Process automation & Monitoring Systems

MOIRA Scientific-Skills training course (S10)

Jacopo Cavalaglio Camargo Molano, Ph.D. – Tetra Pak Packaging Solutions
Marco Cocconcelli – University of Modena and Reggio Emilia

Tetra Pak®
PROTECTS WHAT'S GOOD

This area is intended for 'Source' or 'Reference' information

About me

- Bachelor degree in Industrial Engineering at the University of Perugia
- Master degree in Mechatronic Engineering at the University of Modena and Reggio Emilia
- Ph.D. in Industrial Innovation Engineering at the University of Modena and Reggio Emilia
- Artificial Intelligence & Analytics Engineer at Tetra Pak Packaging Solutions

Agenda

- Tetra Pak presentation
- Motion control application in packaging machines
  - Automatic machine operation
  - Motors and control
- Condition Monitoring 4.0 in Tetra Pak
  - Monitoring parameters for automatic machines
  - Data Cloud Processing
  - Data visualization
- Tetra Pak use cases
- Independent carts system
  - How to approach the diagnostics of a new technology


PROTECTS WHAT'S GOOD
Tetra Pak
Who we are.

We are a world leading food processing and packaging solutions company.

Working closely with our customers and suppliers, we provide safe, innovative and environmentally sound products that each day meet the needs of hundreds of millions of people in more than 160 countries.

Processing.

Solutions and equipment for dairy, plant-based, cheese, powder, ice cream, beverages and prepared food

Services.

Helps you improve your performance, optimise costs and ensure food safety throughout the lifecycle of your operations

Packaging.

A complete carton packaging range for consuming food products offering convenience, easy opening, optimal shelf life and the ability to give maximum brand exposure

Protecting food.

We want people all over the world to have access to safe food of the highest quality

- Food safety, availability and quality
- Integrating and optimising operations
- Innovating for customer growth
- Proven expertise

How we do it?

By continuously innovating to improve safety and quality standards through e.g.:

- eBeam non-chemical sterilisation
- Aseptic Performance Leadership
- Quality Data Management System

Our global organisation.

World-class expertise, everywhere

27 Market companies

>12.775 Net sales 2023 in € billion

>160 Countries where Tetra Pak had sales

8 Technical Training Centres

7 Customer Innovation Centres

100 Sales offices

24,391 Employees

2,302 Processing units delivered

234 Filling machines delivered

810 Downstream equipment delivered

8,426 Packaging machines in operation

21,789 Downstream equipment in operation

108,396 Processing units in operation

6 R&D centres

10 Product Development Centres

51 Production plants

All figures by January 2024.

Motion control applications in packaging machines

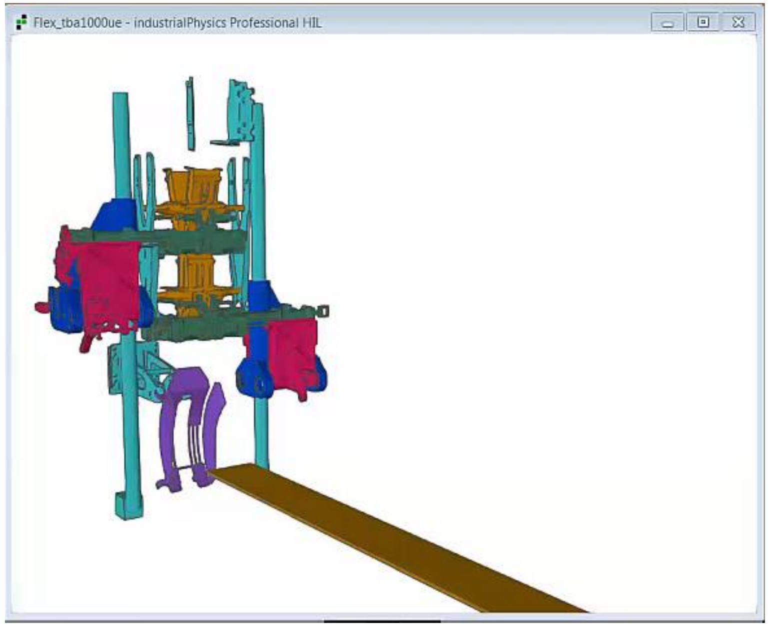
Tetra Pak®
PROTECTS WHAT'S GOOD

Packaging machines

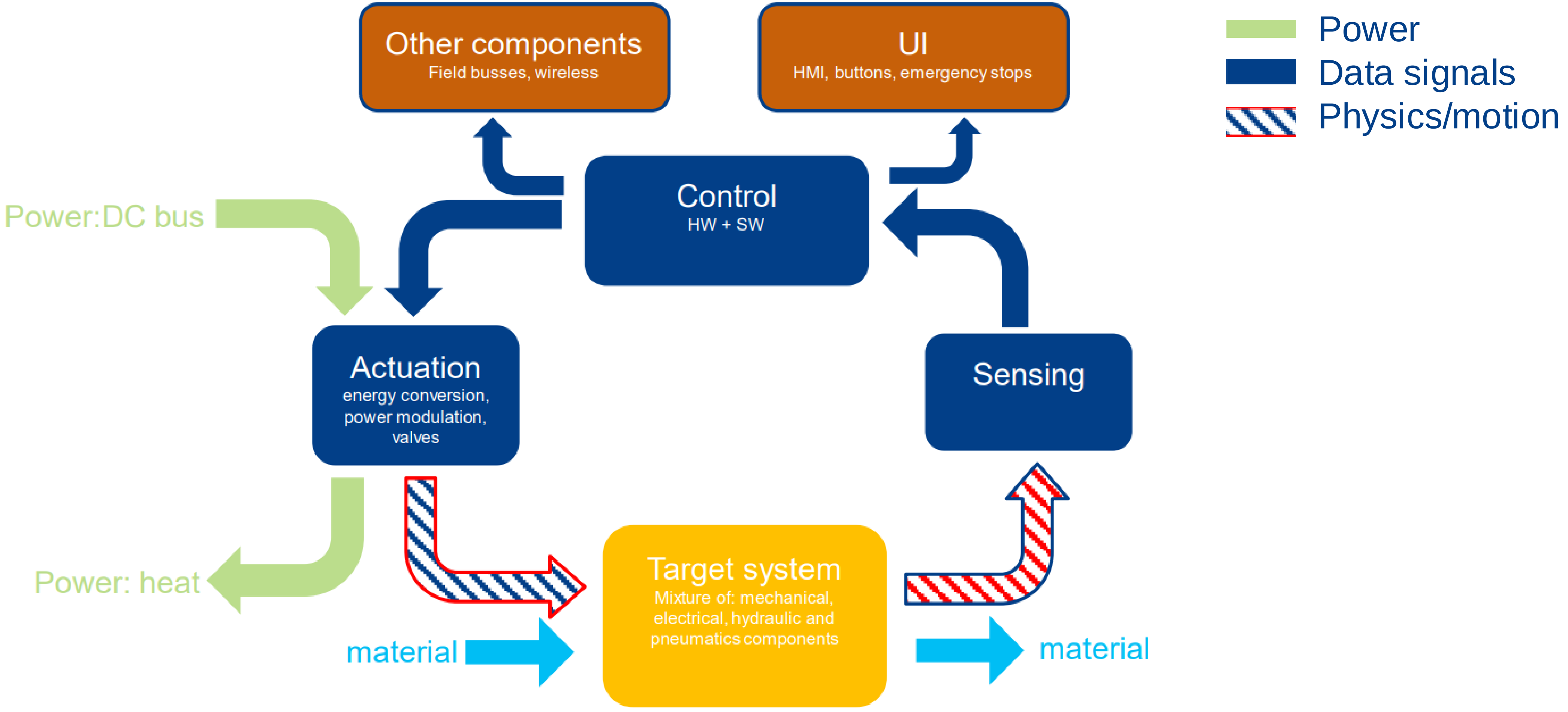
- A packaging machine is characterized by highly coordinated repetitive actions that shape a material into a container, fills the container and seals it.
- There is often some processing treatment of the container e.g. sterilization.
- Typical cycle times are from 70ms to 1,5s.
- Machines for carton packages usually have all functions integrated into one single mechatronic entity (e.g. centralized CPUs and Motion Control for whole machine, Virtual Axes for moving all the Physical Axes in coordination)

Packaging machines

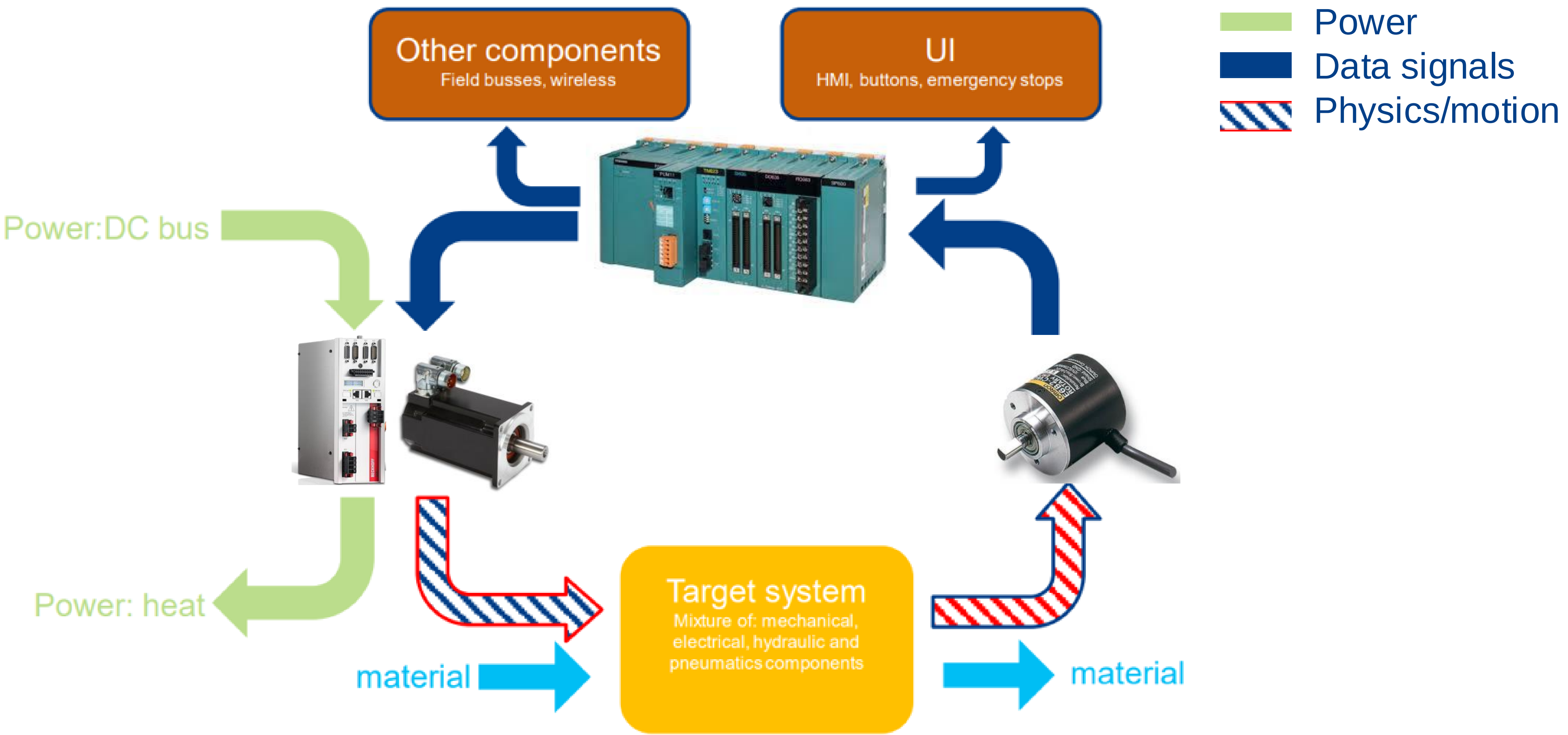
- A packaging machine is characterized by highly coordinated repetitive actions that shape a material into a container, fills the container and seals it.
- There is often some processing treatment of the container e.g. sterilization.
- Typical cycle times are from 70ms to 1,5s.
- Machines for carton packages usually have all functions integrated into one single mechatronic entity (e.g. centralized CPUs and Motion Control for whole machine, Virtual Axes for moving all the Physical Axes in coordination)



Automatic machines flow chart



Automatic machines flow chart

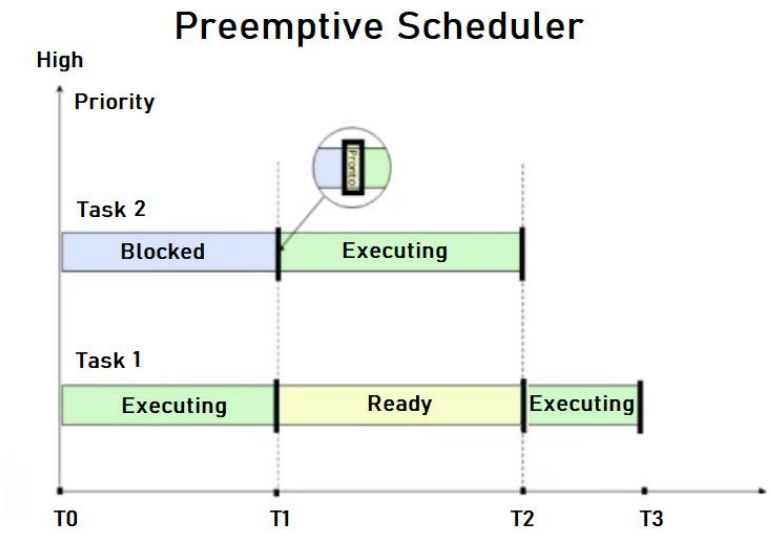


Motors and control

The most typical actuator used in packaging machines are electrical motors. They are used due to their precise control of the position, speed or torque.
The motion system of electrical motor is based on three elements:

Programmable Logic controller (PLC)

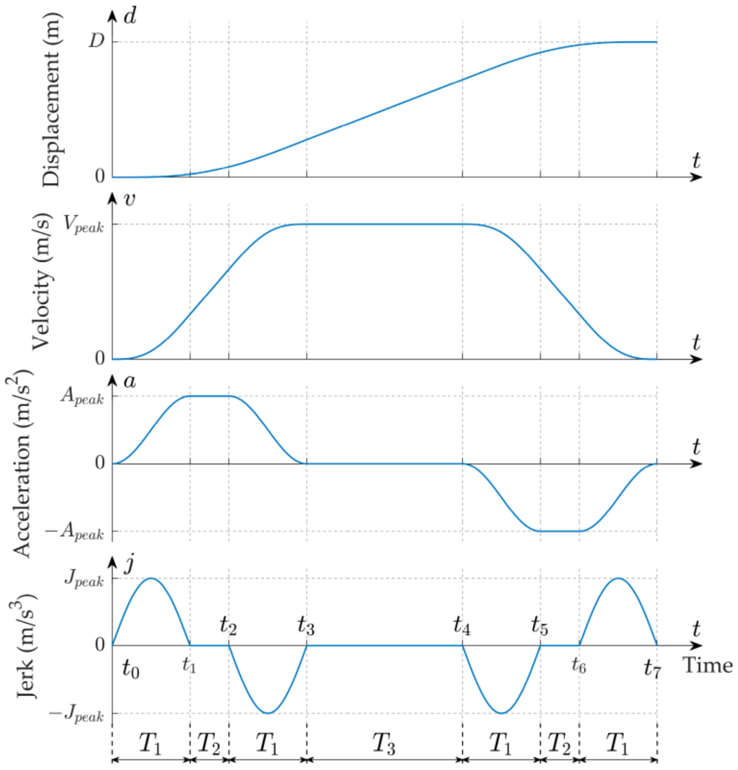
- Is a specialized computer used in industrial control systems to automate processes and machinery.
- It use a **Real Time operative system** that **has** the capability to schedule the execution of specific tasks within a very specific time constraint. Processing must be done within the defined constraints **or the system will fail**.



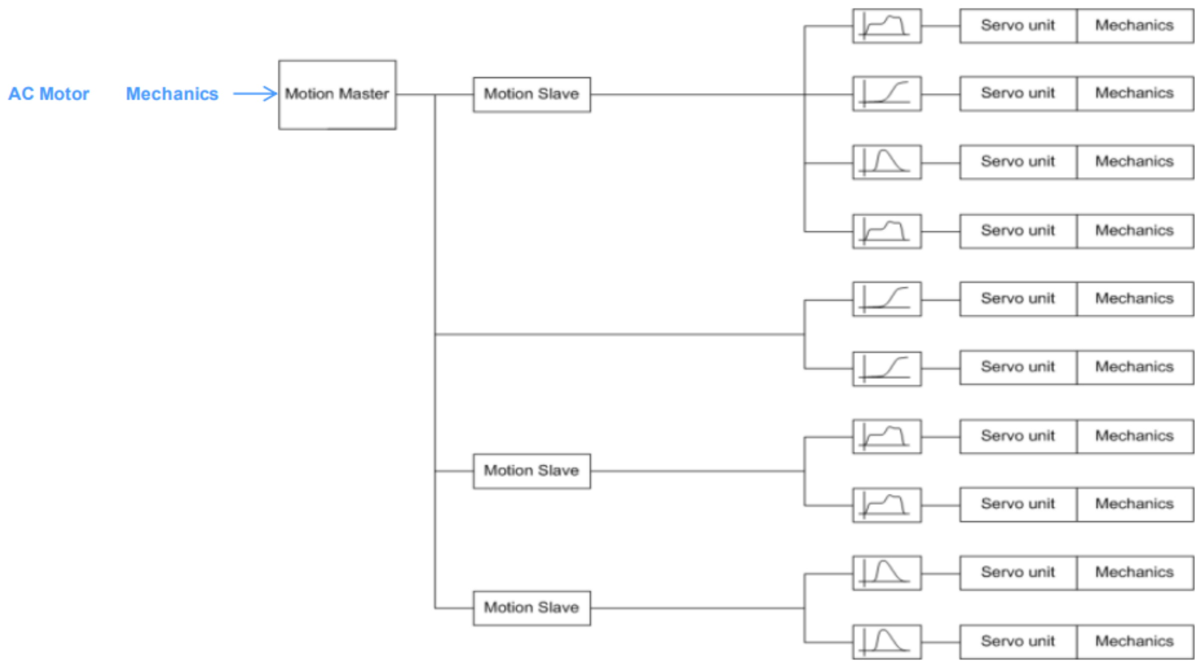
Motors and control

- It is used to compute the trajectory of motion and to give the control signal to the amplifier.
- It allows the motion synchronization for all the actuators.
- To do it is used a Master/Slave architecture.

Motion profile



Master/Slave architecture

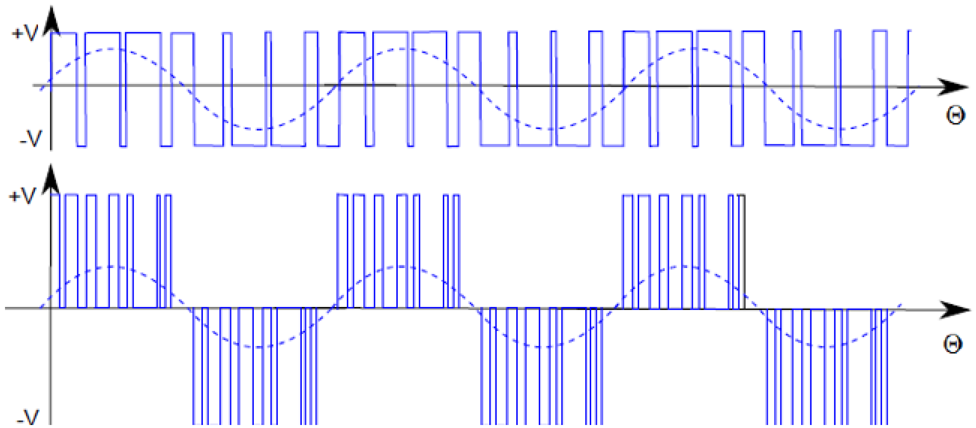


Motors and control

The most typical actuator used in packaging machines are electrical motors they are use due to their precise control of the position, speed or torque.
The motion system of electrical motor is based on three elements:

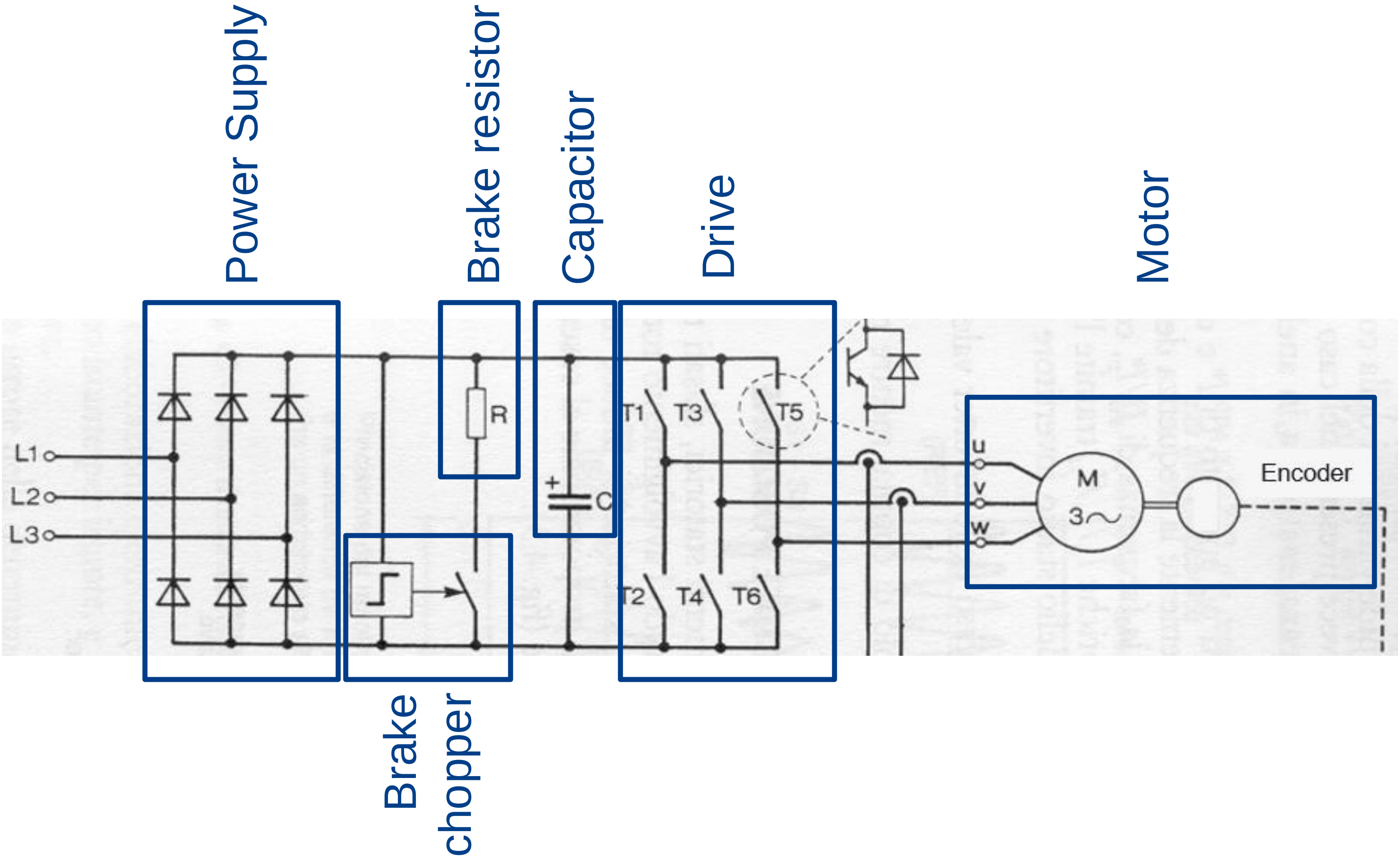
Driver

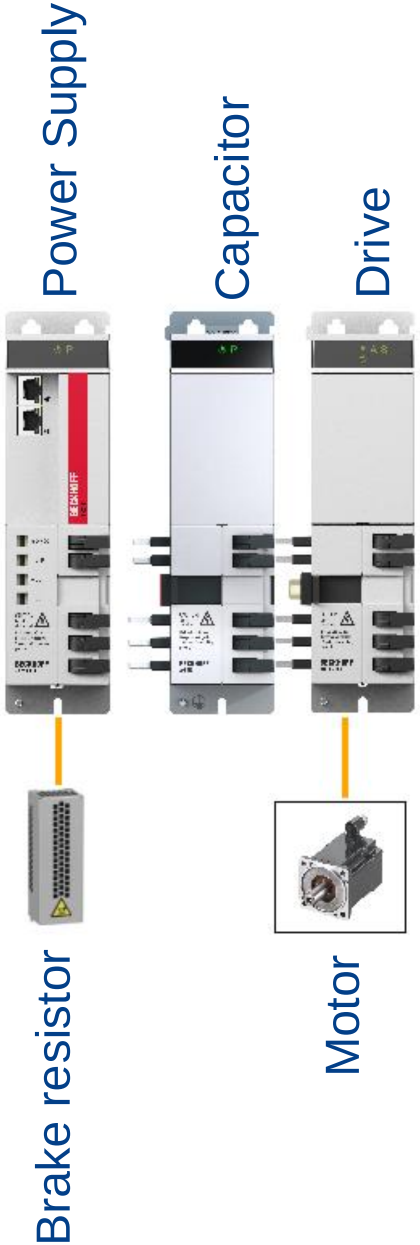
- It **amplifies** the control signal from the PLC controller up to high power, which the motor can use.
- It **rectifies** AC to DC voltage that is supplied to the Drive Controls the DC Bus and manages ”drainage” to Brake resistor or additional Capcitors (It occurrs when the regenerative energy is at it´s peak (motors are braking)
- It **choppes** up the DC voltage (PWM) using IGBT´s (Power transistors) to control the motor Uses Position and/or Velocity and Current feedback to close the controll loop



General

Motors and control

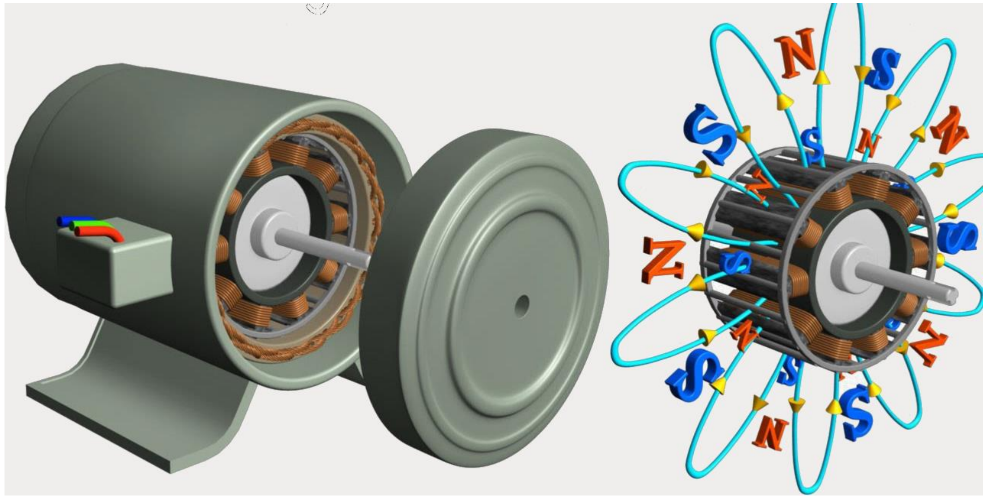


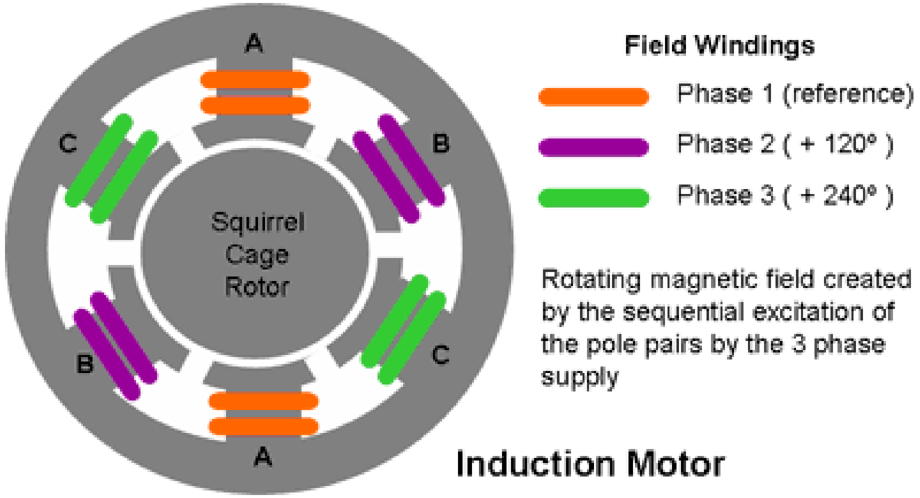


Motors and control

AC Induction Asynchronous Motors

- Cheap, Reliable & Standard
- No feedback required, most often open loop
- Not too dynamic and performant
- Not too energy efficient





Motors and control

AC induction Asynchronous Motors

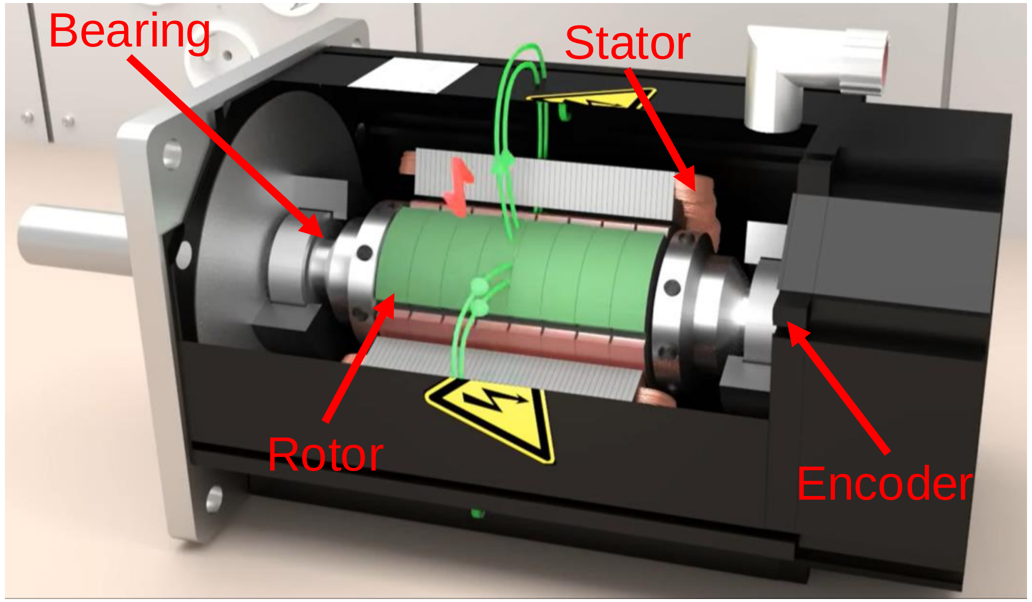
- Used for driving conveyors, fans, pumps etc. with reasonable performance
- Can run directly off the grid
  - The *synchronous speed* is the rotation speed of the magnetic field and is proportional to grid frequency and number of motor poles
    - For 50 Hz grid: - 2 pole = 3000 rpm - 4 pole = 1500 rpm 6 pole = 1000 rpm
  - The actual, true, speed is determined by the motor design and the load the motor is driving. This speed is called the *asynchronous speed*
    - The difference between the two is termed *slip*
- Often controlled by a Variable Frequency Drive (VFD)
  - Enabling variable speed
  - Can adjust for the slip by smart control algorithms

Motors and control

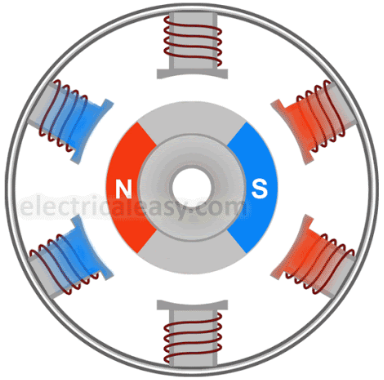
Servo Motors

The most typical actuator used in packaging machines are electrical motors they are use due to their precise control of the position, speed or torque.
The motion system of electrical motor is based on three elements:

Servo motor



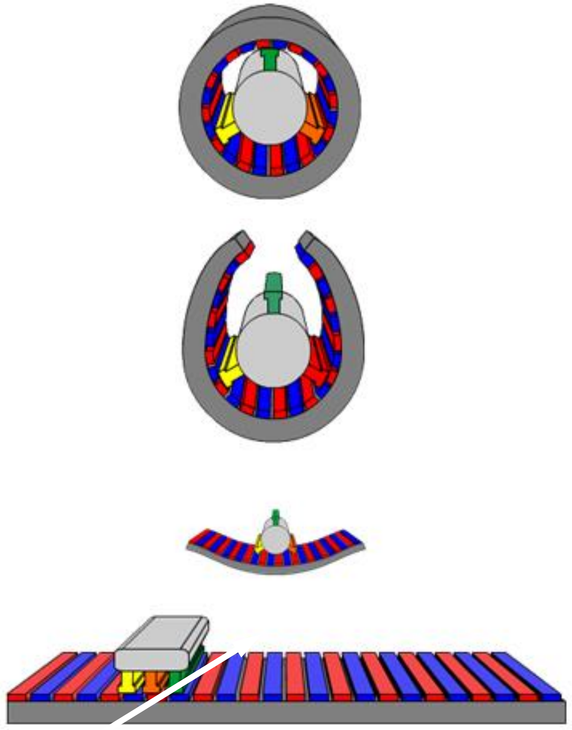
- AC servomotor usually are three phases brushless synchronous motor whose rotor field is excited by permanent magnet
- They have a feedback sensor (resolver or encoder) that send the information about the actual position of the rotor.



Motors and control

Linear Motors

- Basically a “dissected” and “unfolded” rotary motor
  - Width of slider/stator and length of stator decides force performance
  - Add stator modules to increase move length
  - Mechanics (bearings) and encoder must be added
  - Very high attraction force – increase complexity at assembly
  - Full flat or slightly rounded possibilities



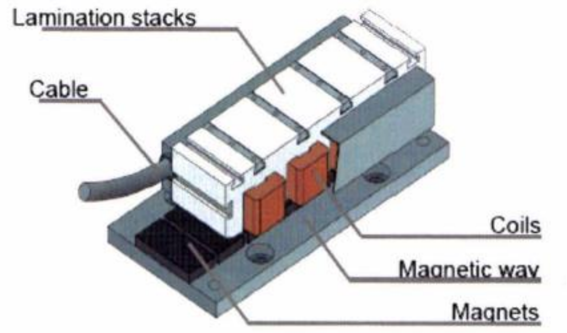
- Very good performance – direct drive
- Rather expensive but eliminates most of the drive train.

Motors and control

Linear Motors

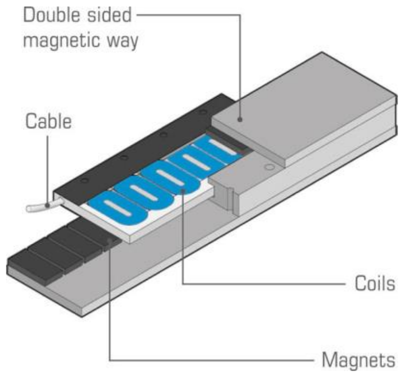
- **Ironcore:** The stator consists of an iron base plate covered with permanent magnets.The moving part consist of a laminated iron core containing coils

  High force, limited speed



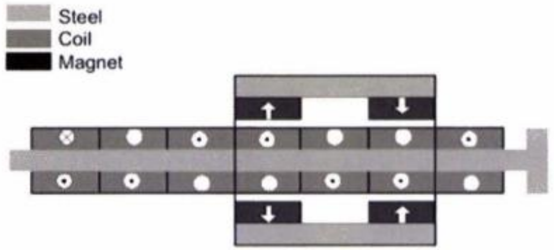
- **Ironless:** The stator consists of two iron base plates covered with permanent magnets configured in a U-form. Between the plates there is the moving part that consist of an epoxy plate that contains the coils that commuted the magnetic field.

  Limited force, very high speed



- **Moving magnets :** Multiple coils are placed in the stator, it required multiple switching amplifier for moving the moving part that contains the permanent magnets.

  High speed , medium force



General

Independent cart system

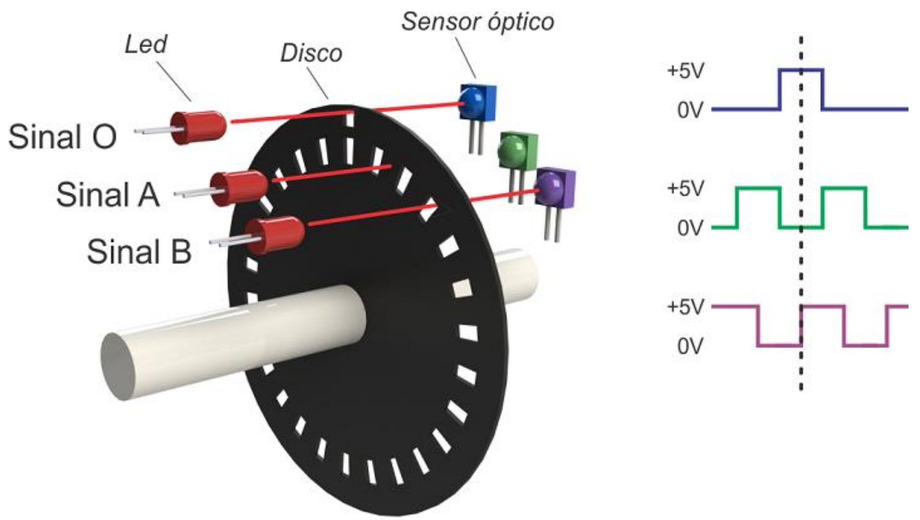
Motors and control

Position feedback

- There are different types of Position feedback devices:
  - Resolver
  - Encoder (absolute or incremental)
- The feedback devices can Incremental or Absolute
- Can be connected directly to the drive or using a real time fieldbus in to close the control loop

Resolver

Encoder

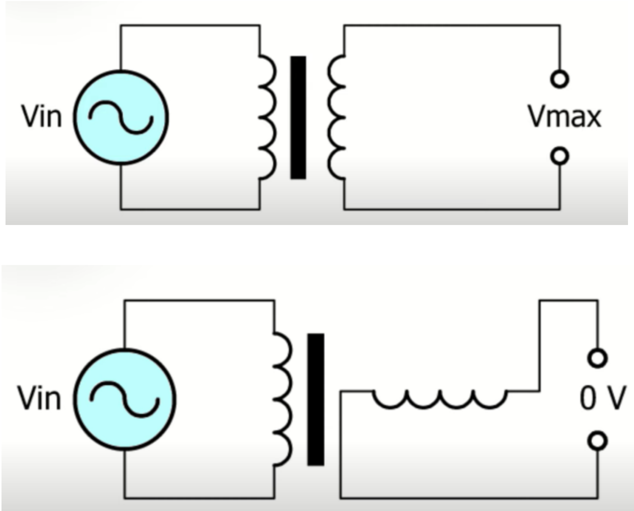


Motors and control

Position feedback: resolver

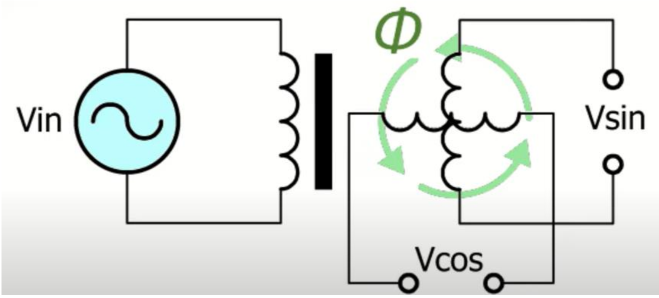
- The resolver is an analog device that produces an *Incremental* position feedback
- Rather robust and cheap, but not too common today because they are not very precise
- Resolution is infinite and based on the AD converter performance
- It is a transformer with a fix widing and a rotating widing
- 2 channels to enhance robustness because with only one is not possible to establish the rotation direction

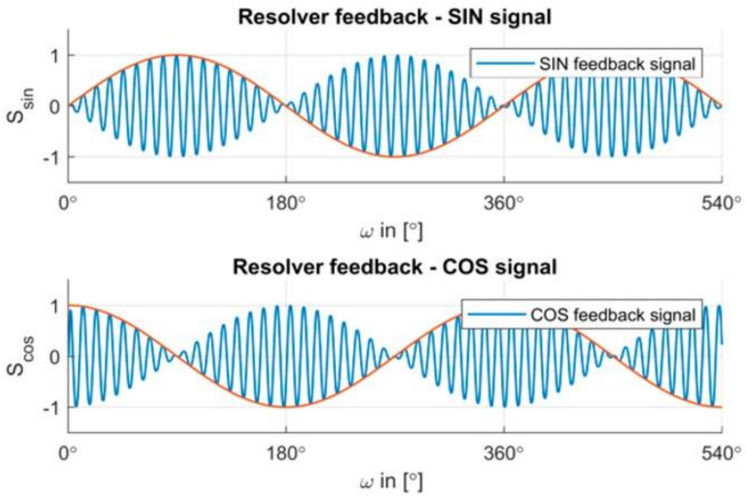
One channel



$$V_{out} = V_{in} \sin(\varphi)$$

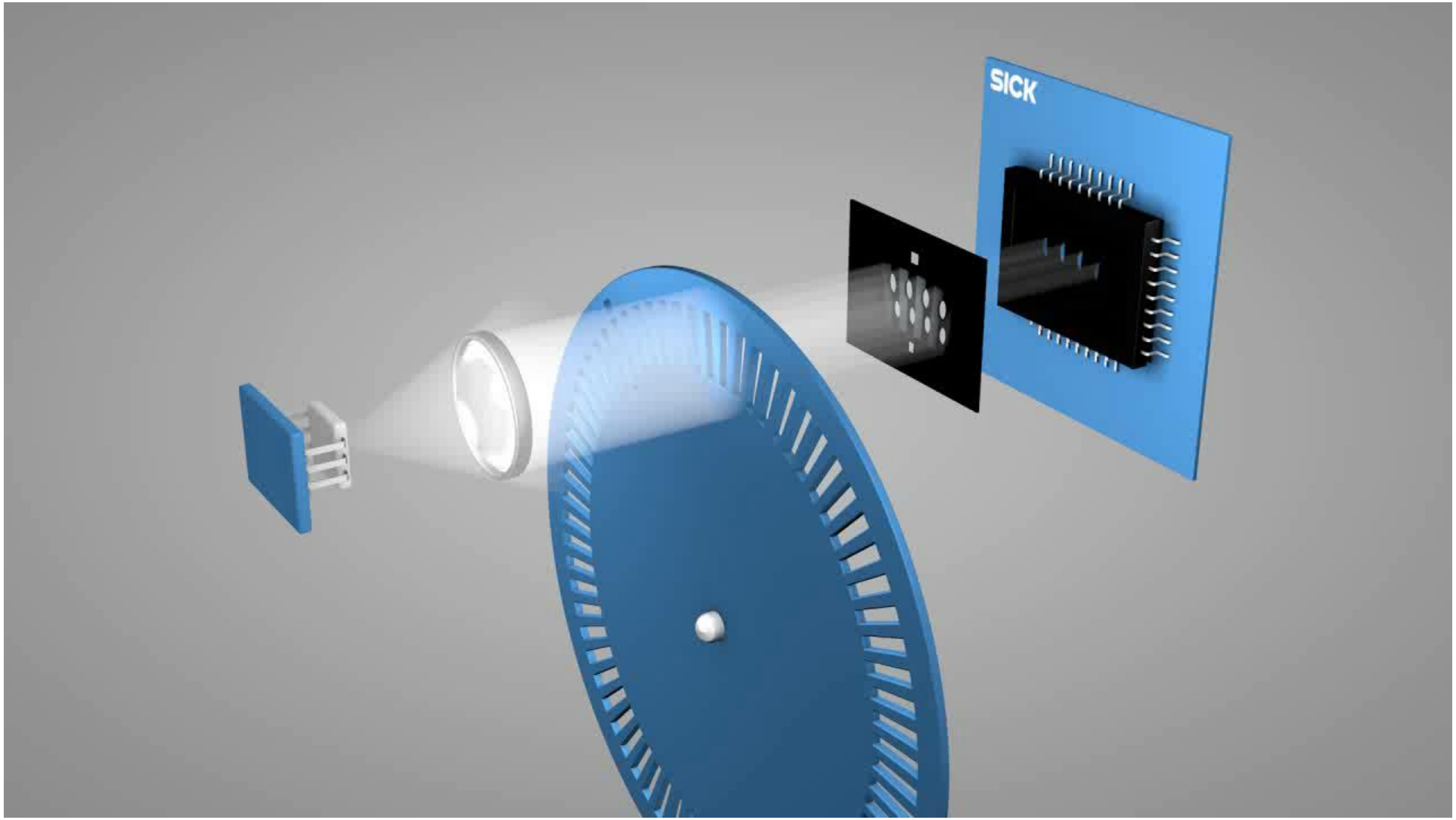
Two channels





Motors and control

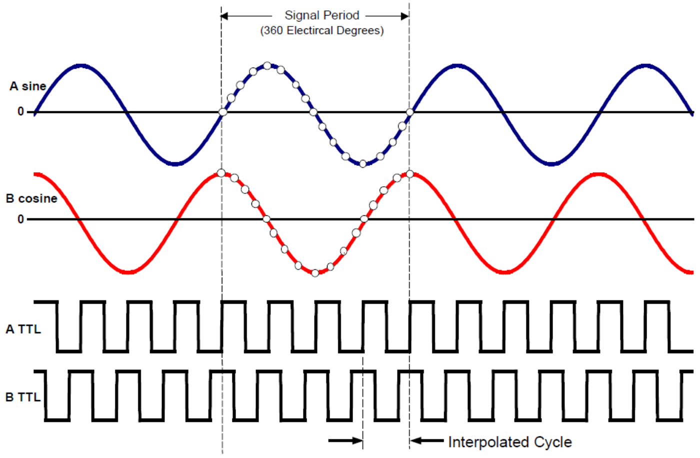
Position feedback: encoder

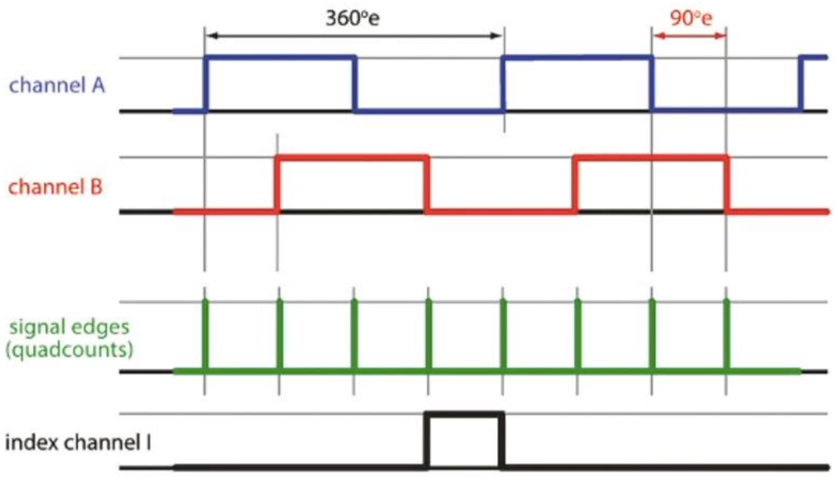


Motors and control

Position feedback: encoder

- Encoder is a device that provides a digital output as a result of rotational or linear displacement
  - Digital superimposed on e.g. Temp wires
  - Analog single turn position, digital multi turn position
  - The single turn resolution is typically 18 bits (262143 incr / rev) and counting…





Available data of the motion system

The data of the motion system are very useful for the condition monitoring.

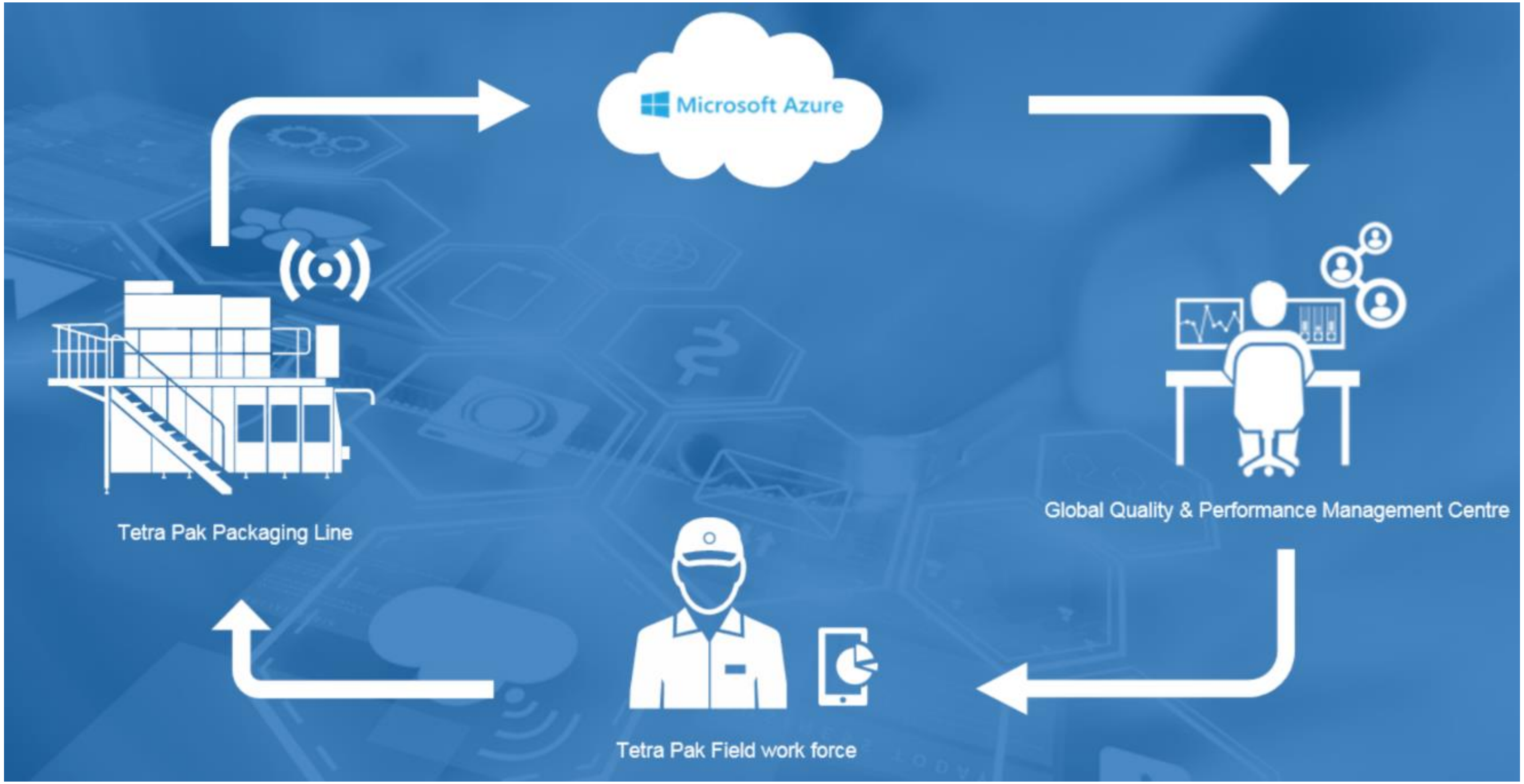
The typical data recorded are:

- Position error (difference between the actual position and the target position of the motor)
- Velocity error (difference between the actual velocity and the target velocity of the motor)
- Actual Current (It is proportional to the torque of the motor)
- Temperature of the motor

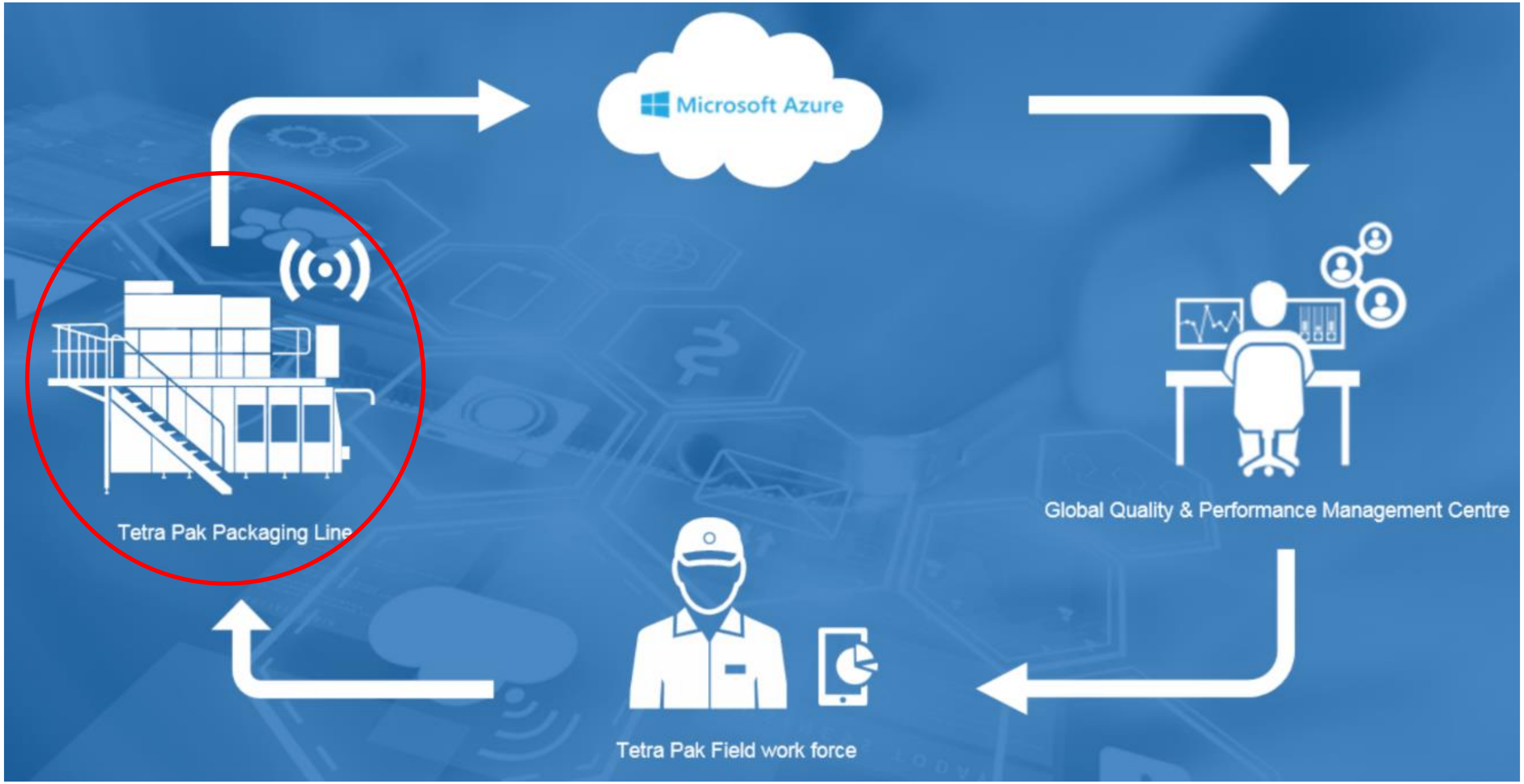
Condition monitoring & predictive maintenance approach within Industry 4.0.

Tetra Pak®
PROTECTS WHAT'S GOOD

Condition monitoring 4.0 in Tetra Pak



Condition monitoring 4.0 in Tetra Pak



Failure Mode analysis

In general, each component of an automatic machine has a peculiar way of failures, cost of failure(COF), mean time to repair(MTTR), etc…

Failure mode effect analysis(**FMEA**) and Failure mode, effect and criticality analysis(**FMECA**) are two methods in order to identify the potential failure modes and estimate the probability of a failure.

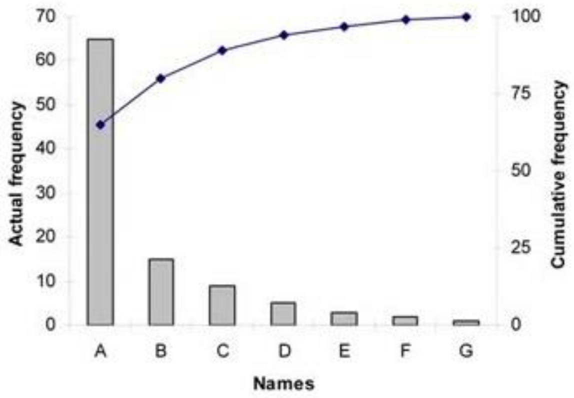
In case exist historical data of component failures is necessary to execute a pareto analysis to find which are the component failure with the higher frequency respect to the cost of the failure.

The choice of the type of the sensors, their placement, and the schedule of the data collection require the knowledge of the process and an analysis of the impact of sensor costs on the process.

FMEA

Severity / Probability	1	2	3	4	5
1	Low	Low	Low	Low	Moderate
2	Low	Low	Low	Moderate	High
3	Low	Low	Moderate	Moderate	High
4	Low	Moderate	Moderate	High	Unacceptable
5	Moderate	Moderate	High	Unacceptable	Unacceptable

Pareto chart



Monitoring parameters for automatic machines

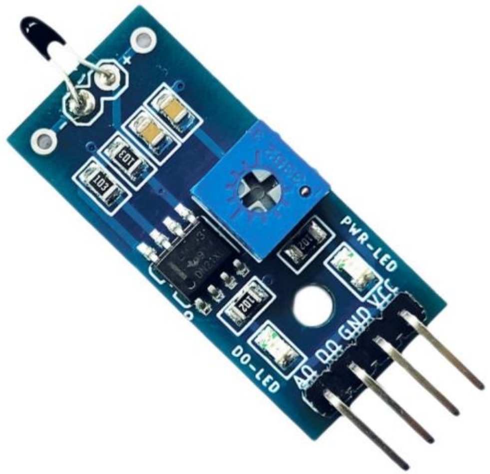
Sensor type

Multi-purpose external sensors: They are the most used sensors for condition monitoring. They can be applied to different components (multi-purpose), measuring the effects of impacts or events in time domain and include for example accelerometers or external temperature sensors.

These sensors are not usually present in the machine and represent an extra cost for maintenance.

Accelerometer

Temperature sensor



Monitoring parameters for automatic machines

Sensor type

- **Specific external sensors**; They are used for a specific measurements in specific parts of the machine. Sometimes multi-purpose sensors cannot be used because of the impossibility of installation, such as environmental conditions or some possible mechanical interference with moving parts during the process. Sometimes a specific measurement is needed in a very limited but critical part of the plant, for example chemical analysis.
- **These sensors are not usually present in the machine and represent an extra cost for maintenance.**

Pressure sensor

Oil quality

Monitoring parameters for automatic machines

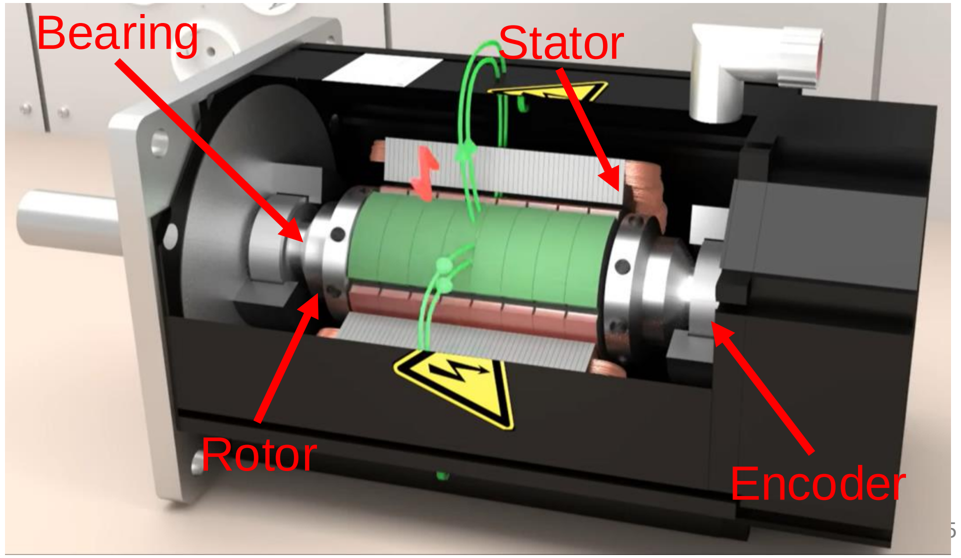
Sensor type

Embedded sensors; They are already present in specific components of the machine, since they are used by control logics for the correct operation of the machinery.

They do not represent an extra cost for maintenance.

For example, in the modern servomotors there is always:

- An **encoder** for position measurement,
- An **embedded amperemeter** (often by means of two simple Hall sensors) for the measurement of the current absorbed by the mains
- A **temperature sensor** (often embedded in the encoder) for the measurement of the heat inside the motor (or at least a positive temperature coefficient (PTC) thermistor in the coils for detection of over temperature).



Monitoring parameters for automatic machines:

Acquisition type

On-Line Data: Is informative data acquired in the working conditions of the machine. They are collected by specific sensors to measure the state variables of the system.

Off-Line Data: Is informative data asynchronous to the working conditions of the machine. This is the opposite of “on-line data” which is collected during events synchronous to the working conditions.
These events cover scheduled service interventions, unexpected service interventions, and production conditions of the machine.

Some off-line data can be acquired and stored automatically, for example the stopping or starting up of the machine, but most of the off-line data is manually inserted by the service engineers that perform the technical interventions or by the after-sales department which defines the scheduled operations.

Off-line data is essential for condition-based maintenance and much more in the development step of the data-driven processing, showing the difference between supervised and unsupervised methods (for more details see [27,28]).

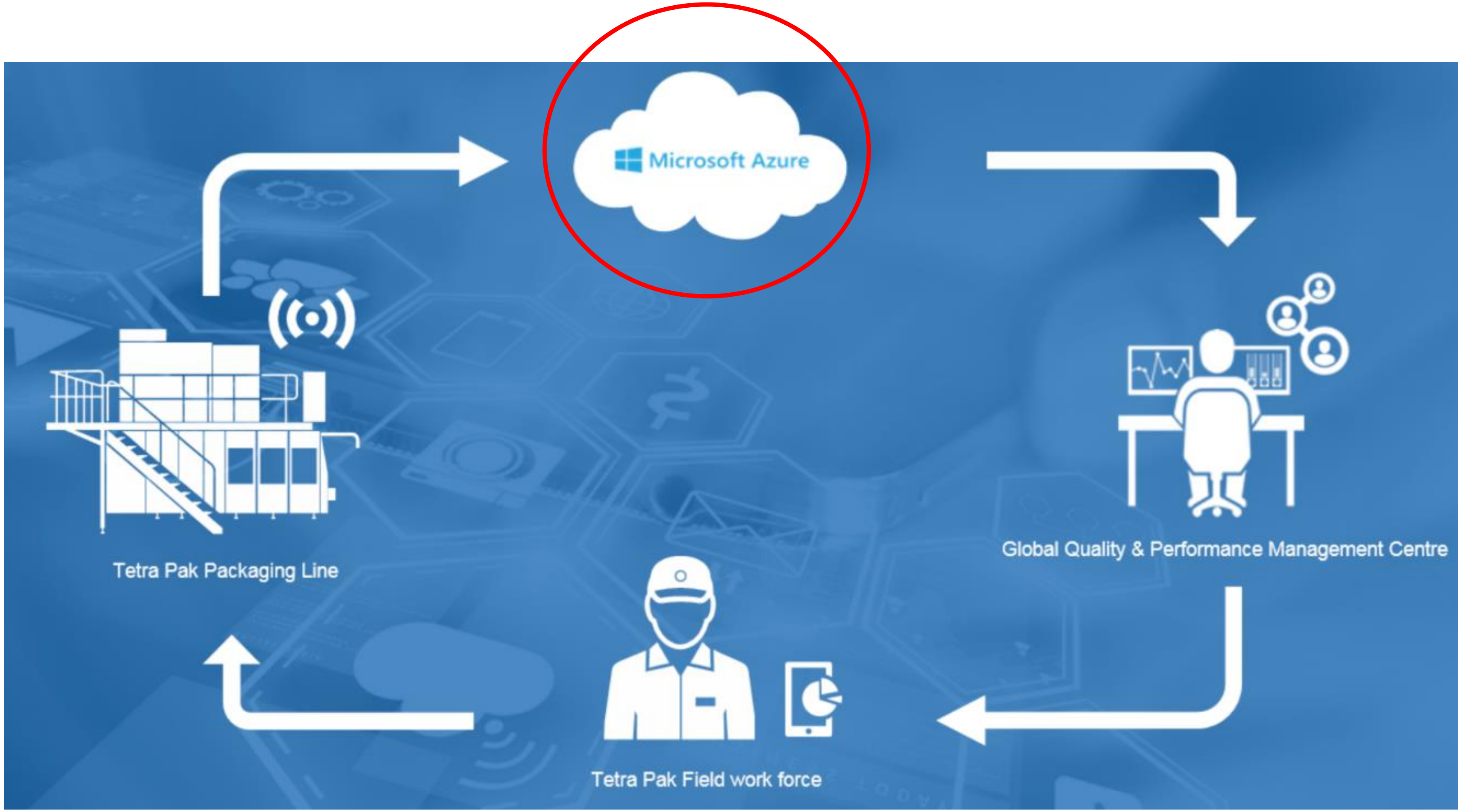
Data Pre-processing

The data collected from a single machine must be pre-processed **locally**, before data is sent to a high-level storage structure to reduce the amount of data to be sent to the cloud platform and to decrease the latency in the decision-making process.
The **cloud platform costs depend on the amount of data processed,** therefore aggregated data is preferable for cost reduction.
The main functions of the pre-processing step are the following:

- **Checking of the sensors**: The measurement files are checked for inconsistency of data. Especially in manufacturing machines, processes are repeated cyclically and the expected data from sensors must contain cyclic components too (e.g., at the productivity frequency of the machine). If the data recorded by a given sensor does not show cyclic components in the spectrum, it is due to a problem on the measurement chain: the sensor, the cable, or the acquisition system. The inconsistency of the data must generate an alarm to the service engineer that will schedule a check of the sensor.

- **Calculation of statistics:** The main advantage is data reduction; each statistic is a single scalar value compared to the thousands of points acquired by each sensor. Statistics are the features that the data-driven diagnostic method uses to make the post-processing analysis.

Condition monitoring 4.0 in Tetra Pak



Data Cloud

The data cloud processing mainly consists of cloud-computing data management.

The main functions of the cloud-processing step are as follows:

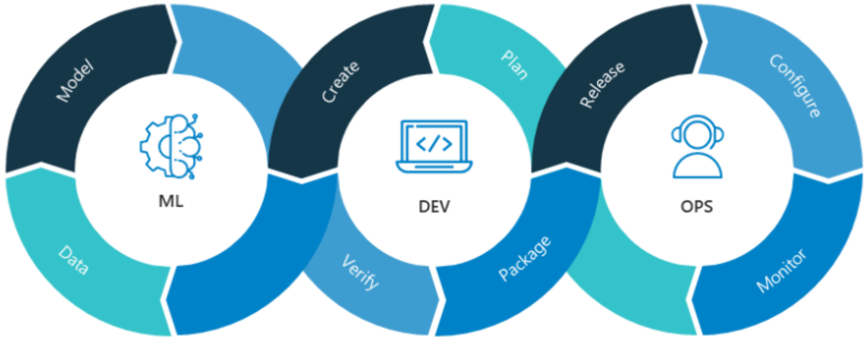
• **Data-storage**: The data needs to be storage in the most efficiently way both for reduce the storage space and to have an efficient way to use data coming from different sources. Fundamental is the data partitioning that can be **Directional Partitioning** , based on different access patterns and continent needs or **Logical Partitioning** based on probability/frequency of access

• **Data transfer**: The off-line data does not need further processing. In this case, the cloud acts as a simple storage device; the analysts pick up the off-line data collected from different machines for the off-line development of condition-monitoring techniques.

Data Cloud Processing

Execute the prediction models: Statistics data from every monitored subsystem of the machine are analysed with Model based, machine learning and statistical techniques. The machine learning system generates alarms to the performance management centre

Machine learning operation(MLOps): All the workflow of the ML models from the training to the deployment and the life cycle is manage in the cloud with software such as Mlflow, Weights & Biases, LakeFS.



Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

1. Business Understanding:

- Gathering background information about the current business situation as precise as possible(ex. Is already exist a similar solution? Or is it an improvement?)
- Define the business objectives and requirements(ex. Define cost and target profit)
- Define the criteria to determine the data mining success from a business perspective.

Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

2. Data understanding:

- Define the amount of data, the value types (numerical, categorical),coding scheme.
- Check the data with the domain knowledge for improve the data understanding.
- Verify data quality(Missing data, bad metadata, measurements error)

Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

3. Data preparation:

- Is one of the most important aspects.
- it is estimated that data preparation usually takes 50-70% of a project's time
- Data preparation consist in several task like merging dataset, data cleaning, splitting the dataset in training and test dataset

Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

4. Modelling

- Decide which type of models are the most promise(possible to use pre-trained model or train a model from scratch)
- Train the model and fine-tune the parameters to respect the target of the required by the business
- It can be re-iterate the data preparation to have a more optimize model

Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

5. Evaluation

- It is based on the business success criteria
- If the model satisfy the business criteria it is possible to deploy it
- In case the success criteria are not satisfy we can elaborate conclusions and findings that can be used for re-start the process or stop it

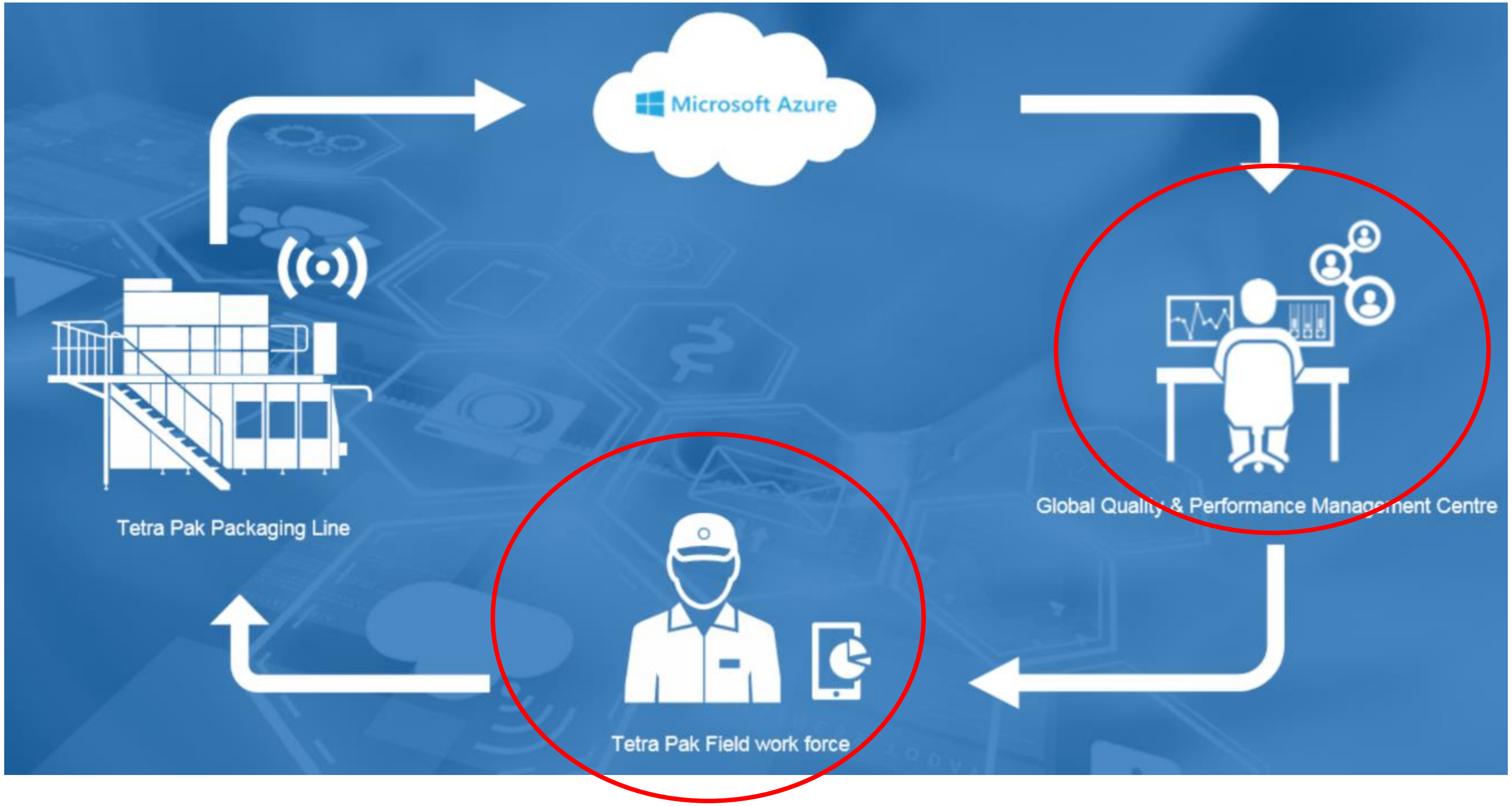
Cross Industry Standard Process for Data Mining (CRISP-DM)

It is a methodology that provides a structured approach to planning, organizing, and implementing a data mining project. It provides a complete overview of the data mining life cycle.
It is based on six phases and the sequence of the phases is not strict. In fact, most projects move back and forth between phases, as necessary.

6. Deployment

- It depends on the type of model and the target (cloud deployment/ edge deployment)
- It is necessary to define a policy for the monitoring of the model result during it lifetime
- It is necessary to define a policy for the re-train of the model

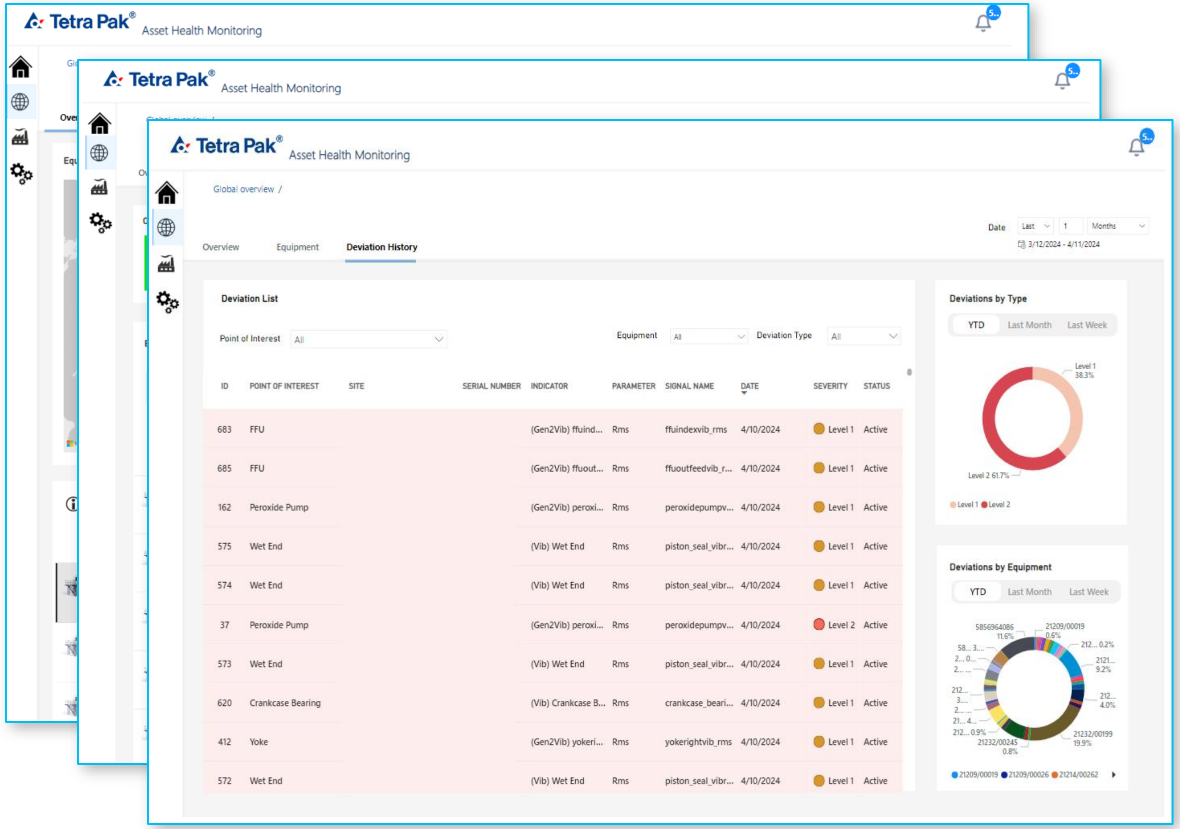
Condition monitoring 4.0 in Tetra Pak



Data visualization

It is very important to show in a clear way the processed data to help both the developer and the service engineer on the field.

- **Overview tab**
  The map shows the geographical location of each plant with at least one asset equipped with CM, along with its status. The color coding of the circles on the map refers to the different health status levels.
- **Equipment tab**
  Reports an overview of the status of all connected equipment, including the overall health and connectivity status.
- **Deviation history tab**
  All the data deviations collected by the CM system are stored and can be retrieved for dedicated analysis.



Tetra Pak Condition monitoring kit

Failure modes

Yoke drive motors
lubrication issue
belt tension loss/wear
Runner block wear
servo bearing wear
Yoke bushing wear

Electrical power
Voltage dip, swell, spikes, phases unbalance
Voltage harmonics/quality
Consumption monitoring (KWh/packs/kg of prod)

Jaw drive motors
lubrication issue
belt tension loss/wear
Runner block wear
servo bearing wear
Jaw bushing wear

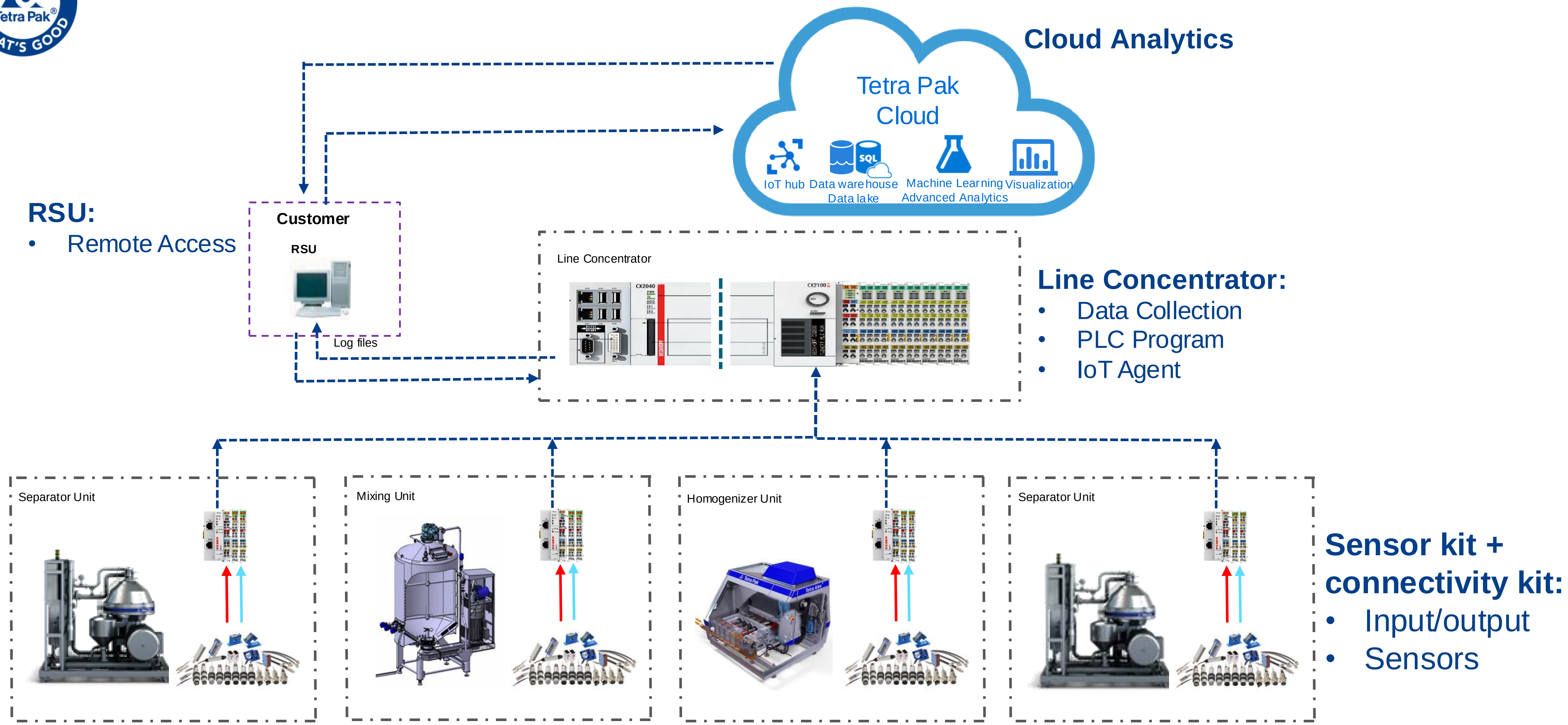
FFU drive motors
belt tension loss/wear
servo bearing wear

Peroxide pump
Motor bearing wear
coupled unit bearing wear
coupled unit looseness, misalignment, unbalance
impeller wheel wear /cavitation

Cutting Function
knives blade sharpness loss
cutting function deterioration

TS components
Inductor corrosion/wear
coaxial cable electrical issue
transformer electrical issue

Tetra Pak Condition monitoring kit

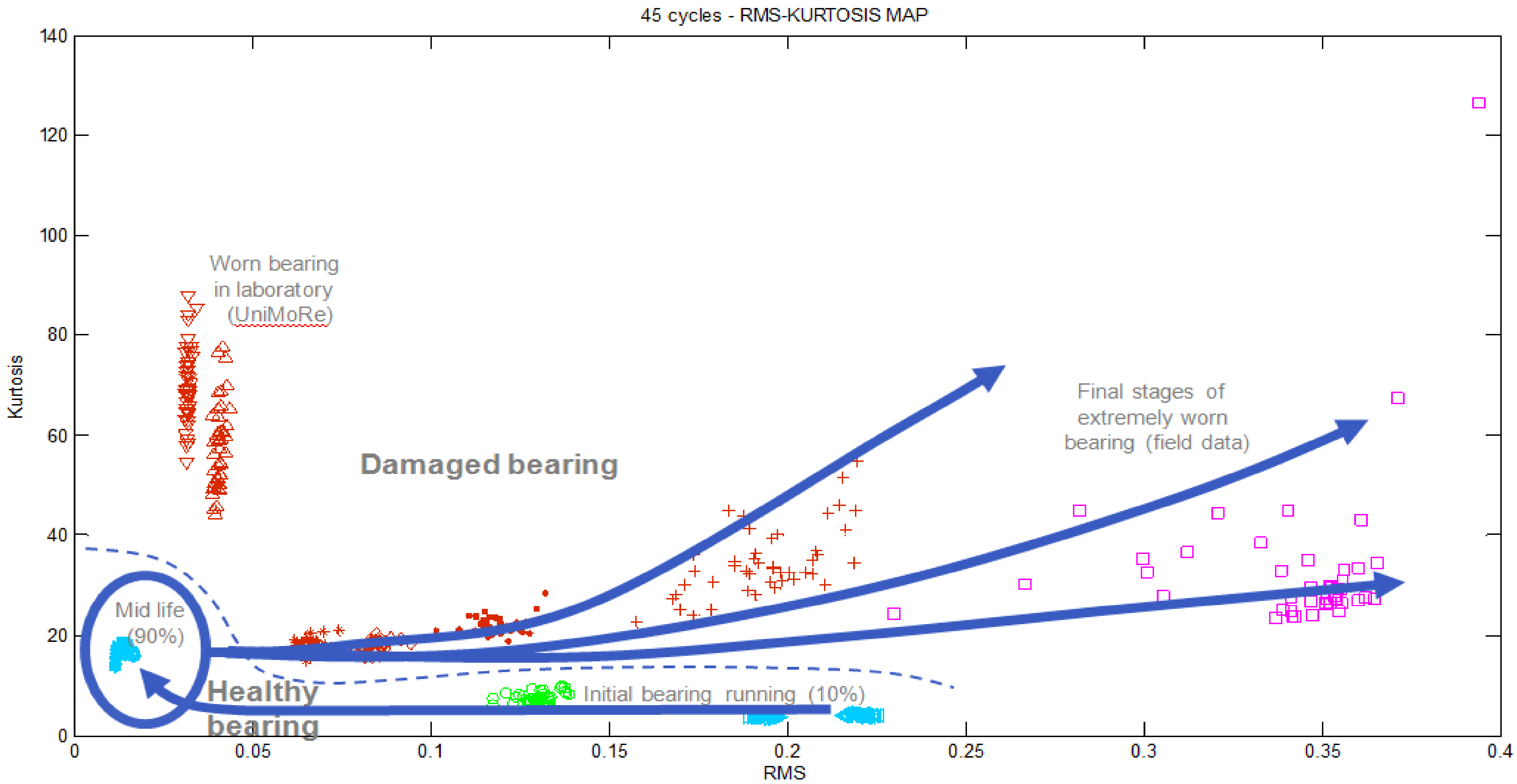


Incipient Fault Prediction

Example of positive cases at Customer Site

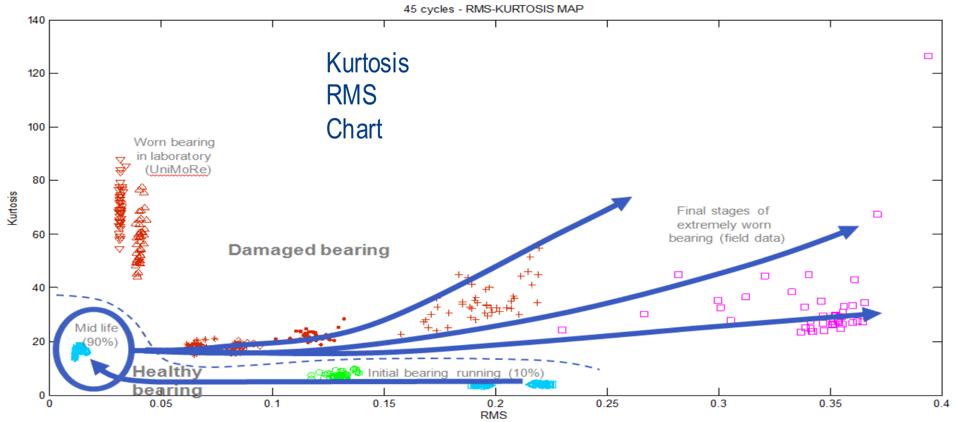
Tetra Pak®
PROTECTS WHAT'S GOOD

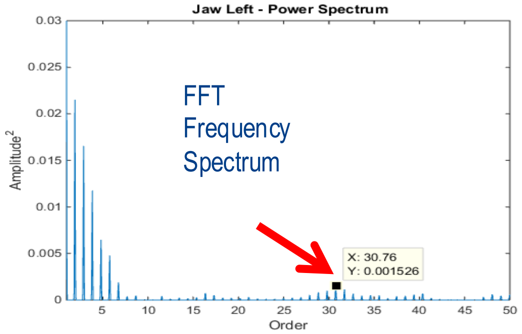
RMS-Kurtosis map

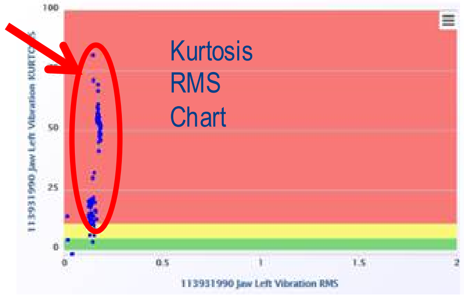


Case #1

- All the algorithms used give the same output: evident signs of incipient faults. This is an example of positive case of incipient fault predicted with CM-Kit.
- FSE during regular maintenance finds the motor as **evidently worn out** (high friction in turning the JSU pulley)
- Motor opened to check the fault







Inner ring incipient failure

Iron dust

Comparison with previous cases

Case #2

Kurtosis increased in the last few weeks

- Market Company informed to check
- **Bellow Coupling mechanical problem** found
- Bellow Coupling changed

Bellow Coupling

Case #3

RMS increased drastically at the same time as Kurtosis decreased

- At this time customer also notice a **screaming sound** from the machine!
- Customer continued to run production without any disturbance from this noise
- At next long production stop the **"Elastic Coupling" was adjusted**, and the noise disappeared!

Case #3

RMS decreased to normal, but Kurtosis increased to a very high value

- Kurtosis increased again, and the service engineer found **wornout belt and bearing**!
- Components have been changed

Case #4

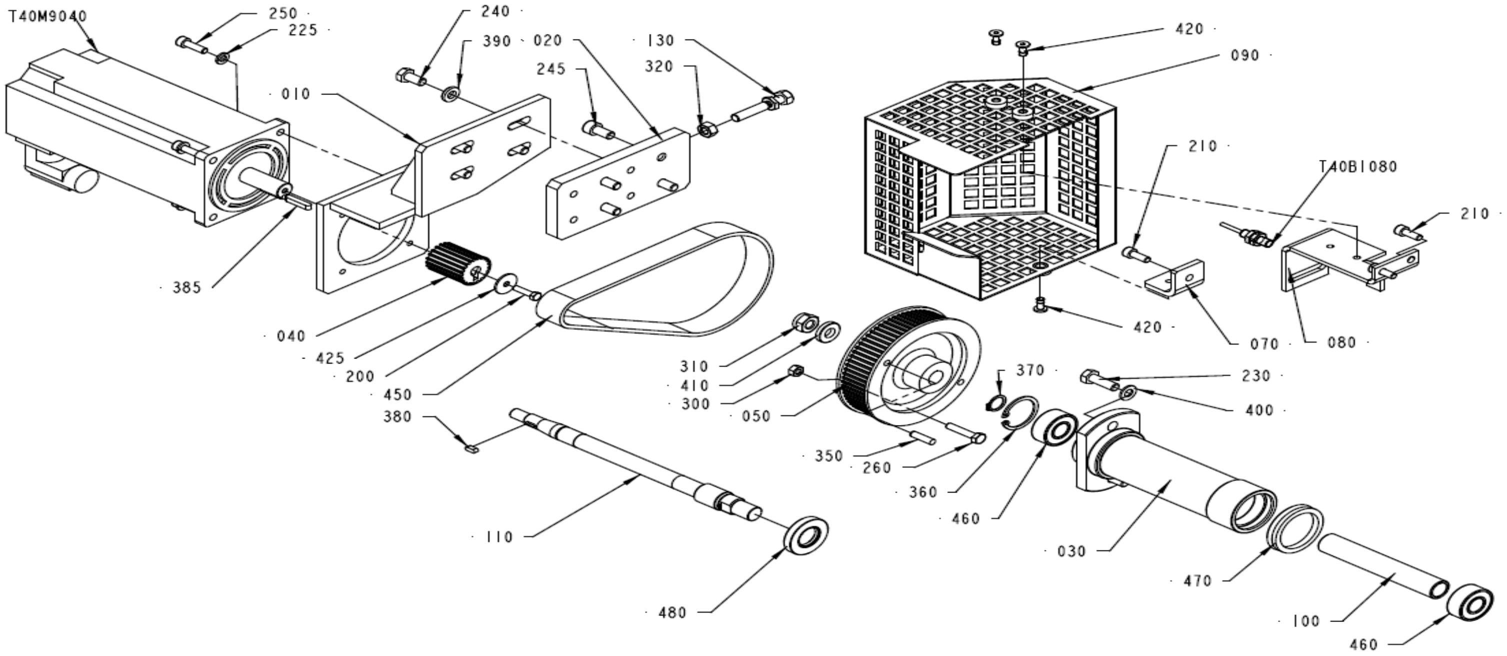
The RMS has been increasing for some time now

- Site engineer has started to investigate
  - Oil level in gearbox ok!
  - Flow of cooling liquid ok!

- Next step will be to dismount the motor and check the ball bearings

- Findings: **Cavity in the lid of the motor was worn out**! Bearings miscoloured (Overheated)

Case #5



RMS increased over time, and so did the "Design Correction" warning from the off- line data of the machine.

- After first inspection, the "Site engineer" found a **worn Belt**! Belt will be changed next TPMS.

Case #6

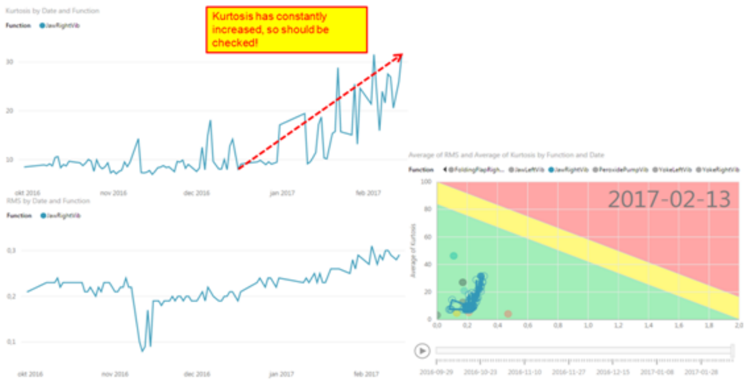
Kurtosis increased on YokeLeft

- Site engineer found the 4 **Traction belts too lose**! Belts were adjusted! Value decreased!

Kurtosis increased again!

- **Belt was found lose again!** Belts were tightened again with good result!

Example of condition monitoring

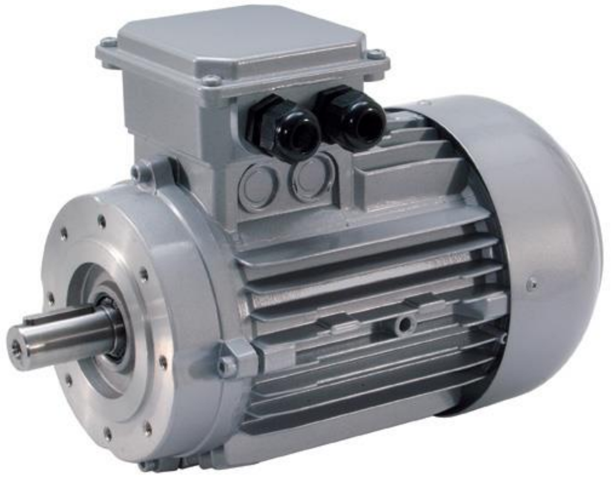
Start date	Customer/Line	Background & Action	Comments
2017-02-15	Sancor Line X JawRight		JawRight has an increased "Kurtosis" over time, and need to be investigated! Site engineer informed via "Weekly report" Site engineer found broken lubrication hose! Was replased! Site engineer checked the right jaw finding mecanic play between the axis and the locator piece **(See video!)** The parts in bad condition was replaced we did basic measures and now the filling machine is running.

Pictures/Movies	Result
 	

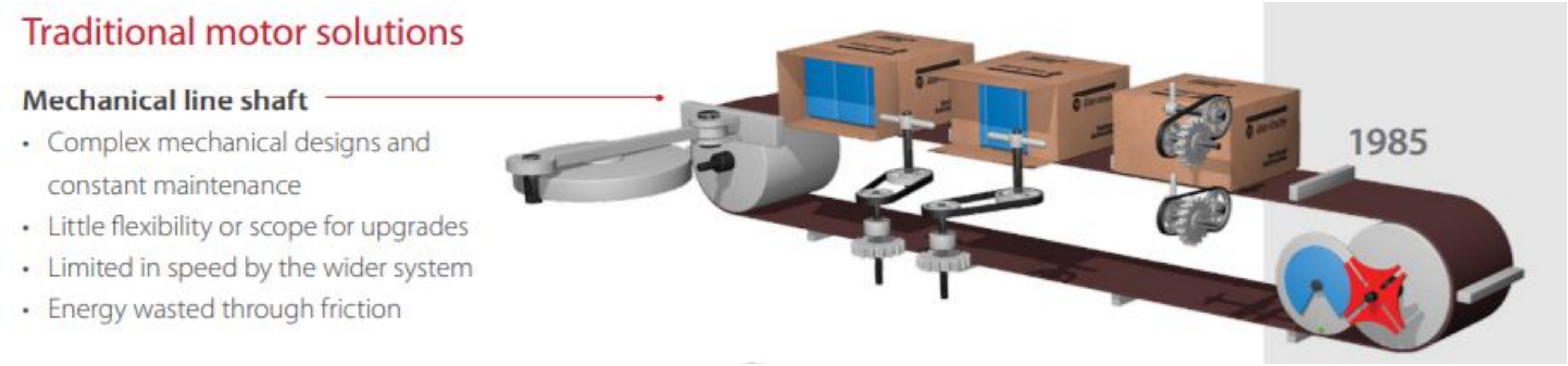
Independent Carts System

Development of condition monitoring for a new technology

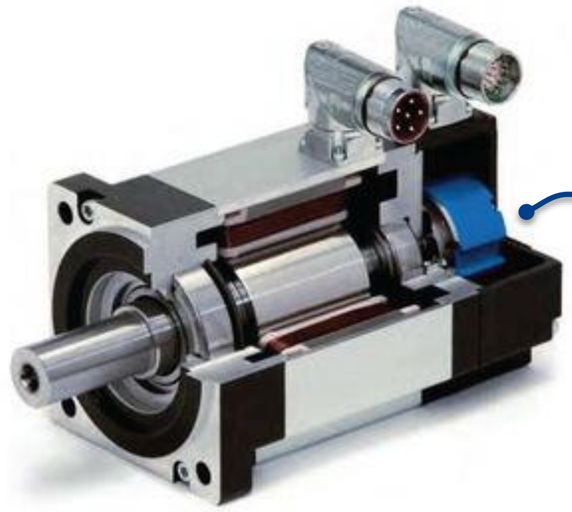
Evolution of electrical motors in Industry



Asynchronous motors working at constant speed



Evolution of electrical motors in Industry



Brushless servo motors can work at variable speed

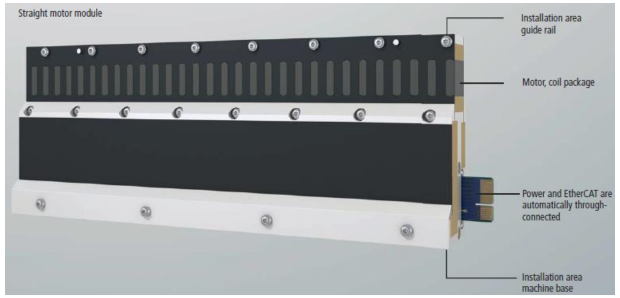
Encoder

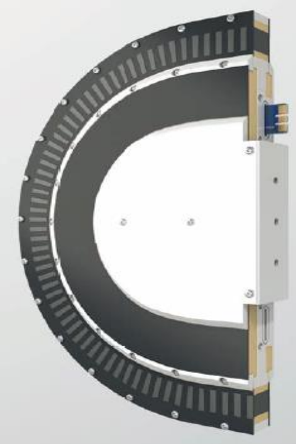
Electronic line shaft

- Reduced maintenance and a degree of flexibility
- Upgrade templates along with new mechanical challenges
- Improved line speed
- Improved energy consumption

Independent Carts Technology

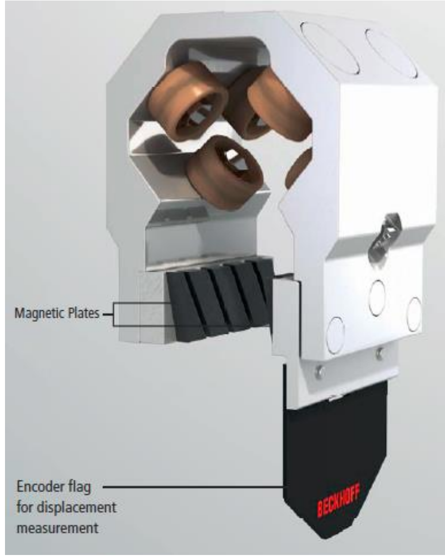
Straight Modules





Curved Modules

Carts



iTRAK pitchless technology

Designed without mechanical constraints to:

- Minimize maintenance
- Change between products at the push of a button
- Simplify mechanical designs
- Upgrade easily by reducing complex tooling
- Operate faster with less downtime
- Reduce energy consumption through direct drive

Independent cart use case

- The Independent Carts System uses linear motors to control one or more movers that are constrained by rollers to follow a track.
- The track can have different shapes with curved and straight parts and it has a flexible architecture to build modular configurations.
- In this way, a high-performance flexible system can be carried out, with this technology each mover can be controlled independently [1] [2].
- The movers can accelerate, decelerate, take an absolute position and produce forces.

Independent cart use case

Advantages

1. High flexibility
2. High production rate
3. Possible to control each cart independently

Disadvantages

1. Each cart has bearings and end-effector that are subject to wear
2. Very complex system

Problems for the creation of a condition monitoring system:

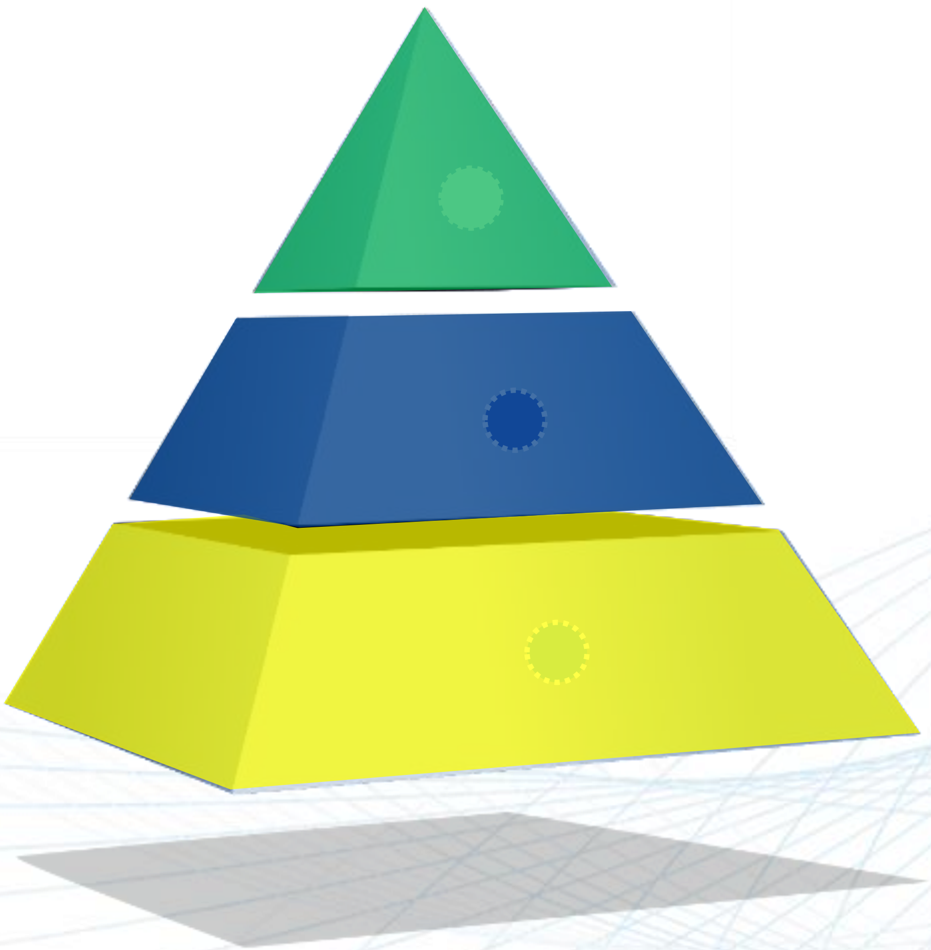
-Slide different of the behaviour of each mover

-No-stationary working conditions

-Not complete know how of the possible failure mode

Condition Monitoring framework pyramid

A continuous learning process



Predictive maintenace

Thanks to the historical data and model of the system is possible to predict a near-future faliure and to predict the Remaining Useful Life.

Fault detection

It is posssible to detect peculiar way of faliure of the machine components.

Anomaly detection

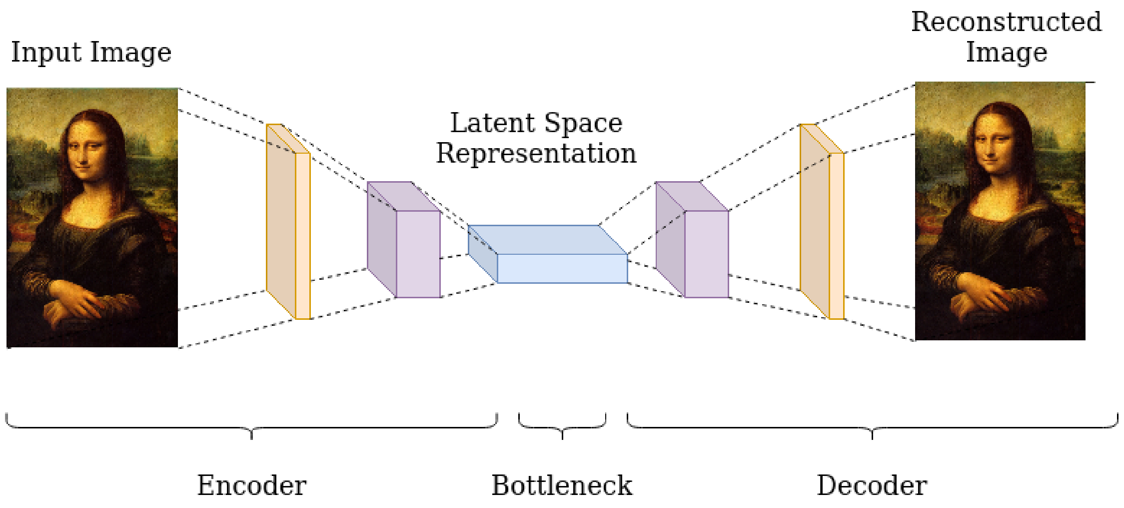
Detect only the behaviour variation of the system but not detect any precise faliure. There are few or nothing historical cases of faliures of the equipment.

Independent cart use case

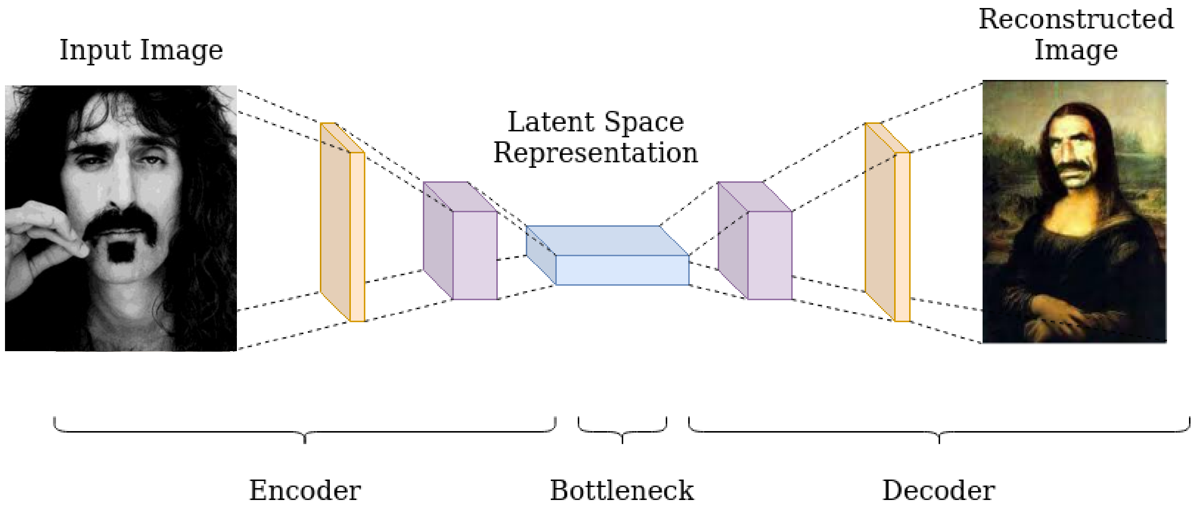
Anomaly detector

- To overcome the problem a data-driven approach has been developed.
- An anomaly detector based on an autoencoder architecture is used to detect anomalies of the system.
- The autoencoder is train to recontract healthy signals with high precision and anomaly signal with lower precision.
- By check the recontraction error it is possible to identify anomalies on the signals.

Normal behaviour



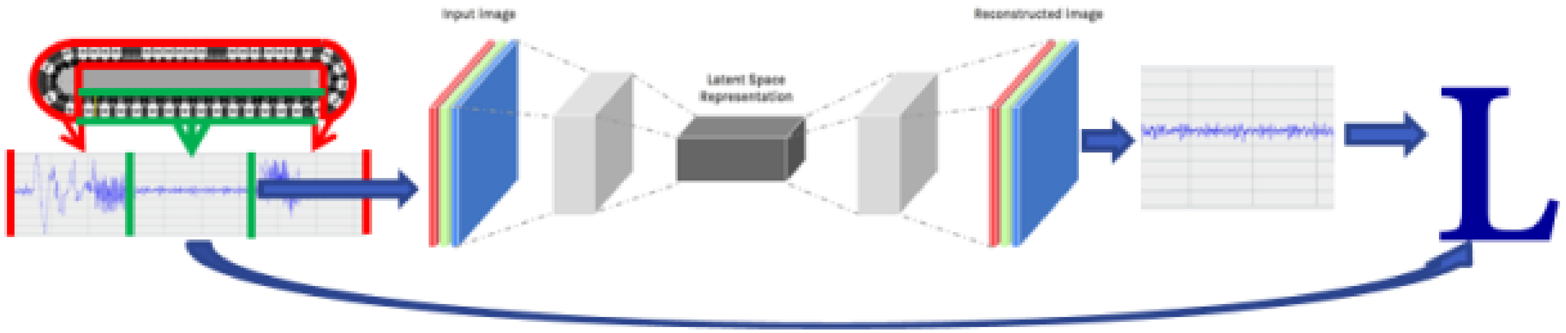
Anomaly behaviour



Independent cart use case

Anomaly detector

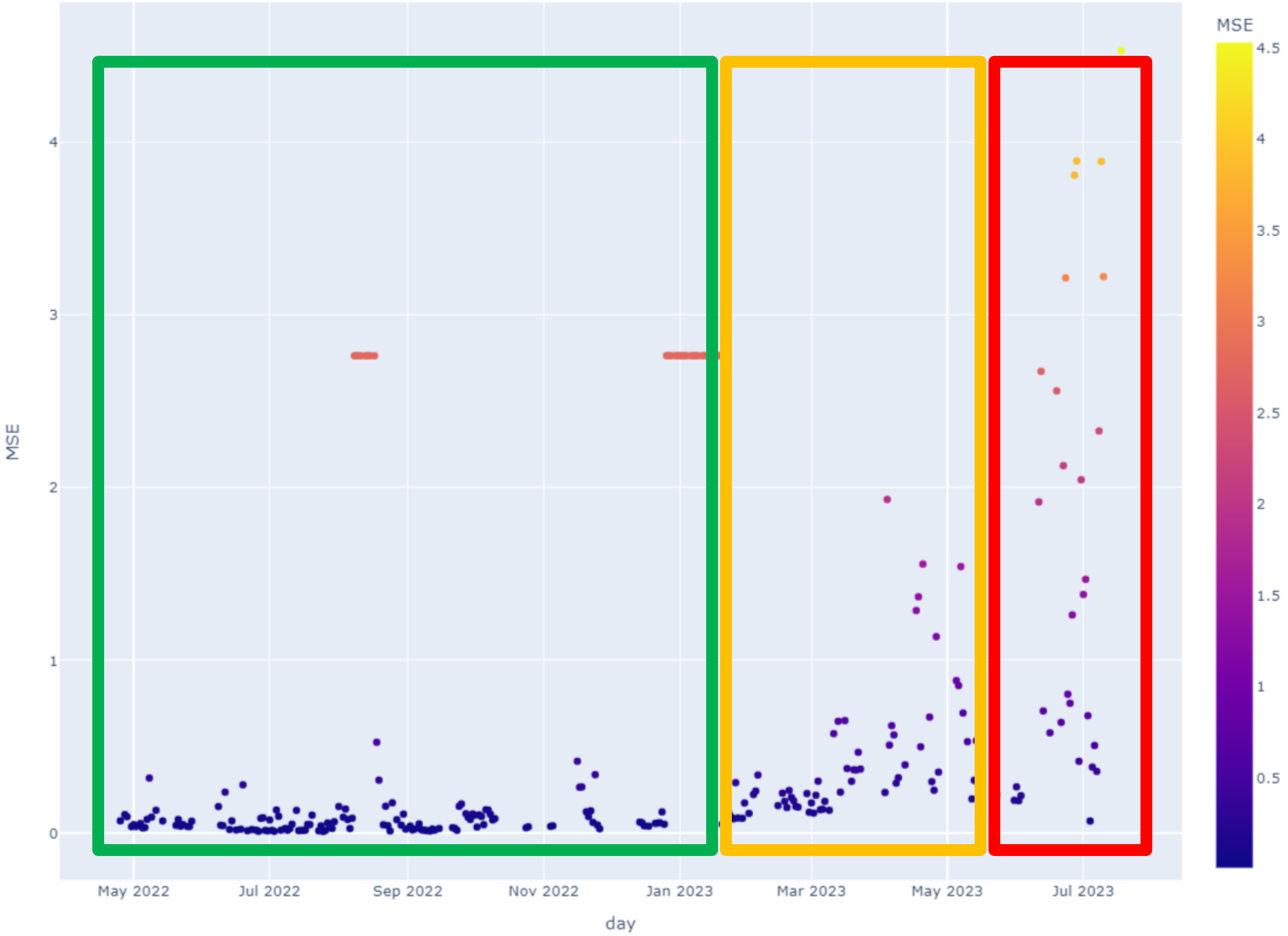
The autoencoder is train to recontract healthy signals with high precision and anomaly signal with lower precision. By check the recontraction error it is possible to identify anomalies on the signals.
For each mover several signal of position, velocity and force in the case of healthy condition are used for the training of the model. It is possible to use convolutional neural networks[2] or Temporal convolutional neural networks[3]



Independent cart use case

Anomaly detector

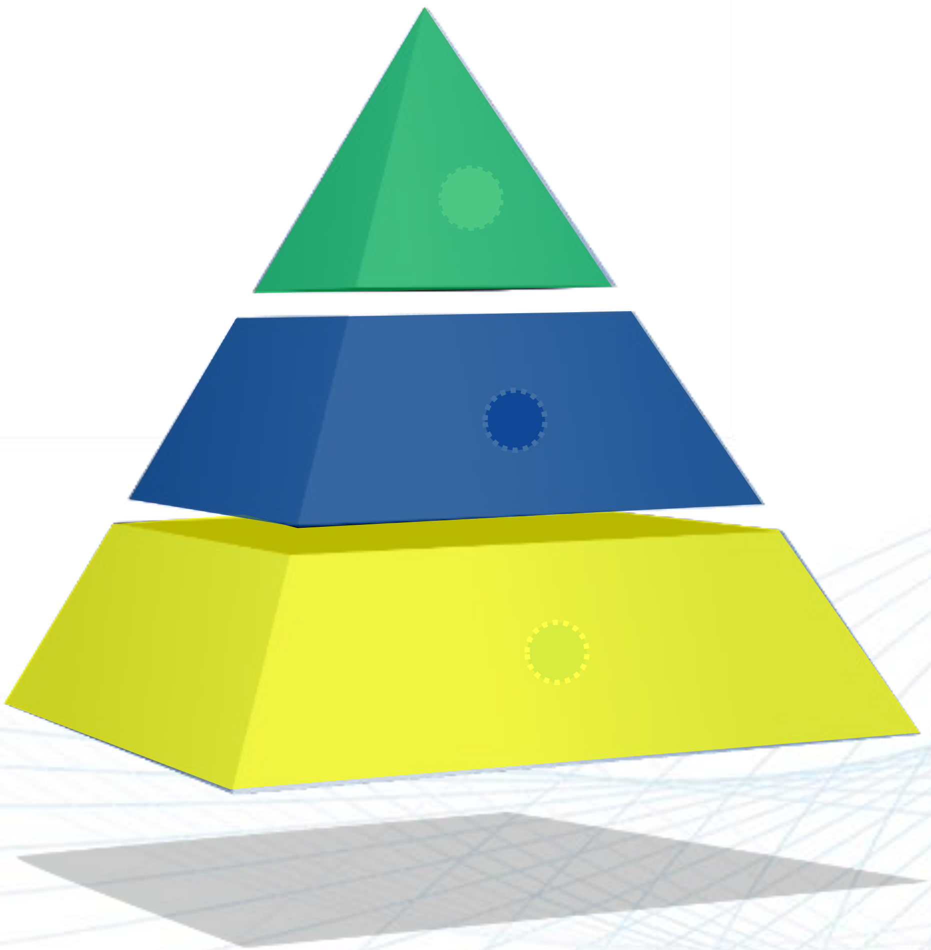
The anomaly detector has been trained with current, position, position error of each cart.
Once per day the model run e generate the signal reconstruction.
The Mean square Error is used as metric for the detection of the anomaly.
In 2023 one cart presents a creasing of the MSE during time.
After a check on the machine, it has been detected that the mover present a cut magnet due to a collision.



General

Condition Monitoring framework pyramid

A continuous learning process



Fault detection

It is posssible to detect peculiar way of faliure of the machine components.

Anomaly detection

Detect only the behaviour variation of the system but not detect any precise faliure. There are few or nothing historical cases of faliures of the equipment.

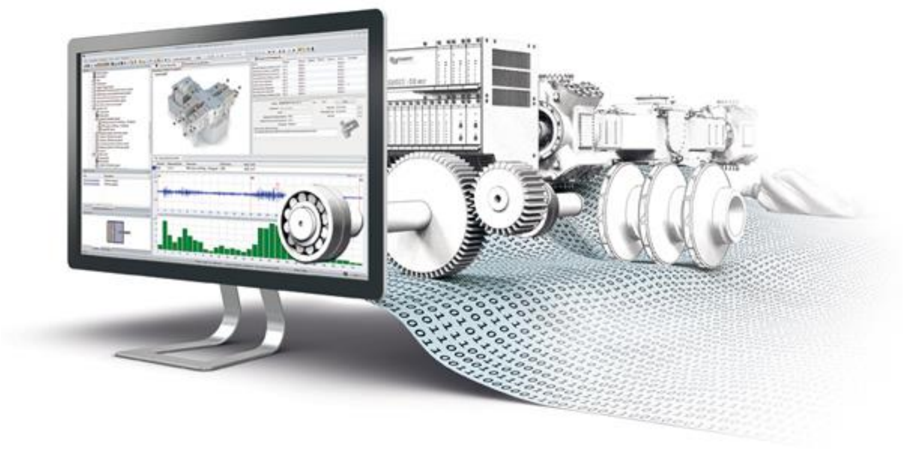
Independent cart use case

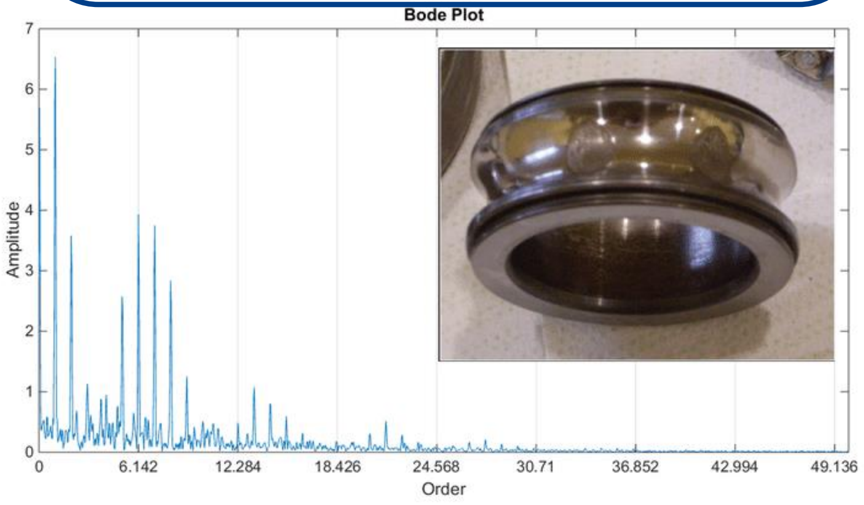
Fault detection- model based approach

Key Idea: to use multibody models of healthy/faulty systems for the implementation of condition monitoring algorithms.

Machine/Deep Learning algorithms: the simulated data can be used in the training phase in order to increase the dataset.

Model-based algorithms: the models are helpful to reduce the complexity of the system by focusing the analysis only on the meaningful effects of the damages.

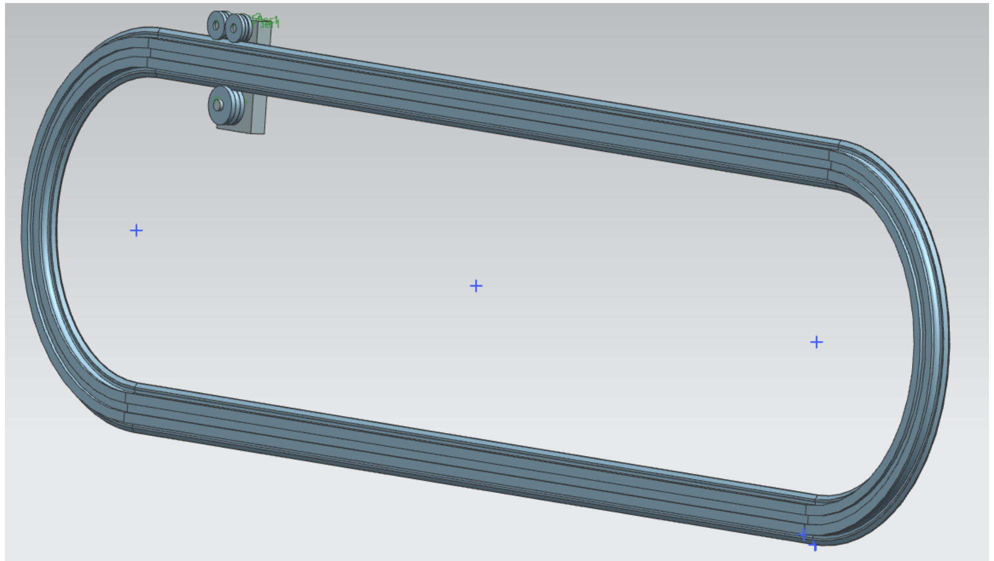




Independent cart use case

Fault detection- model based approach

- The target is to model the XTS system where the bearing roller is modelled with a complete multibody model.
- The model takes into consideration a simplified cart moved by an external driver.



Independent cart use case

XTS model

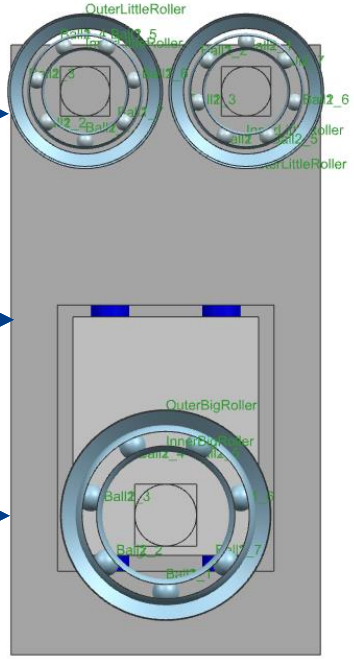
- The cart consists of three double row ball bearings;
- The top bearings are smaller than the one in the bottom;
- The bottom bearing is connected to a spring preload system;
- Each bearing has a double row of rolling elements ;
- The bearing is modelled with analytical contact;
- Each bearing is connected to the cart by a bushing connector.

Simplified Cart

Top rollers

Preload system

Bottom roller



Cart vs. multibody model

Mover's Bearing Configuration

Small Bearing (Top Left)

Small Bearing (Top Right)

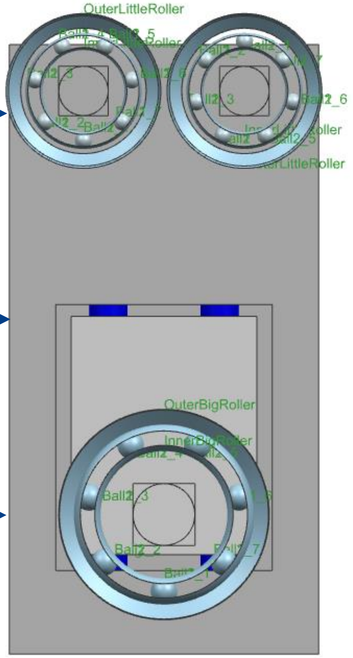
Big Bearing (Bottom)

Simplified Cart

Top rollers

Preload system

Bottom roller

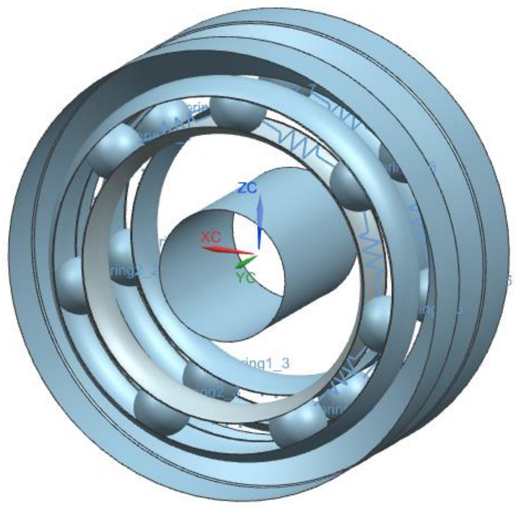


Independent cart use case

XTS model

- The cart consists of three double row ball bearings;
- The top bearings are smaller than the one in the bottom;
- The bottom bearing is connected to a spring preload system;
- Each bearing has a double row of rolling elements ;
- The bearing is modelled with analytical contact;
- Each bearing is connected to the cart by a bushing connector.

Double row deep groove ball bearing

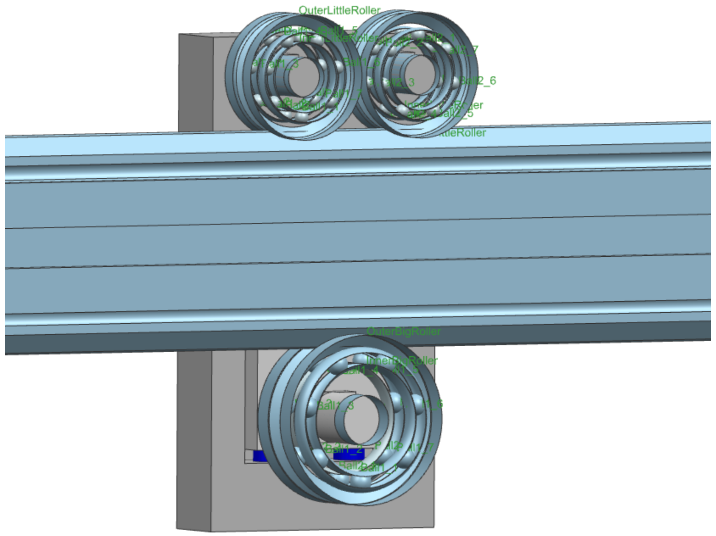


Independent cart use case

XTS model

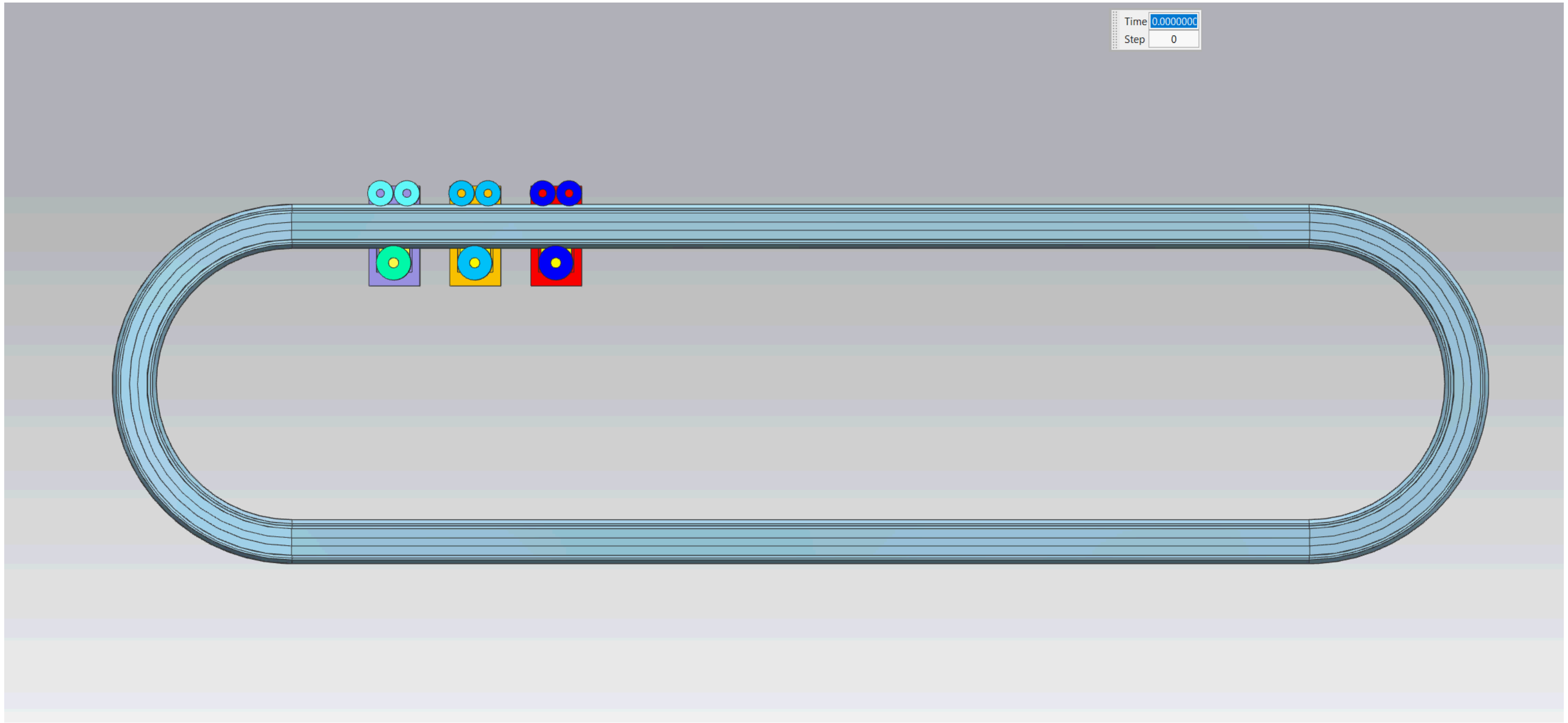
- The contact between the external rolling surface and the rail has been modelled as an analytical contact between the revolution surface of the bearing and the extrusion surface of the roller.
- The cart is moved by a driver that follows a predefined motion profile

Rail connection



Independent cart use case

XTS model



Independent cart use case

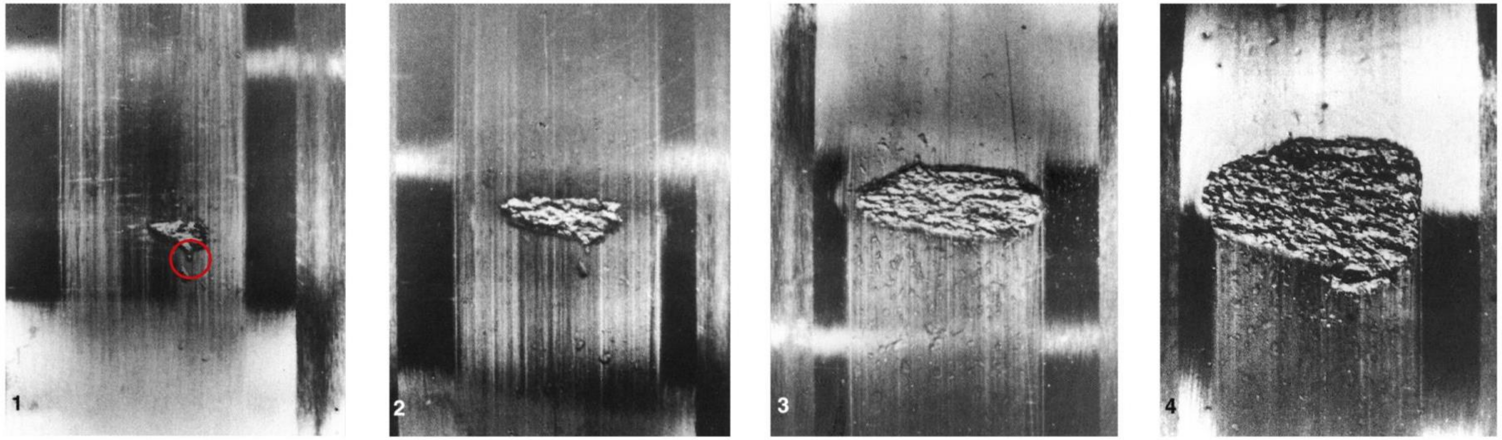
XTS model

One of the most typical bearing damages is **the spall on the raceway**.

Spalling is the result of surface or sub-surface fatigue which causes fractures in the running surfaces.

In the experimental campaign a ball bearing has been artificially damaged in order to reproduce a spall damage.

Typical evolution of a spall damage



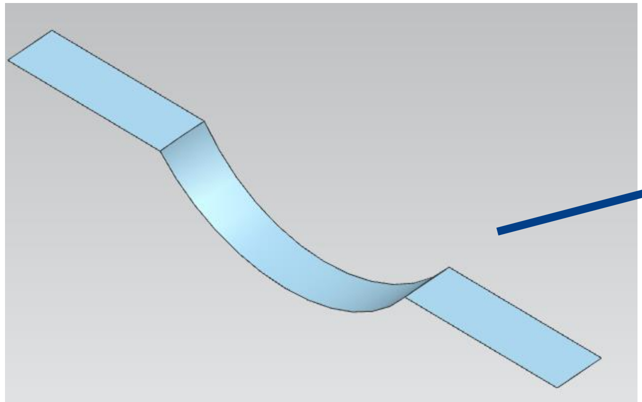
Independent cart use case

XTS model

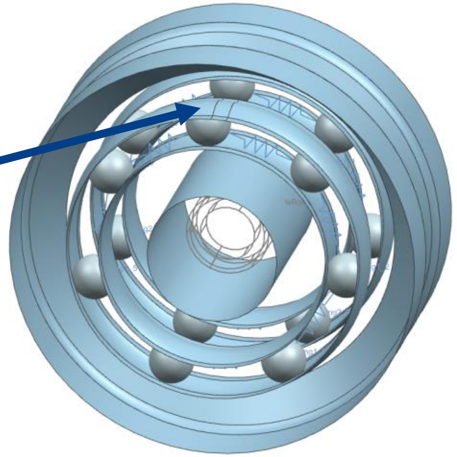
- In order to model a **spall damage on the outer ring with an analytical contact formulation of the ball contact**, a double revolution surface has been created with a dimension comparable to the real damage.

- The validation of the model consists in the vibration comparison between the simulated cart with the damaged bearing and the real cart with an artificial spall damage.

Modelled damage surface with an inner ring curvature 0.01mm higher than the normal one



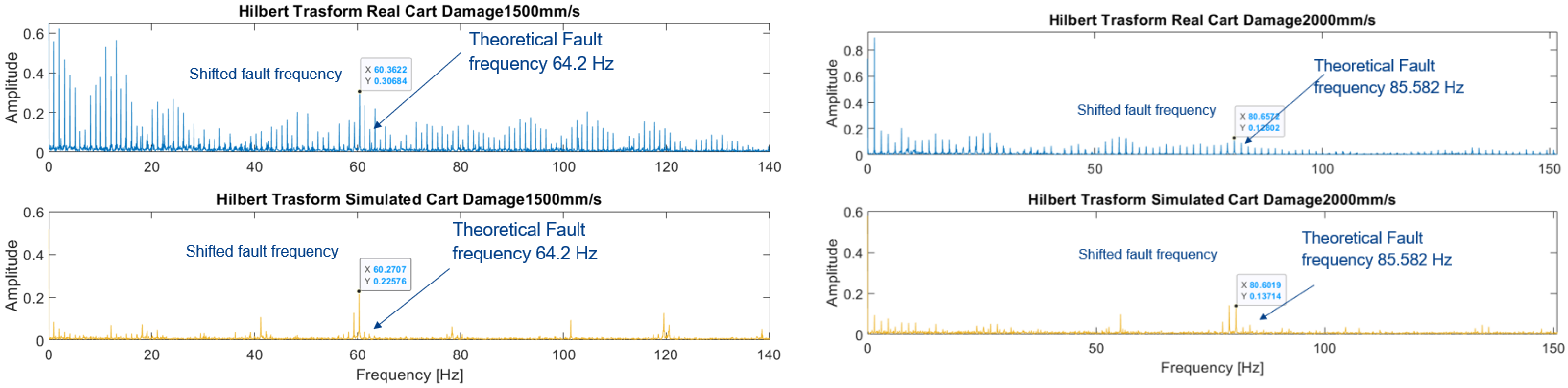
Damaged inner ring bearing



Independent cart use case

XTS model

- A deep grove ball bearing model has been developed and validated;
- The bearing model allows to create internal damage of different dimension in the bearing;
- The healthy and damaged bearings have been developed and validated for an Independent Cart System.



Conclusions

Condition monitoring in Industry 4.0

- Today, machines provide different data for the control of processes and electric motors that can be used in diagnostics
- In the short term, industries are mainly interested in anomaly detection
- Simple statistical indicators, although they do not clearly identify causes, are preferable for alerting the technical service and planning more thorough checks
- Peculiar information is still provided by customer support but is not considered in the current literature which is focused on data processing.

Conclusions

Condition monitoring in Industry 4.0

- In the medium to long term, machine learning (ML) is preferred for ease of use.
- In-depth knowledge of the physical phenomenon is not required, and over time data are stored and they can be used to improve the training step
- The same ML framework can be used to make diagnostics for different parts of the machine.
- Diagnostics with a model-based approach need time to be ready and they are developed mainly for the key components or future re-design

References

- Hastie, T.; Tibshirani, R.; Friedman, J. The Elements of Statistical Learning: Data Mining, Inference, and Prediction; Springer: Berlin, Germany, 2009.
- Albalate, A.; Minker, W. Semi-Supervised and Unsupervised Machine Learning: Novel Strategies; Iste/Herme
- J.Kim, Hyeongwon Kang, Pilsung KangTime-series anomaly detection with stacked Transformer representations and 1D convolutional network, Engineering Applications of Artificial Intelligence April 2023
- Thill, M., Konen, W., Wang, H., & Bäck, T. H. W. (2021). Temporal convolutional autoencoder for unsupervised anomaly detection in time series. Applied Soft Computing,112.
- Scurria L., Cavalaglio Camargo Molano J., Jiranek P., Tamarozzi T., Fauconnier D. , “Rolling Element Bearings-Advanced Modeling for Multibody Simulations”, (2020) SAE Technical Papers, DOI: 10.4271/2020-01-0508
- Cavalaglio Camargo Molano J., Capelli L., Rubini R., Borghi D., Cocconcelli M. , “A bearing fault model for Independent Cart Conveyor System and its validation”, (2020) Applied Acoustics, 159, DOI: 10.1016/j.apacoust.2019.107069
- Cocconcelli M., Capelli L., Camargo Molano J.C., Borghi D., ”Development of a methodology for condition-based maintenance in a large-scale application field”, (2018) Machines, 6 (2), art. no. 17, DOI: 10.3390/machines6020017

MOIRA Scientific-Skills training course (S10)

Process automation & Monitoring Systems

The European Commission is gratefully acknowledged for its support of the Marie Sklodowska Curie Program through the H2020 ETN MOIRA project (GA 955681).

Developed by Tetra Pak and University of Modena and Reggio Emilia

Tetra Pak®

PROTECTS WHAT'S GOOD