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WHITEPAPER

How to balance cost, risk and performance in industrial sensor integration

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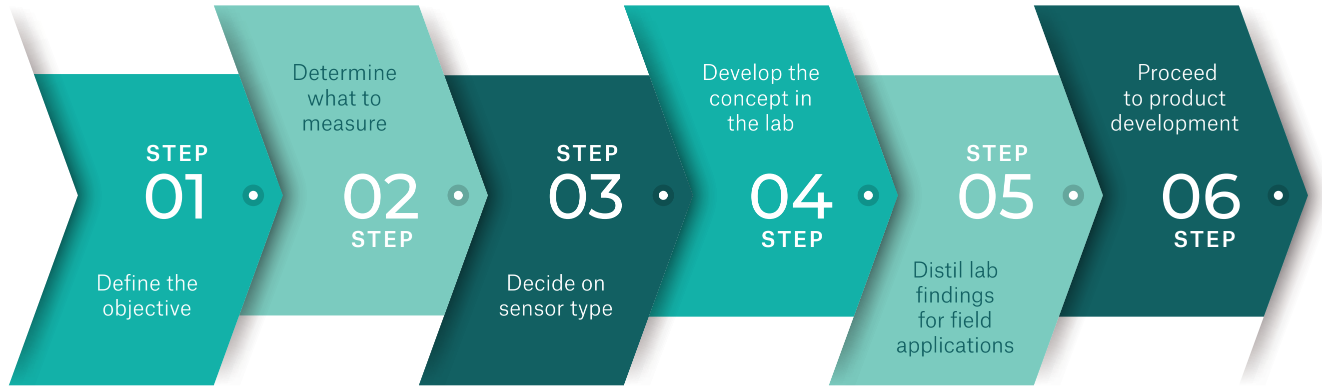
Industrial use of sensors has evolved from simple cause-and-effect applications into more sophisticated data acquisition that enables better understanding of systems. Real-time monitoring provides insights on factors like efficiency, equipment degradation, and product quality that can be harnessed collectively via the Industrial Internet of Things (IIoT). This in turn should inform and facilitate process optimisation and predictive maintenance. It may also provide the bedrock for GenAI-enabled plant control systems in the future. However, various issues can make it hard to derive actionable insights that deliver on these goals. Here, experts in the technology offer practical guidance for equipment manufacturers looking to make their products 'smart' using sensor integration.

A strategic approach to sensor integration



In this whitepaper, sensor technology experts outline six steps to ensure IIoT-enabled products and data analytics offer 'just enough' functionality to address customer needs cost-effectively.

A strategic approach to sensor integration

Global investment in IIoT continues to surge[1] as companies look to harness and derive benefits from performance data. Heightened focus on productivity, cost-efficiency, sustainability, safety and other critical factors is driving the trend while improved affordability of sensor technology is a key enabler.

Manufacturers of industrial equipment can enhance their products' value proposition by integrating sensors that provide customers with actionable real-time insights. Yet the wide scope of sensor applications and sensing methods presents selection challenges for R&D and product managers. Answering simple questions like 'what should we sense?', 'how should we sense it?', and 'will this add customer value?' has become a complex task. There's a high risk of over-specification which results in unnecessary costs and generates vast quantities of data, making it hard to determine what is relevant and harder still to leverage value.

Costs and benefits

Adding sensor systems to products inevitably increases their cost. If this will be passed on to the customer, the path to business value must be clear and straightforward. Alternatively, the manufacturer might shoulder the cost, using the integration of sensors as a mechanism to harness data for continual product improvement, to gain market insight, or to unlock service-based offerings. In this case, the customer may have to be incentivised to share equipment performance data. Whatever route is taken, the sensor system must pay for itself which demands careful cost modelling. The customer also needs to buy into the proposition. Read our 'minimum loveable product' whitepaper for inspiration on how to navigate the path from raw data to actionable insight to customer perceived benefit[2].

Step 1: Define the objective

The first step of sensor selection and integration is to establish what decision or action it will enable. For instance, sensors might inform the customer that maintenance is required or monitor efficiency levels and recommend adjustments to the system. Figure 1 illustrates typical outputs and outcomes of sensor-based industrial equipment monitoring. It's important to focus on these factors at an early stage to ensure the sensor strategy is laser-focused on gathering useful insights which translate into business value.

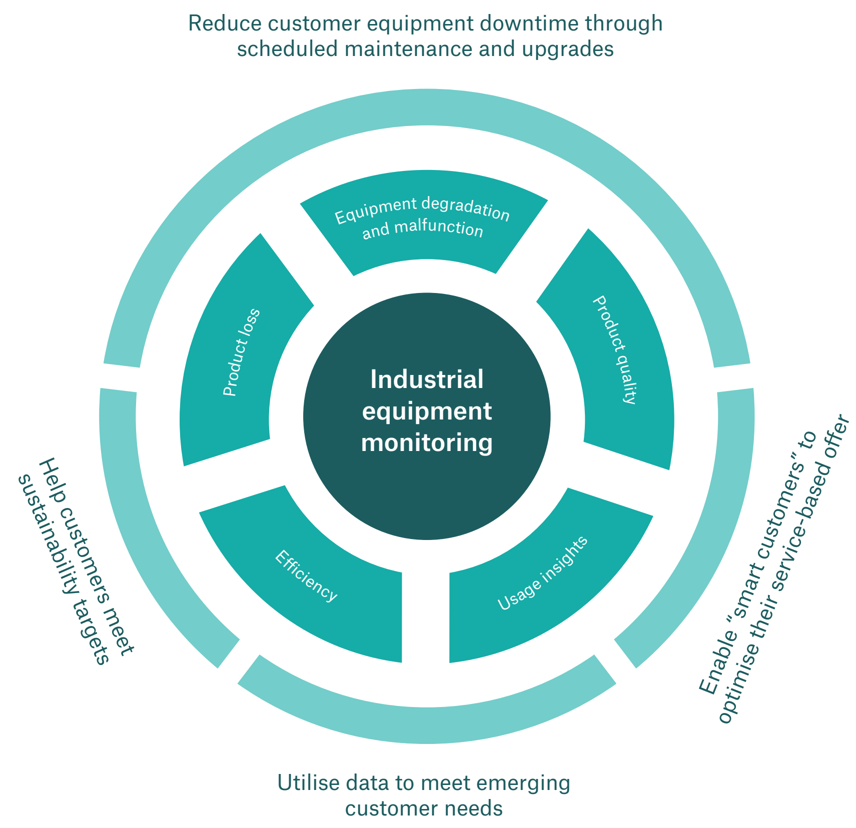


Figure 1: Sensor-based monitoring can be applied across the industrial equipment ecosystem to produce tangible outcomes for businesses and their customers

When defining objectives, it is important to understand all the details of the decision that the sensor system will support. A critical aspect of this is striking an effective balance between false positives and false negatives as the below / opposite example illustrates.

Industry spotlight: air filter replacement

A company that manufactures air filters for industrial machinery engaged Sagentia Innovation to develop a sensor system alerting customers when filters needed replacing. Since machines would be damaged if their filters became saturated, sensors had to be activated when filters were close to capacity. For this application, false negatives could not be tolerated but false positives (early alerts) were more acceptable. Understanding these requirements informed decisions about the type and combination of sensors to employ.

Step 2: Determine what to measure

Once a decision- or action-based objective has been established, the next task is to ascertain parameters which support it. This will vary case-by-case according to science or engineering features which underpin the wider industrial system. A detailed understanding of the equipment and its operational context is essential to right-size the sensor system and ensure only necessary data is collected. Not every piece of information is worth the cost of obtaining it. It's also important to avoid interference or confusion as this may hinder decision making. The below industrial pumps example shows how this principle can be applied in practice.

Industry spotlight: pump performance

It's not always beneficial to measure the most obvious parameter. This was the case when Sagentia Innovation worked with an industrial equipment supplier that wanted to monitor pump system performance. Anecdotally and in the lab it had been noted that as pumps approached end of life, worn bearings caused vibrations in the system. Using an accelerometer to monitor vibrations might have been an effective approach for performance monitoring had it not been for the noisy industrial environments the pumps operated in.

We considered the final decision (should the pump be replaced) and possible sources of interference or confusion (the pump operates in a noisy environment). In this instance, monitoring changes in pressure/flow characteristics or power draw facilitated the same decision as measuring vibrations, with less susceptibility to interference or confusion.

As Figure 2 illustrates, the ideal sensing target sits at the intersection of 'what can be measured' and 'what information is beneficial'. It's also important to consider how value will be derived from the metric and whether the measurement can be performed in a real-world setting. With the industrial pump example, at a high level, it might be understood that pressure and flow rate changes are indicative of degradation. This needs to translate into a plausible strategy for turning raw data into a useful, actionable insight. So, if flow rate drops for a given pressure as a pump degrades, 'pressure/flow to output' might be characterised as a degradation metric.

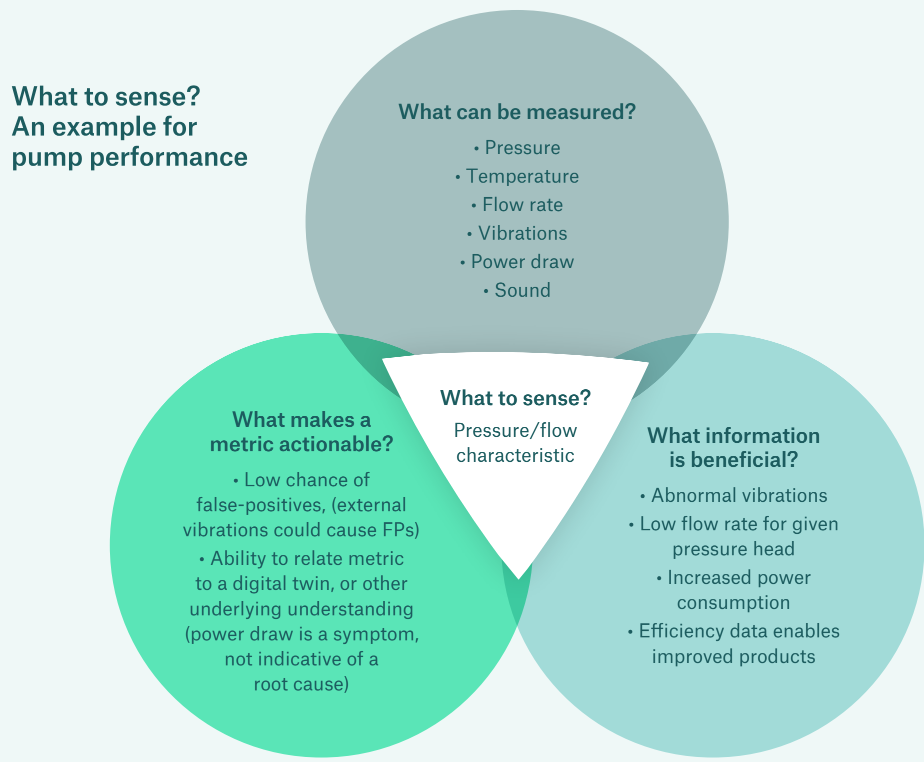


Figure 2: The sensing metric should be measurable, beneficial, and actionable in a real environment.

Step 3: Decide on sensor type

Some metrics have many established ways of sensing, some have only one, and some have none, so there's great variation in the depth and breadth of available options. Compare sound (where a microphone is the standard sensor) with position sensing (where there are multiple methods). On the other hand, there may be a vital metric that cannot be sensed using off-the-shelf technology, such as certain chemical concentrations. In cases like this, it may be beneficial to invest in the development of novel sensor technologies or to adopt lab methods. Mapping the additional R&D costs against potential market gains is a simple but important way to ensure the investment is focused on delivering commercial advantage.

Biosensing in the wastewater industry is a particularly active area where high initial R&D costs could be offset by the market gains. Biosensing approaches such as microbial fuel cells may provide a means for continuous in-flow biochemical oxygen demand (BOD)[3], removing the requirement for a 5-day incubation period during testing. Similarly biochemical approaches are being investigated for PFAS detection[4], which is of particular importance given the tightening regulatory environment around 'forever chemicals'.

The (opposite) section shows how a down-selection process we've devised can be applied to determine the best sensor type to detect the position of a metal object. This approach requires broad knowledge of different sensing methods as well as sensor physics so that relevant calculations can be performed. The model facilitates methodical assessment of candidate sensors encompassing factors such as ease of implementation, cost, existing IP, and robustness. It can quickly determine one or two possible approaches for more detailed lab-based proof-of-concept exploration. If the technology readiness level (TRL) of identified approaches demands attention, this can become an R&D priority.

A down-selection process for competing sensing approaches

The assessment of competing sensor types starts out with an ideation session where Sagentia Innovation technology experts identify all possible approaches. With regards to sensing the position of a metal object, this could include inductive, capacitive, optical, acoustic, mechanical, or radio frequency concepts.

From here, the down-selection process begins, with a quantitative method applied to assess the various concepts. For instance, a capacitive sensor might be considered on the basis that it could detect movement of the metal object, but calculations may determine that signals would not be detectable over the required distance. These calculations also demonstrate what is achievable with off-the-shelf systems, what might be feasible with novel development, and what is unfeasible.

Concepts which satisfy initial calculations are then assessed according to other relevant criteria, which can be plotted onto a Pugh matrix (see Figure 3). This facilitates the scoring of concepts against factors such as: requirements for further development (which involves additional time, risk, and cost), user experience, ease of implementation, bill of materials and manufacturing costs, existing intellectual property, and robustness.

	Technical feasibility	Power consumption	Further development required	User experience	Cost
Capacitive sensing concept	4	4	3	2	3
Inductive sensing concept	5	4	4	5	3
Optical sensing concept	3	1	2	3	1
Acoustic sensing concept	2	2	1	3	2
Mechanical sensing concept	2	5	4	2	4

Figure 3: Pugh matrix illustrating how concepts can be scored against criteria

In the illustrative example in Figure 3, the inductive concept performs strongest in sensing the metal object's position, followed by capacitive and mechanical. While capacitive outperforms mechanical in our example, it may be that power consumption and cost are key drivers, in which case they could be given a stronger weighting.

Step 4: Develop the concept in the lab

Whether there's a single standard approach for sensing (e.g., a microphone) or down-selection has identified a couple of options (e.g., inductive and capacitive sensing), the next step is to establish (i) how the measurement is made in practice, and (ii) how this enables the decision- or action-based outcome.

We advocate development of a lab system using instrumentation of a much higher specification than is anticipated for the final product. Consider the example of using a microphone to listen to sounds from a piece of mechanical equipment. Sound can be generated at many different frequencies and at many different amplitudes. Lab instrumentation that can read across a wide frequency range with high fidelity will reveal the key frequencies of interest.

Exposing the system to possible confounding factors is also critical during this stage. When listening to sound, it is important to understand what other sounds may be generated in the operating environment and how they affect the system. It might be that audible frequencies are saturated by extraneous noise, but ultrasonic frequencies are unaffected. Similarly, when investigating competing approaches for sensing the position of a metal object, capacitive solutions may give false positives when touched by an operator's hand while inductive solutions do not.

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Step 5: Distil lab findings for field applications

Lab-based concept development generates a significant amount of data which needs to be distilled before a field-ready solution can be delivered. To continue with the sound and position examples, this might involve setting the correct frequencies or inductive thresholds respectively. It's an important step which ensures sensors are not over-specified, meaning costs and data handling/processing requirements are proportionate.

Simple data analytics can be employed to investigate the data gathered by lab instrumentation. When listening to noise with a microphone, dimensionality reduction helps to pinpoint the smallest number of frequencies that provide the largest amount of relevant information. This can be achieved using principal component analysis or linear discriminant analysis. Alternatively, it may involve simple classification algorithms such as decision trees to identify the parameters that provide the most useful information.

These classification algorithms can be used to set thresholds too. Equipment monitoring systems generally classify a sensor reading as 'normal' or 'abnormal', with abnormal readings creating an alarm or triggering a recommended action. The key is to choose a system that provides the necessary insight, but also balances false positives and false negatives appropriately.

AI and machine learning (ML) could also play a role in the analysis and interpretation of data. Many data analysis algorithms do not require AI/ML, but there are situations when the associated development and upkeep costs can be justified. AI/ML can also speed up laboratory analysis.

Use of AI during product development lifecycles is becoming increasingly common. However, its incorporation into products is more nuanced and requires additional care. These powerful tools bring implications for power, processing, connectivity, and of course data security. As AI/ML continues to proliferate, 'AI for the sake of it' will no longer be acceptable. Benefits must be clearly laid out (see Figure 4), and costs justified.

Data from lab instrumentation enables deeper consideration of how signals can be combined to provide robust measurements. Its analysis allows sensor capabilities to be specified based on the decisions customers need to make.

For instance, in some cases, temperature compensation might be used to correctly calibrate a flow measurement, in others a ratio-metric measurement may be taken to cancel out unwanted effects. Changes in signal (with time, temperature, or otherwise) may be more important than absolute values. Having access to 'more data than necessary' from the lab campaign, and an understanding of causes for confusion, helps determine how data can be combined to produce the most robust system with 'just enough' functionality in the field.

It is rarely possible to say a priori "the customer application will require a flow sensor with an accuracy of 1%", but after understanding the trade-off between false positives and false negatives, requirements of this nature can be set.

Application	AI/ML benefits
Data processing and analysis	Quickly process large volumes of data, identifying patterns and correlations that human analysis might miss. Apply analysis to customer data or find the most effective lightweight algorithms in the lab.
Predictive analytics	Transformer models surpass all previous methods for predicting behaviour, and generative systems further enhance this functionality. These models can go beyond detecting 'normal' vs 'abnormal' to provide early warning of specific events.
Large Language Models (LLMs)	These models offer an accessible way for customers to investigate data using human language. They can also be used to review academic literature, keep up with emerging research, and to probe data in new ways.
Visualisation tools	AI can aid the creation of intuitive graphs and charts that make complex data easier to understand and visualise. It's even more powerful when paired with LLM. AI visualisation tools can also be used to help engineers understand their data during development.
Error reduction	In the lab, automating repetitive tasks and data entry can reduce the risk of human error. This ensures more accurate and reliable results, which form the foundation of in-operation algorithms.

Figure 4: How AI and ML can aid sensor data analysis

Step 6: Proceed to product development

With a sensor system proof-of-concept in hand, and an understanding of how its implementation will provide actionable information, traditional product development can begin. In an IIoT context, prototyping and A / B modelling needs to consider how to off-board data from the edge, or whether decisions can be taken on the edge, thereby removing the need for connectivity. This is where factors such as communication protocols, data processing and storage, and dashboarding or other methods to push alerts to users, come to the fore. Engineering teams and product teams need to work in close collaboration to ensure decisions remain centred on the target outcome and deliver value to the customer.

Throughout development and even after launch, data should continue to be collected and used to update and improve processing algorithms. Real-world data often provide additional insights that can enhance performance or provide additional functionality. Communicating this to the customer, and implementing a capability for over the air (OTA) updates can provide a powerful justification for collecting usage data and/or employing service models.

Deriving value from sensor integration

The value proposition for sensor-based IIoT is not straightforward because lifetime costs of sensors may go far beyond their initial price tag. Installation, calibration and maintenance costs often outweigh the hardware cost. In some cases, synergistic integration of multiple sensors, or the installation of more sophisticated hardware, can help mitigate this. For instance, the core sensor might be a microphone measuring vibrations, but if lab-based development indicates that sound varies with temperature, the addition of a temperature sensor could account for this variability. The relatively small cost of this additional sensor could deliver significant savings in ongoing maintenance and customer support. Resolving matters like this is crucial to ensure sensor integration delivers tangible value for the end customer.

How Sagentia Innovation can help

IIoT is leading many industrial equipment manufacturers to reevaluate product portfolios with the aim of integrating sensors. Here at Sagentia Innovation, we design and implement industrial sensor systems of all types, and have particular expertise in the development of cost-effective solutions.

Talk to us if:

You're struggling with cost modelling. We bring the industry experience and scientific insight to clarify lifetime costs of sensor integration and ensure it delivers net value.

You can't work out what you should be sensing. Our scientists bring decades of experience in the physics and chemistry that underpin physical systems, and what metrics provide the most insight.

You're gathering data but don't know what to do with it. Our algorithm and data experts can help translate system data into clear, actionable metrics.

You can't decide the best sensing method. Our scientists and engineers have extensive working knowledge of sensors and understand the advantages and pitfalls of different measurement techniques.

You need to develop a novel sensing solution. Our novel sensor solutions often take lab processes and accelerate their TRL or draw on technologies from adjacent sectors. We can support every step of your journey from concept ideation through to transfer to manufacture.

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About Sagentia Innovation

Sagentia Innovation provides independent advisory and leading-edge product development services focused on science and technology initiatives. Working across the medical, industrial, chemicals and energy, food and beverage, consumer sectors, and defence Sagentia Innovation works with a broad range of companies from some of the world's leading and best-known brands, to start-up disruptors, new to the market. Part of Science Group (AIM:SAG), it has more than fifteen offices globally, two UK-based dedicated R&D innovation centres and more than 700 employees. Other Science Group companies include Leatherhead Food Research, TSG Consulting, Frontier Smart Technologies, TPG Services and CMS2.

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