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Practical First Steps Toward Predictive Maintenance

Macnica, Inc.
Global Innovation Office

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Practical First Steps Toward Predictive Maintenance

Chapter 1
Basics of CBM (Condition-based Maintenance)

For over five years, Macnica has helped machinery manufacturers build embedded features that leverages digital technologies such as AI and IoT. In our engagement with customers, the most frequent topic was on the implementation of predictive maintenance and anomaly detection functionality for devices that use sensor data.

This section will explain why this kind of initiative is on the rise, and key points for machinery and infrastructure equipment manufacturers to successfully build CBM functionalities based on our experience with customers, development flow toward product commercialization, and finally, what we consider to be the optimal solution.

Chapter 1: Basics of CBM (Condition-based Maintenance)

What Is CBM?

Currently, the most commonly used standard for the maintenance process is Time-based Maintenance (TBM) that involves inspection, repair, and part replacement at regular intervals.
On the other hand, Condition-based Maintenance involves the utilization of various types of sensor data collected from machines to perform repairs or other countermeasures before malfunctions or anomalies occur.

Conventional TBM mainly presents the following challenges, and there are even cases where depending on the circumstances, this can directly impact the business.

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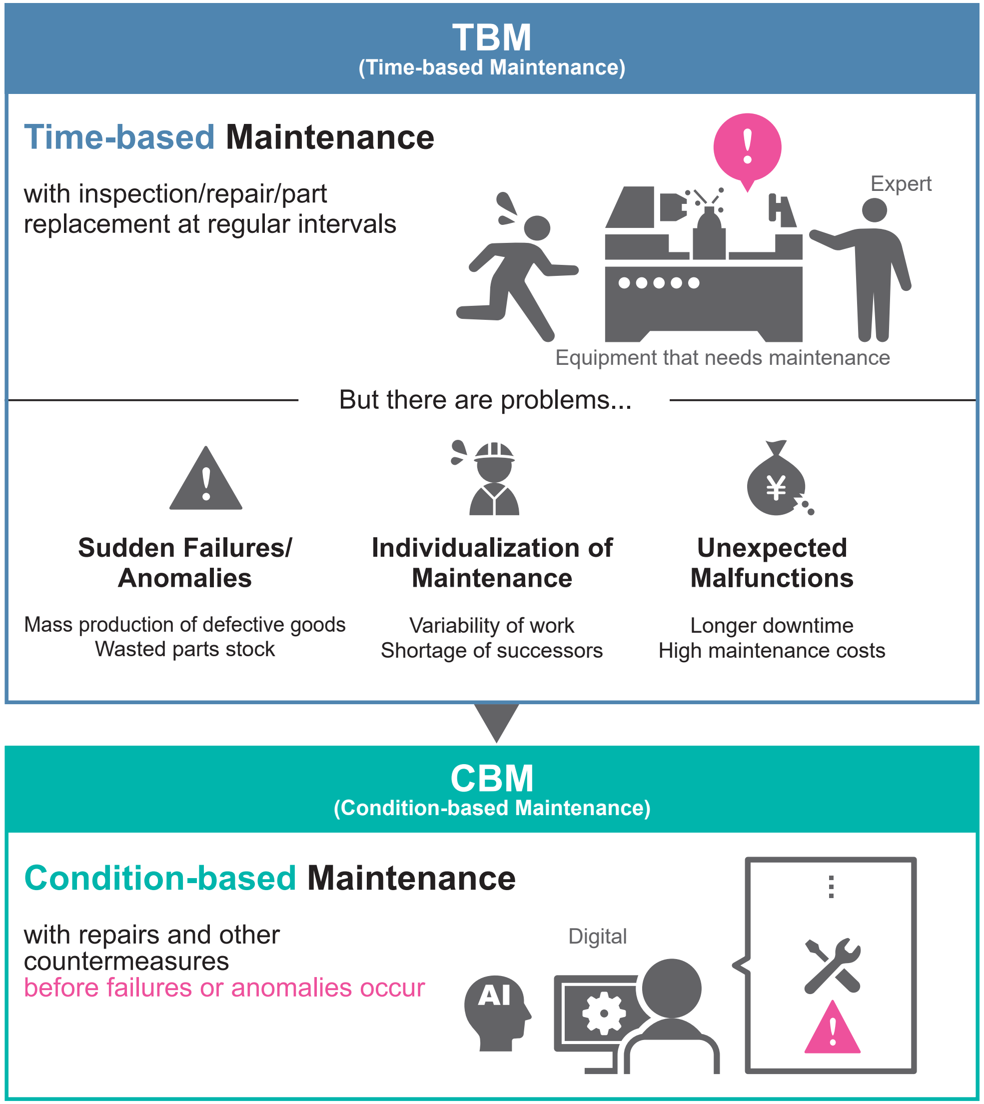
(1) Due to sudden equipment anomalies, manufacturing quality may crash and produce a large volume of defective goods without even realizing it, or an extended downtime may occur due to stopped machines and cause a huge loss in planned production.
Equipment anomalies may cause a serious problem due to the unanticipated time and cost of repairs.

(2) Regardless of the machinery's state, maintenance is performed at a fixed time, so parts that are still usable may be replaced, or the stock of replacement parts required may become excessively large.

(3) Maintenance is individualized, so work is variable, and passing on skills to successors is difficult.

Efforts to solve these problems using CBM are on the rise recently.



Typical Equipment and Challenges

Main Target Equipment Examples

(1) Price of equipment is relatively high
(2) Equipment with large-scale mechanisms or rotating mechanisms
(3) Stoppages have an enormous impact

The target equipment is critical large-scale equipment that corresponds to all of the above. In a typical factory for industrial machinery, the target examples are machine tools that are responsible for manufacturing/production, press machines, injection molding machines, semiconductor manufacturing equipment, industrial printing presses, and the large-scale boilers, pumps, and compressors that supply energy to those devices. Additionally, railways, ships, electricity, and other infrastructure equipment that supports society at its foundations have an enormous impact if it breaks down, and so many of these are also applicable.

Typical Examples of Parts for Detection and Error Modes

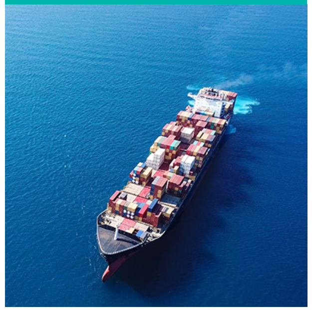
The focus of detection is mainly on mechanical degradation and anomalies in key parts, such as bearing damage or abrasion/shaft unbalancing/ball screw damage/tool malfunction or abrasion.

Recently, there are also efforts to employ CBM for the diverse types of devices that collectively make up infrastructure equipment. In this case, there is a broad range of parts for which to detect anomalies and modes. Therefore, priorities are often established, and milestones are set in terms of years. Additionally, the parameters that contribute the most strongly are determined from the collection of various sensor data. Then the analysis must take into account a variety of domains, such as the mechanisms and leading causes of disturbance/fluctuations for the drive equipment that is characteristic of these devices.

Processing Machines
(Machine Tools/Injection Molding Machines/Press Machines)

Pumps, Compressors

Large Ships



Wind Power

Industrial Robots

Semiconductor Manufacturing Equipment

Railways

Electricity

Increase in Demand: Need for CBM Function Development by Machinery Manufacturers

Why are such initiatives on the rise?
CBM is regarded as the common first step in turning devices into smart devices, and we started to see an increase in such projects from about five years ago when Germany first proposed Industry 4.0 to the world. This was also when Macnica made a full entrance into this market.
Back then, our first impression was that most of these projects were by those who wanted to be at the cutting-edge by trying CBM as the latest trend.

The situation has changed over the past few years, and these projects are increasingly driven by users who are pushing forward with full-scale automation.
For example, one of the goals of process automation and optimization implemented via smart factories is the reduction of manpower, but as the number of on-site technicians and workers decreases, inevitably, a method for monitoring the state of anomalies and degradation in machinery becomes a requirement.
For such cases, where CBM itself is not the goal but rather a method under consideration, accelerated system building also becomes more manageable. Due to the influence of the coronavirus, it is expected that trends in the shift from on-site to remote work will continue and that conditions will be even more favorable for the adoption of CBM systems.

This type of increase in user-side initiatives also provides added value to the manufacturers who supply machines, and is one of the main factors that motivate development. While establishing goals for rapid performance improvement of every machine is difficult, the improvement of these services and undertaking initiatives as a differentiator are nevertheless on the rise.
In many cases, undertaking such development is motivated by the desire to transform the business model from merely selling products to selling products with added value and establishing a continued connection with users even after the initial supply of machines.
With various goals in mind, the development and planning divisions of a large number of manufacturers have started to undertake such initiatives.

Challenges of CBM Function Development: Crossing the Death Valley between PoC and Product Development

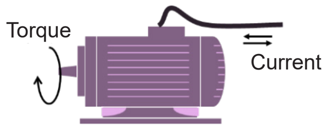
Data collection is one example of a typical problem. Data collection can be further broken down into the following three challenges, all of which inevitably present significant hurdles standing in the way of the transition process from PoC (Proof of Concept) to product development.

Challenges of Data Collection

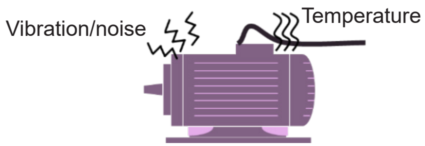
(1) Optimal sensor selection
(2) Hardware cost for mass production/operation
(3) Collection of effective training data

(1) Optimal sensor selection

The selection of a sensor to correctly detect the symptoms of anomalies often starts with an attempt to use a sensor that is already built-in to the machine. However, these sensors are known as main effect parameters, many of whose purpose is to indicate the performance of the equipment itself, such as the current, torque, and pressure, and therefore are not suitable as tools in the diagnosis of the symptoms of degradation or anomalies of the machine itself. The condition is often already critical by the time a change is visible in these parameters.



On the other hand, there are many cases where the secondary phenomena known as quadratic effect parameters, such as vibration, noise, and temperature, are highly effective in indicating the signs of degradation. In particular, a change or increase in vibration often indicates irregularities in dynamic devices, and this physical quantity is a useful indicator of the condition of equipment.



Examples of condition monitoring parameters by machine type

Parameter	Machine Type									
	Electric motor	Steam turbine	Aero gas turbine	Industrial gas turbine	Pump	Compressor	Electric generator	RIC engine	Fan	Power transformer
Temperature	•	•	•	•	•	•	•	•	•	•
Pressure		•	•	•	•	•		•	•	•
Pressure (head)					•					
Pressure ratio			•	•		•				
Pressure (vacuum)		•			•					
Electrical flow			•	•		•		•	•	
Fuel flow			•	•				•		
Fluid flow		•			•	•				
Current	•						•			•
Voltage	•						•			•
Resistance	•						•			•
Electrical phase	•						•			
Input power	•				•	•	•		•	•
Output power	•	•	•	•			•	•		•
Noise	•	•	•	•	•	•	•	•	•	•
Vibration	•	•	•	•	•	•	•	•	•	•
Acoustic emission	•	•	•	•	•	•	•	•	•	•
Ultrasonics	•	•	•	•	•	•	•	•	•	•
Oil pressure	•	•	•	•	•	•	•	•	•	
Oil consumption	•	•	•	•	•	•	•	•	•	
Oil (tribology)	•	•	•	•	•	•	•	•	•	•
Thermography	•	•	•	•	•	•	•	•	•	•
Torque	•	•		•		•	•	•		
Speed	•	•	•	•	•	•	•	•	•	
Length		•								
Angular position		•	•	•		•				
Efficiency		•	•	•	•	•		•		

RIC: Reciprocating internal combustion

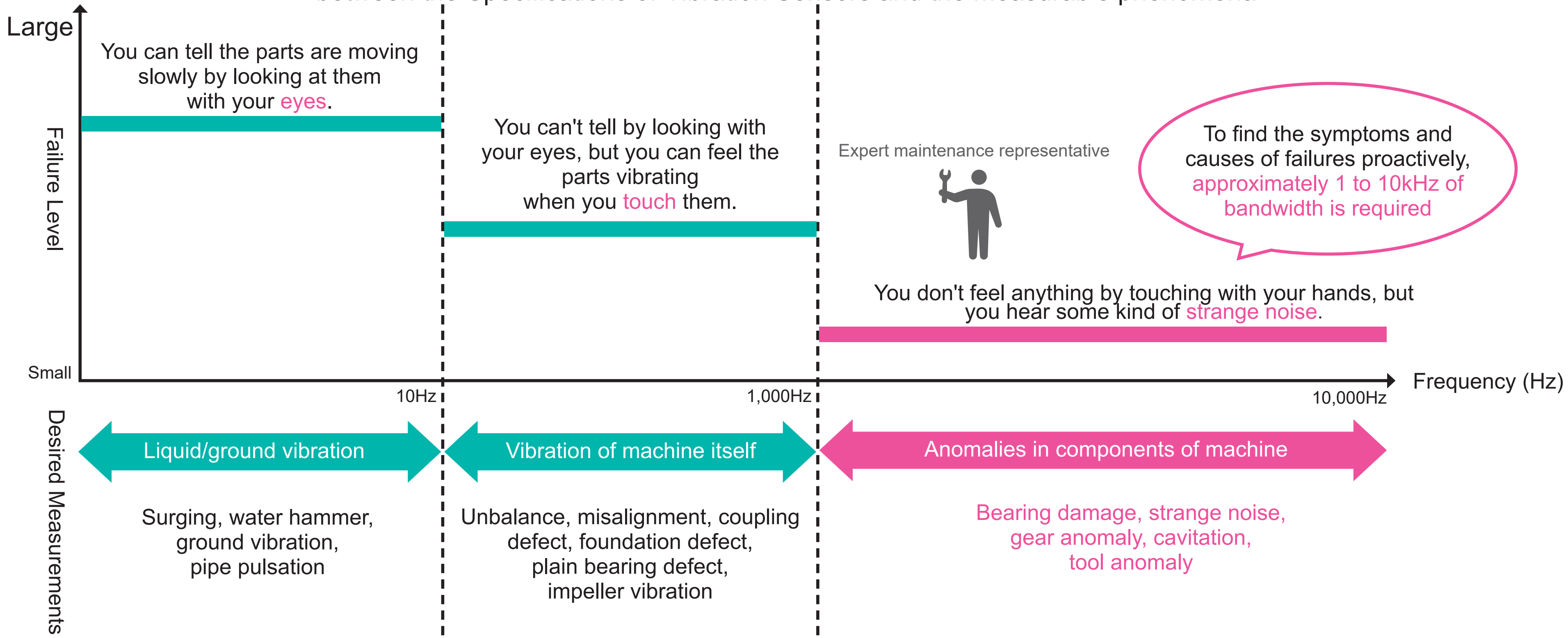
Source: ISO 17359:2018(E) Annex A Table A.1

Chapter 1: Basics of CBM (Condition-based Maintenance)

To detect degradation in high-speed rotating mechanisms, such as bearing damage or degradation, selecting a 1kHz to 10kHz broadband vibration sensor is most effective. These sensors are not usually built-in to machines, so external sensors are utilized.

There are also unfortunate cases where, even though vibration data is specifically supposed to be collected from target devices, information on the phenomena desired for detection is not collected due to bandwidth shortages for key sensors. The most effective approach is to, wherever possible, start the first stage of detection by selecting a sensor with high bandwidth, assess the necessary amount of bandwidth, and then adjust specifications as required to guarantee that operational requirements are met.

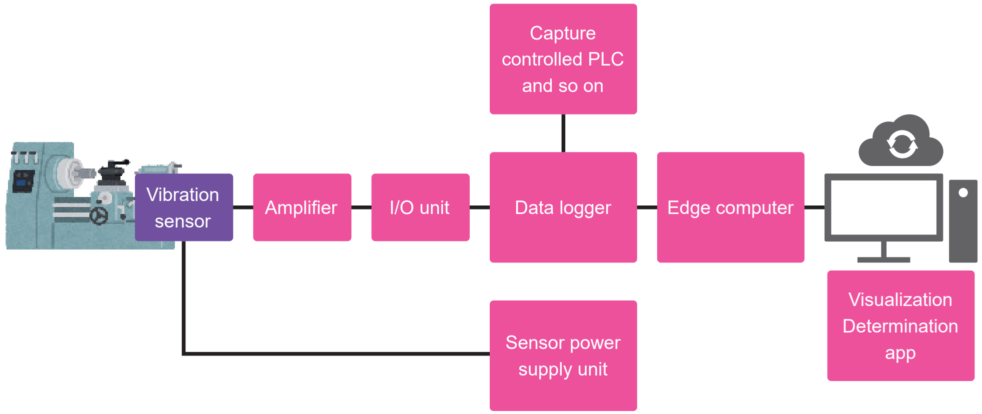
Selection of a Vibration Sensor That Meets Your Needs Is Vital! The Relationship between the Specifications of Vibration Sensors and the measurable phenomena



(2) Hardware cost for mass production/operation

System configurations that utilize such external broadband vibration sensors collect a massive amount of data. Therefore, to reduce the load of processing and transfers, it becomes necessary to build a system separately from the computing resources the machine already possesses. In addition to the sensor itself, when the power supply unit for driving the sensor, the amplifier and logger for data collection, the computer for processing, and other tools are taken into consideration, it becomes an unexpectedly large-scale configuration.
Therefore, even if a system is built to the point of proof-of-concept, there are cases when compromises cannot be made about space and price when implementing mass-produced products. Thus the project gets stuck before the product is finalized. Furthermore, if the hardware configuration changes for the proof-of-concept and the mass-produced products, the characteristics of the data itself also change. Thus the need arises to go back in the verification process to recollect data and reevaluate models. From the beginning of development, it is vital to select the system to make the product first, and afterward to proceed with the verification process.
The best hardware for handling these challenges will be introduced later.

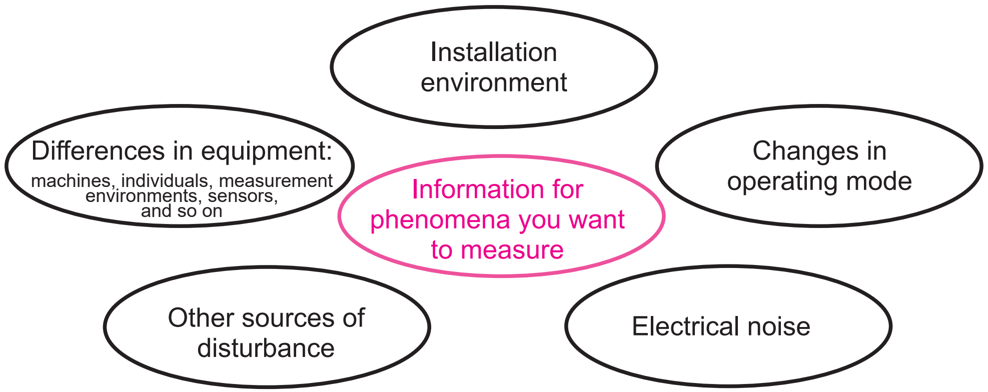
Many System Configurations with Broadband Vibration Sensors Are Complex and Costly



(3) Collection of effective training data

When it comes to collecting effective data to generate determination models, end users tend to be afraid of information leaks and dislike providing real operational data. How real data can be obtained when a problem occurs is a problem that all manufacturing developers struggle with. There are many cases where manufacturers use trial and error to try to reproduce a simulated anomaly, such as by purposely damaging test devices, mixing in sand, removing grease, or replacing the parts in company machines with exchanged parts returned by users during overhauls. However, no matter what, there is always some difference between this data and real degradation. It is not possible to create training data that imagines a scenario for every single anomaly from scratch.
Additionally, there are individual differences and various operation modes/installation environments, even for the same machine. Different ways in which users use the machines create many variables that cannot be predicted. This difference between the development environment and the production environment becomes noise that affects the determination precision when detecting an actual anomaly.

Noise That Affects Sensing Data



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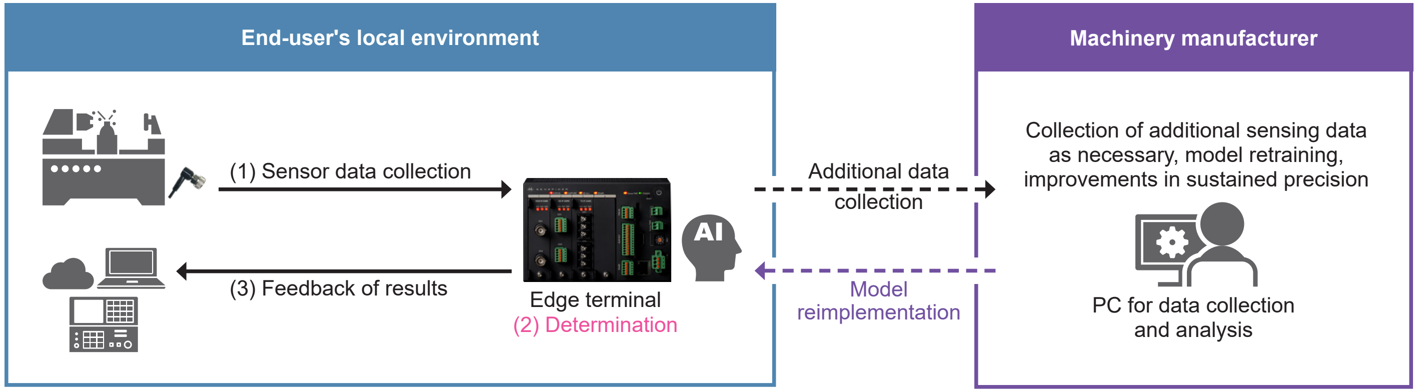
Solution

There are mainly the following two types of CBM system configuration that utilize external sensors, and the selection of the optimal configuration depends on the system that you ultimately want to implement.

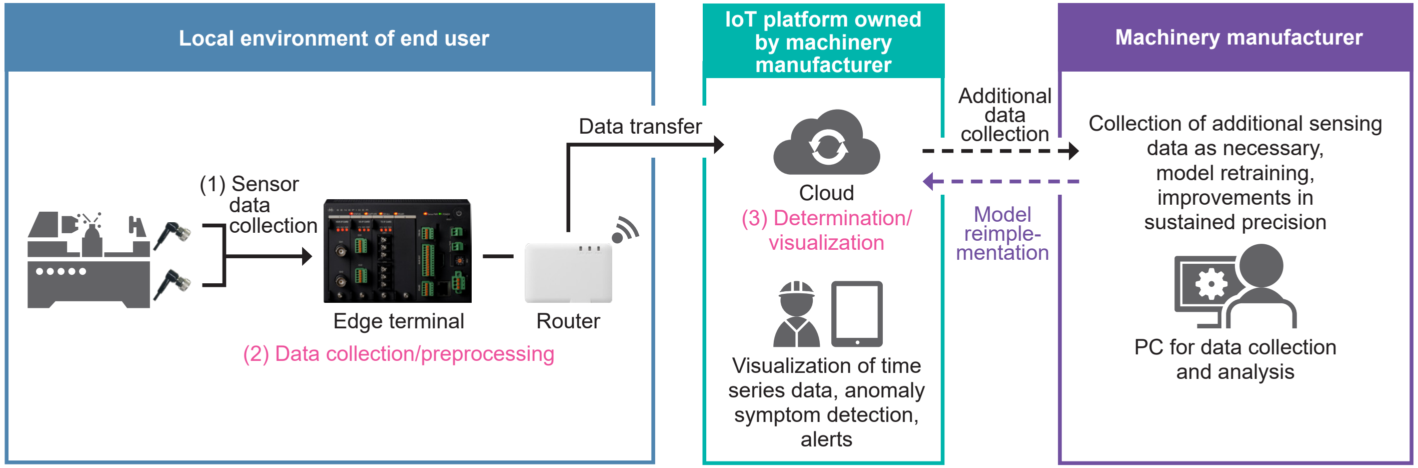
(1) Full processing at the edge

In case it is difficult to use the Internet and send collected data outside of the factory due to security requirement, or when real-time processing or integration with external device controls is required for anomaly detection etc., the edge device must be able to support full processing from data collection to determination independently.



(2) Data preprocessing at the edge + cloud integration

When a manufacturer offers remote maintenance or upgraded maintenance solutions as a comprehensive service, a configuration is often used in which the data of each end user is collected as a batch on the IoT platform, and then determination and visualization of results are performed. In such cases, to reduce the amount of data transferred to the cloud, it is necessary to perform preprocessing at the edge.



Chapter 2

Key Points for CBM System Development

This chapter explains the key points of CBM system development from project management and technical perspectives.

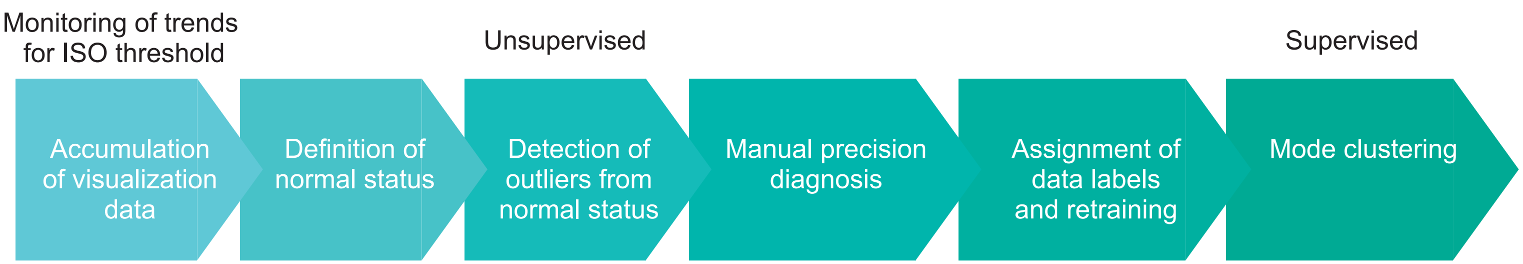
Key Points for CBM System Development

Key Points on Overall Project Management

(1) Do Not Aim for a Perfect System at the Beginning (It Is Impossible)

Machine manufacturers cannot develop a system that plans everything from the very beginning, such as the expected status of anomalies or user environments. Situations that cannot be solved with training models will inevitably emerge. For this reason, the best approach is to periodically retrain for new anomalies that appear while operating on-site and perform one by one enhancement to the system and improvements to precision. Moreover, for this purpose, it is necessary to maintain a steady connection with users even after the initial supply of machines, and plan out operational schemes for both the maintenance and enhancement of precision. The machinery continually changes due to factors such as part replacement/maintenance/changes in operational conditions. Therefore, it is important to monitor the usage situation and perform tuning of the parameters for models and retraining appropriately.

As explained above, it is challenging to collect data when there are anomalies, but even normal data includes a large amount of scattering. The scattering from differences in equipment (by model/individually), differences in measurement environments (individual differences in sensors and so on), electrical noise, differences in operating modes, installation environments, and so on all influence sensing data. For this reason, it is most effective first to use unsupervised learning that utilizes normal data to make a decision model that firmly establishes normalcy and then to proceed with building a system that can detect outliers. It is possible to collect samples of normal data from many individuals, such as the environments of end users and during the machine shipment test process. This significantly lowers the hurdles to data collection, more so than the reproduction of anomalies after the fact.



Retraining periodically while collecting data during operation

One by one enhancements to the system and improvements in precision

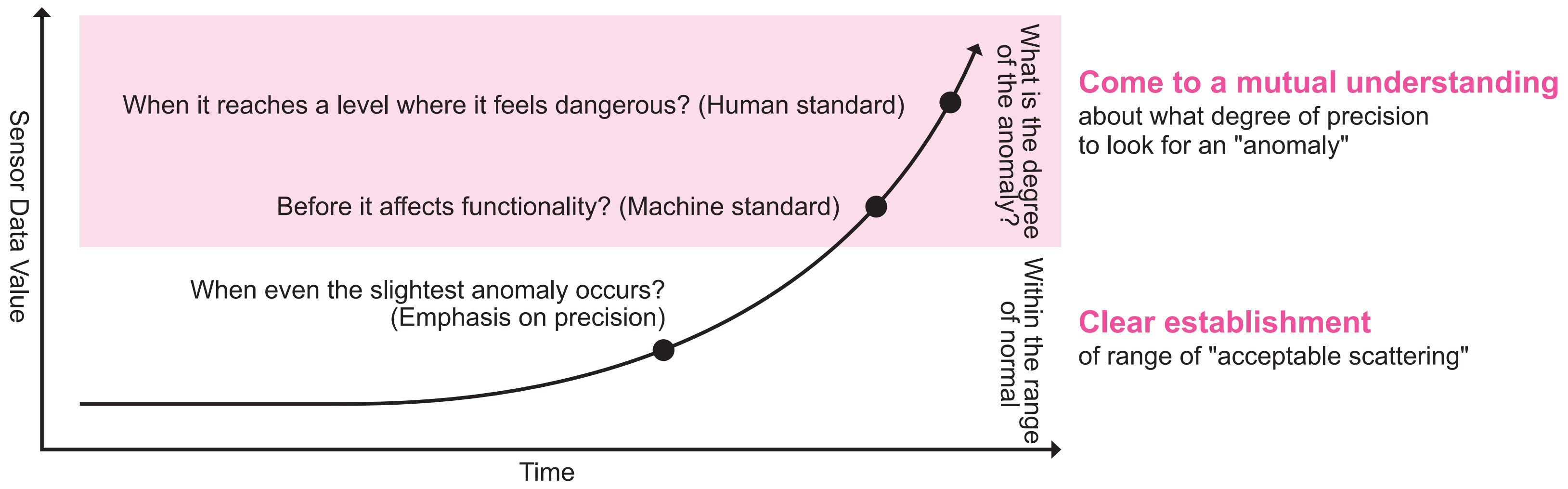
(2) Set a Clear Goal

It is vital first to set qualitative goals that define what is considered an anomaly.

For example, when referring to an "anomaly," understanding what kind of value to look for may vary between the manufacturer and the user.

By first establishing a mutual understanding between all individuals involved in the project, other decisions naturally come together, such as the environment required to perform verification and what degree of scattering (as explained above) should be allowed.

Example: I Want To Use the Bearing to the Max!



Technical Points

(1) Sensing

No matter how good the AI model is, if the quality of the input data is poor, you cannot expect precision. Everything starts with correct sensing, to the point that there is even an idiom, "Garbage in, garbage out," that states the quality of the output depends on the input. Is there a significant difference between normal and abnormal in the input data? Does it have physical validity? Asking these and other questions is vital to deciding on the optimal sensing structure. Vibration sensors are also effective for detecting the symptoms of malfunctions in dynamic devices.

(2) Importance of Preprocessing

For data collection, it is crucial to think about the combined factors of sensing and preprocessing. Preprocessing has two goals: to reduce the size of big data to an amount that is processable, and to clearly reveal the parts of data that indicate anomalies.

Raw sensing data includes not only the signs of anomalies but also unrelated changes and fluctuations. Due to this, even distinct differences may accidentally be missed. It is also necessary to decide what characteristics of the data to focus on when selecting a preprocessing method.

Data Collection =
Combination of Sensing + Preprocessing

Sensing

Does the input data...
- Have a significant difference between normal and abnormal?
- Have physical validity?

×

Preprocessing

For normal data and abnormal data...
- Are there clear, distinct differences?
- Does it include unrelated changes or fluctuations?
- Were any distinct differences deleted or missed?

Chapter 2: Key Points for CBM System Development

For example, there is the RMS for calculating the effective value and dimensionless feature quantities used in the interpretation of the kurtosis, skewness, crest factor, and other factors. Additionally, when an anomaly occurs, to interpret changes in the frequency response, the FFT (Fast Fourier Transform) that extracts the frequency components and the STFT (Short Time Fourier Transform) that extracts the time variations in frequency components are used.

For preprocessing, multiple feature quantities are used simultaneously to perform CBM in many cases. The RMS only shows the size of the signal as one scalar value, so when changes occur in the signal, there are a significant number of cases where it is not appropriate to use this as a feature quantity. For example, in cases such as when the vibration has spiked the RMS does not change in many instances. Therefore, it is necessary to take measures such as looking at the crest factor as well. Likewise, in cases when damage to the bearing is detected, generally, a band pass filter is used to perform filtering. Then the FFT and the enveloping process can detect the fundamental frequency, which indicates a moving object hitting the defective part. Next, by dividing the average value of the top peak of the envelope FFT by the median, a unique dimensionless feature quantitycan be obtained and used for the operation. This indicates the size of the vibration and the nature of the vibration and, therefore, can be used for many different devices with different sizes. For preprocessing performed in this manner, it is crucial to use multiple dimensionless feature quantities or a unique feature quantity of the user, as described above.

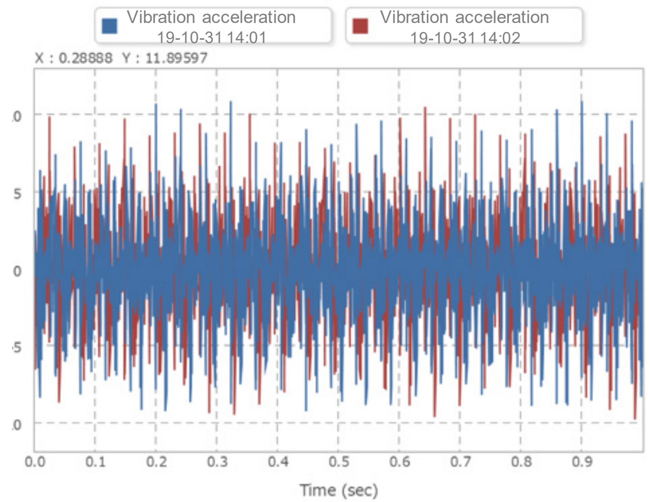
Reference (Diagrams on Right)

The diagram is a real example of how preprocessing execution reveals the anomalies included in data.

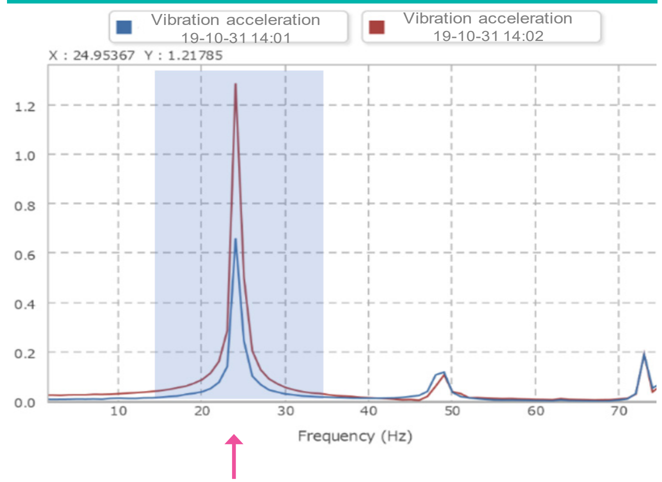
In the upper diagram, blue represents normal raw data, and red represents unbalanced raw data.

If you only look at the raw data, you cannot determine which data is the anomaly, but if you use preprocessing with the FFT to check the frequency, you can verify that the peaks in the frequency of the rotation of the axis are higher when there are anomalies.

Raw Data



FFT



It is beneficial to restrict the range of the frequency such that distinctions become obvious, and then calculate the root mean squared value (RMS) of that range

(3) Cooperation with External Partners

CBM function development by necessity incorporates many technical fields such as sensing, data analysis, and IoT that are not the specialty of mechanical manufacturers. Therefore, if these manufacturers try to complete everything with their in-house technical resources, this often fails halfway through the process. For the best results, you need to see a specialist. By cooperating with external partners who specialize in the relevant fields, it becomes easier to proceed smoothly from development to productization.

At Macnica, we also supports the development process for a multitude of manufacturers. Of course, the structure, and characteristics of machines are only known to the manufacturers, so it is first necessary to enter into a non-disclosure agreement before starting a project and to proceed while sharing information about the machines as necessary. In particular, consultations focusing on the specific theme for future productization are on the rise recently.

We publish articles about real cases studies, so please take a look!

Case Study of Okamoto Machine Tool Works, Ltd. and MACNICA, Inc.

Transplanting the Knowledge of Skilled Workers to AI to Solve the Problem of Knowledge Belonging to Only a Limited Number of Workers

The Goal: A Grinding Machine for High Quality Manufacturing That Can Be Performed by Anyone

Go Behind the Scenes of a Real Development Project!

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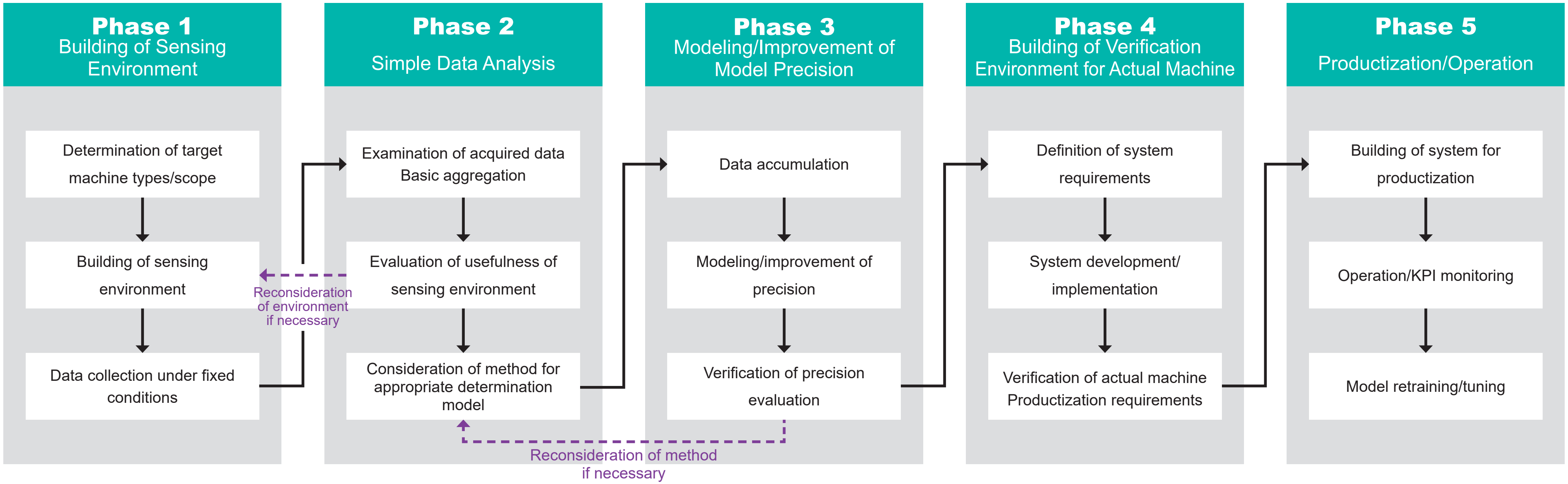
Development Flow

The basic steps for building a system up until operation are as follows.
The next page explains the goals and actions for each phase.



Chapter 2: Key Points for CBM System Development

<Phase 1: Building Sensing Environment>

- Build optimal sensing environment for what you want to implement
- Consider types and specifications of sensors, where to install sensors, and so on
- Decide on the system configuration referring to the information on the right

<Phase 2: Simple Data Analysis>

- Check the usefulness of the data collection environment built in phase 1
- Run a quick & simple analysis of collected data, mainly to verify whether the data properly includes the correlation with anomalies

- Additionally, consider the approach for the optimal preprocessing method and the optimal model structuring

<Phase 3: Modeling/Improvement of Model Precision>

- Collect additional data patterns in other possible environments. Then, run modeling, and precision verification

- Consider the optimal approach from among multiple methods, based on data trends, data amount, multivariate/univariate, explainability of output values, determination processing speed, and so on

Examples of Methods

Linear regression, multiple regression, machine learning (MT, Kernel regression, random forest), neural network (CNN, RNN/LSTM/Autoencoder)

Item	What To Check
Confirmation of target machine	- xxxxx
Confirmation of abnormal status	- Specifically, what is an anomaly? (damage/injury/partial breakage/rupture/wear/contamination/electrical error value) - What kind of anomaly would cause problems in particular? Also, why is it necessary to catch that kind of anomaly? - Frequency at which anomaly occurs - At what stage do you want to catch the anomaly? - Can changes in the data be seen when an anomaly occurs?
Confirmation of structure of target equipment	- Form/size/plan for understanding the movement pattern and movement range of operating parts
Confirmation of materials of target equipment	- Material number (for confirmation of whether it is possible to install an external sensor)
Current maintenance procedures	Are there any points you know you are dissatisfied with or want to improve about the maintenance procedures that are currently being performed?
Past initiatives	- Have you performed data analysis in the past? - What kind of state was the device data in when you performed the analysis, and what were the analysis results? - Is there any data left that was measured before?
Existence of data/type	- Data amount (how much is there, both normal and abnormal?) - Time series (vibration/electric current/reverberation) - Images

Chapter 2: Key Points for CBM System Development

<Phase 4: Building Verification Environment for Actual Machine>

- Implement the model created in phase 3 to the system, and build an environment in which operation of the actual machine can be verified
- Check the operation of the entire system, as well as the detection precision, and put together requirements for productization

*At this stage, in addition to in-house lab tests, if it is possible to perform a pilot test in the end user environment, you can obtain even more useful feedback for productization.

<Phase 5: Productization/Operation>

- Develop system based on the productization requirements in phase 4
- Improve detection precision of the model and to the reliability of operation of the system itself
- Perform retraining/tuning of model according to the usage environment of the end user even after the real product release, to maintain and improve the precision

Introduction to the Macnica Solution

Finally, this section will introduce the solution for how to overcome the wall between PoC and productization.
To resolve the problem of hardware cost, which becomes particularly challenging at the time of mass production, we developed "SENSPIDER" dedicated hardware that specializes in embedded CBM functionality. We will also introduce software that enables the unrestricted implementation of preprocessing to SENSPIDER.

"SENSPIDER", Sensing and Edge Computing Unit

SENSPIDER has a high sampling rate (maximum 48kHz). SENSPIDER makes it possible to collect a maximum of 8ch high-quality analog sensor data with broadband vibration sensors and other devices. User-customized algorithms (developed with Developers Package) can also be implemented to enable determination/inference.

For a configuration that utilizes a data logger or PLC, depending on the type of sensor, it may be necessary to prepare a dedicated I/O slot. In particular, if you want to connect a high-speed vibration sensor, an external amplifier and power supply to operate the sensor are necessary in addition to an I/O slot, and this may cost close to ten thousand dollars just for data collection. Moreover, if you want to implement AI, usually a separate computer is required, and the structure becomes quite large. This product instead collects all necessary functions into one box and its size is compact enough to easily put into the control panel, making SENSPIDER the perfect product for mass production with built-in CBM functionality.

Product Main Unit

[Product Name] SENSPIDER
[Model Name] SSP1000
[Summary] Standard equipment of one high-speed vibration sensor interface card (SSPC1310)
Expansion card slots: 3
Maximum number of channels: 8

Hardware	Specifications
CPU	ARM Cortex-A9 800MHz Dual Core
Memory	3GB
Storage	13GB

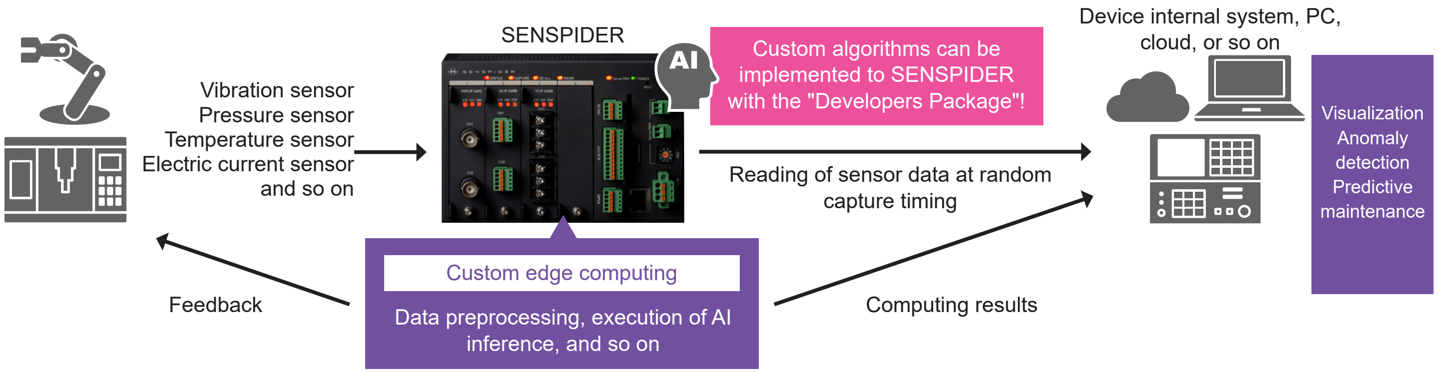
Sensor Interface Card

[Product Name] High-speed vibration sensor interface card
[Model Name] SSPC1310
[Summary]
Install to card slot on main unit to use
Sensor to connect: Model equipped with an amplifier
Number of channels: 2

[Product Name] All-purpose sensor interface card
[Model Name] SSPC1320
[Summary]
Install to card slot on main unit to use
Sensor to connect: Electric current/voltage output
Number of channels: 2

[Product Name] Temperature sensor interface card
[Model Name] SSPC1330
[Summary]
Install to card slot on main unit to use
Sensor to connect: J/K thermocouple, RTD, thermistor
Number of channels: 2

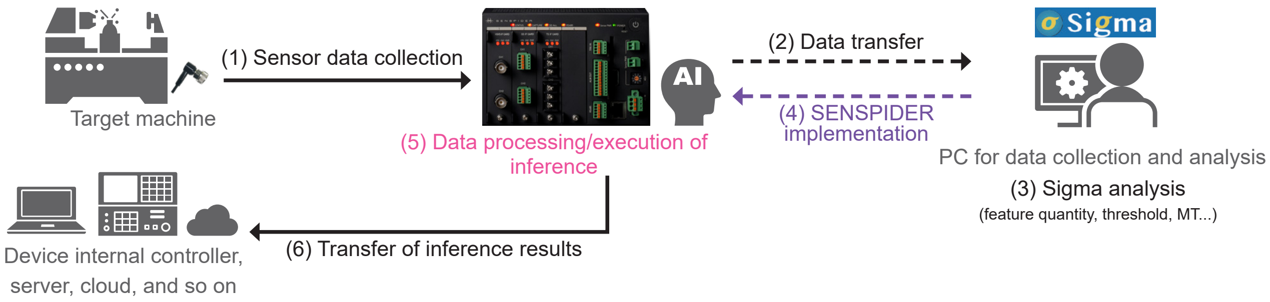
System Configuration for CBM Function Development with SENSPIDER



Introduction to the Macnica Solution

Sigma Feature Quantity Implementation Function

As explained before, preprocessing is extremely important for CBM system building. You can implement feature values, thresholds, and other custom preprocessing models designed on your PC to SENSPIDER as-is to instantly build an operating environment.



Multiple feature quantities can also be combined from the menu. This makes it possible to define user-customized feature quantities and to improve precision according to the usage environment. Models can be created based on a GUI without the need for specialized knowledge such as Python. After data collection, you can quickly proceed with system building.

This function can, of course, be used as an edge preprocessing tool for a system that makes decisions on the cloud, or when you make requirements for the system you want to implement, even if you do not utilize AI such as deep learning or machine learning, there are also cases when you can still perform a considerable amount of operations just by defining these feature quantities and thresholds. Thus this can also be used as a system for the determination of anomalies on the edge.

Main Category	Sub Categories
Preset feature quantity design	- RMS - Average value - Crest factor - Integral RMS - EFP
User-defined feature quantity design	- Standardization of the average as 0 - Standardization of the standard deviation as 1 - Band pass filter - Band stop filter - Integral - Average value - Kurtosis - Skewness - Maximum value - Minimum value - Peak value - Constant factor - Addition, subtraction - Absolute value
Threshold setting	- Selection of threshold for 4 stages, 3 stages, 2 stages, upper limit, lower limit, both sides - Selection of ISO standard threshold - Selection of EFP (high-speed bearing diagnosis) threshold
Monitoring setting	- Setting of sensor input channel for SENSPIDER (feature quantity, unit, conversion factor)

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Summary

CBM has become a key initiatives among machinery manufacturers. We have discussed the key points and flow for CBM development, but in particular, the first stage of setting the right problem is vital.

(1) Broadband vibration sensor should be effective for detection of anomalies/degradation in rotating mechanisms
(2) As much as possible, data collection should be started with a hardware structure that will be the same as the design being built-in to the product to minimize reworking of the verification process
(3) Without aiming for a perfect system from the beginning, the initiative should start from the use of normal data, followed by the raising of precision during operation

As noted in the first half, there is value in working toward the transformation of the business model from simply selling products to selling products with added value, and as the first step in these efforts, to take on the initiative to build a CBM system.

At Macnica, we have experience in providing development support to a broad range of machinery manufacturers. Contact us below to start your first consultation.

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