PMEinCPPS

Predictive Maintenance Experiments in Cyber Physical Production Systems

Nomad Tech
A Nomad Digital & EMEF Joint Venture

9th November 2017

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Introduction

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Nomad Tech

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- **Joint venture** between **EMEF** and **Nomad Digital**;

EMEF
PORTUGUESE RAILWAYS GROUP
ROLLING STOCK MAINTENANCE

CP (Comboios de Portugal) **group**

Nomad Digital

Leading global provider of ICT enablement and **connectivity** solutions to the **transportation sector**

- **Over 20 years** of real-life, hands-on **experience** in Rolling Stock & Rail;
- **Experience** in Condition Based Maintenance (**CBM**), **Predictive Maintenance**, Data **Analytics** and **Big Data**.

Deployed and current projects

Portugal

Norway

Germany

Australia

UK

USA

Switzerland

Finland

Sweden

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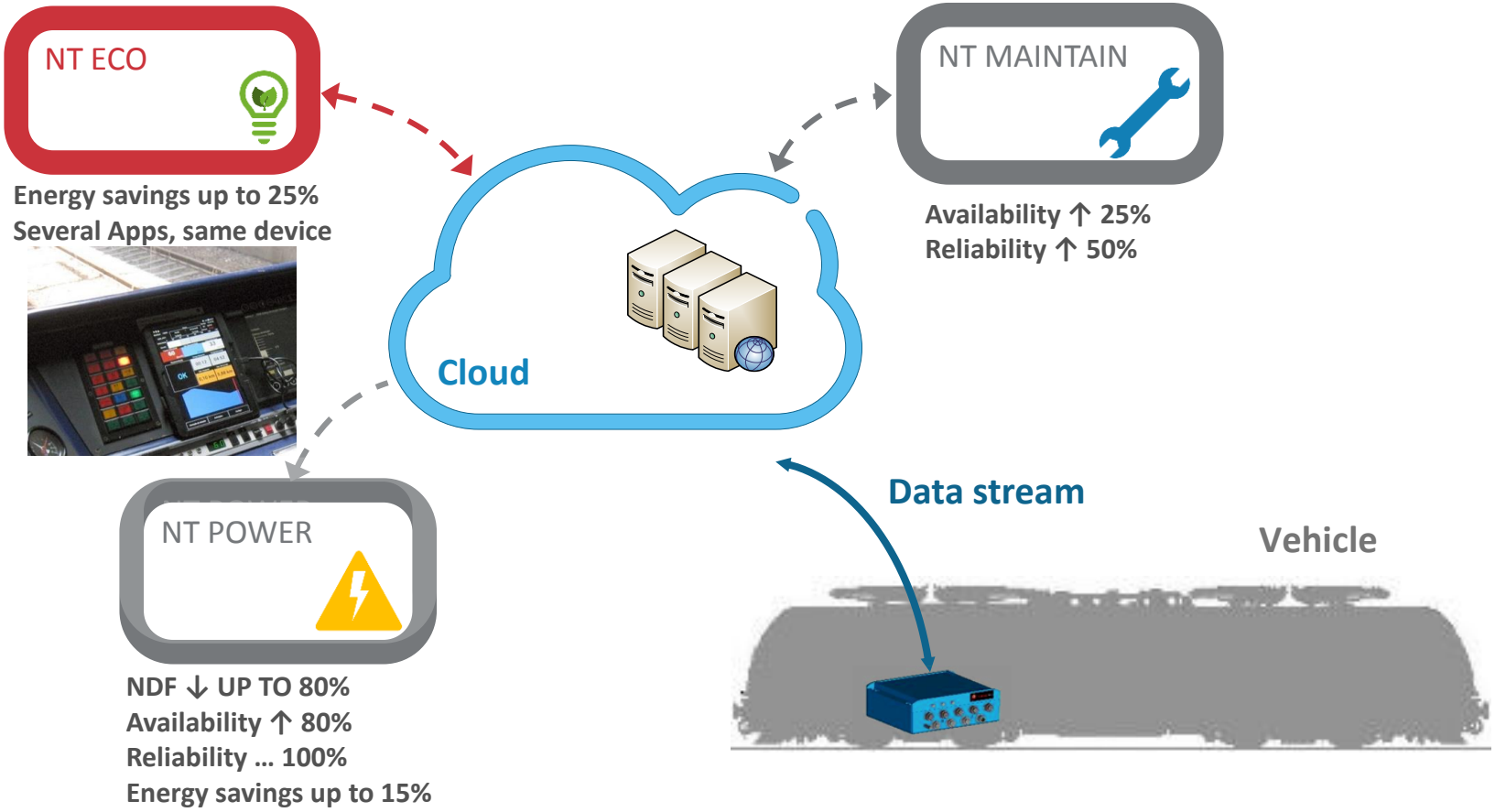
IOT: Internet Of Things / Intelligence Of Trains

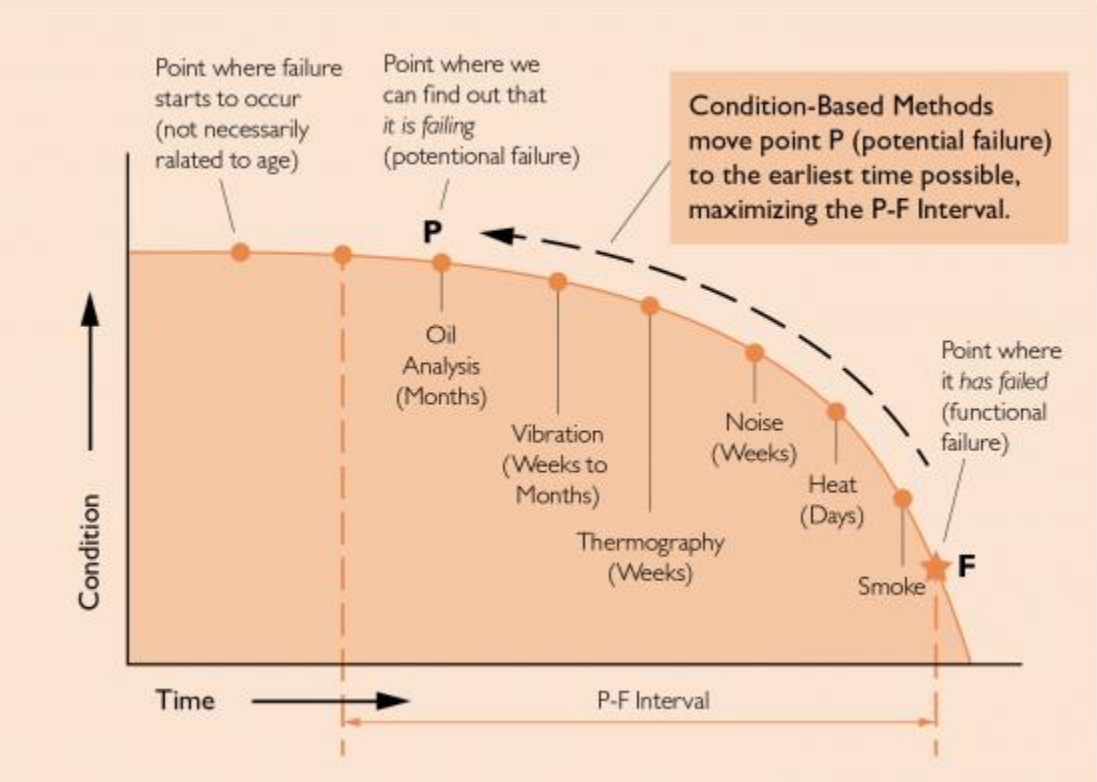


The same IOT platform, multiple system applications.

Real-life impact on the rolling stock Life Cycle Cost!

CBM vs Predictive Maintenance

The P-F curve



- Is there a clear Potential failure condition (**P point**)?
- What is it?
- What is the **P-F interval**?
- Is it **long enough** to be of **use**?
- **Predictive Maintenance** allows to **prevent** the **failure** of occurring:
  - Reduce **maintenance costs**
  - Increase **availability**
  - Increase **reliability**

Source:
http://www.maintworld.com/Applications/Maximizing-the-P-F-Interval-Through-Condition-Based-Maintenance

Nomad Tech

Nomad Tech has been **involved** in the **Predictive Maintenance** area in projects such as:

- Sponsoring a master thesis on the use of doors sensors to predict door failures (***Failure Prediction - an Application in the Railway Industry***, *2014 - Pedro Mota Pereira, Rita Ribeiro and João Gama*)
  - Data from suburban trains - England
  - Use of technique such as SVM's
  - Received the Carl H. Smith Student Paper Award at the conference Discovery Science 2014, in Slovenia.
- Sponsoring a master thesis on the use of alarms signals to prevent train door failures (***Predictive Modelling using Railway Event Alarms System***, *2015 - Carlos Rodrigues, Hélder Ribeiro, João Moreira*)
  - Data from suburban trains - Norway
  - Use of techniques such as SMOTE (Synthetic Minority Over-sampling Technique) and C4.5 (Decision Trees)
- In-house project to analyze the signals and behavior of trains when braking to detect anomalous braking (***Detect Abnormal braking***, *2016 - Hélder Ribeiro, Gonçalo Pereira*)
  - Data from metro trains - Australia
  - Use of techniques such as Clustering, NNs and SVMs
  - Obtained better results with LOF (Local Outlier Factor)

PMEinCPPS

- **PMEinCPPS** developed under the umbrella of **BEinCPPS**.
- BEinCPPS initiative is **funded** under the European Commission's **Horizon 2020**.
- Aims to **improve the adoption of CPPSs all over Europe** by means of the creation, nurturing and flourishing of CPS-driven regional innovation ecosystems.
- **Focused in 5 European regions**, including Northern Portugal.

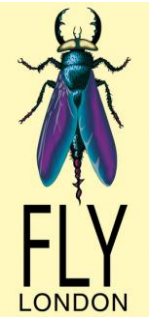
The High Speed Shoe Factory (HSSF)

- Built in **Fly London**'s factory, KYAYA ;

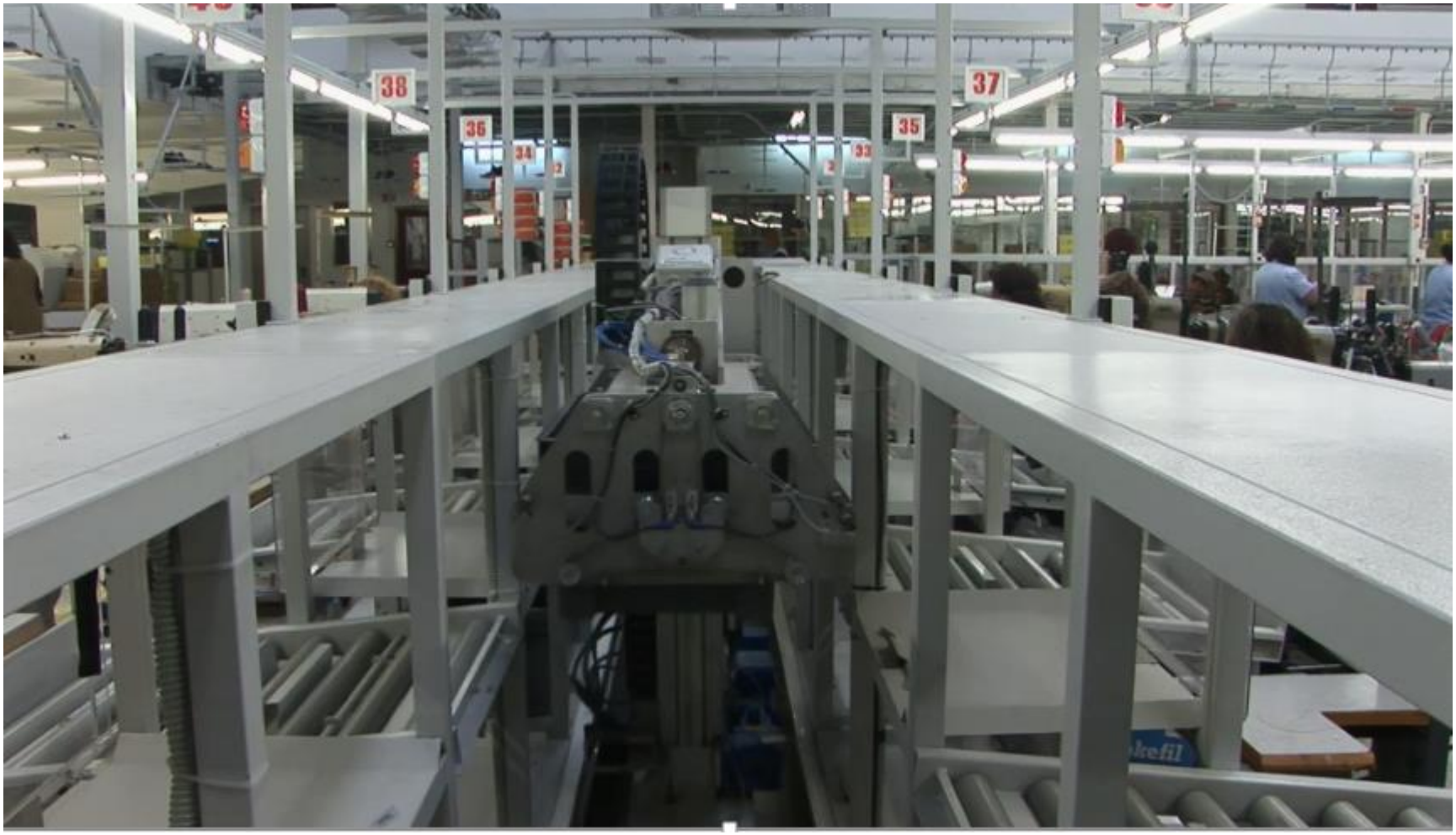
- Aimed at **agile** response factory work;
  - Response in 24 hours oriented to the unit production
    - **Value-added market** values **bespoke** products
  - Answer **without stocks to:**
    - ✓ **online sales**,
    - ✓ small orders,
    - ✓ **replacement** of the product in the **stores**,
    - ✓ quick manufacturing of **samples** for **new collections**

- Not being exploited at full **efficiency**;

- **Anomalies** in the production lines disrupt the workflow.



The High Speed Shoe Factory (HSSF)



PMEinCPPS Project

We propose a **predictive maintenance** solution that **relies** heavily on the field of **machine learning**.

Developed jointly with Flowmat (factory logistic systems).

To address the problem that troubles the most:

- **Production line disruption**

The solution is split in two distinct applications:

- Predictive maintenance monitoring application (**PREDITAIN**)
- Statistical data reporting on-the-fly application (**STATSFLY)**

Applications

PREDITAIN

- Give the user a clear **warning** of when a **failure** is about to **occur**;
- The history of **predicted** failures;
- The **context** where they **occurred**;
- What were the most **common points of failure.**

STATSFLY

- Provides access to **historical** and **statistical** data;
- The data will be in an easily interpretable format;
- Allows the users to take well **informed decisions** regarding their production systems.

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The Data

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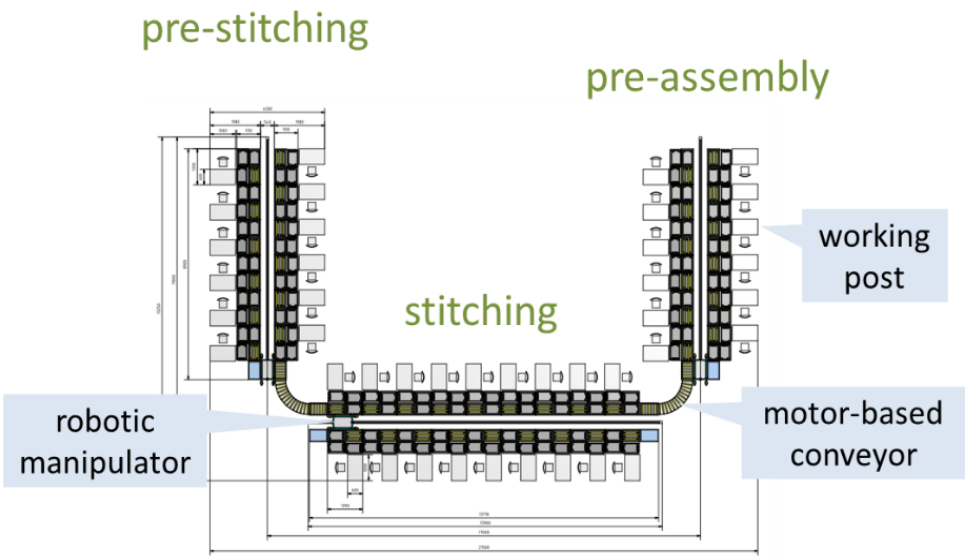
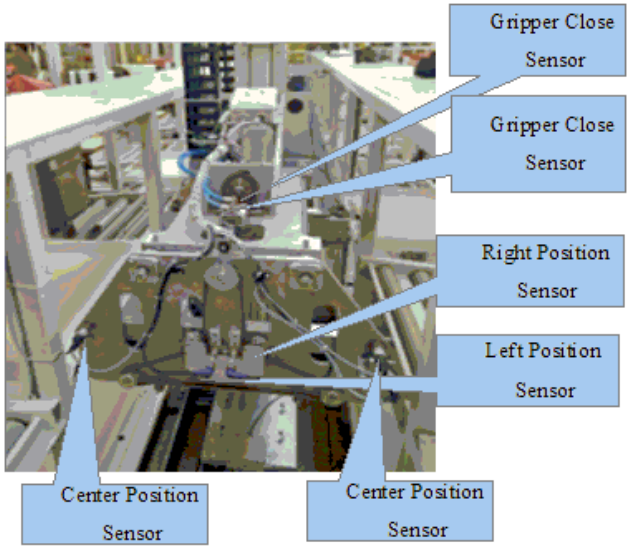
Collected data since 2016-10 until 2017-09

Sensor event	Description	Data Volume
Robot Manipulator signals	Signals from each production line robot	20000-45000 messages per day
Conveyor Signals	Signals from the conveyors connecting multiple lines	1000-3000 messages per day
Workpost Signals	Signals from the box positions on a workpost	1000-2500 messages per day
Alarm signals	General HSSF Alarm signal	occasional



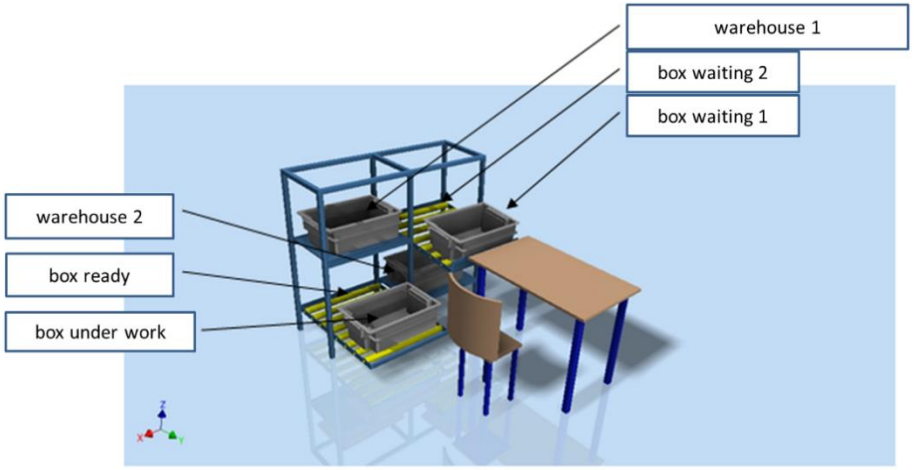
Signals received

Manipulator Signals (x being the line number)	Meaning
LxGripperLeftOpen	Manipulator's gripper is on the left side
LxGripperRightOpen	Manipulator's gripper is on the right side
LxGripperCentered	Manipulator's gripper is centered
LxGripperOpen	Manipulator's gripper is open
LxGripperClosed	Manipulator's gripper is closed
LxGripperGoLeft	Manipulator's gripper is moving to the left side
LxGripperGoRight	Manipulator's gripper is moving to the right side
LxGripperOpenClose	Manipulator's gripper is opening



Signals received

Work Post Signals (x being the line number and y the work post number)	Meaning
LxPCUy	Box is in the up position
LxPCDy	Box is in the down position
LxPCRy	Box is in the ready position
LxPBUy	Id of box in the up position
LxPBDy	Id of box in the down position



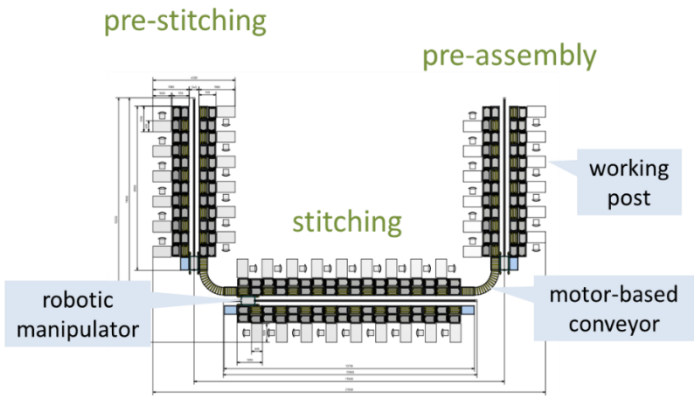
Signals received

Conveyor Signals (x and y being the line numbers)	Meaning
LxToLyS1	Boxed passing in the 1st section of the conveyor
LxToLyS2	Boxed passing in the 2nd section of the conveyor
LxToLyS3	Boxed passing in the 3rd section of the conveyor
LxToLyS4	Boxed passing in the 4th section of the conveyor

Other Signals	Meaning
LxEmergency	HSSF alarm is on
LxGripperError	There was an error in the gripper

Other data:

- Maintenance logs



Robotic Manipulator Movements

Manipulator's Gripper Picks Boxes (on the right)		
1st Phase	**2nd Phase**	**3rd Phase**
LxGripperGoRight ->1	LxGripperOpenClose ->0	LxGripperGoLeft ->1
LxGripperCentered ->0	LxGripperOpen ->0	LxGripperRightOpen ->0
LxGripperLeftOpen ->1	LxGripperClosed ->1	LxGripperLeftOpen ->1
LxGripperLeftOpen ->0		LxGripperLeftOpen ->0
LxGripperRightOpen ->1		LxPCRy->0
LxGripperGoRight ->0		LxGripperGoLeft ->0
		LxGripperCentered ->1

- This sequence occurs when it **picks a box on the right side**, when picking of the left, a similar sequence occurs except the signals representitive of a direction get replaced for the oposite direction signals
- **1st phase** represents the **manipulator** arm **moving** to the workpost to **place a box**
- **2nd phase** represents the **manipulator** gripper **opening** to **leave a box**
- **3rd phase** represents the **manipulator** arm **retracting** to it's original position **without the box**.

Conveyor and Workposts Movements

Box traverses conveyor sequence

LxToLyS1 -> 0 to LxToLyS1 -> 1

LxToLyS2 -> 0 to LxToLyS2 -> 1

LxToLyS3 -> 0 to LxToLyS3 -> 1

LxToLyS4 -> 0 to LxToLyS4 -> 1

Notes: As the box tranverses through the conveyor, each sector sensor is activated in sequence

Work post Starts working sequence

LxPCUy==1 AND LxPBUy!=0 AND LxPCDy==0

1. LxPCUy->0
2. after 2..5 secs: LxPCDy->1
3. LxPBDy->nrBox

Notes: Box is moved from up to down position where work on its content begins

Work post Finishes working sequence

LxPCDy==1 and LxPBDy==nrBox (between 20 secs and 60 secs) AND LxPCRy==0

1. LxPCDy->0
2. after 2..5 secs: LxPCRy->1
3. LxPBDy->0

Notes: After a certain period of time the work on a box is accomplished and is put on a ready position

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Knowledge Discovery Methodology

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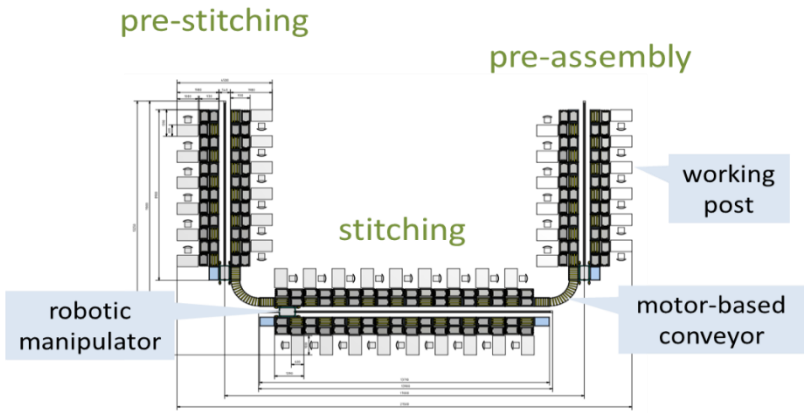
Problem focus for the experiment

Issue:

- Conveyor manipulator **failures** due to **material degradation (belt)**.

Objective:

- Attempt to **predict** this **failures** before they manifest.



Initial challenges

- **Small amount of data** available;
- **Unreliable** data.
- **No** systematic **report of failures** and failure types

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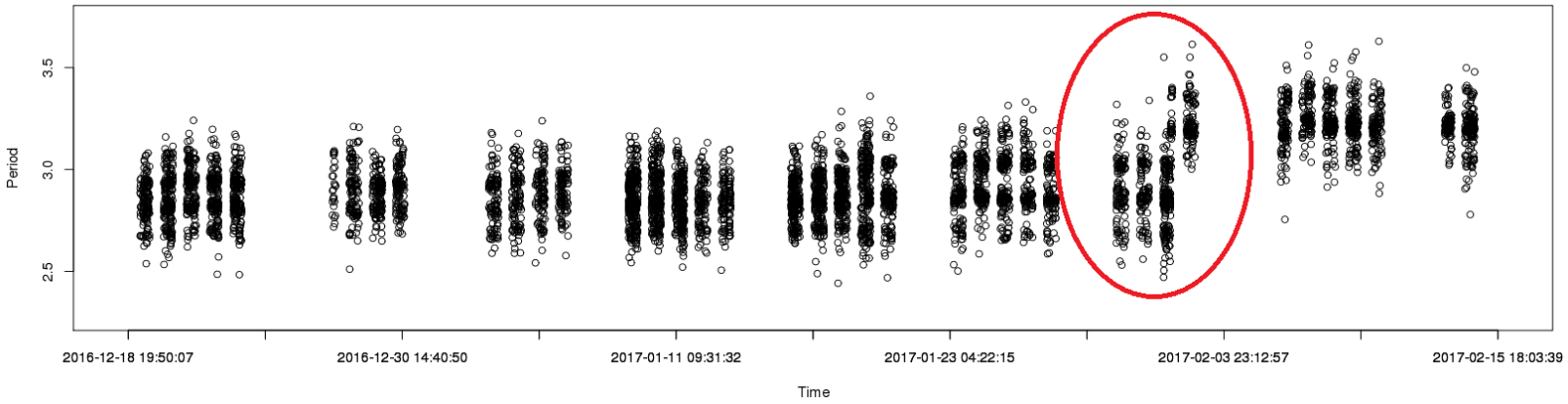
Initial approach:



Assumption:

- Just **before** the **failure** there is a continuous **increase in time**

Methodology:

- Analysis of the time windows before the failures to see if the assumption is correct
- No discernible pattern detected

Second approach

Assumption:

- When **degradation starts to manifest**, the movement times (placing and picking boxes) **start presenting anomalous behaviours**.

- Not necessarily just an increase in time

Example of an approach: Statistical patterns

- The **number of transitions between states** for all the gripper signals;
- The **Average time in each state** for all the gripper signals ;
- The **maximum time in each state** for all the gripper signals ;
- The **minimum time for each state**.

11	3.005800	3.083	2.92299986	18	3.016588	3.096	2.89000010	6	3.045000	3.124	2.95199990	10	3.054556	3.182	2.96199989	15
18	3.016588	3.096	2.89000010	6	3.045000	3.124	2.95199990	10	3.054556	3.182	2.96199989	15	3.047143	3.141	2.95799994	8
6	3.045000	3.124	2.95199990	10	3.054556	3.182	2.96199989	15	3.047143	3.141	2.95799994	8	3.076000	3.152	2.98099995	6
10	3.054556	3.182	2.96199989	15	3.047143	3.141	2.95799994	8	3.076000	3.152	2.98099995	6	3.022000	3.061	2.99399996	18
15	3.047143	3.141	2.95799994	8	3.076000	3.152	2.98099995	6	3.022000	3.061	2.99399996	18	3.007235	3.102	2.92600012	4
8	3.076000	3.152	2.98099995	6	3.022000	3.061	2.99399996	18	3.007235	3.102	2.92600012	4	2.988000	3.053	2.94600010	8
6	3.022000	3.061	2.99399996	18	3.007235	3.102	2.92600012	4	2.988000	3.053	2.94600010	8	2.995571	3.066	2.92400002	6
18	3.007235	3.102	2.92600012	4	2.988000	3.053	2.94600010	8	2.995571	3.066	2.92400002	6	3.050000	3.148	3.00600004	4
4	2.988000	3.053	2.94600010	8	2.995571	3.066	2.92400002	6	3.050000	3.148	3.00600004	4	3.005333	3.038	2.98000002	11
8	2.995571	3.066	2.92400002	6	3.050000	3.148	3.00600004	4	3.005333	3.038	2.98000002	11	3.044900	3.141	2.94900012	4
6	3.050000	3.148	3.00600004	4	3.005333	3.038	2.98000002	11	3.044900	3.141	2.94900012	4	3.027333	3.053	2.97900009	0

Methodology

Approach:

- Creation of sliding windows with **calculated** event **times per action** for **movements periods**:
  - Placing box – extension
  - Placing box – retraction
  - Picking box – extension
  - Picking box – retraction
- Obtain the **trends of the time per action** (based on the **regression**) for the **time windows**.

Methodology

Approach:

- Ensemble learning with various outlier detection unsupervised algorithms (z-score, chi-quare, etc…)
  - Of which Local Outlier Factor (LOF) provided the best results

Local Outlier Factor:

- Measures the **local density deviation** of a given data point with respect **to its neighbors**
- Parameters to **optimize**: **Number of neighbors** to consider, **outlier threshold**
- The **farther the score** of a point is **from 1**, the **more outlier it is**.

Methodology

Evaluation:

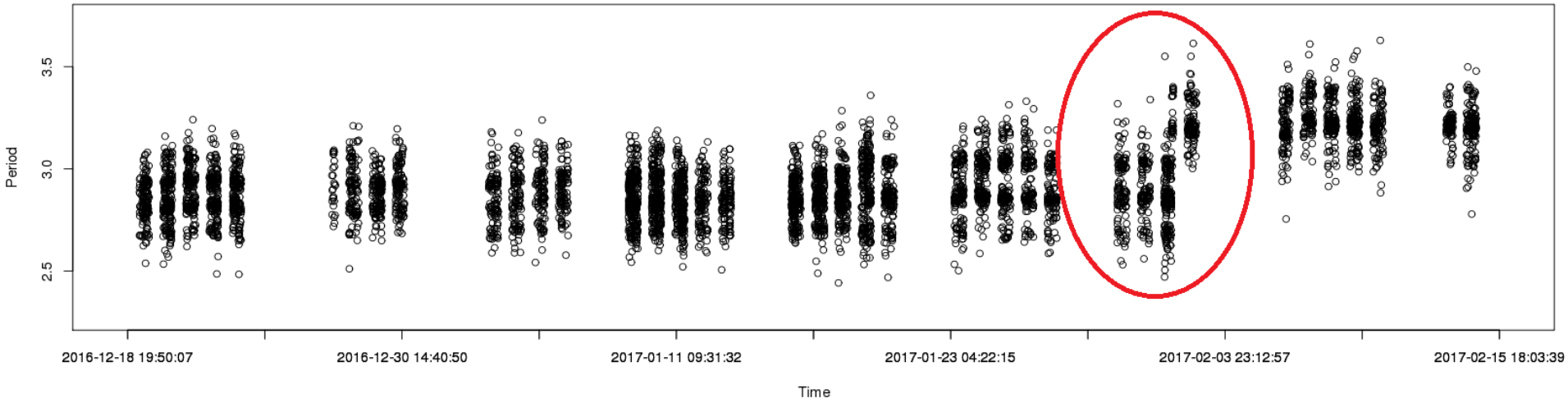
1st phase, **batch** :

- **Measuring accuracy** of the algorithm by **evaluating the outlier scores** on the periods **before the failures**;
- **Consistent scores** for the **4 types of movements** was **important**;
- **Multiple window sizes** and **score thresholds** were attempted in **search for the best results**;

2nd phase, **near real time**:

- Definition of the **periodicity** of the algorithm;
- Evaluation of **how early** the **detection occurs**;
- **Addition** of more **redundancy** to **avoid false positives** by establishing a time based **margins of error**;
- Long term testing;
- **Results validation** with **factory experts**;

Example: 17th of December to the 2nd of February



- Failure occurs on the 2nd of February.
- Movements in graphic represent the times the robot takes to **place a box**
- **Outlier threshold** >1.2

Example: 17th of December to the 2nd of February

- Outlier threshold >1.2
- Timestamp represents the first value in a multiple (four) day window

Date	Outlierness
2016-12-20 12:00:00	0.9913227
2016-12-21 00:00:00	0.9995602
2016-12-21 12:00:00	0.9884457
2016-12-22 00:00:00	0.9818683
2016-12-22 12:00:00	0.9795458
2016-12-23 00:00:00	0.9884601
2016-12-23 12:00:00	0.9967698
2016-12-27 12:00:00	0.9890297
2017-01-03 00:00:00	0.9931669
2017-01-06 00:00:00	0.9896425
2017-01-06 12:00:00	0.9902859
2017-01-09 00:00:00	1.1721319
2017-01-11 12:00:00	1.0803050
2017-01-12 00:00:00	0.9877868
2017-01-12 12:00:00	1.0667149
2017-01-13 00:00:00	0.9989022

Date	Outlierness
2017-01-16 00:00:00	0.9818960
2017-01-18 12:00:00	0.9954320
2017-01-19 00:00:00	0.9875748
2017-01-19 12:00:00	1.0087404
2017-01-20 00:00:00	0.9869893
2017-01-20 12:00:00	1.0549522
2017-01-23 00:00:00	1.1211794
2017-01-25 12:00:00	1.0418890
2017-01-26 00:00:00	**1.2450527**
2017-01-26 12:00:00	1.0279704
2017-01-27 00:00:00	**1.3717708**
2017-01-27 12:00:00	**1.3642077**

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Architecture

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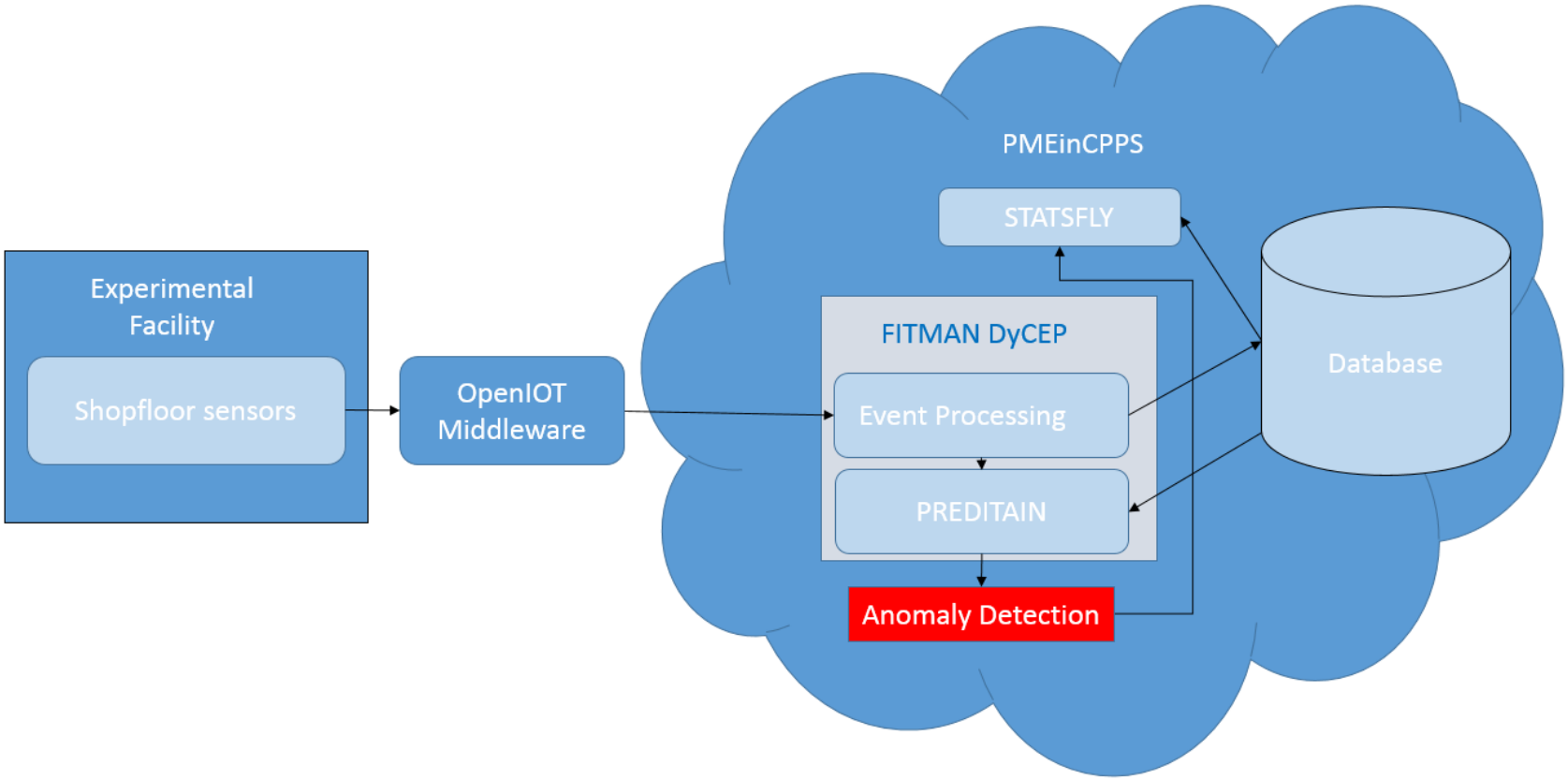
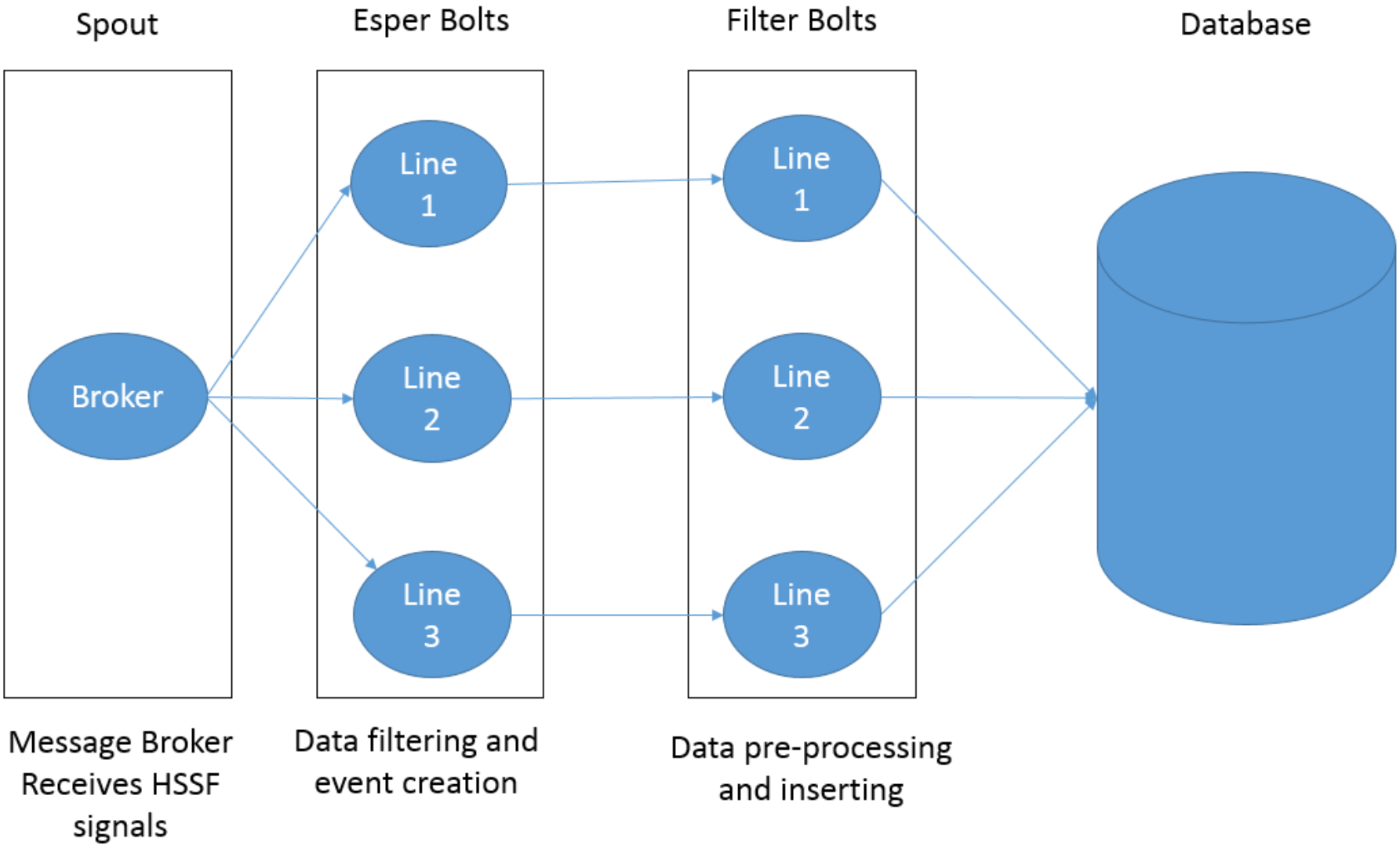
Architecture



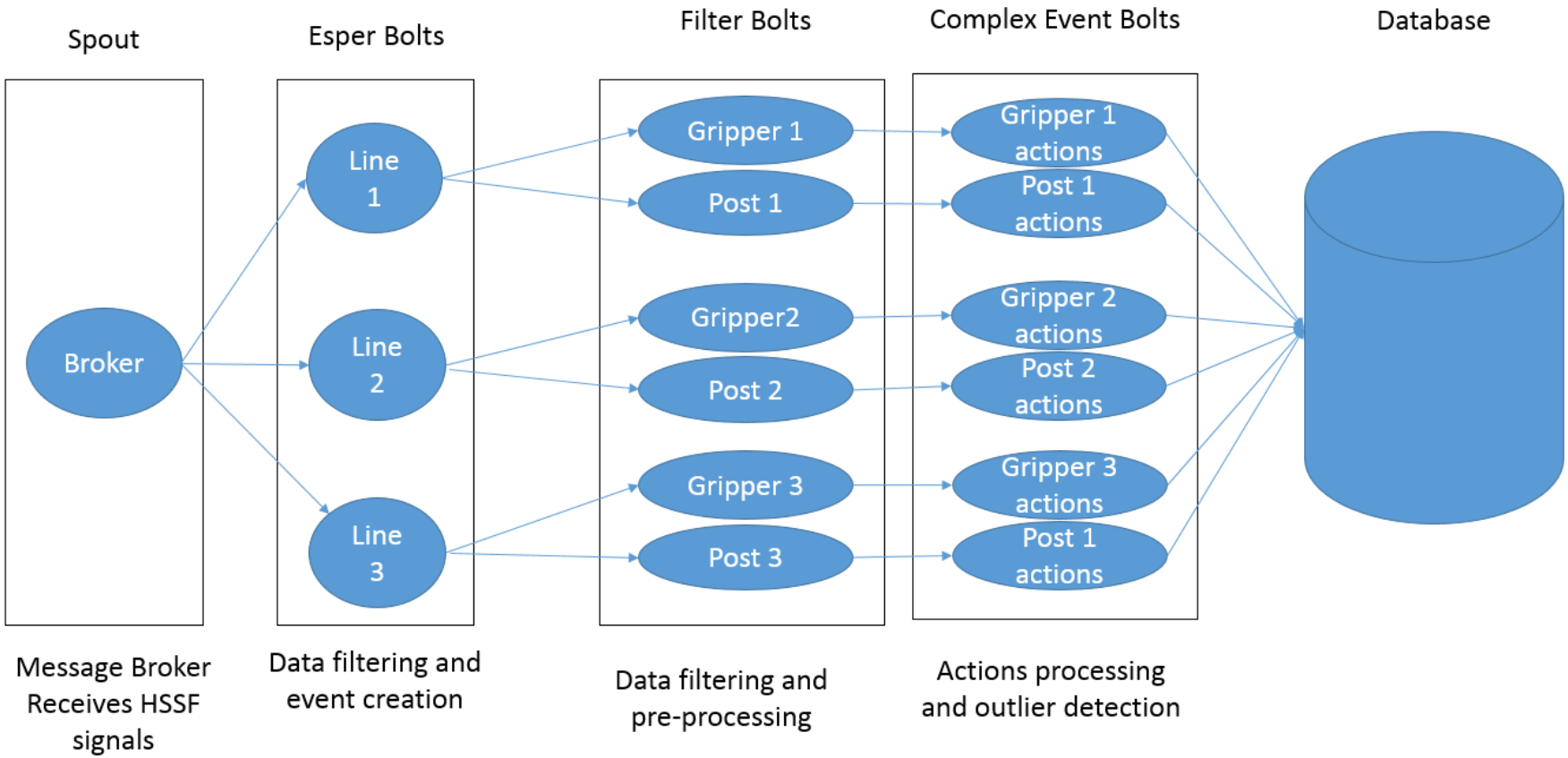
What is FITMAN DyCEP?

- **DyCEP** is a CEP (Complex Event Processing) system made for shop-floor events and other events relevant for manufacturing process which **support complex real-time processing pipelines**;
- Part of the BEinCPPS ecosystem;
- Architecture **based on Apache Storm**;
- Used to build a **distributed architecture**;

Distributed architecture



Distributed architecture



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Results and Conclusions

Results :

Failure Detection (True Positives)

Failures:	Place 1	Place 3	Pull 1	Pull 3	Total
30-03-2017					3
02-02-2017					2.5
05-12-2016					3.5
30-11-2016					2

- Green: Correctly predicted
- Yellow: Potential prediction
- Red: Didn't predict

- When **more than two types of movements** present **anomalous behavior**, there is a **strong indication** that a **failure** is **about to occur**

Results:
False positives

False Positive	Placing extension	Placing retraction	Picking extension	Picking retraction	Total
24-10-2016					2
08-11-2016					4
20-12-2016					2
30-01-2017					1

- Green: False positives detected
- Red: False positive not-detected

- When **more than two types of movements** present **anomalous behavior**, there is a **strong indication** that a **failure** is **about to occur**
  - Only **one False positive** would be **detected**… **real failure that wasn't reported**?

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Benefits and Outlook:

- With the implemented predictive model, it **would be possible to detect 3 of those 4 real failures**, which **would reduce the downtime of the manipulator gripper**
  - **Reduce downtime** and **improve production line workflow**
- With the **STATSFLY** module it is possible to have **detailed information about the system** status, thus allowing to user to fully **monitor the system status** and **reduce the intervention times**
- The inclusion of FITMAN DyCEP allows a **scalable solution**

Lessons learned:

1.Importance of the existence of a **data log**

2. Importance of **close work with factory experts**

3. **Danger of human interference** can skew results

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Thank you

Questions?

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