working as usual.

4.5 Intelligent Functions in the Sensors and Edge Servers

In the present section, the main categories and their subcategories regarding intelligent functions are presented, the main distinction being whether the function falls in the "intelligent" or "smart" category. Nonetheless, other possible categorizations arise, and are briefly discussed. Later on, a list of intelligent and smart functions is given, depending on the way the data is handled, and details on the implementations are also given, based on real-life sensors developed for various use cases.

Smart vs Intelligent

A sensor is a combination of one or many sensing elements, an analog interface, an analog to digital converter (ADC) and a bus interface all in one housing. A *smart* sensor can be defined as a sensor that, in addition to the pure sensing, provides communication and preprocessing, which are needed in most Maintenance 4.0 applications, and possibly more complex capabilities pertaining to the following categories:

- outlier detection (from historical data);
- false value detection (from data);
- combine and choose the best value.

An *intelligent* sensor has got some level of self-awareness, and for example can provide functions such as self-testing, self-identification, self-validation, self-adaptation, etc. (see Figure 4.15). These functions can also support the

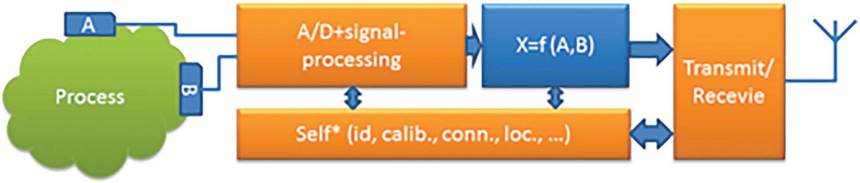


Figure 4.15 Schematic outline of a process measured by a sensor with sensing elements A and B.

maintenance of the sensor itself, or they could give additional information about the accuracy, the confidence of the measurement result or about the sensor's own "health status", and can support in more sophisticated ways the distributed collaborative decision-making concept for monitoring and proactive/predictive maintenance.

The most common intelligent function found in the industry is self-validation. In many use cases the intelligent functions are implemented at a higher level than the sensor level, therefore they are not directly associated to the sensor. In the edge tier, this set of functions is commonly implemented in the Raspberry Pi based gateways, where considerable processing power is present.

Domains of the measurements

Most sensing aspects relate to six well-defined physical domains, listed in Figure 4.16.

Most of the use cases of the MANTIS project monitor environmental data such as environmental temperature, humidity. More often than not, use cases have special sensors, not shared by other use cases. This was expected, as different use cases have case specific sensors.

However, there are some sensors that are common for many industrial use cases. Such examples include:

- Oil quality;
- Vibration;
- Temperature (not environmental);
- Air pressure sensor;
- Power sensor (electrical);
- Current sensor.

More information on this topic can be found in [Albano, 2018].

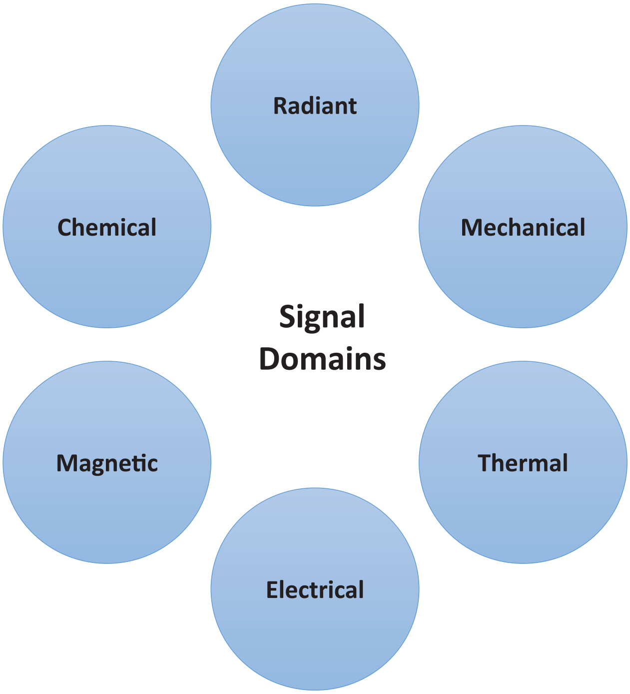


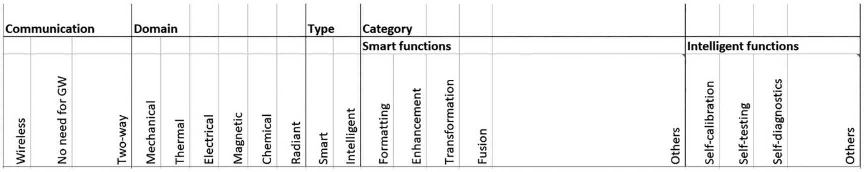
Figure 4.16 Sensing Physical Domains.

Communication

The sensors can communicate through a wired or wireless technology.

From the communication perspective, the sensors can use unidirectional communication (just upstream, uploading data) or bidirectional, where sensors can also receive commands. The bidirectional communication enables additional intelligent functions and interaction between different levels of processing, such as collaborative decision making.

The sensors may be able to communicate directly to the cloud, or they may require a gateway for communication. In many cases the sensor is only capable to send the actual sample, using simple wired/wireless communication. In these cases a gateway is needed which can run a more complex communication stack capable of uploading data to the cloud with the required context and security. The analysis of the collected data showed that many of the use cases have complex devices, such as gateways, that are used as aggregation point for sensors and perform smart/intelligent functions and communication.



Communication			Domain						Type		Category								
											Smart functions					Intelligent functions			
Wireless	No need for GW	Two-way	Mechanical	Thermal	Electrical	Magnetic	Chemical	Radiant	Smart	Intelligent	Formatting	Enhancement	Transformation	Fusion	Others	Self-calibration	Self-testing	Self-diagnostics	Others

Figure 4.17 Categories table header.

Function categories

It is possible to compile a table for the categories of smart and intelligent functions, to find commonalities along the categories. This approach can provide a further level of refinement to three subcategories cited above (self-calibration, self-diagnostics and self-testing), and the same is true for the smart functions.

The categories table is reported in Figure 4.17. No straightforward hierarchical characterization and listing of sensors emerge from the table, and the proposed taxonomy considers "intelligent" and "smart" as the two main categories for intelligent function distinctions, considering additional characteristics (those regarding aspects like communication or measurement domain) as implementation details for a given function. In the following sections, the defined intelligent functions are explained and practical examples are given.

4.5.1 Intelligent Function: Self-Calibration

Sensors are used to measure different physical magnitudes, and their outputs are correlated to the absolute values of the latter. This correlation can consist in an absolute value correspondence between the output value and the measured property, or can also consist on a relative change representing the variation of the magnitude under measurement. Whatever the case, be it absolute or relative measurement, one desirable property of a sensor is that of being able to compare its present output value against a predefined input, the latter emulating the effect that the magnitude under measurement exerts upon the sensor. This way it is possible to check whether the outcome of the sensing follows the expected performance. Sensors that incorporate the ability of self-calibrating function substitute thus the actual magnitude under measurement with known input values and check the corresponding output, in order to apply the needed corrections.

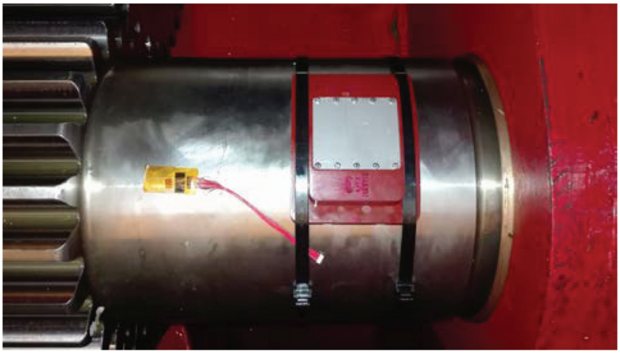


Figure 4.18 Torque sensor.

4.5.1.1 Practical application: Press machine torque sensor

The strain gauges used in the press machine for the torque sensing, represented in Figure 4.18 and further described in Chapter 7 Section 3, require a good initial settlement to enhance dynamic range and avoid signal saturation. Two techniques have been implemented to achieve this initial settlement: auto-zeroing and offset cancellation. The self-calibration intelligent function is handled by the microcontroller through programmable interface electronics in an iteration loop until both the pursued zero value and the elimination of the offset are reached.

4.5.1.2 Practical application: X-ray tube cathode filament monitoring

In the monitoring of health equipment, described in Chapter 7 Section 9, an X-ray tube is connected to a so-called High Voltage generator to enable and control its operation. There are three basic functions that the generator has to perform to enable the X-ray generation:

- It needs to supply the high voltage (in the range of 40 kV to 125 kV) between the cathode and the anode;
- It needs to supply a heating current to the cathode to control the amount of electrons emitted;
- It needs to power the electromotor to spin the anode disk, so the electrons hit an ever moving "focal track" to avoid too much damage in one position.

The X-ray tube can electronically be seen as a passive component without any intelligence. The control intelligence and sensing are mainly built into the generator. In the use case on X-ray tube monitoring some extra intelligence was added to the sensing already available.

The X-ray tubes are used for making medical images. Depending on the type of image desired, the properties of the patient, the technique used and considerations of physical and regulatory limitations, an optimal regulation strategy was designed. This makes it possible to obtain very similar imaging results for a wide range of patients with different weights and bone structures. It is important for the Image Quality that images are taken at correct set points for tube voltage and emission current. The first time a X-ray tube is used a number of properties of this tube are measured and stored to enable the generator to actually reach the desired settings. The usage of the tube will cause the actual behavior to deviate increasingly from the stored properties. During a semi-annual recalibration cycle, the properties need to be measured again. The self-calibration intelligent function implemented in the context of the MANTIS project, was able to remove the need for this recalibration cycle.

There are three reasons why it is desirable to eliminate the need for recalibration:

- For the recalibration it is necessary to produce X-ray for a non-medical purpose. For reasons of radiation-safety it is highly desirable to limit this as much as possible;
- The further the tube starts to deviate from the stored properties the higher the probability that regulatory constraints or image quality are compromised;
- The recalibration takes time of field service engineers and the faster they can perform their jobs the lower the cost is.

The proposed intelligent function limits itself to the direct relationship between a particular high voltage generator and the X-ray tube connected to it. The algorithm provides means to automatically adjust the initially established properties to the changes caused by the wear of X-ray tube parts. The algorithm to perform this adjustment runs inside the generator itself. It also provides a means to monitor X-ray tube wear.

The algorithm is represented in Figure 4.19, and it proceeds as follows. When a filament heating current ($\mathrm{I_{fa}}$) is applied, given a tube voltage, this produces an actual emission current ($\mathrm{I_{ea}}$), this allows to look-up the corresponding filament current at this tube voltage in the adaptation table: ($\mathrm{I_{ft}}$). For the next run it is possible to find the set-point for the filament current: ($\mathrm{I_{fn}}$) by looking-up the filament current for the desired emission current and tube voltage: ($\mathrm{I_{fd}}$) with the formula:

$$(\mathrm{I_{fd}}) = (\mathrm{I_{fn}}) * (\mathrm{I_{fa}})/(\mathrm{I_{ft}}) \tag{4.4}$$

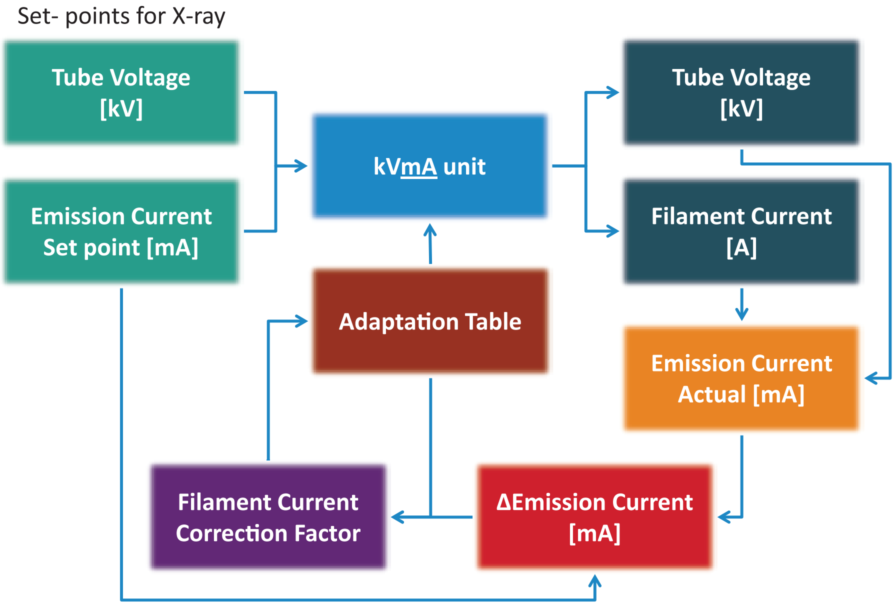


Figure 4.19 Filament heat/emission correction.

Figure 4.20 Sphere Avisense.

The factor: $(I_{fa}) / (I_{ft})$ that actually adjusts the adaptation table is a correction factor called the C-factor (F_c).

4.5.1.3 Practical application: Compressed air system

The Air pressure sensor called Sphere Avisense, represented in Figure 4.20 and used in the use case on pultrusion described in Chapter 7 Section 2, supports the user by displaying the different steps to follow for analog outputs calibration. The output calibration procedure consists in measuring the current for 5mA and 19mA current set by the sensor. After entering those real values, a correction is done on board to calibrate the output. This calibration needs to be done for the 2 analog outputs and then must be stored locally.

4.5.2 Intelligent Function: Self-Testing (Self-Validating)

The performance of wireless sensor networks could be greatly improved by self-testing or self-validation techniques. Fault tolerance is a highly desirable property for any control system. Fault-tolerant controllers typically rely on some sort of fault detection algorithm, and self-testing or validating devices extend this concept, supplying the user with an estimate of measurement reliability as well as measurement value and its associated uncertainty. Generally, this type of function relies on data analysis techniques applied to aggregated information, gathered from several distinct sensors. This aggregated data can be analysed and mathematically processed to obtain a basis for the identification and quantification of inconsistent data, and evaluation of reference values and associated uncertainties. Self-validation thus becomes more important when various data from multi-sensors or multi-measurements are sent to the system.

4.5.2.1 Practical application: Oil tank system

The algorithm of Software Based Testing with Compressed is used for the Oil Condition Sensor in Figure 4.21 and employed in the monitoring of pultrusion process (Chapter 7 Section 2). The algorithm combines SBST testing with CS and can improve some limits such as limited time testing, limited energy and limited processing capability in WSNs. The framework contains six major steps:

- Step1. The SBST produces test vectors for each WN and test vectors development to all units of WN such as power supply, communication and sensing units;
- Step2. The test-result is compared with a result known in each WN to uncover any fault;
- Step3. The BS collects all compressive test-results of all WNs with recovers the original test-result for each WN;
- Step4. The WN is implemented UT that is Test Driven Development (TDD) that produces different test vector than SBST program and new test-result is written on WN;
- Step5. The WN is sent the new test-result to BS.

Figure 4.21 Oil condition sensor.

4.5.2.2 Practical application: Air and water flow and temperature sensor

The sensor in Figure 4.22 is used to monitor the pultrusion process, described in Chapter 7 Section 2. The sensor incorporates a red/green display for clear identification of the acceptable range. If the measured value is outside the measuring range or in the event of an internal error, the current or frequency signals indicated in Figure 4.23 are provided.

For measured values outside the display range or in case of a fault, messages are displayed

The analogue signal in case of a fault is adjustable:

[FOU] = On determines that the analogue signal goes to the upper final value (22 mA) in case of an error.
[FOU] = OFF determines that the analogue signal goes to the lower final value (3.5 mA) in case of an error.

4.5.2.3 Practical application: Sensors for the photovoltaic plants

When reviewing irradiance sensors in the field, it was found that they often tend to underestimate the solar resource. This phenomenon has been

Figure 4.22 Air/water Flow and temp: SA5000, IFM electronic.

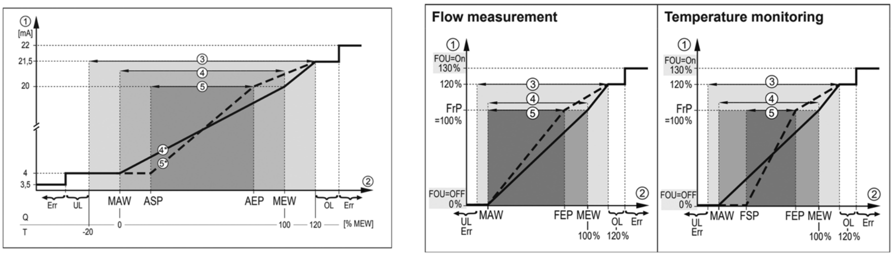


Figure 4.23 Air/water/temperature sensor: Error signals for self-test result indications.

identified by analysing data from a random selection of 88 sensors recorded by 3E, who is the use case owner and built the monitoring platform SynaptiQ, and comparing it with irradiation data derived from satellite images, which has proven to have a very low error for annual irradiation. The results, collected on the use case described in Chapter 7 Section 7, show that 50% of all sensors tended to underestimate the yearly irradiation by 7% or more. It is therefore possible to conclude that many resource assessments or PR calculations based on these sensors and data will be biased in the same way.

A Solar Sensor Check has been developed and applied to check the integrity of irradiance sensors based on measurements and indicate if their measurements are wrong or imprecise. The PV Sensor Check checks for a selection of most important faults and imprecisions in an automated process based on measurements. It returns a conclusion on whether a fault could be detected or not. If a fault is detected, the Sensor Check specifies and quantifies the error and indicates the most probable root causes (see Table 4.2), so that the user can decide on alleviation actions. The effects considered in the developed work are plausibility (data completeness, minimum and maximum values, overall data bias), soiling (reduction on the measured irradiance relative to the real irradiance) and shading (reduction on the measured irradiance in dependence of the sun position in a highly nonlinear way).

Table 4.2 Sample output of the Solar Sensor Check

Check	Fault Illustrator	Fault Illustrator Value	Conclusion
Recording: maximum irradiance	Maximum Irradiance	1126 W/m^2	OK
Recording: minimum irradiance	Minimum Irradiance	0.75 W/m^2	OK
Recording: sensor data complete	Daytime recording fraction	68.5 %	Not OK
Total irradiation	Mean bias error	−6.48 %	Not OK
Clock synchronization	Time shift	0 min	OK
Sensor orientation	Estimated azimuth & tilt	58°, 10°-> − 20°, 29°	Not OK
Sensor calibration: offset	Sensor offset	1.8 W/m^2	OK
Sensor calibration: slope	Sensor slope	0.968	OK

4.5.3 Intelligent Function: Self-Diagnostics

Broadly speaking, self-diagnosis can be thought of as the process by which a sensor self-applies a method to detect or evaluate a failure in its functioning. These methods often rely on "pulling" different state indicators from the sensors (e.g., connectivity metrics, current or voltage consumption, historical measurements…) and conducting then the pertinent analysis upon the gathered data. The sensor can be represented for example as a state-machine that, in accordance with the given inputs, transits from state to state, reporting (based on constructed fault detectors) back to the central analysis unit and taking decisions based on the estimated performance and possible failures. The state of the sensor can be checked for detection of lost calibration. For example, if after the self-diagnosis a sensor presents offset behavior, an alarm should be triggered. Other sensors correlated to this sensor need to be checked to distinguish a sensor anomaly from a component and/or compressor anomaly. If redundant or highly correlated sensors are available, relationship between the sensor can be used to perform further tests.

4.5.3.1 Practical application: Environmental parameters

A number of alarms can be configured for the sensor in Figure 4.24. In the use case of pultrusion described in Chapter 7 Section 2, two different alarms can be configured for each of the three different parameters measured by the device: minimum (low) and maximum (high) levels can be specified in the device.

The device is continuously verifying the voltage of the battery. If the level of mV falls under a certain threshold (where the device still runs but the situation starts to be dangerous), an alarm is raised.

Figure 4.24 ZED-THL-M ZigBee sensor for temperature, humidity and light.

4.5.3.2 Practical application: Intelligent process performance indicator

The production process of shavers, described in Chapter 7 Section 1, consists of several physical manufacturing processes. Electrical, chemical and mechanical elements are working together in order to produce the products, making it a highly complex process where interactions between different signals can be easily overlooked when just monitoring every signal individually. A soft sensor that combines all different signals and processes them together will give better insight in these interaction effects via computational intelligence. This sensor fusion mechanism will deal with signals of disparate sources that do not have to originate from identical sensors.

The PCA algorithm in combination with the Hotelling's T^2 score is used to get insight in the interaction effect of all different process parameters. The process parameters are first preprocessed by the PLC-PMAC system, after which they are stored in a database to serve as input to train algorithm. To train the model, the data is extracted from this database and analyzed to make sure that the historical dataset consists of data that indicates only normal process behavior, without any deviations or outliers. This is an important step, since this data will serve as a reference for future predictions.

For real-time calculations the trained PCA model is deployed on a server and data from the PLC-PMAC system is fed into this model in order to obtain the new weighted scores that indicate how close new observations are related to the historical dataset. Because the PCA algorithm is a 'white box' algorithm it can have self-diagnostics abilities. For example, the model can be instrumental to determine the root causes for fluctuations, trends and outliers.

This results in a single value to monitor if the machine is still operating within its stable operating window and triggers trends and outliers. Furthermore, the interaction effects between parameters can be taken into account in a multivariate manner.

4.5.4 Smart Function: Formatting

Data formatting consists of using predefined data "shapes" or types, for exchange of information between the sensor and the central unit. The sensor data, usually in analogue format, has to be translated to the mentioned digital representation, and this conversion usually involves an appropriately chosen representation format that avoids transmitted data increase due to unnecessarily complicated protocols or data length in excess of what actual accuracy requires, like the number of bits/bytes used in the codification of the data sample.

4.5.4.1 Practical applications: Compressed air system

The sensor in Figure 4.18 on page 128 is used in the pultrusion use case (Chapter 7 Section 2) and it sends the collected data via a Modbus field bus protocol. In the present case, the data formatting can be either Float or int32.

4.5.5 Smart Function: Enhancement

In addition to simply collecting data, it would be desirable that a sensor developed further data processing function upon the data. This functionality not only increases added value on the performance of the sensor but also relaxes the burden of overall data processing requirements on the central node(s). These are, in general, the units upon which relies the duty of calculation and decision, and an appropriate mathematical manipulation of the locally sensed quantities would shorten the reaction times upon data collection events and improve the overall sensor network performance. Various functions like averages, moving windows, transforms and statistical indicators fall in this category.

4.5.5.1 Practical application: Air and water flow and temperature sensor

Hysteresis or window function: When the hysteresis function of the sensor in Figure 4.21 on page 131, used in the pultrusion use case of Chapter 7 Section 2, is set (Figure 4.25), the set point SP and the reset point rP are defined. The rP value must be lower than the SP value. The distance between SP and rP is at least 4% of the final value of the measuring range (= hysteresis). If only the set point is changed, the reset point is changed automatically, since in this way the difference remains constant.

By setting the window function, it is possible to use the curve to compute proper values for the upper limit value FH and the lower limit value FL. The distance between FH and FL is at least 4% of the final value of the measuring range. FH and FL have a fixed hysteresis of 0.25% of the final value of the measuring range. This keeps the switching status of the output stable if the flow rate varies slightly.

Damping of measured value: The damping time is the number of seconds that are waited before considering new values after there has been a change in the output values. In fact, whenever a signal gets out of the limits, there is a

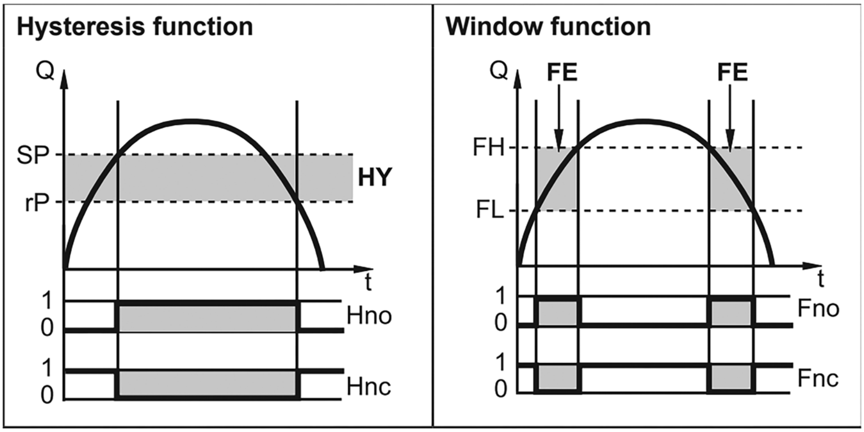


Figure 4.25 Window function (Hysteresis) indications.

change in the outputs, the displayed values and the process value transfer via the IO Link interface. The damping time is able to stabilize these elements against flow values that change suddenly.

4.5.5.2 Practical application: Railway strain sensor

The focus in the use case on railway maintenance (Chapter 7 Section 6) is on optical strain sensors used in train check points. Train "check points" are installations at certain locations in a railway network that monitor key parameters of passing trains to establish a number of safety relevant features of a train and to produce an automated warning in case safety critical limits are exceeded. These train parameters are derived from the strain introduced into the rail by the train's axle loads and by dynamic parameters, such as wheel out of roundness. This strain can be measured by fiber-Bragg-grating (FBG) sensors attached to the rail.

The core functionality of the FBG sensor is to measure strain applied to the sensor. The measured strain is derived from an optical resonant peak in a reflected light spectrum. The core measurement parameter is represented by the position of the resonance peak in the spectrum, measured in wavelength units.

Laser pulses are sent to the FBG by a device (Interrogator) via an optical fiber cable. The reflected light is then analyzed for the presence and location of the resonant peak in the spectrum. A number of FBGs, characterized by their individual resonant frequencies, can be "daisy chained" along one optical fiber cable for a finer measurement of the strain, by investigating for the presence of a resonant peak at different frequencies.

4.5.5.3 Practical application: Conventional energy production

The monitoring of rolling element bearings, such as the ones described in Chapter 7 Section 8, is based on using vibration measurements made with accelerometers. Since measurements of this kind are made at high frequency i.e., the data is collected at e.g., 10 kHz frequency, a lot of data is collected, assuming the measurements are made continuously. Consequently, it is natural to try to do the signal analysis, diagnosis and prognosis close to the monitored machine in order to avoid the need to send enormous amounts of data to a central processing unit. In the Mantis project these analysis functions are processed in a Raspberry processor which is located close to the accelerometer.

The commonly known envelope analysis [Randall, 2011] is used for signal analysis for the detection of possible bearing faults. With envelope analysis the indication of upcoming failures can be detected at an early stage, as well as the fault type i.e., outer or inner race etc. can be detected. The used band pass frequencies are tuned based on the geometry of the bearing.

The diagnosis of a bearing fault is based on comparison of the amplitudes of the envelope spectrum at the bearing fault frequencies to the amplitude levels at neighboring frequencies. The used mathematical formulas are simple enough that the functions can easily be handled at local level (Raspberry) and naturally, if needed, as Web services and at a service center.

4.5.6 Smart Function: Transformation

In some cases, the estimation of a magnitude is calculated in terms of manipulation of acquired data that refers to a different type of measurement. Data has thus to be transformed from one domain to the other via models, estimators and other mathematical tools. The transformation could range from a simple proportionality factor up to a complex signal processing algorithm involving Fourier transforms, statistical models, Kalman filters etc. From a different point of view, transformation can also be considered as the process by which commands or data in a given protocol have to be translated to a different one. An example of this can consist on a group of neighboring sensors, interconnected via some type of field bus (e.g., Modbus). These sensors can then be connected to a second type of network, such as 802.3 based Industrial Ethernet. There is a clear need for a "gateway" that transforms commands and information from one realm to the other and vice-versa.

4.5.6.1 Practical application: Pressure drop estimation

The aim of the present function is to determine the relationship between the pressure drop and the flow velocity with a data driven approach and to track the change of this relationship overtime in order to follow the degradation of the filter. An ARX parametric model (see Figure 4.26) was used to model the relationship between the input (air velocity) and output (pressure drop). A recursive least square approach with forgetting factor was used to estimate the model parameters of the system.

The Kalman filter was used to recursively estimate the model parameters whenever new data was acquired. The principle of the Kalman filter is that the estimation of new parameters $\hat{\boldsymbol{\vartheta}}\,(\boldsymbol{k}+\mathbf{1})$ at time ***k+1*** depends on the predicted error and on the previous parameter estimation $\hat{\boldsymbol{\vartheta}}\,(\boldsymbol{k})$ at time ***k***.

Considering equation $y=$ Zϑ+e, when new data arrived in form of input and output, the new problem consisted in estimating the new parameters ***w*** based on the old data [**y Z**] and the newly gathered data [$\tilde{y}$ $\tilde{z}$]. The problem was solved by minimising the 2-norm of the following equation:

$$\min_{\boldsymbol{w}} \left\| \begin{pmatrix} \mathbf{y} \\ \tilde{y} \end{pmatrix} - \begin{pmatrix} \mathbf{Z} \\ \tilde{z}^T \end{pmatrix} \boldsymbol{w} \right\|_2^2 \rightarrow \ \boldsymbol{w}= \left(\boldsymbol{Z^T Z}+ \tilde{z}\tilde{z}^T\right)^{-1}\left(\boldsymbol{Z^T y}+ \tilde{z}\tilde{y}\right) \qquad (4.5)$$

The formula can be computed by using the Woodbury-Sherman-Morrison equation (Sherman and Morrison 1950) and after some simplifications, the formula can be described as follows:

$$\boldsymbol{w}=\hat{\boldsymbol{\vartheta}}\,(\boldsymbol{k}+\mathbf{1}) =\hat{\boldsymbol{\vartheta}}\,(\boldsymbol{k}) +\boldsymbol{G}[\tilde{y} - \ \tilde{z}^T \hat{\boldsymbol{\vartheta}}(\boldsymbol{k})] \qquad (4.6)$$

where $\left[\tilde{y} - \ \tilde{z}^T \hat{\boldsymbol{\vartheta}}\,(\boldsymbol{k})\right]$ is the error of the prediction and ***G*** is the gain:

$$\boldsymbol{G} = \frac{\left(\boldsymbol{Z^T Z}\right)^{-\mathbf{1}} \tilde{z}^T}{1 + \tilde{z}^T \left(\boldsymbol{Z^T Z}\right)^{-\mathbf{1}} \tilde{z}} \qquad (4.7)$$

By estimating the model parameters, the relationship between the sensor and the data is learned and the deviation between the estimated model and the actual measurement can be calculated by using the model residuals:

$$\boldsymbol{residual}= |\widehat{\mathrm{y}} - y| \qquad (4.8)$$

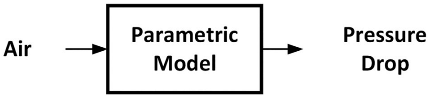


Figure 4.26 Parametric model used to estimate the relationship between the air velocity and the pressure drop.

The model obtained can be therefore used to recalculate the pressure drop at a reference air flow (50% of the flow range), allowing tracking the degradation of the component, or for anomaly detection.

4.5.7 Smart Function: Fusion

Health monitoring strategies usually require that more than a single magnitude be measured by a single or multiple sensors. In case a sensor is devoted to measuring different quantities, a data fusion process could be pertinent. In this case, several data from various different measured magnitudes are sent together to the central node(s) in a single transmission. Plus, if the aforementioned measurements are of different nature (analog and digital), an appropriate data formatting could also be necessary.

4.5.7.1 Practical application: Off-road and special purpose vehicle

The purpose of the practical case described in Chapter 7 Section 5 is to perform a fusion between data obtained from an inertial measurement unit (IMU) and an ultra-wideband localization device (UWBL), for indoor location services. The proposed algorithm is based on the IMU and UWBL measurements. This sensor fusion efficiently combines the advantages of both methods. Accelerometer and gyroscope measurements are useful to track the inertial move of the vehicle with a really high refresh rate, but suffer from the measurement error and perturbations, such as drift. UWB measurements provide global positions in the navigation environment, and are accurate enough to determine the IMU measurement drift. The sensor fusion can be solved using extended Kalman filter principles. An initial estimation on the position and direction is calculated. Then, when new data are available, comparison of estimated and actual position and direction values gives correction factors that are further utilized by the filter to improve the estimation quality for the following iterations. Refer to Figure 4.27 for a graphical representation of the process.

4.5.7.2 Practical application: MR magnet monitoring (e-Alert sensor)

The e-Alert sensor is described in Chapter 7 Section 9 and in [Albano, 2018], and it is a stand-alone sensor, which can autonomously, 24/7, monitor environmental conditions such as temperatures, humidity, magnet field, mains power, in the vicinity of a Philips MRI system. The e-Alert

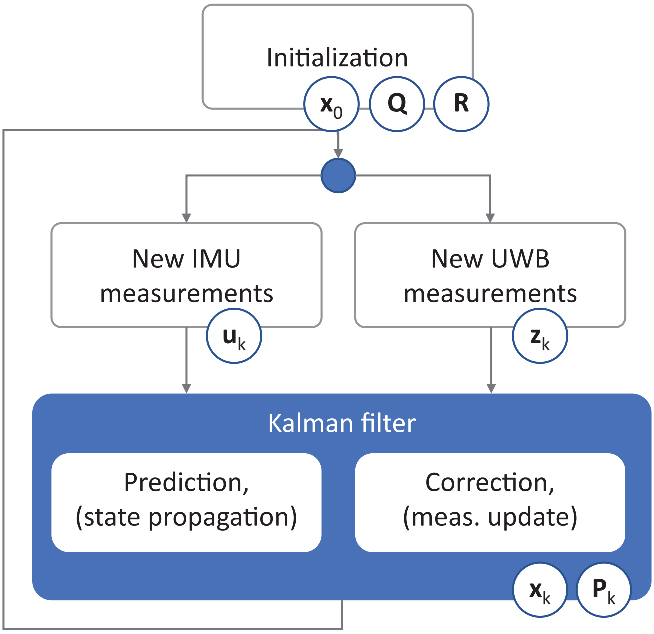


Figure 4.27 Kalman filter based process for sensor data fusion.

controller is wall-mounted in the technical room of the MRI system and its sensors are physically connected to those parts of the MRI system where environmental conditions are measured. The e-Alert sensor (Figure 4.28) is based on a Raspberry Pi mini-computer. The embedded software is developed specifically for this purpose, and is built on GPLed libraries and APIs. The sample values and logs are stored on an internal SD-card.

The temperature sensors are off-the-shelf one-wire sensors. These sensors are connected to an interface box (max 8 sensors per interface box). The

Figure 4.28 e-Alert controller to monitor environmental conditions in a medical device.

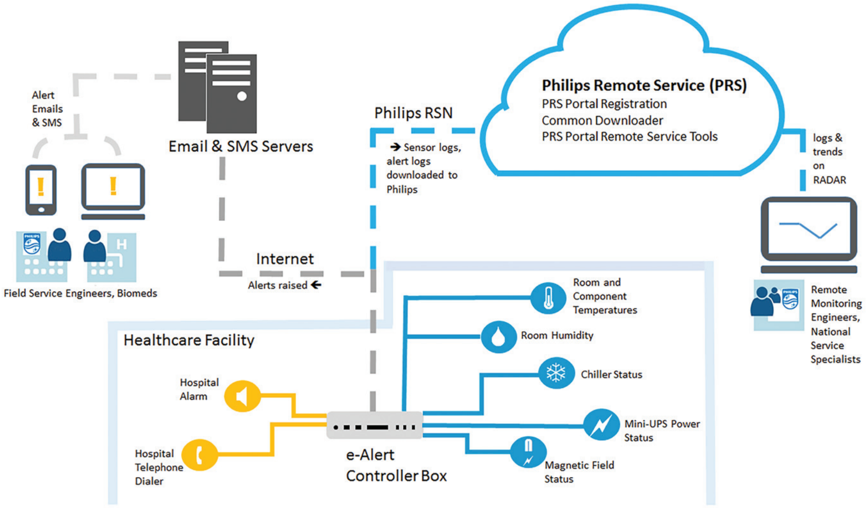


Figure 4.29 e-Alert control sensor context diagram.

interface box is connected to one of the inputs of the e-Alert sensor. Multiple interface boxes can be daisy-chained. This provides a scalable sensor platform that can be tailored for the specific device under monitoring.

As represented in Figure 4.29, the e-Alert sensor acquires sensor values once per minute and checks these values against configured control limits. To avoid false positives, a sensor value must exceed the control limits for a number of consecutive samples before an alert is sent. In that case, the e-Alert sensor sends an E-Mail or text message to the configured alert receivers.

4.5.7.3 Practical application: MR critical components

The performance of critical components in a medical device is monitored, as described in Chapter 7 Section 9. Intelligent components were developed, able to record their own state in real-time and provide access to this data via a software interface. The next generation high-power amplifiers will offer capabilities that enable data-driven diagnostics. Recorded data can be summarized as follows:

- Identification – critical parts of the amplifier contain identification data such as serial numbers, firmware versions. This data can be used to track component and firmware changes;
- Firmware upgrade – amplifier firmware can be upgraded via a remote connection. This capability can be used to upgrade amplifiers in the field, without physical presence of a field service engineer;

- Monitoring – physical characteristics (e.g., temperatures, voltages, and currents) are measured periodically and stored in memory as time-series data. This capability can be used to define the exact conditions of the amplifier;
- State logging – the state of the internal state machine of the amplifiers' firmware is stored in memory as time-series data. These data can be used to reproduce the exact conditions under which the amplifier goes into an error state;
- Clock synchronization – the internal clock of the amplifier is sync'd periodically with the clock of the medical device.

The medical device periodically retrieves the data that is stored in the amplifier's memory and combines these data with data from other components in the medical device, to reconstruct the operational conditions of the amplifier in the medical device.

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