Tamturbo
JUST AIR

100 % OIL-FREE INDUSTRIAL
TURBO COMPRESSORS

Machine learning in condition monitoring

Beckhoff; Automation update seminar

23th November 2023

Timo Oksanen

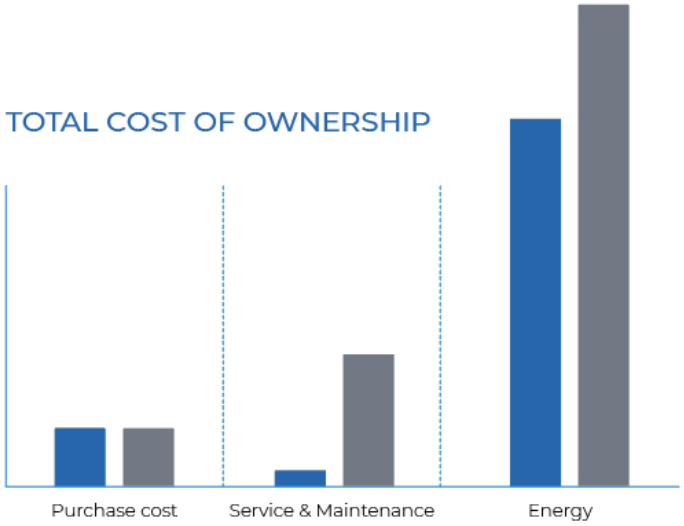
Company purpose

Tamturbo develops, manufactures, and sells industrial direct drive turbo compressors with active magnetic bearings

- 100 % oil-free
- The most environmentally sustainable solution on the market
- With the lowest total cost of ownership

The lowest total cost of ownership

- The product line addresses the most common capacity need (power and volume) for different uses in different industries.
  - From 100 to 350 kW
  - From 10 to 60 m^3 per minute



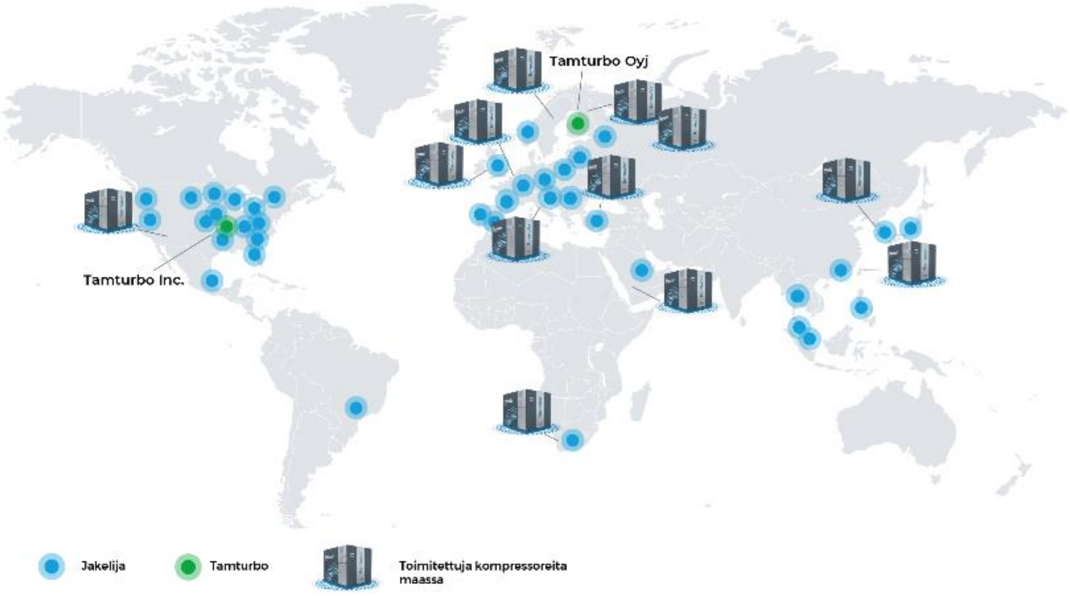
Tamturbo

DISTRIBUTORS AND COUNTRIES WITH INSTALLATIONS

N Americas **50%**

Europe **44%**

Others **6%**



REVENUE MODELS

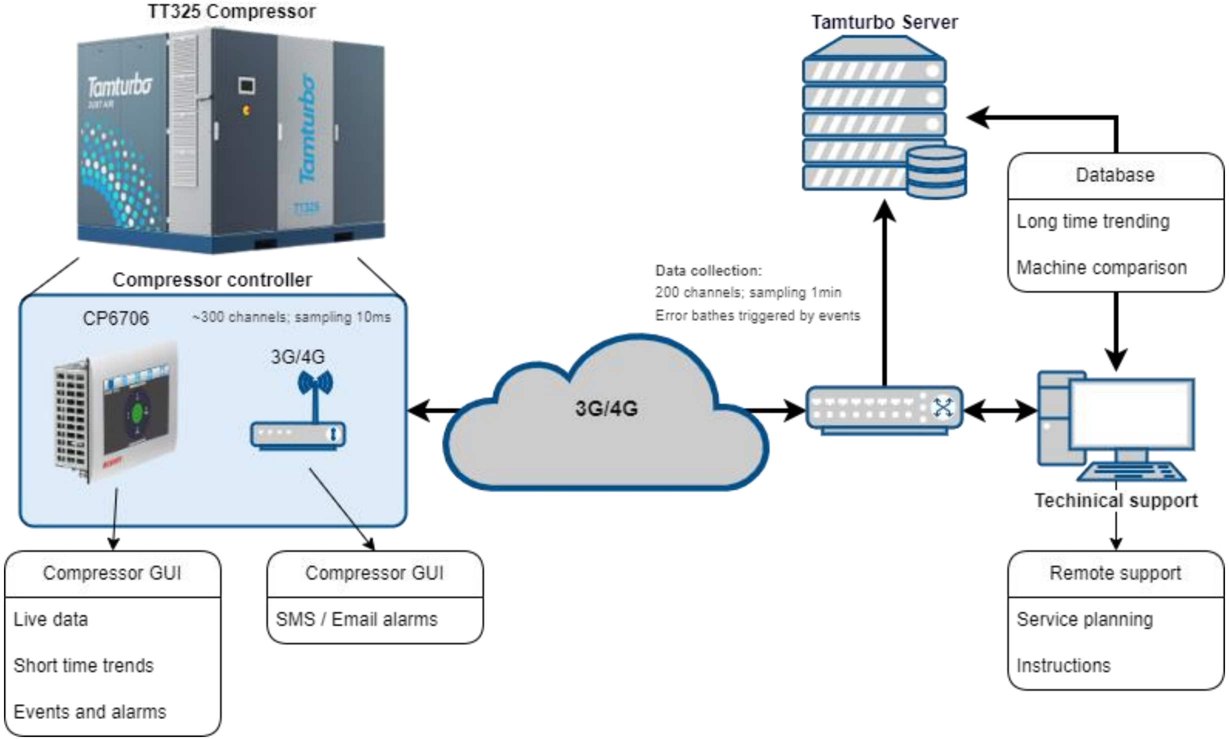
- Most of the compressors are sold with service contract
- Uptime is the most important parameter for customer to buy
- Preventive maintenance helping to do action proactively
- Real-time remote monitoring already used part of the service

Investment + maintenance
Traditional compressor business

Investment + extended warranty
Up to 10 years. All consumable parts, spare parts and labor included

Touch-Free™ Air
Compressor + all related expenses included
Pricing: €/m^3 , €/kW, or €/month
→ production changes easy, adaptive to customer needs, OPEX

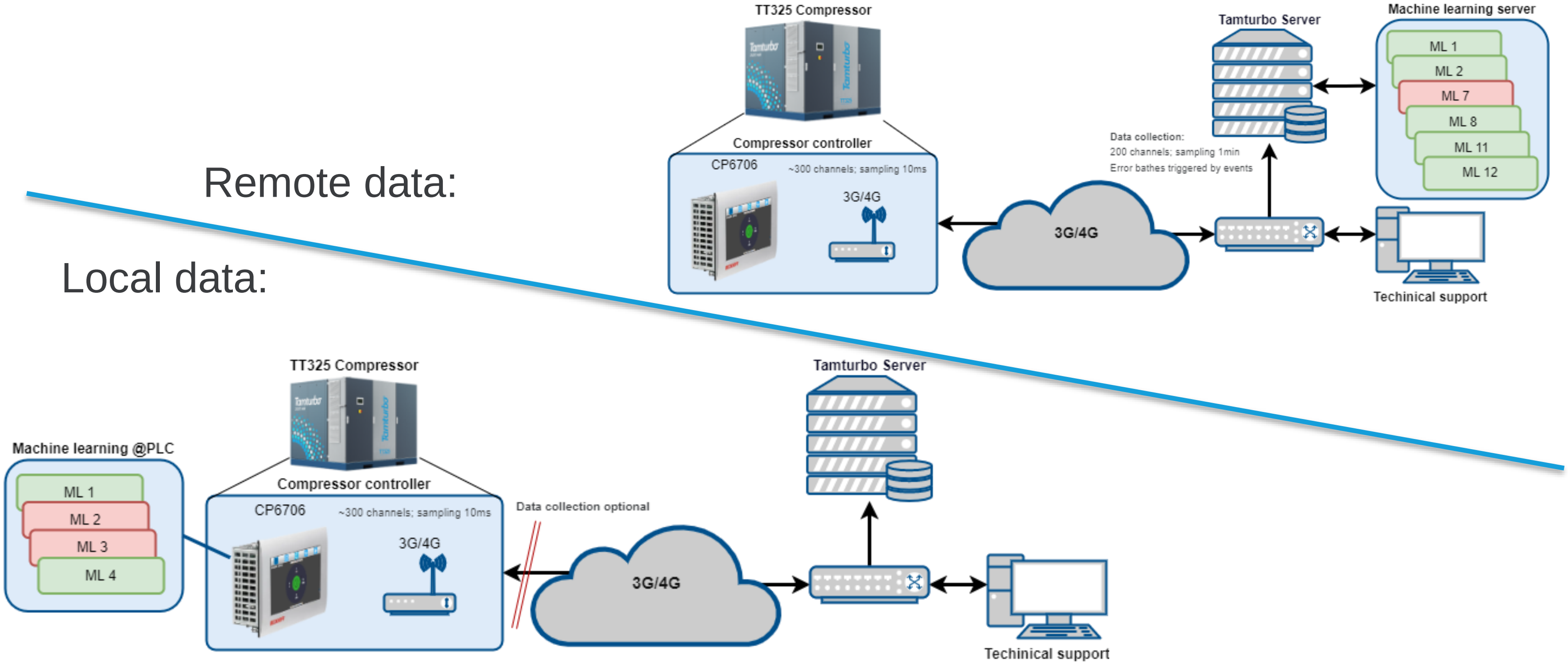
TAMTURBO OPERATION MODEL



MACHINE LEARNING IN ACTION

Remote data:

Local data:



MACHINE LEARNING STEPS TO OPERATION

1. Case to solve with Machine learning; soft sensor, etc.
2. Data for the modelling; field data, test data, and simulation data
3. System physical understanding; design team for process
4. Machine learning model creation
5. Platform to run machine learning model; PLC with Beckhoff library

Presentation: Henri Vainio, TAU

Presentation: Henrik Pammo, Beckhoff
Demo and results: Timo Oksanen, Tamturbo

Tampere University

Mechatronics Research Group

Prof. Kari T. Koskinen, TAU/ENS

Research Questions:

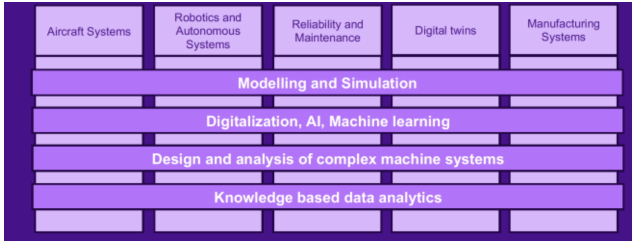
- How to improve and predict **availability, reliability and maintenance** of complex machine systems?
- How to design, analyse and control **autonomous vehicles, robots and multi-robot systems**?
- How to improve the performance of **aircraft systems** and human performance in aviation?
- How to analyse the operation and condition of a machine systems with **knowledge-based analytics**?

Staff: 26 persons including Industry professor, Senior Researchers, University Instructors, Doctoral Researchers and Researchers, Research Assistants

Teaching in Mechanical Engineering –study program: Aircraft Engineering, Mechatronic System Design, Reliability Engineering and Maintenance

Awards: ***Tampere Innovation Award 2020***

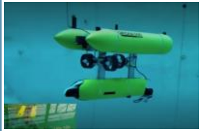
Mission:
More Sustainable Future Machinery by Smart Design and Optimized Life-cycle

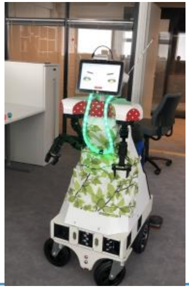


Main projects:
Unexmin (EU-H2020)
Unexup (EIT)
Robominers (EU-H2020)
Dig It (EU-H2020)
PVTO
SMARAGDI
SNOBI
MASTERMINE (HE)
AIRSHIP (HE)

Funding:
EU, EIT, Business Finland, Defence Forces, Industry

Annual project volume: ca. 1 MEURO





Contact:  Prof. Kari T. Koskinen kari.koskinen@tuni.fi

@TUT_MRG

Implementation of Machine Learning Algorithms to TwinCAT

Tampere University

The Application of Simulation in Compressor System

Turbo Compressor Simulation Model

- Dynamic model of physical phenomena in a turbo compressor
- 1D simulation software

- Multiple uses
  - Control design
  - Sales
  - Tech support
  - Condition monitoring, anomaly detection
- Slower than real time

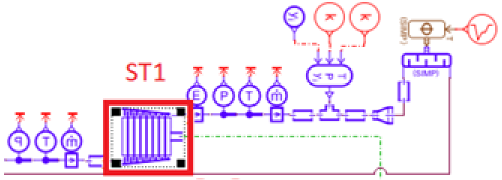
Surrogate modeling

- Mimics the behavior of the simulation model as closely as possible
- Many times faster than the original model

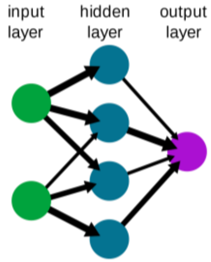
- Surrogate modeling methods
  - Response surface models
  - Bayesian networks
  - **Neural networks**

Physical System

Simulation Model

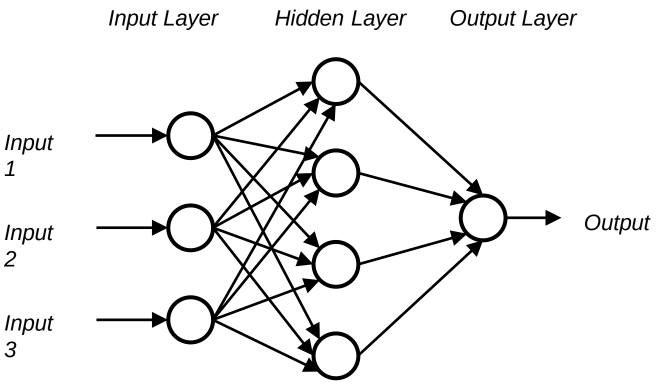


Surrogate model: Neural Network



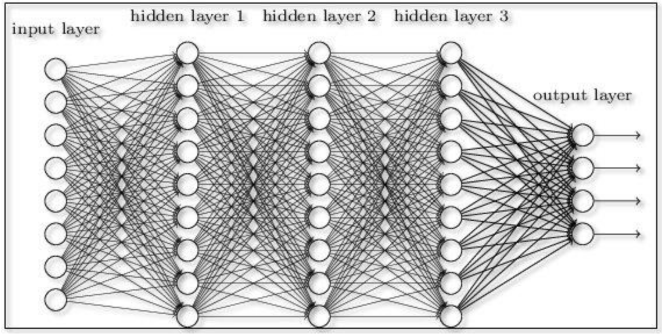
Basic Principle of Neural Networks

- Biologically inspired models
- Learn patterns in the data by updating the parameters of the individual neurons
- Faster than other surrogate methods, and easy to integrate with automation systems



TensorFlow

- Google’s tensor library, Open source since 2015
- GPU support
- Good support for deploying trained models on various platforms
    - Mobile devices, single board computers etc.



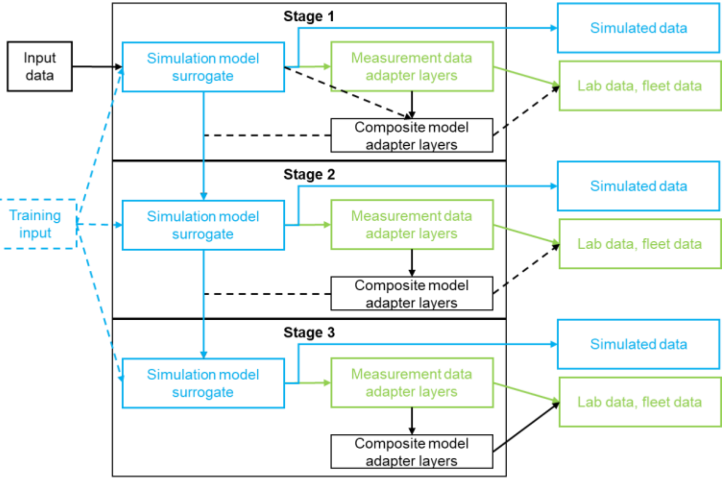
Deep Neural Network = network with many layers

The Application of Surrogate Modeling in Compressor Automation System

- Physical phenomena based modular neural network
- Training of layers of a neural network with simulated data
- Freezing of trained weights
- Training of new layers with data measured from the real machine

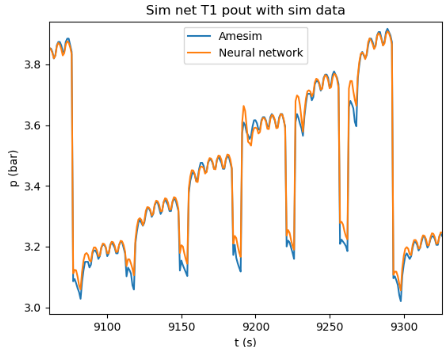
- Simulated, laboratory measurement and field measurement data can be used, or all combined
- Sub-models of known physical phenomena make training and re-training easy
- Individual phenomena models can be selected

1. Training with simulated data
2. Training with measured data
3. Training all stages together

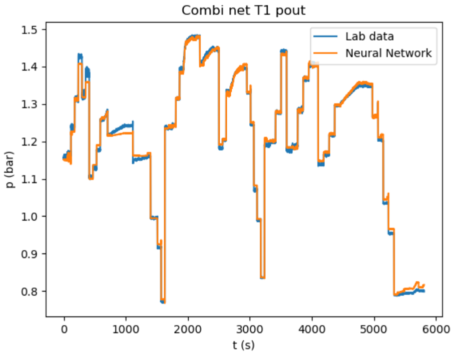


Surrogate model structure: Turbo compressor with three turbo stages

Surrogate model simulation results



Neural network test with simulated data



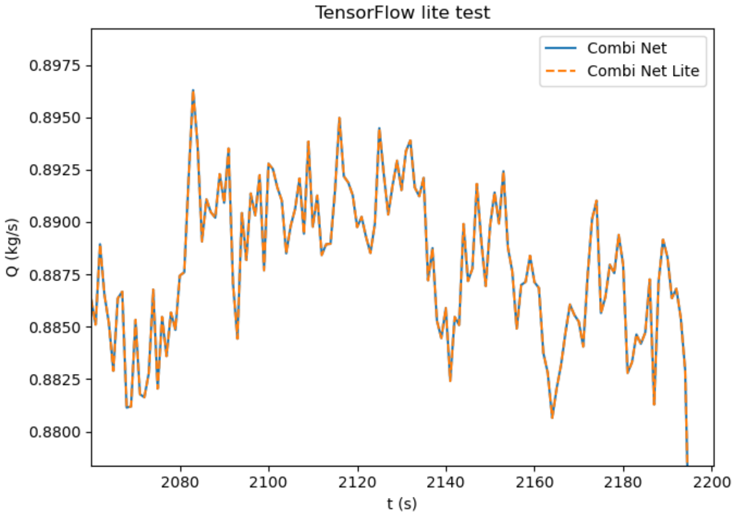
Neural network test with measured data

TensorFlow Lite Library for Implementation

- TensorFlow Lite is a version of TF designed for microcontrollers and mobile devices
- Lighter and faster than TF with some limitations
- Models trained with TF can be converted to TF lite

Case example

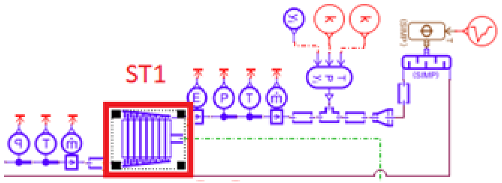
- Simulation times for 5809 steps (i.e. seconds) on a laptop PC:
  - Surrogate network: 4.3125 s (1347 x real time)
  - TensorFlow lite version: 0.015625 s (371776 x real time)
- Note that data pre- and postprocessing (e.g. scaling) may take additional time!



Identical output behavior from both TF and TF lite models

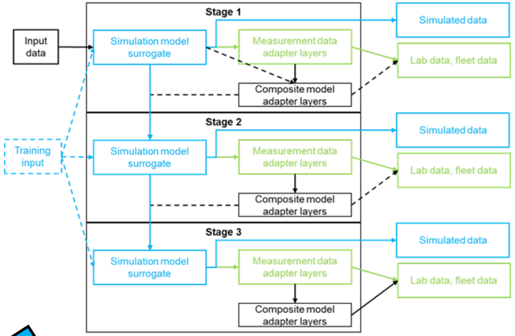
Summary

Knowledge



Simulated Data

Measured Data



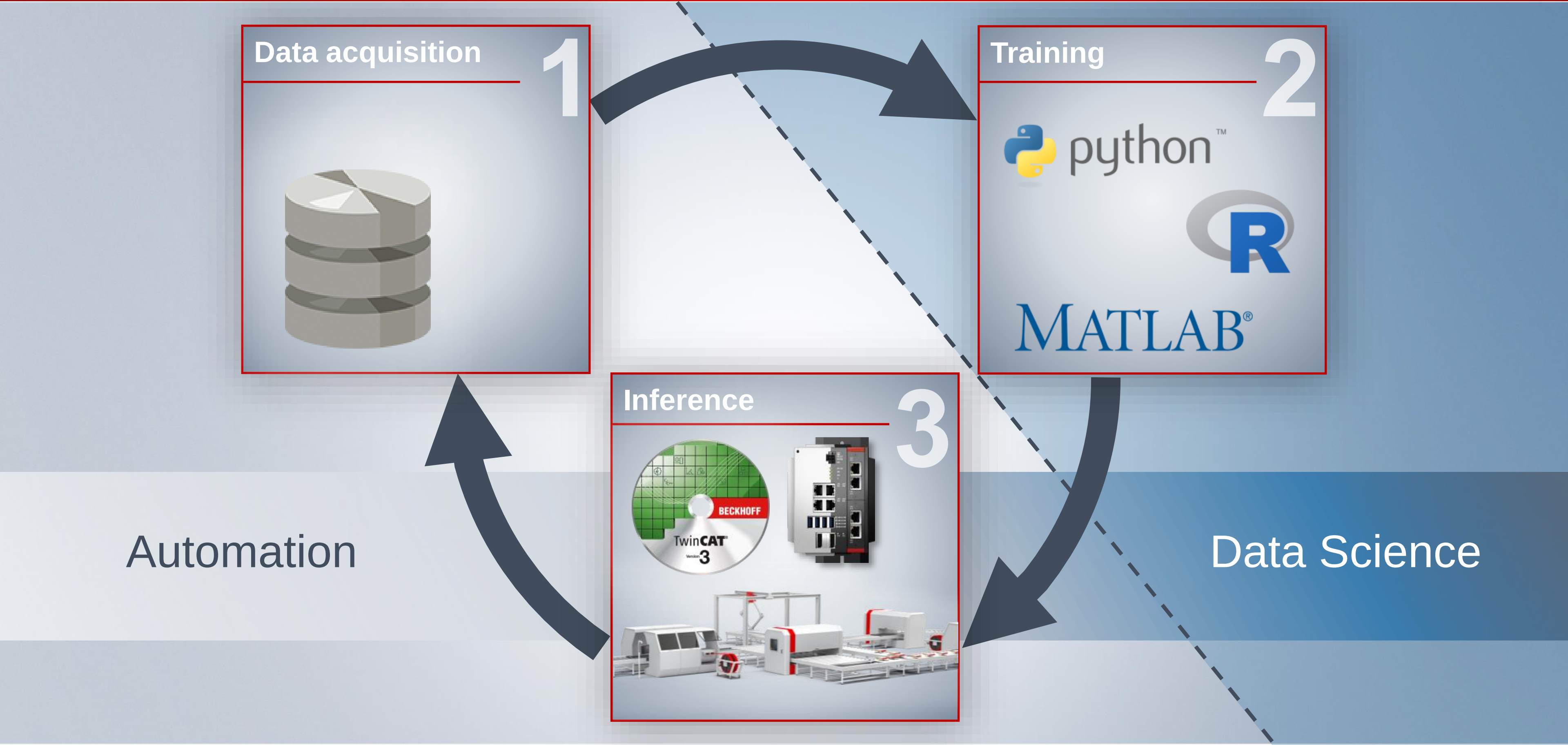
Information

Surrogate Model

TwinCAT Machine Learning

BECKHOFF

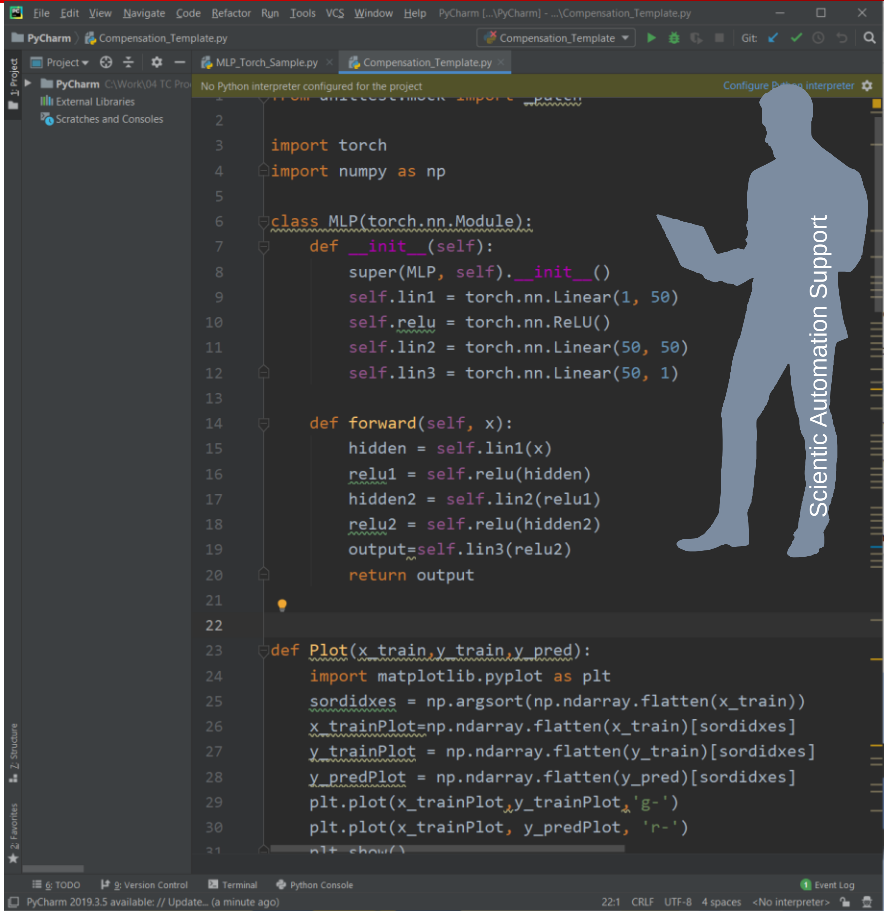
Automation and Data Science



Data modelling, training of AI models

- more than 80% of all data scientists work with Python or R code
- most of the libraries used for data labeling, cleaning and modelling are free of charge
- heterogeneous AI frameworks are often used even in data science teams of one department
- according to a broad variety of computational costs for AI applications, many target hardware devices exist for deployment
- **an interoperability standard is essential:**

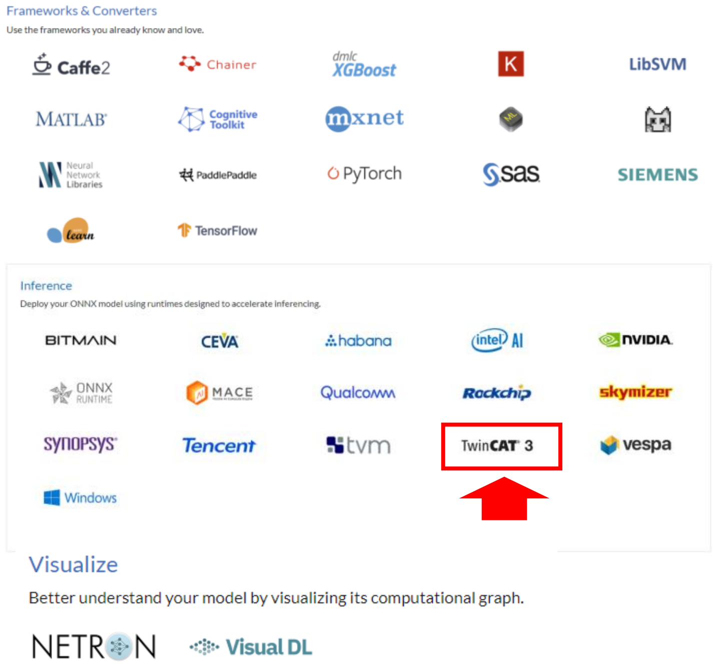
ONNX



Basics on ONNX

- **O**pen **N**eural **N**etwork E**x**change
- Open format to represent Neural Networks and Machine Learning models
  - Interoperability between AI Frameworks
  - Easy access to inference hardware
- Fast growing consortium on supported frameworks, runtime converters and compilers

"**ONNX is an open format built to represent machine learning models.** ONNX defines a common set of operators - the building blocks of machine learning and deep learning models - and a common file format to enable AI developers to use models with a variety of frameworks, tools, runtimes, and compilers."
http://onnx.ai/



http://onnx.ai/supported-tools.html

TF3800, TF3810 | TwinCAT Machine Learning- and Neural Network Inference Engine for real-time inference in TwinCAT

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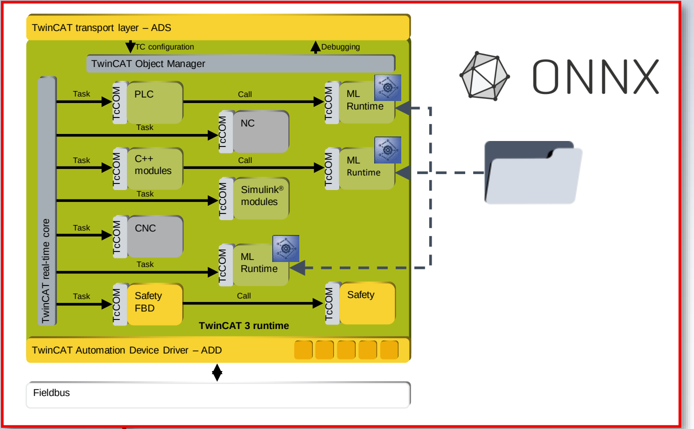

www.beckhoff.ai
www.onnx.ai

TF3820 | TwinCAT Machine Learning Server
Hardware accelerated inference using TwinCAT 3

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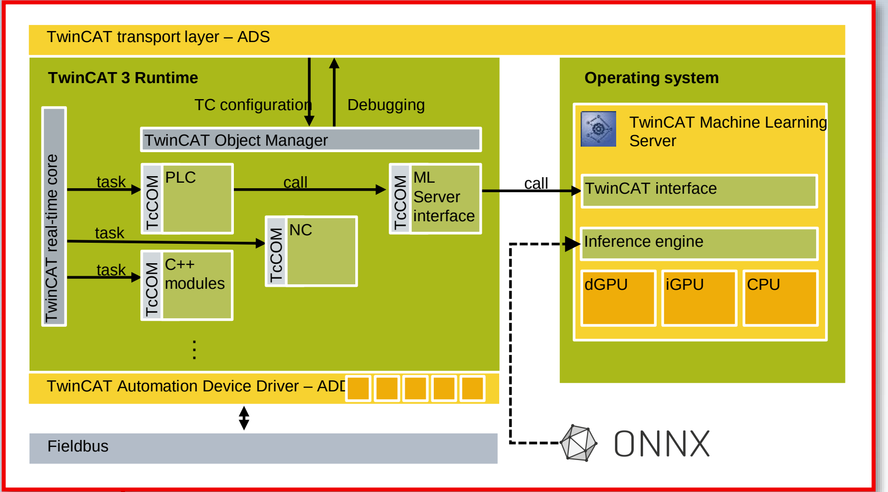
NEW
Q2/2024



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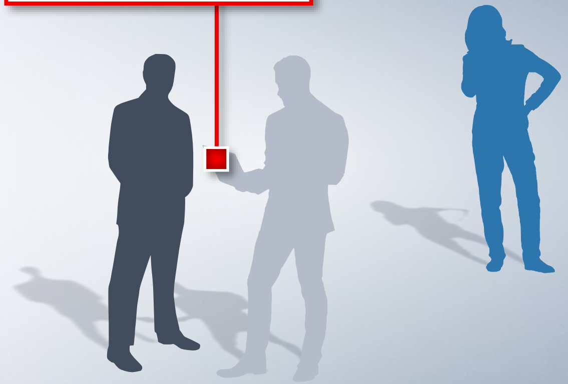
TF3820 ♥ C6043-0090



Real-time Inference | PLC API

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```
PROGRAM MAIN
VAR
    fbprediction : FB_MllPrediction;  // ML Interface
    sModelFile    : T_MaxString := 'C:/models/TrigonometryMLP.bml';  // converted onnx file
    nInputDim,nOutputDim  : UDINT;
    dtype : ETcMllDataType := ETcMllDataType.E_MLLDT_FP32_REAL;
    nnInput  : ARRAY[1..10] OF REAL;
    nnOutput :  ARRAY[1..10] OF REAL;
```

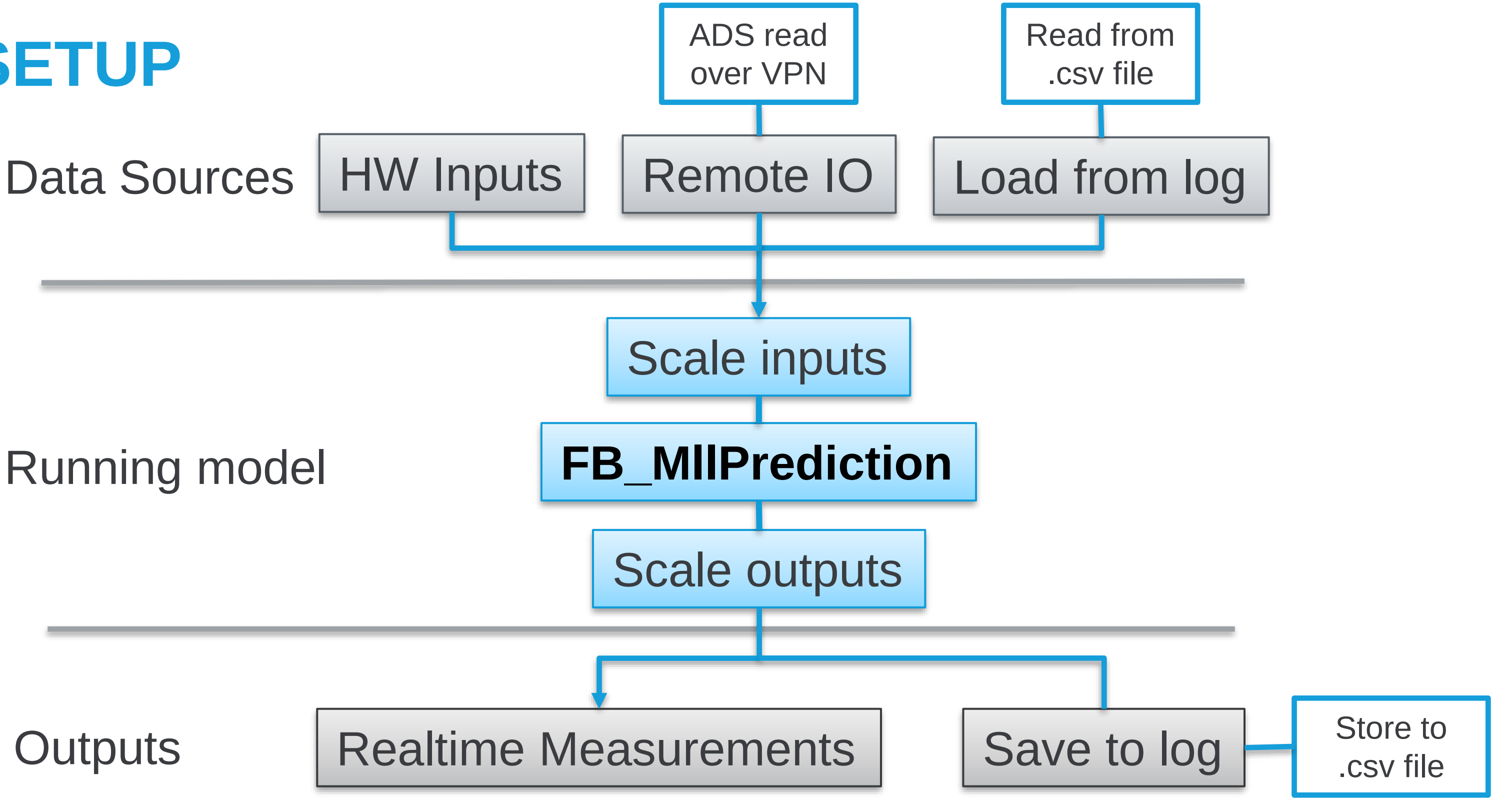
```
CASE nState OF
    0:  // idle state
        IF bLoadConfig THEN
            bLoadConfig:=FALSE;
            nState:=10;
        END_IF
    10: // config state
        fbprediction.stPredictionParameter.MlModelFilepath:=sModelFile; // provide model path and name
        fbprediction.stPredictionParameter.MaxConcurrency := 1;          // no concurrent calls to this fb
        IF fbprediction.Configure() THEN // load model
            // check input/ouput dimensions and datatype
            bFailed:=fbprediction.GetInputDim(nInputDim);
            _FAILED(bFailed);
            bFailed:=fbprediction.GetOutputDim(nOutputDim);
            _FAILED(bFailed);
            bFailed:=fbprediction.CheckPreferredIODataTypes(ETcMllDataType.E_MLLDT_FP32_REAL,ETcMllDataType.E_MLLDT_FP32_REAL,bPreferred);
            _FAILED(bFailed);
            bFailed:=fbprediction.CheckSupportedIODataTypes(ETcMllDataType.E_MLLDT_FP32_REAL,ETcMllDataType.E_MLLDT_FP32_REAL,bSupported);
            _FAILED(bFailed);
        END_IF
    20: // Predict state
        fbprediction.Predict(
            pDataInp:=ADR(nnInput) ,
            nDataInpDim:= nInputDim,
            fmtDataInpType:= dtype,
            pDataOut:=ADR(nnOutput) ,
            nDataOutDim:= nOutputDim,
            fmtDataOutType:= dtype,
            nEngineId:= nCurrentEngineID,
            nConcurrencyId:= 0);          // concurrency not in use in this sample. see concurrency sample in infosys for non-blocking parallelization

        IF fbprediction.bError THEN      // error handling
            nState := 999;
            hrErrorCode := fbprediction.hrErrorCode;
        ELSIF bLoadConfig THEN           // load (updated) model
            bLoadConfig := FALSE;
            nState := 10;
        END_IF;

    999: // Error state
        // add error handling here
END_CASE
```

load model

execute model

update model

TEST SETUP



Tamturbo

FINDINGS

SNOBI_Compressor_machine_learnign_test									
		HW measurements to model							
		HW measurement output							
		Soft sensor output							
	Input parameters to the model							HW measurement	Soft sensor measurement
Data tag	Comp_Turbo1_IN_P	Comp_M1_RPM_fb	Comp_M2_RPM_fb		Comp_Turbo1_IN_T	Comp_Turbo2_IN_T	Comp_Turbo3_IN_T	Comp_Turbo1_IN_qm	Sim_Turbo1_IN_qm
	mbarg	1/min	1/min		°C	°C	°C	kg/s	kg/s
2022-11-23-13:54:26.567	-0.014	31436	33322		22	32	35		0.79	0.78

SNOBI_Compressor_machine_learnign_test

PLC_Timestamp	Comp_Turbo1_IN_T	Comp_Turbo1_IN_P	Comp_Network_P	Comp_M1_RPM_fb	Comp_Turbo2_IN_T	Comp_M2_RPM_fb	Comp_Turbo3_IN_T	Comp_Turbo1_IN_qm	Comp_Turbo1_OUT_P	Comp_Turbo2_IN_P	Comp_Turbo2_OUT_P	Comp_Turbo3_IN_P	Comp_Turbo3_OUT_P	Sim_Turbo1_IN_qm	Sim_Turbo1_OUT_P	Sim_Turbo1_OUT_T	Sim_Turbo2_IN_P	Sim_Turbo2_OUT_P	Sim_Turbo2_OUT_T	Sim_Turbo3_IN_P	Sim_Turbo3_OUT_P	Sim_Turbo3_OUT_T	Sim_Turbo3_OUT_qm
2022-11-23-13:54:26.567	22.3	-0.014388334	6.622	31436	31.90001	33322	34.90002	0.7930106	1.353408	1.30196	4.578506	4.636297	6.642768	0.7784547	1.176533	122.80498	0.9895043	4.333556	153.1713	4.195183	7.978894	77.01935	1.092155
2022-11-23-13:54:27.567	22.3	-0.014419949	6.621526	31438	31.90001	33322	34.90002	0.7963153	1.353087	1.302139	4.576783	4.635307	6.643585	0.7784322	1.176548	122.80236	0.9894938	4.333645	153.1663	4.195325	7.97903	77.02387	1.092128
2022-11-23-13:54:28.567	22.3	-0.014416401	6.621229	31434	31.90001	33322	34.90002	0.7973268	1.353869	1.301563	4.577575	4.634974	6.643179	0.7784739	1.176635	122.80551	0.9896019	4.334149	153.1755	4.195949	7.979361	77.02151	1.092149
2022-11-23-13:54:29.568	22.3	-0.014378578	6.62198	31436	31.90001	33322	34.90002	0.7967928	1.353186	1.301874	4.578049	4.635238	6.642288	0.7784527	1.176518	122.80544	0.9894987	4.333529	153.1718	4.195132	7.978931	77.01891	1.09216
2022-11-23-13:54:30.568	22.3	-0.014455276	6.621149	31436	31.90001	33322	34.90002	0.7972362	1.354309	1.30277	4.578057	4.635369	6.642954	0.7784575	1.176653	122.80235	0.9895812	4.334115	153.1694	4.195964	7.979236	77.02526	1.092119
2022-11-23-13:54:31.568	22.3	-0.014509448	6.621323	31438	31.90001	33324	34.90002	0.8016911	1.352873	1.301756	4.577438	4.635144	6.642206	0.7784351	1.176674	122.79313	0.9895372	4.333958	153.1588	4.195877	7.979007	77.0289	1.092078
2022-11-23-13:54:32.568	22.3	-0.014381925	6.620332	31436	31.90001	33322	34.90002	0.7988476	1.353018	1.301806	4.57753	4.635128	6.641763	0.7784333	1.176558	122.80618	0.9895633	4.334165	153.1749	4.195872	7.979937	77.02389	1.092156
																				4.196479	7.981689	77.02773	1.092182
																				.197362	7.980439	77.03533	1.092079
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																				.199117	7.984254	77.04646	1.092121
																				.199403	7.986397	77.05033	1.092174
																				.201723	7.986446	77.06526	1.092045
																				.202269	7.987285	77.07237	1.092022
																				.202106	7.987737	77.07067	1.092053
																				4.20172	7.988872	77.06658	1.09213
																				.203135	7.98942	77.07325	1.092097
																				.202583	7.989125	77.07323	1.092084
																				.203735	7.989949	77.07757	1.09208
																				4.20352	7.989094	77.08013	1.092032
																				.203078	7.989393	77.07342	1.092087
																				.201992	7.988306	77.06925	1.092087
																				.201509	7.987166	77.06231	1.092104
																				.199831	7.985766	77.05995	1.091944
																				.199646	7.986089	77.05255	1.092143
																				.202499	7.984761	77.04216	1.092079
																				.200552	7.98513	77.05643	1.092076
																				.203505	7.984716	77.0542	1.091686
																				.200036	7.984284	77.05457	1.091749
																				.202131	7.983748	77.04774	1.091706
																				4.19989	7.981654	77.03245	1.091749
																				.199615	7.981959	77.0259	1.091818
2022-11-23-13:55:03.573	22.3	-0.014327806	6.618016	31440	31.99999	33326	34.94782	0.7929258	1.352465	1.30066	4.574741	4.631937	6.637645	0.7785144	1.175786	122.75703	0.9900708	4.333285	153.1349	4.197156	7.981323	77.03304	1.091798
2022-11-23-13:55:04.573	22.3	-0.014394811	6.618809	31438	31.99999	33326	34.90005	0.7944922	1.353488	1.301964	4.576543	4.63467	6.639076	0.7784814	1.175229	122.74706	0.9898471	4.332052	153.1436	4.195786	7.9808	77.03921	1.091781
2022-11-23-13:55:05.573	22.3	-0.014337778	6.619525	31438	31.99999	33324	34.90002	0.7952643	1.353609	1.302491	4.576336	4.634348	6.641435	0.7784901	1.175141	122.7545	0.9898053	4.331656	153.1485	4.195204	7.98042	77.03436	1.091815
2022-11-23-13:55:06.573	22.3	-0.014210752	6.61977	31438	31.99999	33324	34.90002	0.7934031	1.35249	1.302228	4.575897	4.63395	6.641794	0.7784675	1.174941	122.76025	0.9897109	4.331114	153.1547	4.194316	7.980612	77.02712	1.091883
2022-11-23-13:55:07.573	22.3	-0.014470446	6.620744	31438	31.99999	33324	34.90002	0.7940461	1.352858	1.302451	4.576574	4.634787	6.639424	0.778531	1.175319	122.74769	0.9898481	4.331662	153.1392	4.195486	7.97931	77.03759	1.091746
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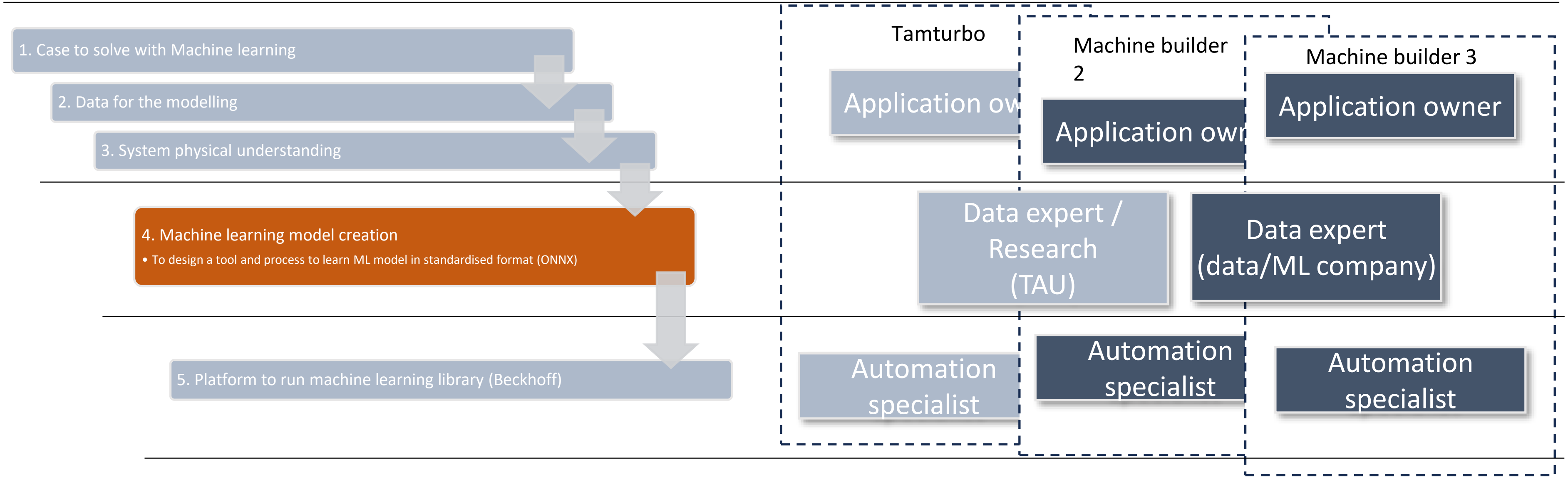
NEW BF Project: Machine Learning to enhance global industrial (remote or edge) services



Consortium Participants and contacts

Tamturbo
Juha Lammi
Technology Director

+358 40 740 1737
juha.lammi@tamturbo.com

Tampere University
Kari Koskinen
Professor, Mechatronics

+358 40 063 4242
kari.koskinen@tuni.fi

Beckhoff
Mikko Heikkilä
Tukipalvelut

+358 40 1715 960
m.heikkila@beckhoff.com