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Asemapäällikönkatu 12 B, 00520 Helsinki, Finland, www.automaatioseura.fi



SUOMEN AUTOMAATIOSEURA RY
FINNISH SOCIETY OF AUTOMATION

Fredrik Hellman*, Janne Hakala, William Antus, André Norrback, Andreas Lundell, and Jerker Björkqvist

Automated Life Cycle Assessment in Scalable and Flexible Manufacturing

Abstract: Traditional Life Cycle Assessment (LCA) procedures are time-consuming and rely heavily on manual input. In collaboration with Mirka, a Finnish manufacturing company producing abrasives, we integrate real-time data flows between production databases and LCA tools. This collaboration is ideal due to Mirka's extensive product portfolio, containing thousands of different products, providing a strong foundation for demonstrating the scalability and versatility of the automated LCA framework. We utilize a data lakehouse architecture to enable seamless handling of diverse datasets often required for LCA, supporting near real-time updates to sustainability metrics. This automated solution minimizes manual effort, adapts dynamically to operational data changes, and delivers a continuous overview of environmental performance.

Keywords: Life Cycle Assessment, Data Lakehouse, Real-time Data Integration, Automated LCA, Manufacturing

***Corresponding Author: Fredrik Hellman:** Åbo Akademi University, Information Technology, E-mail: fredrik.hellman@abo.fi

Janne Hakala: Åbo Akademi University, Information Technology, E-mail: janne.hakala@abo.fi

William Antus: Mirka Ltd, E-mail: william.antus@mirka.com

André Norrback: Mirka Ltd, E-mail: andre.norrback@mirka.com

Andreas Lundell: Åbo Akademi University, Information Technology E-mail: andreas.lundell@abo.fi

Jerker Björkqvist: Åbo Akademi University, Information Technology, E-mail: jerker.bjorkqvist@abo.fi

1 Introduction

Life Cycle Assessment (LCA) evaluates the environmental impacts of a product throughout its entire life cycle. LCA plays a key role in driving sustainability, supporting frameworks like Environmental Product Declarations (EPDs) and Digital Product Passports (DPPs), both essential for complying with circular economy (CE) principles. Yet, traditional LCA methods remain manual, time-consuming, and static [11], which limits their usefulness for current sustainability needs. With the European Union's Corporate Sustainability Reporting Di-

rective (CSRD) requiring transparent reporting on sustainability [6], companies are pushed towards more sustainable production, and could benefit from implementing more dynamic and automated processes in calculating sustainability metrics.

For companies with extensive product portfolios, often containing over thousands of products, automation is essential to make the LCA process more effective. Additionally, automating LCA calculations unlocks further benefits, such as real-time visualization of emissions during production, supporting data-driven management and continuous performance monitoring.

In this study, we describe an automated life cycle assessment (ALCA) framework implemented at Mirka. The goal is to demonstrate how automating LCA calculations can reduce manual effort and enhance the scalability of sustainability assessments. By leveraging a data lakehouse architecture, we enable near real-time integration of production data with LCA tools, allowing for dynamic updates to sustainability calculations. This approach could improve efficiency and provide Mirka with continuous insights into environmental performance, promoting data-driven decision-making for more sustainable production.

2 Background

2.1 Automated Life Cycle Assessment

LCA is becoming increasingly relevant, especially for manufacturing companies, both to comply with regulatory requirements, as well as, reducing emissions as lower emissions are becoming a competitive advantage. A traditional LCA consists of four steps in accordance with ISO14040 [3] and ISO 14044 [4]: goal and scope, life cycle inventory analysis, life cycle impact assessment, and finally the interpretation. LCA require a substantial amount of data, and current LCA practices are not scalable and rely heavily on manual input.

As the authors are aware, there is currently no framework with full support for automated LCA calculations. However, commercial LCA software solutions,

such as SimaPro Synergy [12], and Sphera [13], have recently released application programming interfaces (APIs), enabling programmatic communication with their systems, underlining the need for automated solutions in industry. Additionally, the framework proposed by [11] presents an ALCA process for manufacturing companies, and [9] solved their defined challenges by developing a life cycle inventory (LCI) modeling approach, allowing automated assignments of a component's attributes, to pre-defined LCI models using commercial LCA tools; all of these indicate an active research area. These advancements, both in industry and academia, highlight a clear trend toward automation in LCA. However, fully scalable and integrated solutions remain an ongoing challenge.

2.2 Data Lakehouse Architecture

According to [9], automated LCA for complex products faces several significant challenges, e.g., balancing accuracy with efficiency, managing the heavy manual workload of mapping input data to LCI datasets, dealing with inflexible LCI modeling, and the absence of automation support in many commercial LCA software packages. Further, [10] also highlights that LCI is the most resource-intensive part of the assessment.

Given that the main challenges are inherently data-related, a robust and scalable data management solution is essential for enabling automation. A data lakehouse architecture offers a promising approach by integrating structured and unstructured data within a governed, query-optimized, and scalable environment. Originally introduced by Armbrust et al. [5], a data lakehouse combines the advantages of data lakes and data warehouses, supporting ACID (atomic, consistent, isolated, durable) transactions, metadata management, and data sharing.

These features align well with the requirements of automated LCA, as they enable programmatic data ingestion, continuous updates to LCA models, and support for AI-driven analysis of environmental impacts. Cloud-based implementations further enhance the scalability and efficiency of LCA workflows by providing cost-effective, high-performance storage and compute capabilities. Leveraging a data lakehouse approach enables organizations to overcome data scalability and accuracy challenges in automated LCA, resulting in more efficient, real-time assessments of environmental impact, and better alignment with evolving sustainability regulations.

2.3 Mirka Ltd

Mirka is an essential partner for this project due to several key factors. First, their broad product portfolio provides a good test case for demonstrating the scalability of the ALCA framework. With thousands of distinct products, the system can be tested for its ability to handle diverse materials, processes, and environmental impacts at scale.

Second, Mirka's established data lakehouse infrastructure supports integration capabilities for LCA tools. Real-time in this context is defined at least once per day down to on a minute basis. It is worth noting that there are no technical limitations preventing even more frequent calculations, however, the chosen update frequency aligns with Mirka's specific requirements and operational needs. Their existing systems ensure that the automated framework can access reliable and well-organized data for processing. Additionally, Mirka's strong sustainability focus, including initiatives like transitioning to fossil-free electricity to reduce emissions, shows clear willingness to adapt to sustainability efforts.

Therefore, the combination of product portfolio complexity, data readiness, and sustainability alignment makes Mirka an ideal collaborator for implementing and showcasing the ALCA system.

3 ALCA Framework

The objective with this study is to describe the ALCA framework that integrates real-time production data into LCA tools, assess its scalability and flexibility by applying it to Mirka's extensive product portfolio, and demonstrate continuous sustainability monitoring through real-time visualizations of key environmental indicators.

The ALCA workflow implemented in this study is illustrated in Figure 1. Mirka integrates real-time data from Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), and sensor systems into a centralized data lakehouse, which acts as a storage repository to enable automated, dynamic LCA updates. Python scripts then query, process, and map the data to OpenLCA models, with the obtained results fed back into the repository, for example, for usage in dashboards that support near real-time monitoring.

The ALCA framework is here applied to two distinct cases:

1. **Real-time monitoring of manufacturing:** This approach visualizes how fluctuations in electricity consumption and raw material usage affect emissions during a single production process.
2. **Batch-level LCA calculations:** This method calculates the LCA for an entire production batch after completion, using a gate-to-gate approach that automatically generates sustainability metrics and supports the preparation of an EPD.

By applying the ALCA framework in these two scenarios, this study demonstrates both the real-time functionality of monitoring sustainability metrics and the ability to perform batch-level LCA calculations across multiple production processes. Since certain processes depend on the completion of others before LCA calculations can be performed, the batch-level approach ensures accurate assessment of the entire production cycle.

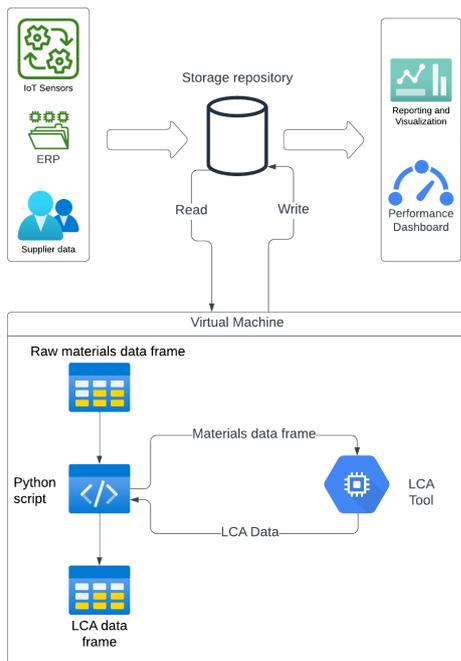


Fig. 1. An illustration of the workflow in the ALCA framework

4 Implementation

4.1 Data structure

Firstly, to automate LCA practices, a standardized data structure is required. Databricks [1], a cloud-based data management platform, serves as the centralized stor-

age repository. The data lakehouse architecture within Databricks provides a unified environment that integrates data from various sources, such as production systems, ERP databases, and supplier datasets. For a single process, all relevant inputs should be systematically documented alongside the corresponding process name, ensuring scalability and applicability to other processes, as illustrated in Table 1. This table is updated dynamically with new values during the production, and sent to the LCA software for calculation, which allows for real-time monitoring of relevant sustainability metrics. In this table layout, the primary flow for each process is defined from the process name. It should be noted that the names and data presented in the tables are illustrative examples and do not represent actual values or proprietary information.

Once all processes for a product are completed, the table structure, as illustrated in Table 2, consolidates the data for the final product. All relevant process inputs are aggregated within the table and sent for calculation. The selected impact assessment method dictates the specific environmental impact values that are calculated and returned. The upstream process column defines the sequence of processes, ensuring that outputs from one process serve as inputs for the next. The process with no downstream dependencies represents the final stage, while the process with a null upstream value marks the starting point. Based on this structure, we can systematically trace material and energy flows and ensure accurate impact calculations.

4.2 Data processing

When data is sent for processing, it should be correctly mapped in the LCA tool. In this study, OpenLCA is used as it provides an API for inter-process communication (IPC). OpenLCA is a free, open-source LCA software that can be used for professional LCAs [8]. It is designed to be flexible and customizable, allowing for adoption of the software to suit the users specific needs and conduct a wide range of sustainability assessments [8]. The IPC protocol is provided by an OpenLCA server that can be a running instance of the OpenLCA desktop application or a webserver with an OpenLCA backend that exposes this protocol. In our case, the IPC server is running on a virtual machine, that fetches the data from Databricks using databricks-connect Python package [2].

OpenLCA's Python package `olca-ipc` [7] allows for programmatic communication with OpenLCA. The

Column	Description
Process ID	Unique identifier for each process step.
Process	Name of the process
Upstream	The previous process that serves as input to the current process
Raw Material	The material or resource used in the process
Unit	Measurement unit for the raw material
Chemical Classification	Categorization of the raw material based on its classification in the LCI
Amount	Quantity of raw material used in the process
Impact Method	Environmental impact assessment method applied to the process

Table 1. Description of table columns

Process ID	Process Name	Raw Material	Unit	Chemical Classification	Amount	Impact Method
P004	Production3	Final paper product	kg	Paper, coated, printing	1000	ReCiPe 2016 Midpoint (H)
P004	Production3	Ink	kg	Pigment, organic, printing	10	EF 3.0
P004	Production3	Polyethylene	kg	Polyethylene, low density	15	EF 3.0
P004	Production3	Electricity	kWh	Electricity, high voltage	200	ReCiPe 2016 Midpoint (H)

Table 2. Example table layout for a single process

Process ID	Process	Upstream	Raw Material	Unit	Chemical Classification	Amount	Impact Method
P000	Transportation	NULL	Paper roll	kg	Pulp, mechanical, bleached	1000	ReCiPe 2016 Midpoint (H)
P001	Storage	P000	Paper roll	kg	Pulp, mechanical, bleached	1000	ReCiPe 2016 Midpoint (H)
P002	Production1	P001	Paper roll	kg	Pulp, mechanical, bleached	980	EF 3.0
P002	Production1	P001	Starch	kg	Starch, from maize	20	EF 3.0
P002	Production1	P001	Electricity	kWh	Electricity, medium voltage	150	ReCiPe 2016 Midpoint (H)
P003	Production2	P002	Coated paper	kg	Coating, polymer-based	970	ReCiPe 2016 Midpoint (H)
P003	Production2	P002	Calcium carbonate	kg	Calcium carbonate, precipitated	50	EF 3.0
P003	Production2	P002	Steam	MJ	Heat, from steam, in chemical industry	300	ReCiPe 2016 Midpoint (H)
P004	Production3	P003	Final paper product	kg	Paper, coated, printing	1000	ReCiPe 2016 Midpoint (H)
P004	Production3	P003	Ink	kg	Pigment, organic, printing	10	EF 3.0
P004	Production3	P003	Polyethylene	kg	Polyethylene, low density (LDPE)	15	EF 3.0
P004	Production3	P003	Electricity	kWh	Electricity, high voltage	200	ReCiPe 2016 Midpoint (H)

Table 3. Example Table Layout for Multiple Processes for a Finished Product

Python script in the ALCA framework will dynamically create, or update product systems, processes, and flows based on incoming data. For existing product systems, flows will be updated, while new models will be generated for new products.

Once each LCA calculation completes, impact assessment results are extracted from OpenLCA through the same programmatic interface. These outcomes are then written back to Databricks as newly versioned records, where they become available for visualization or further analysis. In an effort to ensure transparency and support a continuous improvement cycle, Mirka's monitoring dashboards can track changes in impact indicators in near real-time, enabling stakeholders to respond promptly to unexpected variations in energy use, raw material consumption, or transportation routes.

4.3 Results

In collaboration with Mirka, we tested the proposed ALCA framework on a single process in the manufacturing process and on multiple processes once the product is finished. The framework is adaptable to other products as we have a defined standard way of storing the data going into an LCA. For the single process, we dynamically updated the model with different values for the measured electricity consumption, and visualized the results using a dashboard in Databricks. For the batch process, we aggregated results for one product from all processes in a gate-to-gate approach for 1000 meters of final product.

By adopting an automated approach to LCA, we achieve a higher level of automation while reducing the risk of manual errors. Moreover, this method promotes reusability and scalability across different products and processes by using a standardized data structure. In the future, it could also be extended into a simulation tool to explore strategies for minimizing emissions.

5 Conclusions

This study demonstrates a structured, scalable, and automated way to calculating LCA. The proposed framework handles both real-time visualizations of emissions from a single process and a batch calculation once a product is finished. The implementation was successful for the tested product, both for a single process and multiple processes.

This study reaches the same conclusion as previous research, identifying data mapping as a primary challenge in automated LCA. The current implementation maps process flows to their corresponding entries in the LCI database in OpenLCA using flow names. While functional, this approach introduces potential difficulties, as naming conventions may vary across datasets. A more robust solution would involve mapping flows using unique identifiers, such as Chemical Abstracts Service (CAS) numbers. However, this would require an enriched LCI database containing CAS numbers, as well as ensuring that the company's internal databases also include CAS information. Integrating such identifiers would improve the accuracy and consistency of automated LCA calculations by minimizing discrepancies in flow matching.

Overall, the proposed framework successfully enables automated LCA calculations, demonstrating its applicability for both real-time emissions visualization and batch-level assessments. While some challenges remain, particularly in data mapping, the implementation proves effective for the tested product and provides a foundation for further refinement and scalability.

5.1 Limitations

The ALCA framework demonstrated scalability by being tested on multiple single processes. However, it was only applied to one aggregated process. Potential challenges, such as long calculation times, may arise when calculating sustainability metrics across multiple processes with extensive data points. While the framework enables near real-time LCA calculations, actual real-time processing depends on multiple factors, including data transfer speeds, computational resources, and software limitations. The capability of the framework should be further evaluated to determine the extent to which LCA calculations can be performed in real-time.

LCA databases are typically large, which can compromise performance in LCA software. Optimizing database performance by limiting the dataset to only the necessary flows could be an area for improvement.

Future research could explore alternative tools beyond OpenLCA. However, as of this writing, the availability of open-source LCA tools with API functionality is limited. While commercial alternatives exist, they may introduce limitations in terms of flexibility and accessibility.

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Mikko Haikonen*, Hannu Toivonen, and Jerker Björkqvist*

Stress test evaluation of classifiers for audio based bearing diagnostics in HVAC machines

Abstract: Condition based monitoring aims to measure the situation of industrial equipment or processes. This is important for detecting equipment changes or damages. Servicing mechanical devices has traditionally been relying heavily on aural observations. Accurate audio diagnostics require profound understanding and experience. Such skills are not always available on site, especially at remote locations. Therefore automated or assisted diagnostics are very interesting topics in predictive maintenance. Automating the diagnostics may involve using machine learning classifiers. Classifiers are trained using finite training sets. Trained classifiers are then expected to diagnose situations in varying operating conditions. If the classifier is being overfit, it would not perform well in production use. In this work we investigated ways to stress test the audio classifiers by using compression techniques to degrade audio quality for evaluating robustness of trained audio classifiers. We found a practical procedure to provide an additional measure to prevent selecting an overfitted classifier.

Keywords: Diagnostics, Machine learning, Bearing monitoring, Audio classification, HVAC maintenance, compression

*Corresponding Author: Mikko Haikonen: Solita Oy, E-mail: mikko.haikonen@solita.fi

Hannu Toivonen: Åbo Akademi University, E-mail: hannu.toivonen@abo.fi

*Corresponding Author: Jerker Björkqvist: Åbo Akademi University, E-mail: jerker.bjorkqvist@abo.fi

1 Background

Condition based monitoring consists essentially of measurements and diagnostics of industrial processes. It is appealing to be able to monitor an industrial process continuously for 24 hours a day seven days a week. Occasionally it would be feasible to store audio measurement data for later processing and analysis. Data storage, however, has costs involved. These costs increase with the amount of data stored. Therefore it is desirable to be able to reduce the storage need by compressing the measured audio data.

At the same time we need to maintain the quality of diagnostics. That means keeping the classification accuracy as high as possible.

We can compress the data in order to reduce its size. If we use a lossy compression algorithm we will lose information. If the lossy data are then applied to perform classification we would like to know how the compression affects the classification results.

When applying machine learning classifiers in condition based monitoring there are two practical problems. The first one is the overfitting of classifiers. That may cause problems whenever the situation at the monitored process changes after training data have been collected and the classifier has been trained. The second problem is the cost of audio data storage. Data compression is one of the ways to decrease data storage costs. However, it is not always clear how much information we can afford to lose in order to maintain an acceptable classification performance.

2 Objectives

The objective of our study was to evaluate classifiers in their capacity to detect the relationship between the selected audio features and bearing changes. Audio samples from HVAC (heating, ventilation, and air conditioning) system were used for classification experiments. We refer to individual audio recordings as samples. The main focus in the evaluation was to prevent overfitting. The ability to correctly classify audio signals measured before and after overhaul was our primary objective. Attention was also paid to the computational cost of the classifiers. Our main goal was to provide additional sanity check mechanisms to avoid selecting a classifier which is overfitted. For this we examined how lossy compression of input data affects the classification performance. We also used additional test samples recorded at a number of rotational speeds of the system under test. This is how we estimated the reliability of k-fold cross validation results.

To summarize, we examine the following questions in this study:

- How does the audio quality affect the classification?

- What would be the appropriate level of audio compression in classification application?
- Which combinations of features and classifiers should be selected?

3 Methods

We used audio samples collected from an HVAC system before and after overhaul. In the overhaul one of the two drive and fan units was replaced with a new one. Audio signals from air- and contact microphones were recorded. To avoid excessive computations the amount of data was reduced by random sampling of training and testing audio files. Our classification task was to determine for each individual audio sample whether it was recorded before or after the overhaul.

In our example we assigned each testing audio sample a label "before" or "after" based on whether it was recorded before or after the drive unit change. Those labels can be referred to as ground truth. In other words they describe the situation from which the data is being collected. That situation often reflects a property of a system under test. That property may be e.g. whether the system being healthy or faulty. Those kinds of labels are subjective, and therefore we wanted to use a label that is objective, such as whether the sample originates from before or after the overhaul.

In our study we did make use of the information loss that lossy speech encoding causes. We stress tested the trained classifiers by classifying test data which were weakened by applying a lossy data compression at different quality levels. The data were being compressed before computing features for that test sample.

In this way we learned how the lossy compression affected the classification results for different classifiers and feature sets.

3.1 Audio features

A feature can be thought as a statistic or key performance indicator (KPI) that represents some essential property of an audio sample. Classifiers were trained using those features for training. There was one trained classifier per each classifier type and feature set.

In audio related classification tasks it is fairly typical to resort to well known sets of audio features that have been reported in the other studies. At high level, the features can be grouped under e.g. temporal, spec-

tral, cepstral and chroma feature spaces. Those features may include indicators like energy, zero-crossing rate, (spectral) centroid, entropy, crest factor, etc. [1]. The benefit of using those well known features is that they are known to capture some important properties of audio samples.

While those well-established features provide rich and interesting information about the audio and its source, they also have some downsides. If the model uses a large mixture of those statistics weighted and selected by possibly complicated rules, it would be a challenge to find a link between the classification results and physical realities of the system under test. In addition, it may also be necessary to repeat some of the feature-engineering if and when the system under test changes.

The audio classification features we selected attempt to reduce the need for additional feature engineering if the detection task changes. We used a feature space that allows linking the classification results back to the physical process. Therefore we used features like spectrum (DFT), autocorrelation (ACF) and partial autocorrelation (PACF). A particular benefit of ACF and PACF features is their close link to data generating process characteristics [2]. Autocorrelation feature can also bring insights into summative- and modulation effects [3]. Both autocorrelation and partial autocorrelation are also closely linked to linear predictive coding used in human speech processing [4].

The only hyper parameter of our feature sets is the number N of features being used. In autocorrelation and partial autocorrelation case, it is the maximum lag for which the coefficients are being used. In FFT case it stands for the number of frequency bins that is used. We used the empirically selected value $N=64$. It provided enough reach to the low frequencies for the autocorrelation type of features, while providing reasonable frequency resolution for FFT features. Our attempt was to keep N as low as reasonably possible, because unnecessarily high values of N would be a form of overfit which we wanted to avoid. We kept the value N constant to keep managing and analysing results relatively simple.

One trade-off that N involves is the handling of the first (lag 0) autocorrelation coefficient. It always equals 1 for lag value zero. We kept that unnecessary value in feature sets, despite the fact that it caused zero variance for that feature. The reason for including this (unnecessary) value is that in otherwise, omitting lag 0 and taking including an additional lag value from higher lags, would have given different frequency information for ACF and PACF feature sets. That difference could in some unlikely cases cause differences in performance of

classifiers if the value N is relatively low and the system dynamics have not attenuated sufficiently from PACF responses at the lag $N+1$.

By this feature selection we also aimed to avoid having two-dimensional feature sets for each audio sample. Keeping the features in one dimension reduces significantly the feature-engineering work and the need of selecting additional hyper parameters for the audio processing purposes. Restricting ourselves to one dimensional feature vectors eliminated the need to split the input audio into time slices or frames, eliminating the selection of frame length parameter and possible processing window types.

We could say that the feature selection we have done is positioned somewhere between system identification and machine learning [5].

Since analysis of audio samples and speech analysis have many similarities it is very natural to use speech compression as a vehicle for stress testing the classifiers and consider audio samples as "machine speech".

3.2 Experiment setup

In this study we used an affordable and compact Zoom H6 audio recorder. As microphones we used the recorder's air microphones and an external Schertler Unidyn P48 active contact microphone. The audio was collected at 44100 samples per second and stored with 16 bit resolution. The sampling rate and resolution were kept moderate in order to avoid excessive storage and computations.

3.3 System under test

The HVAC machine fans and mechanics are enclosed inside steel chassis with a removable top lid. There are two blower units inside the chassis. The HVAC machine was Enervent LTR-6. It has a 1210 mm wide, 670 mm high and 658 mm deep sheet metal chassis. The removable lid of the chassis was considered most suitable surface to mount the contact microphones on. The lid is 1210 by 658 mm in size. For measurement purposes, adhesive tape was attached, on which it was easy to mark the positions. Positions were arranged into rectangular grid of 66 locations. The grid consisted of six parallel rows, 100 mm apart, each containing 11 marks 100 mm apart. Markings of measurement positions were used in order to record corresponding locations for before and after scenario. For mounting the microphone to this lid, we

used the slightly adhesive putty that comes with the microphone. In retrospect, it would have been better to use standard length strips of two-sided adhesive tape, since the putty gradually wears out and the way microphone is attached to surface changes within the measurement batch. The adhesive putty was replaced for the separate batches.

According to human judgement most of the excess noise disappeared after the blower unit replacement. The unit has not been dismantled for mechanic inspection, but is kept in case there would be need to take any mechanical control measurements. We attempted not to make judgement of the blower condition before the overhaul. The only fact we know is that it was replaced.

We can not state anything about the relative condition of the second blower unit. That unit was not changed. Whatever our subjective judgement of the condition of any of those two units, we are not able to quantify them with measurements.

3.4 Classifier selection

We selected models that have different properties in order to understand how sensitive different type of models are to audio quality changes. Recursive partition (RPART) model was selected since it is very easy to interpret. Vector quantization is used in speech applications as mapping of audio features into code words [4] and as similarity metric in song identification [6] and therefore we used learning vector quantizer (LVQ) as model candidate.

For classification we used random forest, support vector machines (SVM), learning vector quantization and decision tree. We used relatively simple models to maintain the link between results and a physical process. That link is useful when the classification results are taken into operational use. Support vector machine has good generalization performance and is tested to perform well against the most popular classifiers [7] and is being reported being used in vibration analysis applications [8].

3.5 Model validation

The process of training and cross-validating classifiers was used as tool to understand how well the selected feature space reflects the mechanics and the class of samples. Our stress test complemented the results from traditional cross validation results.

Samples are divided into three sets: training set, test set and validation set. The training set is used for model training and the validation set is used to guide the model training procedure. We used 60% of the training set for model training and 40% for validation. Models were trained using the R language package `caret` [9]. The `caret` package offers a common interface for model training and testing.

Traditional cross validation methods including K-fold [10] cross validation were used [11]. We used 5 folds that were repeated 15 times. Our key idea was to extend e.g. K-fold cross validation by stress testing the classifiers. In stress testing the trained classifiers are stressed by testing them with samples of varying audio quality. For each classifier and validation sample, we used several levels of audio quality to examine how the prediction accuracy reacts to this stress. The purpose of the stress test was to examine how sensitive the classifiers were to changes in input data. From this experiment, we obtained a stress profile for each classifier and each type of audio feature. We used these stress profiles to find the best combination of classifier and feature set for the task at hand.

Since analysis of audio samples and speech analysis share many similarities it is natural to use speech compression as a vehicle for stress testing the classifiers and consider audio samples as "machine speech".

4 Classifier stress testing

Various strategies are used in testing classifier performance. In addition to basic cross validation there are several noise injection strategies to emulate real life situations, where the operating conditions or the process under examination changes. In speech recognition tasks various ambient noises are added to input signals [12].

Another metric we use in analyzing the classifier performance is a compression metric. Those compression metrics can be considered either features or metrics.

4.1 Classification model performance metrics

In order to compare the relative performances of classifiers we need evaluation metrics. We decided to use balanced accuracy for cross validation tests for two reasons. It is a fairly simple metrics that can be calculated

from confusion matrix in different test scenarios. Another reason is that we had some class imbalance in our testing and training sets. Balanced accuracy is the arithmetic mean of sensitivity and specificity metrics. Sensitivity is the proportion of positive cases being classified as positive. Specificity is the proportion of negative subjects being classified as being negative [13]. This means that if 95 percents of subjects would actually be positive, would it be possible to reach high accuracy by classifying all the cases as positive. Using balanced accuracy would give a penalty of doing that. In our case the subject corresponds to individual audio recording sample.

The imbalance in our case stems from the fact that in the first measurements we only had two sets of measurements at the same rotational speed (RPM), giving us good balance in class representation. However, we later decided to record additional samples to see how changing the rotational speed or fan unit affects the classification performance. Therefore we have many times more samples from the "after" scenario than we have from the "before" scenario. Therefore we needed to select a metric that addresses that class imbalance problem we have in our data.

4.2 Stress test procedure and metrics

Ideas of using compression metrics are used in song identification. There Normalized Compression Distance (NCD) is used to measure similarity between two audio samples [6]. We applied this idea in a simplified form by only compressing the samples and using the final file size relative to the `speex` [14] encoded (`speexenc`) file size to estimate the information that is available in the `speex`-encoded files. This measure was then used as a proxy for the information. We used this measure to interpret our classifier stress test results. It is worth noting that this procedure was applied to the encoded audio which was used as input in the classifier testing but not training phase. It means that we bypassed the feature generating in classifier training and therefore the training feature engineering does not affect the measure. In other words, that does not measure how much information the features extract from input data. We wanted the final classification results to show that.

The classifiers were trained only by using the original audio samples (WAV). Classifier training and cross validation used only these original audio data. Then the idea was to simulate the unwanted but evident changes in system under test, the operating conditions,

changes in audio recordings or ambient interferences. Those changes were simulated by gradually decreasing the quality of audio. We thought that this decreasing would in some way be application relevant and not just adding some noise to the input data. Therefore we used "speex" audio encoding to perform the task. The audio encoder's purpose is to reduce the amount of data while keeping the audio quality sufficiently good. It compresses the audio according to the target audio quality level. That level is naturally also reflected in the resulting file size. Since using the encoded audio in the classification system is unnecessarily complicated, we decoded (speexdec) the encoded audio back to WAV format keeping track of the quality levels for each file. The resulting WAV files are of equal size regardless of encoding quality, but the actual audio quality is different.

To measure the proxy for information content in the test files we used the standard gzip algorithm [6] so that every encoding quality and every sample file can be estimated in terms of its information content. That gives us a way to estimate how consistent the classification results are in this stress test. The classifier clearly can not create information that does not exist in the input. Therefore we can expect that with less information the performance of the classifier will degrade.

We run the training procedure of classifiers using the original audio. Also the cross validation of the classifiers is done using original audio samples. Those results are stored. Then we precomputed the speex encodings of all test audio samples at every quality level from 0, corresponding to the worst quality, to 10, corresponding to best quality. All the files were then decoded back (using lossy process) to WAV files which were used for generating the features for stress testing. Then for all the encoded files the gzip was run. Finally we calculated the original sizes of encoded audio files and the gzip compressed the files. By simple division operation we computed compressing ratio per file. In figure 4 we can see how the audio information decreased when speex encoding quality decreases.

The trajectories seen in figure 4 show the compression ratio per each subclass of the input audio. Subclasses that begin with "ARPM" stand for "after" case, and are at different RPMs, with "1" corresponding to the lowest and "4" to the highest rotation speed. The subclass "FOLDER01" is the initial measurement of the "before" case and "FOLDER03" is the initial measurement of the "after" case. The additional subclass "SAW" refers to the audio that was recorded from a slightly bearing faulted industrial table saw. According to the

indicator, "SAW" has the highest information content. Human perception of audio recordings is in agreement with this indicator.

We conducted the stress tests in two severity levels. The first level follows the procedure described above and used audio samples collected at the same RPM. These results are seen in the figure 2. We call that stress test 1. Then we conducted a more demanding test where the test samples were selected randomly from "before" and "after" samples from original recordings and different RPMs that correspond to subclasses ARPM1, ARPM2, ARPM3 and ARPM4. We see the stress test results for RPM3 in figure 3.

To be sure that compression ratios are proportional to Shannon entropy of the speex encoded files a short C++ program [15] was slightly modified so that it takes the filename as argument and the entropies were generated for all the encoded files. In figure 5 we see that the Shannon entropies are quite well in proportion to the compression ratios. Therefore the compression ratios can be used as an information content metric. Using gzip is more practical than the custom C++ program which lacks installation procedures and documentation. In addition the gzip would be easier accessible to anybody wishing to use this method.

5 Discussion

We need to compare the image 2 and 3, and keep in mind that the information available to the classifier is at most relative to figure 4. First observation is that the plain ACF features are not withstanding the stress test 2 very well. The accuracies drop consistently from about 90% of balanced accuracy to less than 70%. It is also notable that the ACF results do not seem to reflect the available information very well. Where the information content decreases, the ACF feature performance stays almost constant across quality levels. We do not consider that a good indication. That is why we would avoid using the ACF features altogether. From figure 1 we see different results. Classical K-fold cross validation gives quite optimistic results.

With FFT features random forest performs well in stress test 1 but in stress test 2 the accuracy improves when available information decreases. That would lead us to reject random forest at least in FFT case. As a feature the partial autocorrelation performs most consistently. In comparison to the ACF it is logical, since the PACF theoretically reduces the dependencies with

lag value L and the smaller lags, thus making the feature space less correlated.

Simple decision tree RPART would be eliminated, since its performance improves some times at very poorest audio qualities while the available information decreases. We consider that as a warning sign. Candidates that remain are LVQ, and both SVM classifiers. According to these results it appears that linear SVM performs better than radial one. The choice between lvq and linear SVM is not trivial. The lvq produces stress test results that are more consistent with the audio information content seen in figure 4.

Selection of appropriate compression level can be done with help of Figure 3. Once we have a candidate feature set and classifier selected, we can determine the balanced accuracy level which is considered sufficient for the application. This is up to the requirements of the application. If our selection of classifier would be e.g. lvq using PACF feature set, it would appear that compression qualities between 5 and 10 (inclusive) would be possible.

In this case we would select the lvq classifier with PACF feature set and apply compression qualities from 5 to 10 depending on the exact data storage costs and how critical the classification accuracy would be in the application.

6 Conclusion

We have developed and experimented with two stress test methods for extending the classical classifier cross validation tests. The stress test 1 uses gradually degrading input audio as test material. In the results seen in figure 2 those profiles are useful in estimating how consistently given classifier works.

Stress test 2 seen in figure 3 is more difficult for classifiers since it uses test data from several rotation speeds and it is degraded in quality. It probably gives more realistic estimate regarding the performance we can expect from given classifiers and feature sets in real world application.

We consider the gradual and quantified scale of test information contents as a very useful tool. That tool allows us to make common measure comparisons between the classifiers and feature sets.

Ability to quantify and compare information content against classifier performance is not something a human has. That is where we consider this method outperforming or helping human perception. We would

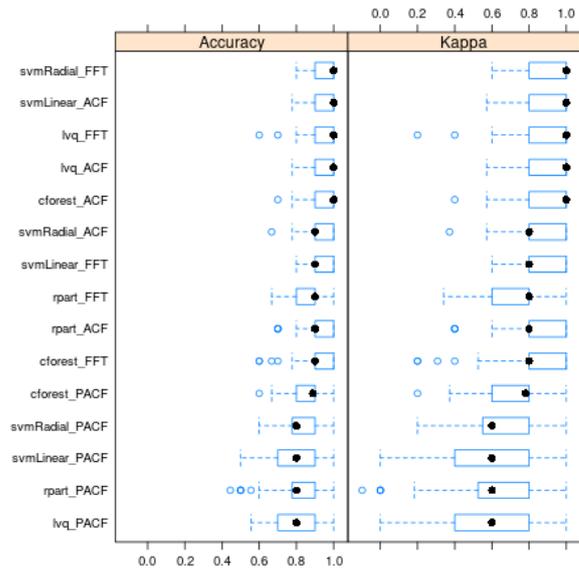


Fig. 1. Cross validation results

conclude the classifier evaluation by selecting LVQ as our primary and linear SVM classifier as our secondary choices. We would use PACF feature set to perform bearing change detection in production conditions.

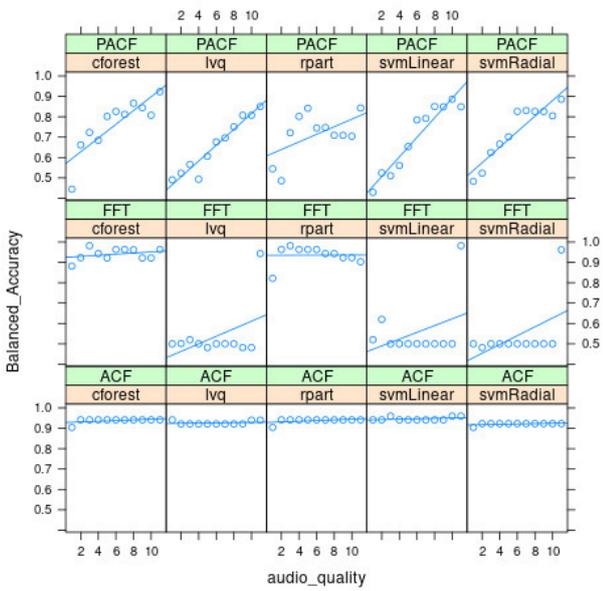


Fig. 2. Stress test 1: Impact of changing only audio quality to balanced accuracy. Every subplot represents combination of classifier and feature set. Within subplots the horizontal axis is audio quality indicator where 0 stands for poorest and 11 is original audio recording. Vertical axis is balanced accuracy.

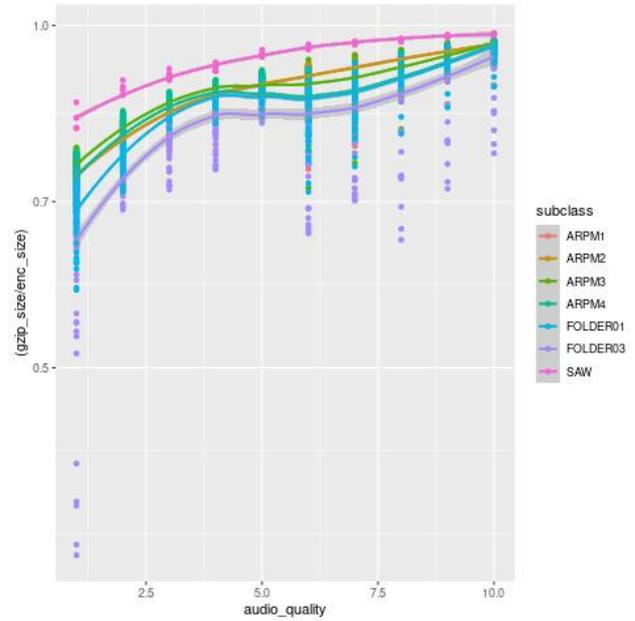


Fig. 4. Estimate of information in speex compressed audio samples. Vertical axis shows gzip compressed speex encoded file size divided by speex encoded file. The ratio shows approximation of information still available in speex encoded files. Value 1 would signify speex encoded file that does not compress at all using gzip compression, whereas low numbers close to 0 indicate files that are compressed a lot and do not initially carry much information

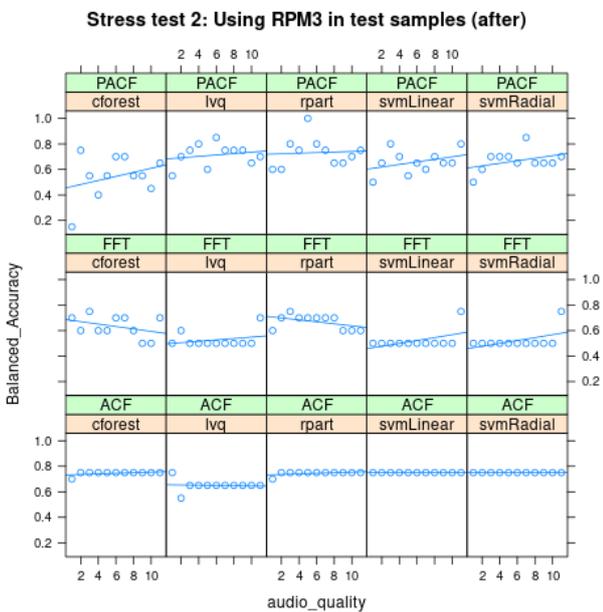


Fig. 3. Stress test 2: This test is more challenging than stress test 1. In this case the input data contained audio samples from different rotation speeds (RPM) and the audio quality is gradually reduced as in stress test 1. The ACF feature results are negatively affected for all classifiers.

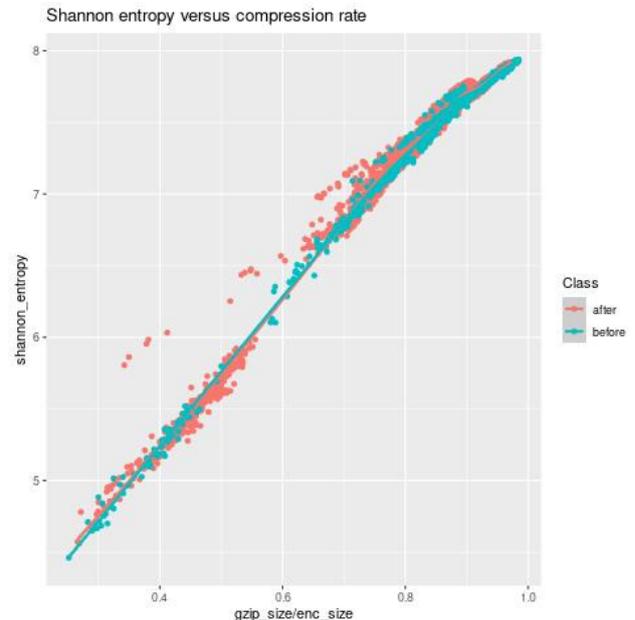


Fig. 5. Shannon entropy versus compression ratio of speex encoded files

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Antti Välimäki*, Outi Rask, David Hästbacka, Tero Hietanen, Manne Tervaskanto

Tekoälytutkimukseen liittyvän valmisteluhankkeen tuloksia

Tiivistelmä: AIKO-tekoälyhankkeen valmistelussa pidettiin kaksi työpajaa, joiden kaksi päätulosta esitellään tässä paperissa. Ensimmäiseksi käydään läpi osallistujille tehdyn kyselytutkimuksen sisältö, ja sen jälkeen esitellään työpajoissa pidettyjen yritysten esityksiä, joissa on kerrottu miten tekoälyä on sovellettu eri yrityksissä ja heidän asiakkaillansa.

Avainsanat: tekoäly, RAG, koneoppiminen, LLM, kielimalli

***Antti Välimäki:** Tampereen ammattikorkeakoulu, antti.valimaki@tuni.fi

Outi Rask: Tampereen ammattikorkeakoulu, outi.rask@tuni.fi

David Hästbacka: Tampereen yliopisto, david.hastbacka@tuni.fi

Tero Hietanen: Oulun ammattikorkeakoulu, tero.hietanen@oamk.fi

Manne Tervaskanto Oulun ammattikorkeakoulu, manne.tervaskanto@oamk.fi

1 Johdanto

Tampereen ammattikorkeakoulu (TAMK) haki rahoitusta tekoälyn ja automaatioon liittyvän hakemuksen valmisteluun Etelä-Savon ELY-keskukselta, joka myönsi rahoituksen vuoden 2024 alusta. Tämän pohjalta käynnistimme valmisteluhankkeen, jossa olivat mukana Oulun ja Tampereen ammattikorkeakoulut sekä Tampereen yliopisto. Tärkeimmät toimenpiteet olivat kahden työpajan järjestäminen uusimpien tekoälysovellusten ja -työkalujen esittelyyn, varsinaisen hakemuksen vaatimusten täyttämisen ja hakemuksen lähettäminen, joka sisälsi riittävän laajan ekosysteemin ja ulkoisen rahoituksen. Tässä paperissa esitellään sekä työpajojen yhteydessä tehtyjen kyselyjen tulokset että työpajojen esitysten keskeisimmät asiat.

2 Tutkimusasetelma

Tutkimuksen materiaali kerättiin yrityksiltä kolmessa eri vaiheessa seuraavasti:

- Yrityshaastattelut.** Tässä vaiheessa kontaktoitiin tekoälyn ja automaatiosuunnittelun parissa toimivia yrityksiä ja kerättiin tilannekuvaa heidän tämänhetkisistä toimenpiteistä asiassa. Keskusteluja käytiin yli 10 yrityksen kanssa tässä vaiheessa. Tätä tietoa hyödynnettiin sekä kyselytutkimuksen kysymysten asettelun että työpajojen sisältöjen suunnittelussa. Niitä tuloksia ei tässä artikkelissa käydä sen tarkemmin läpi.
- Työpajat:** Työpajoihin koottiin aiheesta kiinnostuneita yrityksiä keskustelemaan ja työstämään asiaa eteenpäin. Työpajoissa oli myös alustuspuheenvuoroja eri tyyppisistä automaatio- tai tekoälyalaan liittyvistä yrityksistä. Työpajoja järjestettiin 2 ja niihin osallistui yhteensä 56 osallistujaa 31 eri yrityksestä. Tulokset on esitelty tämän artikkelin luvussa 3.
- Kyselytutkimus:** Kyselyä jaettiin vielä laajemmalle osallistujakunnalle mm. välittämällä sitä suorilla yrityskontakteilla Tampereen ja Oulun alueella sekä LinkedInissa. Kysely lähetettiin myös työpajoihin ilmoittautuneille henkilöille sähköpostilla ennen työpajoja. Kyselyyn vastasi 21 eri yritystä, joista 3 oli mikroyrityksiä, 11 pk-yrityksiä ja 7 suuryrityksiä. Vastausten määrä ei ole riittävä kovinkaan kattavaan analyysiin, mutta suuntaviivoja sen ja muiden materiaalien pohjalta voidaan kyllä vedellä. Tulokset on esitelty tämän artikkelin luvussa 4.

3 Työpajojen tuloksia

Työpajat järjestettiin 25.4.2024 ja 6.6.2024 hybridimuotoisena, ja ne toteutettiin TAMKin seminaarihuoneessa sekä Teams-työkalulla. Työpajoissa oli pitämässä esityksiä kuusi eri tekoälyä

soveltavaa yritystä, joiden esitysten pohjalta saatiin hyvä kuva tekoälyn tilanteesta eri yrityksissä.

Tekoäly on yhä tärkeämmässä roolissa teollisuuden automaatiassa. Esityksissä korostettiin, että tekoälyä voidaan hyödyntää monin eri tavoin tehtaiden prosessien optimoinnissa ja tuotannon tehostamisessa.

Tekoälyä sovelletaan yrityksissä usein joko koneoppimis- tai generatiivisen tekoälyn työkaluilla ja menetelmillä. Erään esityksen mukaan tekoälysovelluksista tehdään noin 70 % koneoppimissovelluksina ja loput generatiivisina tekoälysovelluksina, mutta nämä suhteet ovat hyvin yritys- ja toimittajakohtaisia. Toimittajilla voi olla käytössä valmiita työkaluja sovellusten nopeampaan kehittämiseen tai toisena vaihtoehtona voidaan räätälöidä yksityiskohtaisempi sovellus, jos valmiiden työkalujen ominaisuudet eivät riitä.

Esimerkiksi koneoppimismallit voivat opastaa operaattoreita tekemään parempia päätöksiä, mikä parantaa tuotteen saantoa ja tuottoa. Esimerkkinä esiteltiin tapaus, jossa tehostettiin kalanrehun valmistusta opastamalla operaattoreita ohjaamaan panosprosessia neuroverkko pohjaisen tekoälyn ehdottamien operointisuureiden avulla [1]. Oleellista on, että operaattori tekee lopulliset päätökset koneoppimissovelluksen ehdotusten tai oman asiantuntemuksensa pohjalta. Tässä esimerkissä lopputuloksena tuotteen saanto ja tuotto saatiin nostettua tasolle, joka vastasi kehitystyölle asetettuja vaatimuksia.

Koneoppiminen tarjoaa monia mahdollisuuksia teollisuuden eri osa-alueilla. Esityksissä esiteltiin eri tapoja tehdä tekoälysovelluksia sekä niiden toiminnallisuutta joko lähellä varsinaista PLC-sovellusta, pilviratkaisuna tai näiden välimuotona. Tavoitteena on luoda työkalut, joilla automaatiosuunnittelija voi itsenäisesti kehittää koneoppimissovelluksia.

Koneoppimisen sovelluskohteita ovat esimerkiksi laadunvarmistus, jossa halutaan parantaa tuotteen laatua ja vähentää virheitä. Muita kohteita ovat hukan vähentäminen optimoimalla prosesseja, jotta raaka-aineiden hukka minimoidaan. Robottien integroinnissa tehostetaan tuotantoprosesseja. Näiden lisäksi ennustavassa ylläpidossa ennakoitaan laitteiden huoltotarpeet ja vähennetään seisokkiaikoja.

Koneoppimissovelluksissa on tyypillisesti kolme pilaria: laboratorio-, asiakas- ja ground truth -pilarit (totuuden lähde). Laboratoriossa tekoälymalli luodaan ja koulutetaan asiakasdatalla, ja mallin parametreja optimoidaan parhaan tarkkuuden saavuttamiseksi.

Haasteena on, että laboratoriossa saavutettu sovellus ei aina täysin vastaa todellista tuotantoympäristöä. Asiakaspilarissa mallia käytetään ja sovelletaan tosielämän tarpeisiin ja ympäristöihin sekä kerätään palautetta siitä, miten hyvin mallin vastaukset vastaavat asiakkaiden tarpeita. Ground truth -pilarissa kerätään esimerkiksi oikeita vastauksia, joita käytetään mallin uudelleen koulutukseen, kun dataa kertyy lisää.

Generatiivista tekoälyä voidaan soveltaa esimerkiksi automaatiosuunnittelun tehostamiseen käyttämällä erilaisia kielimalleja, joiden avulla voidaan integroida ChatGPT:n kaltaisia työkaluja työskentelyn avuksi. Näillä työkaluilla suunnittelutyötä voidaan tehostaa esimerkiksi generoimalla alustavia ohjelmia sekä PLC-että käyttöliittymäsovelluksille, lisäämällä kommentteja nykyisiin sovelluksiin ja vastaamalla suunnittelijan kysymyksiin liittyen sovellusten tekoon.

Generatiivinen tekoäly tarjoaa myös uusia mahdollisuuksia erityisesti asiakaspalvelussa ja tuottavuuden parantamisessa. Sovelluskohteina voivat olla esimerkiksi asiakaspalvelu, jossa LLM-pohjaiset ratkaisut voivat vastata asiakkaiden kysymyksiin etukäteen tarkastetuilla vastauksilla, mikä vähentää hallusinoitio ongelmia. Sovellus voi auttaa myös liiketoimintamahdollisuuksien tunnistamisessa sekä dokumenttien käsittelyssä, jolloin tarkistetaan dokumentin kirjoitusmuotoa, käännetään teksti eri kielelle tai muut dokumenttien automaattiset käsittelyt.

Kielimalli eli LLM-työkaluilla on kuitenkin omat riskinsä, kuten hallusinoitio ongelmat. Tämän vuoksi on tärkeää rajoittaa vastauksia ja varmistaa niiden oikeellisuus. LLM-ratkaisuissa on yleistä toteuttaa sovellus Retrieval Augmented Generation (RAG) -tyyppisenä, jossa yhdistetään yrityksen oma dokumenttien tietokanta ja muut vastaavat tietolähteet sekä LLM-työkalun kyvyt.

Tekoälysovellusten kehittäminen kannattaa aloittaa pienistä sovelluksista, joissa takaisinmaksu on nopeampaa. Asiakas on keskeisessä roolissa, kun valitaan käyttötapaukset ja oikea tekniikka tavoitteen saavuttamiseksi. Sovellusten kehittämistyökalut valitaan tyypillisesti projektikohtaisesti, esimerkiksi Azuren, Google Cloudin, Amazonin tai Tableaun tarjonnasta tai yrityksen omista tekoäly-työkaluista.

Eräissä esityksissä korostettiin tekniikan kehittymisen nopeutta ja käytiin läpi erilaisia asiakasprojekteja. Esityksessä kuvattiin myös, miten työntekijöille on hyödyllistä käyttää esimerkiksi ChatGPT:tä ja Microsoftin Copilot-työkaluja henkilökohtaisella tasolla. Lisäksi esiteltiin yritykselle kehitettyjä työkaluja, joissa on hyödynnetty esimerkiksi Azurea, Googlea ja OpenAI:n välineitä. Yrityksen sisäisen

toiminnan tehostamisessa käytetään muun muassa SAP-, Salesforce- ja M-Files-dokumenttien hallintavälineitä, jotka sisältävät tekoälyominaisuuksia. Yritystasolla hyödynnetään myös RAG-pohjaisia ja koneoppimisovelluksia. Yrityksille voidaan lisäksi kehittää räätälöityjä AI-sovelluksia esimerkiksi prosessien optimointiin ja ennustamiseen. Tuotetasolla asiakkaille voidaan tarjota älykkäitä huoltopalveluja, jotka ennustavat asiakkaan prosessien toimintaa. Tuotekehityksessä voidaan luoda erilaisia asiakastuotteita, jotka sisältävät räätälöityjä tekoälysovelluksia.

4 Kyselytutkimuksen tulokset

Kyselytutkimukseen osallistui 21 henkilöä yhtä monesta yrityksestä. Yritykset edustivat sekä automaatiosuunnittelua tuottavaa yritystoimintaa että tekoälypalveluita yleisemmin tuottavaa liiketoimintaa. Näissä tuloksissa ei ole huomioitu muista tiedonkeruulähteistä (työpajat tai yrityskohtaiset haastattelut) kerättyjä tuloksia vaan keskitytään ainoastaan kyselytutkimuksen tuloksiin.

Kyselyssä kysyttiin seuraavia asioita:

1. Miten tällä hetkellä teidän yrityksessänne käytetään tekoälyä liiketoiminnassa?
2. Miten tällä hetkellä teidän yrityksessänne käytetään tekoälyä automaatiosuunnittelussa ja muissa suunnittelutehtävissä?
3. Mitä ja millaisia tekoälytuotteita tai – palveluita teillä tällä hetkellä on tuotevalikoimassanne?
4. Miten arvioisit tekoälyn hyödyntämisen muuttuvan /kehittyvän seuraavan 5 vuoden aikana mm. Tuotteiden, palveluiden ja suunnittelumenetelmien yhteydessä tai niiden kehittämisessä?
5. Millaisista tekoälyyn liittyvistä sovellutuksista voisi olla hyötyä yrityksenne sisäisessä toiminnassa

Vastauksista tehtiin kevyt sisällönanalyysi jaotteleamalla vastauksia isompiin teemakokonaisuuksiin seuraavasti: 1) suunnittelutehtävät, 2) dokumentointi, 3) data-analyysi, 4) kuvat ja piirroksset, 5) työskentelyprosessit, 6) myynti, markkinointi ja kirjanpito, 7) asiakastoimitukset ja 8) ongelmanratkaisu. Tulokset on esitetty näiden kategorioiden mukaisesti.

Tällä hetkellä kyselyyn vastanneissa yrityksissä tekoälyä sovelletaan yleisemmin liiketoiminnassa tai suunnittelutehtävissä seuraavasti (kysymykset 1 ja 2):

1. **Suunnittelutehtävät.** Päälimmäisenä tässä nousi esille ohjelmointitehtävät, joissa tekoälyä käytetään ohjelmoinnissa ja se apputyökaluina. Konkreettisenä ohjelmointikohteena mainittiin mm. PC-valvomoiden ohjelmointi ja konenäkösovellukset. Myös laadunvalvontaan liittyvät tehtävät mainittiin.
2. **Dokumentointi.** Jonkin verran tällä hetkellä tekoälyä hyödynnetään raportoinnissa ja dokumenttipohjien luonnissa. Lisäksi dokumenttien kääntämiseen käytetään tekoälyä. Jotkut tuottivat tekoälyn avulla myös suunnitteluohjeita suunnittelutyökaluihin.
3. **Data-analyysi.** Tekoälyä käytettiin jossain määrin tiedon analysointiin ja kategorisointiin sekä ennustemallien laadintaan. Nämä vastaukset nousivat esille liiketoimintakysymyksen (kysymys 1) yhteydessä, joten oletamme, että tämä ei liity suunnittelutehtävissä syntyvän datan vaan liiketoimintaprosesseista saatavan datan analysointiin.
4. **Kuvat ja piirroksset.** Kuvia tehtiin tällä hetkellä lähinnä kuvituskuviksi tekoälyn avulla myynnin ja markkinoinnin tarpeisiin.
5. **Työskentelyprosessit.** Sisäisen toiminnan tehostamiseen ja mm. Suunnitteluohjeistuksen laatimiseen tekoälyä sovelletaan tällä hetkellä.
6. **Myynti, markkinointi ja kirjanpito.** Myynnissä ja markkinoinnissa tekoälyä hyödynnettiin ehkä laajimmin tällä hetkellä. Mainittiin mm. sosiaalisen median postausten ja kuvituskuvien tekeminen konkreettisinä toimintoina.
7. **Asiakastoimitukset.** Asiakkaille tehdään tällä hetkellä jonkin verran jo tekoälyä soveltavia ratkaisuita. Vastauksista ei selviä mitä nämä asiakkaat tarkemmin ottaen ovat, joten arvoitukseksi jäi, tarkoitetaanko asiakkaalla tässä esimerkiksi automaatiosuunnittelua tekeviä toimijoita.
8. **Ongelmanratkaisu.** Tähän kategoriaan liittyviä sovelluksia ei noussut tuloksissa esille.

Käytössä olevia konkreettisia työkaluja kysyttäessä (kysymys 3) vastaus oli melko suppea. Suurimmalla osalla ei ollut käytössä mitään tiettyä työkalua ja muutamissa vastauksissa nousi esille yleisesti käytössä oleva generatiivisen AI:n työkalu Microsoft Copilot. Lisäksi mainittiin yleisemmin GenAI -työkalut.

Kysymyksessä 4 visioitiin, millaisissa tehtävissä tekoälysovellusten käytön arvellaan lisääntyvän seuraavan 5 vuoden aikana. Tässä on käytetty samaa jaottelua kuin aikaisemmassa kohdassa, jotta vastauksia on helpompi vertailla nykyhetken ja tulevaisuuden näkymien välillä.

1. **Suunnittelutehtävät.** Ohjelmoinnissa nähdään tekoälyn roolin kasvavan merkittävästi seuraavien vuosien aikana. Sitä arvellaan käytettävän enenemissä määrin ohjelmointikomponenttien luonnissa ja ylipäättään kaikessa ohjelmoinnissa ja niiden testauksessa. Oletetaan, että suunnittelutehtävissä yleisemminkin tekoäly tulee poistamaan manuaalista työtä. Arvellaan jopa, että AI saattaisi korvata yksinkertaisempaa logiikkaa.
2. **Dokumentointi.** Dokumentoinnissa selkeä lisäys tai muutos nykyhetken vastausten mukaan olisi se, että suunnitteluohjeistukset suunnittelutyökaluissa muuttuisivat entistä enemmän chat-avusteisiksi.
3. **Data-analyysi.** Tätä kohtaa ei yllätyksekseni erikseen mainittu näissä vastauksissa.
4. **Kuvat ja piirroset.** Tekoälyavusteisen piirustustuotannon lisääntyminen on vastausten mukaan odotettavissa. Näillä tarkoitetaan nimenomaan suunnitteludokumentaatioon liittyviä piirustuksia.
5. **Työskentelyprosessit.** Näihin liittyen odotetaan tekoälyn muuttavan ihmisten ajattelua sekä parantavan työhyvinvointia. Lisäksi suunnittelumenetelmien kehittämisessä yleisemmällä tasolla odotetaan tekoälyn tuovan muutosta tulevien lähivuosien aikana.
6. **Myynti, markkinointi ja kirjanpito.** Tässä kategoriassa erityisesti tarjouslaskentaan liittyvien sovellusten nähtiin tulevan toimintaan mukaan. Lisäksi kirjanpidon tehtävissä tekoälysovellusten odotetaan ottavan lähivuosina isompaa roolia.
7. **Asiakastoimitukset.** Näihin odotetaan merkittävää palvelutarjonnan lisääntymistä tulevina vuosina.
8. **Ongelmanratkaisu.** Ongelmanratkaisun apuvälineenä tekoälyä myös uskottiin tulevan mukaan lähivuosina.

Yleisesti 5 vuoden kuluessa uskotaan, että tekoälysovellusten lisääntyminen suunnittelualoilla

toimivien yritysten toiminnassa tulee olemaan eksponentiaalisesti kasvavaa. Yksinkertaisten ja toistuvien asioiden toteuttamiseen uskotaan tekoälystä olevan erityisesti hyötyä ja uusien toimialojen uskotaan liittyvän tekoälyä soveltavan toiminnan hyödyntäjien joukkoon. Muutosvistarintaa löytyy ja se on varmasti aiheellistakin pohdintaa monissa yrityksissä, mutta vastausten perusteella näytettäisiin kuitenkin uskovan, että nyt meneillä oleva muutos on vääjäämättä etenemässä ja tekoälyn soveltaminen työelämässä tulee lisääntymään joka tapauksessa.

Viimeinen teema (kysymys 5) johdatteli vastaajia pohtimaan asiaa enemmän siitä näkökulmasta, millaiset tekoälysovellukset auttaisivat juuri häntä itseään ja omaa yritystään sisäisessä toiminnassa.

1. **Suunnittelutehtävät.** Toiveissa ja tarpeissa nousi tässä kohdassa vahvasti esille ohjelmoinnin, koodin generoinnin ja ohjelmien testauksen apuvälineet. Tekoälyn toivotaan tulevan hyödyntämään ohjelmistosuunnittelua yleisemminkin.
2. **Dokumentointi.** Tekoälysovellusten toivotaan tuovan lisää hyötyä ja tehokkuutta myös raportointiin tulevaisuudessa. Lisäksi hyödylliseksi koetaan tekoälyn soveltaminen tiedonhaussa, yksinkertaisten dokumenttien luomisessa sekä dokumenttien tarkastuksissa ja laajempien dokumenttien yhteenvedojen tuottamisessa.
3. **Data-analyysi.** Yleisesti tekoälyn toivotaan tulevan avuksi datan analysoinnissa, ennusteiden laatimisessa datan pohjalta, datan kategorisoinnissa ja kuvantunnistukseen liittyvissä tehtävissä.
4. **Kuvat ja piirroset.** Kvanttunnistus mainittiinkin jo edellisessä kohdassa, mutta se sopisi yhtä hyvin myös tähän kohtaan. Lisäksi tekoälyn toivotaan tuovan apuja piirustusten tuotantoon ja niiden tarkistamiseen.
5. **Työskentelyprosessit.** Erityisen hyödylliseksi todettiin tekoälyyn pohjautuvat työkalut, joilla saadaan joko ajanhallintaa tehostettua tai sitten poistettua nyt manuaalisesti tehtävää työtä. Näin tekoälyn uskotaan tuovan lisää työhyvinvointia, kun resurssia vapautuu muihin suunnittelutehtäviin.
6. **Myynti, markkinointi ja kirjanpito.** Laajemmin tekoälysovellusten uskotaan tuovan helpotusta myyntiin ja markkinointiin liittyviin tehtäviin. Erityisesti insinööriyöhön liittyvissä

tehtävissä tässä osuudessa tekoälysovelluksia toivotaan tarjoustentekoprosessien automatisointiin.

7. **Asiakastoimitukset.** Näitä ei noussut tässä kysymyksen kohdalla esille. Se johtunee kysymyksen asettelusta (kysyttiin sisäiseen toimintaan liittyviä toimintoja).
8. **Ongelmanratkaisu.** Tähänkään liittyviä asioita ei noussut esille. Uskaltaisiko tästä vetää sellaisen hataran johtopäätöksen, että päättelyyn ja ongelmanratkaisuun liittyviä teemoja joko pidetään vielä liian vaikeina tekoälylle tai niin ihmismielelle mielekkäinä tehtävinä, että ne halutaan pitää ihmisten ratkaistavina jatkossakin? Siitäkin huolimatta, että se kuitenkin kysymyksen 4 kohdalla tätä asiaa hieman nostettiin esiin.

5 Tekoälyn mahdollisuudet automaatioissa

Tekoäly tarjoaa lukuisia keinoja kehittää automaatiota eri tasoilla. Se on noussut teollisuusautomaatioissa merkittävään rooliin jo nyt osana teollisuuden digitalisaatiota ja Industry 4.0 ylipäättään. Kehittynyt automaatio, data-analytiikka ja järjestelmien verkottuminen ovat mullistaneet tuotantoprosesseja, ja AI tarjoaa uusia keinoja tehostaa tätä muutosta. Lisäksi tekoälyn avulla voidaan parantaa tuotannon tehokkuutta, optimoida prosesseja, mukauttaa tuotteita yksilöllisiin tarpeisiin sekä vähentää operointikustannuksia. Toisaalta käyttöönotto näin laajassa ja nopeassa mittakaavassa on aiheuttanut myös haasteita. Tekoälyjärjestelmät voivat olla teknologisesti monimutkaisia, alan asiantuntijoista on pulaa ja organisaatioiden rakenteet eivät ole riittävän ketteriä, jotta ne pysyisivät tekoälyn leviämisen rivakassa tahdissa. [2]

Tärkeää on kuitenkin valita tehtävään soveltuvat työkalut ja menetelmät. Aina tekoälysovellus ei ole paras tapa ratkaista ongelma, vaan perinteisillä ohjelmistoilla päästään edelleen pitkälle. Koneoppimisen (ML) ja tekoälyn menetelmiä sovelletaan lähes jokaisella modernin teollisuuden osa-alueella datan analysointiin, toimintojen automatisointiin, prosessien optimointiin ja tapahtumien ennustamiseen entistä tehokkaammin. Itse asiassa tekoälyjärjestelmät voivat nykyään tehdä itsenäisiä päätöksiä esimerkiksi laitteiden kunnossapidon ajoituksesta tai materiaalien hankinnasta tehtaissa [3].

Tekoäly tarjoaa teollisuusautomaatiolle myös joukon laskennallisia menetelmiä, jotka matkivat inhimillistä

päätelyä ja oppimista: esimerkiksi sumea logiikka, neuroverkot ja geneettiset algoritmit tuovat automaatiojärjestelmiin ”pehmeän laskennan” älykkyyttä, jäljitellen ihmisen päätelyä ja sopeutumiskykyä [4].

Tyypillisiä tekoälyn sovelluskohteita teollisuusautomaatioissa ovat muun muassa ennakoiva huolto, toimitusketjun optimointi ja tuotannon personointi [2]. Erityisesti ennakoivassa huollossa hyödynnetään antureista kerättyä dataa ja koneoppivia algoritmeja, joiden avulla voidaan ennustaa laitteiden vikaantumista jo ennen varsinaista rikkoutumista [5]. Tällöin huoltotoimenpiteet voidaan ajoittaa oikea-aikaisesti, mikä vähentää suunnittelemattomia seisokkeja ja parantaa järjestelmän kokonaissuorituskykyä.

Tekoälyn roolin odotetaan kasvavan edelleen automaatiotekniikassa tulevana vuosina. Nousevia teknologioita ovat esimerkiksi digitaaliset kaksoset, generaatiivinen tekoäly, entistä kehittyneemmät yhteistyörobotit sekä tekoälyn ja IoT:n syvempi yhdistäminen. Samoin korostuvat tekoälyjärjestelmien luotettavuus ja eettisyys [5]. Näiden innovaatioiden avulla pyritään kohti älykkäämpiä ja itseohjautuvampia tuotantojärjestelmiä: esimerkiksi digitaalisten kaksosten avulla voidaan luoda virtuaalisia malleja prosesseista, mikä mahdollistaa optimoinnin ja vikasietoisuuden testaamisen reaaliaikaisesti ennen toimenpiteiden tekemistä fyysisessä ympäristössä.

Mallit ovat kuitenkin monesti hyvin monimutkaisia ja yksi keskeinen haaste varmasti tulevaisuudessa onkin riittävän osaavien asiantuntijoiden löytäminen, jotka pystyisivät ymmärtämään tekoälyn tekemien mallien algoritmiikkaa. Mallien ymmärrettävyyden heikkeneminen taas tarkoittaa luottamuksen heikkenemistä joka jälleen hidastaa teknologian omaksumista teollisissa sovelluksissa. Luotettavuus on kuitenkin erittäin keskeinen asia teollisuuden automaatiotratkaisuissa. [2]

6 Yhteenveto ja jatkotoimenpiteet

Yhteenvetona voidaan todeta, että tekoälyn ja automaation yhdistäminen uudistaa teollisuutta perustavanlaatuisesti. Tulevaisuuden älykkäät tehdasjärjestelmät voivat saavuttaa ennennäkemättömän tason tehokkuudessa ja autonomiassa, mikäli nykyiset selitettävyyteen, luottamukseen, osaamiseen ja integraatioon liittyvät haasteet onnistutaan ratkaisemaan. Tämä edellyttää jatkuvaa tutkimusta, kehitystyötä ja moniammatillista yhteistyötä muun muassa automaatiotekniikan ja

tietotekniikan välillä, jotta tekoälyn koko potentiaali voidaan turvallisesti ja vastuullisesti valjastaa osaksi tulevaisuuden teollisuutta.

AIKO-tekoäly-valmisteluhanke päättyi vuoden 2024 kesäkuun lopulla, jonka jälkeen aloitettiin varsinaisten hakemusten teko Tampereen yliopiston, Oulun ja Tampereen ammattikorkeakoulujen toimesta. Jatkohankkeet ovat kunkin tutkimuslaitoksen omia, mutta niiden välillä pyritään luomaan hyvä koordinaatio, jotta voidaan hyödyntää eri osapuolten osaamista nyt ja tulevaisuudessa. Jatkohankkeet menivätkin läpi, jolloin tekoälyn tutkimus automaatiossa jatkuu vuosina 2025-2026.

Lähteet

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Timo Malm*, Taru Hakanen, Josepha Berger and Sami Karadeniz

Uncertain information related to situational awareness of mixed fleet and AMR - Safety perspective

Abstract: Situational awareness is a key to enable safe mixed fleet operations. Mixed fleets in internal logistics consist of Autonomous Mobile Robots (AMRs), Automated Guided Vehicles (AGVs), and manually operated mobile machines such as forklift trucks, and overhead cranes. In mixed fleet material handling operations uncertain information is the puzzling factor, which affects safety of the system. Uncertain information may be used sometimes, when reliable information is not available, for example due to limited Performance Level (PL), disturbances, environment, or poor visibility. The question here is, how uncertain information can be applied for safety purposes. Safety must not be jeopardized. Case specific risk assessment is needed to ensure safety. Safety measures based on uncertain information may be acceptable if they are limited to specific conditions, such as a defined time frame, reduced speed, controlled distance, adequate visibility, or a particular mode of operation.

Keywords: uncertainty, autonomous mobile machine, AGV, AMR, mixed fleet

***Corresponding Author: Timo Malm:** VTT, Finland,
E-mail: timo.malm@vtt.fi

Taru Hakanen: VTT, Finland,
E-mail: taru.hakanen@vtt.fi

Josepha Berger: VTT, Germany,
E-mail: josepha.berger@vtt.fi

1 Background

This study focuses on industrial mixed fleets, which operate in material handling tasks indoors in factories and warehouses. Mixed fleets consist of various mobile machines, such as AGVs, AMRs, manually driven forklift trucks, and overhead cranes. Thus, it is a combination of autonomous and manually controlled mobile machines. In addition, humans operate in the same space.

In order to ensure the safety of such mixed fleet systems, situational awareness is a central prerequisite for safe operations. By definition, Situational Awareness (SA) consists of the following elements or phases: “perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of

their status in near future” [1], [2]. In MixedFleet project, we complement the original definition by applying it on mixed fleets including both autonomous and manual systems as well as both M2H (Machine-to-Human) and M2M (Machine-to-Machine) perspectives [3].

We propose that situational awareness is one central component in ensuring the safety of mixed fleets. Autonomous systems use complex sensing, software, and communication solutions for perception, navigation and obstacle avoidance. In our study, we emphasize shared situational awareness (SA) so that SA is created both by humans (e.g. forklift truck drivers or factory employees) of machines and between machines in order to operate safely (Figure 1).

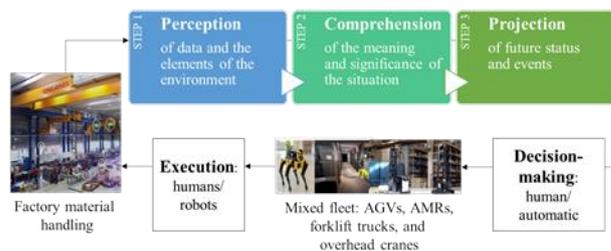


Figure 1 Mixed fleet situational awareness framework (Hakanen et al., 2024 [3]; based on Endsley, 1995 [1] and Bavle et al., 2023 [4]).

Our study pinpoints that uncertainty involved in all phases of mixed fleet situational awareness (perception, comprehension, and projection) as mixed fleet SA heavily relies on data and information. Inherently, the concept of information is closely connected with the concept of uncertainty. For instance, problem-solving always involves some information deficiency [5]. Zhu et al. address challenges in autonomous systems from the “unknowns” – the unexpected disturbances from component faults, environmental interference, and malicious attacks, as well as the inherent uncertainties in system inputs, model inaccuracies, and machine learning techniques [6]. However, this study does not aim to address all potential uncertainties related to mixed fleet operations. Instead, it focuses specifically on the uncertain information associated with situational awareness that is crucial for ensuring the safety of mixed fleets. Thus, mixed fleet SA framework provides the first framework guiding this study. Another framework used in this study is derived from

computational modelling and simulation domain defining and classifying the concept of uncertainty [8].

Situational awareness refers typically to on-board systems to the vicinity of the mobile machine and in peripheral protection systems to situational awareness of fleet control. Situational awareness can be also dynamic so that it depends on, for example, the phase of the process or the traffic density. Situational awareness can be related also to persons (M2H), which means that a person receives information and forms his own situational awareness notion. All these different situational awarenesses are related to safety.

Situational awareness can be based on

- reliable information gathered from sensors and safety PLCs having adequate (safety) Performance Level (PL) and applied according to device manual, or
- uncertain information based on information from sensors having inadequate PL, inadequate physical capability (e.g. detection range), information is not up to date, or the information may contain errors.

Performance Level (PL) means “discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions”. [8]. PL describes the safety ability and probability to operate in control system well, but it does not give any estimate of the performance related to sensor detection capability, calculation capability of a logic, or capability to resist difficult environments. These factors and their uncertainties need to be estimated separately according to the need in the application.

2 Aims and methodology

The aim and research question of this study is: How can uncertain situational awareness information be applied for safety purposes?

The method is here first to get information from interviews, group discussions, standards, and literature. Then the gathered ideas related to uncertainty have been discussed with researchers and experts from companies. Finally, the conclusions are made based on the material gathered.

3 Classification of uncertain information

There are many definitions for uncertainty depending on the domain it is applied [8]. This section presents some examples for classification of uncertain information.

As situational awareness of mixed fleets foremost rely on data and software, we use computer science related theories for studying uncertainty. In the

computational modelling and simulation domain, uncertainty is associated to lack of knowledge or incomplete information (Figure 2). Incomplete information can refer to vagueness, which characterizes information that is imprecisely defined, unclear or indistinct. Nonspecificity refers to possible alternatives in given situation. Dissonance refers to the existence of conflicting evidence. [8] Variability is defined as inherent variation associated with physical system or the environment under study. Error is a recognizable deficiency that is not due to lack of knowledge. Furthermore, all of the definitions presented in the model in the Figure 2. can be found also in specific mixed fleet cases.

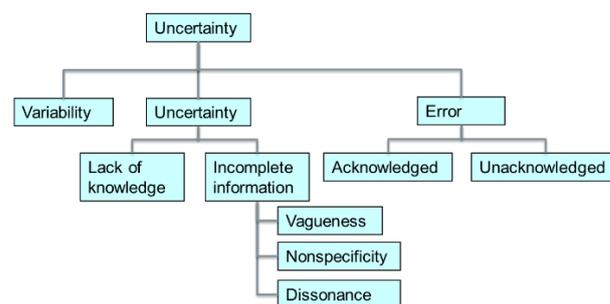


Figure 2. Uncertainty classification used in computational modelling and simulation. [8].

According to Andreas Kreuz, uncertain knowledge can be defined as “Any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system” [9]. Uncertainty can be distinguished from Aleatoric uncertainty, which is related to inherently random processes in nature, like human behaviour. The other type is Epistemic uncertainty, which is related to lack of knowledge [9]. In our case lack of knowledge (epistemic) is more common, because in most cases of the Table 1. safety is tried to be realized with reliable components, which have high reliability and low failure rate. However, in some cases uncertain phenomenon increases randomness (e.g. sunlight and lack of calibration) and aleatoric (random) uncertainty is present.

Uncertainty in situational awareness for a mobile machine refers to the lack of precise or complete information about the environment and the machine’s state within it. Uncertainty can be associated to the steps of situational awareness of mixed fleet as described in Figure 1. Here are the steps and related uncertainties [3], [4], [1]:

1. **Perception.** Inaccuracies or limitations in the sensors used to perceive the environment can lead to incomplete or erroneous data. Using state-of-the-art sensors, suitable sensors for various environments and conditions, regular calibration of sensors, and maintaining the system can help to ensure that the data remains accurate and reliable.

2. **Comprehension** of the significance and meaning of the situation. Machine needs to comprehend when it needs to slow down in a case of an approaching obstacle or human, and when an emergency stop needs take place. At all times, the machine needs to “know” its location in the map and the next control actions to be taken in autonomous navigation. Uncertainty can be related also to the next control action, which means that although the machine knows the situation, it does not know what to do, like how to bypass another machine. Changing environments can make it difficult for the machine to maintain an accurate and up-to-date understanding of its surroundings. Up-to-date digital terrain maps (layouts) are essential tools for fleet and mission control. Combining data from multiple sensors to form a coherent picture of the environment can introduce errors and inconsistencies.
3. **Projection** of future status and events. Delays in the transmission of data between sensors, processors, and actuators can lead to wrong, insufficient or outdated information being used for decision-making.
4. **Decision making and execution.** When machines comprehend that there is e.g. a human close by, it needs to take action that is slowing down or stopping. Safety zones around the machine need to be correctly defined, stopping time needs to be short enough, and all delays so short that the machine does not harm a human. Incorporating redundant systems and fault-tolerant designs can help to mitigate the impact of sensor failures or data inaccuracies. Machine Learning and AI can help in better interpreting sensor data, predicting environmental changes and improving decision-making processes. Human-Centered Design can help to reduce cognitive load and improve the overall situational awareness of operators.

In mixed fleet systems uncertainty can be categorized also according to input, logic and output.

- **uncertainty in input** information is related to object detection, localization, environment observations, situational awareness, status information, commands, and intentional and unintentional cyberattack/misuse,
- **uncertainty in logic** is related to models, calculation, missions, commands, and decision making,
- **uncertainty in output** is related to performing actions, like stopping performance, implementing specific speed and direction, intentional or unintentional wrong human actions.

4 Cases of uncertain information in mixed fleets

Uncertain information is applied sometimes in the industry in safety-related applications. Uncertainty is more common in outdoor environments, where rain, fog or snow may reduce visibility remarkably. The focus is here on indoor applications, but some examples are related to outdoors use.

Situational awareness is associated here to mixed fleets, including AGVs, AMRs, and manually operated machines, which all are capable to model their environment to avoid collisions. This is related to detection of objects, adequate separation distance, and concluding results with adequate safety logic.

Common reason for uncertain information is inadequate Performance Level (PL). PL means discrete level used to specify the ability of the safety-related parts of the control system to perform a safety function under foreseeable conditions. PL can be associated with the probability of failed safety function [10][8]. Typically, designers and integrators of the system try to choose equipment that fulfill the PL requirements.

The origin of uncertain information related to indoor applications can be caused by poor sensor perception due to e.g. high speed, object surface properties, too long distance, misalignment of sensor (temporary or permanent), disturbance caused by other objects, object dimensions in specific height (e.g. forklift truck), lying person below detection field, inclined ground surface, a hole in the floor, or an object approaching behind a corner. Other origins for uncertain information coming outside of the machine are for example disturbed communication, obsolete terrain map and incorrect position information. Uncertain information can also be related to the situational awareness of a person. The person does not have correct information and makes a hazardous decision due to misinterpretation of the situation.

Usually, the designer tries to keep the system safe by avoiding use of uncertain safety-related information. One can apply, for example, type examined, safety classified devices, which guarantee the performance on defined conditions. However, in many cases additional uncertain information can be used as complementing solution to improve safety.

Table 1. describes cases of uncertainties related to situational awareness and hazardous performance of mixed fleet. Table 1. is gathered from expert group discussions in VTT and with companies. In total, 10 persons participated the study.

Table 1. Uncertainties related to mixed fleet situational awareness and hazardous performance.

Uncertainty	Description
Uncertainty related to the load	The load height, length, mass, or center of gravity may be uncertain. The load may also be unstable, poorly tied or attached to another object. In addition, the pallet carrying the load can be broken.
Objects (other than load) with unusual dimensions or height can be difficult to detect.	Unusual dimensions of objects (narrow or specific height) can cause collisions, when applying only the usual sensors, like laser scanners.
The speeds and masses of the machines are different and this may cause uncertainty, when the machines are approaching each other	When different machines (AMR, forklift truck, and crane) are approaching each other, it is common that only the stopping performance of the machine itself is considered, but the situation should be considered in system level by taking into account the stopping performance of all related machines.
Too long distance for reliable detection	Long range sensors (low PL) can support detection of an object and reduce the speed of an AMR before actual safety sensors initiate stopping within adequate stopping distance.
Blind spots of sensors and difficult object detection due to unusual location, like above in the air or behind a corner	Objects are detected with sensors (low PL), which have 3D capabilities or detection field is directed to unusual direction. These sensors can detect objects, which are in unusual direction, height, or they have too narrow legs to be detected. Also, UWB sensor detects distance to another UWB sensor and limit the speed to avoid collision, e.g. in far distance or behind a corner.
Moving blind spot in the detection field.	Laser scanners are relatively large to be mounted on a mobile machine, especially beside hoisting equipment. Mounting can be difficult for specific models, and this may cause blind spots, which move along with the machine.

Uncertainty	Description
Lack of calibration and testing of sensors cause uncertainty in sensor outputs.	E.g. odometers need to be reset in specific locations to minimize errors related to slipping. Also, other sensors and systems need to be tested and calibrated regularly.
Errors and insufficient updates of terrain maps (of fleet controls) cause uncertainty of special locations. Terrain maps may have low PL.	Changes of machines' surroundings, like moved large objects or constructions, areas under construction, ramps, fire doors, narrow places, and crossings need to be put and updated as changes take place on the terrain map. Each area can have specific rules, like, reserved, require slow speed, avoid stopping or follow area access control commands.
Free routes during emergency situation (e.g. fire) may be blocked	Autonomous machines should not stop in front of fire doors or crossings. The fleet control is supervising the situations. However, objects, failures, or fleet management errors may cause stopping at a forbidden place.
Security issues cause uncertainty to the automated performance	Security issues can be related to poor passwords (no password, easy or written to easy place), cyberattack or mechanical sabotage.
Software compatibility problems	Issue is realized at update but detected only during use. For example, limit values may have changed.
Changing environment can make sensor detection uncertain	Since the focus is on indoor applications exposure to water (splashes, puddles, steam/fog) and extreme temperatures are quite rare. However, sunlight coming from window can disturb optical sensors as well as similar sensors from other vehicles and cause changes in lighting. Also, large reflective objects can disturb optical and radio sensors. High currents related to specific process phases can disturb nearby devices and systems. Broken floor (hole) can cause many kinds of problems related to sensors' field of view and driving performance.

Uncertainty	Description
Difference between different location systems in different machines brings uncertainty to location accuracy and safety	Different machines can have different location systems, like, SLAM, UWB, odometers, IMU, magnetic navigation and laser-guided navigation, which cause different accuracies for location information. The accuracy difference can be safety issue, since in some cases the accuracy can be inadequate, although usually there are no problems. The differences need to be considered on system level.
Uncertainty related to human actions, when driving manual machines	When driving trucks, do humans follow the rules related to speed limits and do they choose safe routes. The situational awareness of AMRs could be improved by adding manual machines to the terrain maps.
Malfunction of traffic lights, warning system, or personal supportive system reduce situational awareness of persons	Traffic control and warning systems have typically low PL. Broken traffic lights initiate often blinking of the yellow light and a person can detect the uncertain performance. ISO Technical report Safeguarding supportive system (ISO/TR 22053) shows some means for personal communication with other systems [11]. Personal communication is usually more vulnerable than continuous communication, since it is established when needed.

One general aspect is related to legislation and related changes. New Machine regulation (EU) 2023/1230 [7] describes autonomous mobile machinery and related basic requirements and it will be in force 20.1.2027. According to the new regulation the collision avoidance system is based on either a peripheral protection system or on-board devices intended to detect human or any other obstacle in its vicinity to avoid collisions. The peripheral protection system is typically related to fleet management, which is capable of controlling access into parts of the system to avoid collisions. Fleet management controls the situational awareness of the fleet. An on-board protection system forms a situational awareness area around the mobile machine to maintain safe distance to obstacles and humans.

Figure 3. shows some means to control uncertainty. Uncertain sensor information can be redundant, and the results can be compared. A terrain map can show places which require e.g. reduced speed, or no stopping is allowed or the area can be forbidden. Fleet control gives information related to the terrain map. Uncertainty can be caused by exceeded maintenance or updating intervals, which both should be supervised. Communication uncertainty can be related to disturbances, which cause delays or omission of messages. In some cases, the message can be changed intentionally (cyberattack) or unintentionally. The presented cases are general examples of how to deal with uncertain information.

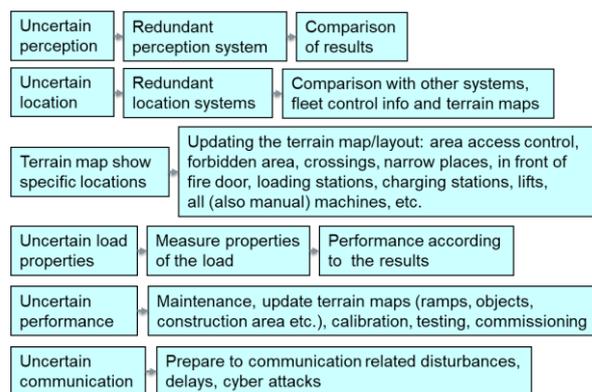


Figure 3. Uncertain information and examples of solutions for managing uncertainty.

5 Conclusions

As seen, there are many causes for uncertain information. In some cases, uncertain information may exist for a specific time, in a specific operation mode, for individual loads or in specific situations.

Usually the aim is that safety-related safety functions are based on reliable information, which have also adequate safety performance level (PL). However, one can find several cases, which are complex and not all needed reliable information is available.

For example, AMRs have typically laser scanners at about 20 cm height, but if the object is “flying” in the air and therefore it is not detectable at that particular height, because it is not touching the floor. The fork and load of a forklift truck can be at almost any height, and it is possible that the laser scanner would not see the object although it is very reliable. The laser scanners cannot see negative objects, i.e. holes in the floor or stairs downwards either.

Further, one AMR can stop within its detection range, but if two AMRs are moving towards each other at full speed they cannot stop within their sensor detection range, if there were no additional safety margin in the detection range.

Also, the load to be handled can cause uncertainties related to its weight, dimensions, stability, and rigidity. In addition, the load can be loose or attached. All these factors can cause collisions, falling of the load or AMR.

The examples in the previous paragraphs as well as those listed in Table 1 show that there are hazardous situations, which are difficult to detect with usual safety devices. Something additional is needed and it is common that the required detection capability differs from the usual safety devices. It may be difficult to find devices/system with a specific PL, but if the situation is rare, as described in the examples, the PL requirement might be lower. Usually, fleet control prevents collisions by giving the AMRs routes, which do not intersect with other routes, but typically, fleet control does not have any PL. The fleet control can also dynamically adjust speed, direction and separation distance to other objects according to the location information. However, some means to deal with uncertainty increase complexity which furthermore increases probability of errors, and the uncertainty remains. Anyway, an adequate level of safety can be achieved by increasing redundancy and accepting uncertain information in a controlled manner. Risk assessment is a suitable tool to estimate if the uncertain information is acceptable [12][11]. However, it is not feasible to make universal rules for applying uncertain information for safety-related applications, instead the situations need to be solved on case-by-case basis.

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Mats Friman*

Tuning of Control Loops with Valve Problems

Abstract: Control valve non-linearities may cause control loop oscillations. Usually, it is not possible to instantly replace a valve in operation just because it causes oscillations in the process, but with proper controller tuning we can minimize valve wear and reduce oscillation amplitudes, and sometimes even eliminate the oscillations. We discuss two major valve non-linearities, backlash and stick-slip, and how to tune the PID controller for such valves.

Keywords: backlash, stick-slip, oscillations, PID tuning

*Corresponding Author: Valmet Automation, E-mail: firstname.lastname@valmet.com

1 Introduction

Control valves play a crucial role in the process industry, regulating the flow of fluids, such as gases, liquids, and slurries. These valves are essential for maintaining the desired process conditions, such as pressure, temperature, and flow rate, ensuring the efficient and safe operation of industrial processes.

An industrial control valve package consists of a valve body, a pneumatic actuator, and a valve positioner. All these components consist of mechanical parts that are subject to wear and dirt (Kirmanen et al. 1997).

Control valves can encounter several problems that may affect their performance and reliability. Example problems include increased friction in valve body and actuator, pneumatic leakage in actuator and positioner, wear in mechanical parts, and design problems, most commonly improper sizing of valve or actuator.

Valve problems frequently cause oscillations in the PID control loop. Instant replacement of a faulty valve because of loop oscillations is usually not an option. Instead, we can re-tune the PID controller to minimize oscillations and reduce valve wear.

In this study we discuss how to decrease the oscillation amplitudes (in both process value (PV) and control output (CO)) to minimize impact of oscillations on the process. Moreover, increasing the period of oscillations

reduces valve wear. To our knowledge, PID tuning recommendations for faulty valves have not been previously reported. Still, we believe that special tuning recommendations for faulty valves are useful and that there is a great possibility to stabilize oscillating processes and improve quality and economic performance in the entire process industry.

2 Introductory Example

As an example, consider a simulated level control loop with some 1 % backlash in the control valve. We model the level using a first-order-plus-deadtime model (with gain $K = 80$, time constant: $T = 200$, dead time $L = 1$) and employ a PI controller (with ideal tuning: gain $K_p = 1.0$, integration time $T_i = 10$, tuned by SIMC rules, Grimholt and Skogestad, 2012). Simulations suggest that this loop oscillates with a period of 38 and PV oscillation amplitude 0.60, as illustrated in Figure 1 (blue lines).

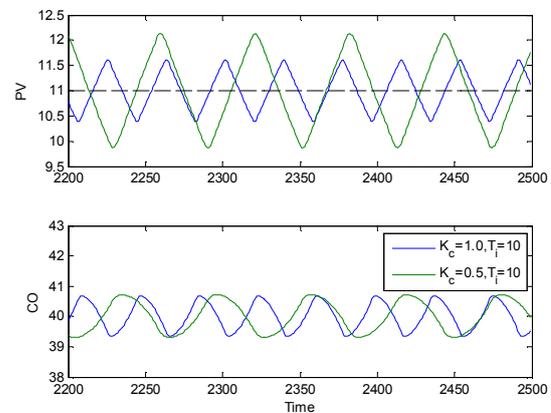


Figure 1. Example control loop oscillating because of backlash in valve. Original tuning in blue and detuned (gain 50% of original) loop in green.

At this point a natural question is: how should we tune the PI controller to reduce impact of oscillation generally on the process (to reduce PV amplitude), and to reduce valve wear (by increasing period of oscillation and decreasing amplitude of CO)? A surprising result, even to experienced control engineers, is that detuning controller gain by 50 % ($K_p = 1.0 \rightarrow 0.5$) is a bad option, as it *increases* the amplitude of PV oscillations, in this case by 88% (green trends in Figure 1). A tighter tuning ($K_p = 1.0 \rightarrow 1.5$) decreases the PV amplitude, but with a

cost of increased valve wear due to faster oscillations (not shown).

In this example case the loop will stabilize when we select a large enough integral time ($T_i=160$), which is very far from the ideal tuning recommendations ($T_i=10$).

3 Modeling Common Valve Non-Linearities

In this paper we will consider two valve non-linearities: stick-slip and backlash. Stick-slip is useful to model sticky valves with high friction. In that case, the positioner must increase actuator pressure extensively to move the valve. Stick-slip movement makes it impossible to position the valve properly. Valve stick-slip is also useful to model a control valve with an undersized actuator. On the other hand, valve problems where friction is not an issue are best modeled with simple backlash. A very common example is a worn-out link between the shaft and the body of a rotary valve. Such a case is best modeled using backlash.

To model non-ideal valve behavior, we consider two non-linearities: 1) backlash and 2) stick-slip. These non-linearities are illustrated in Figure 2 below.

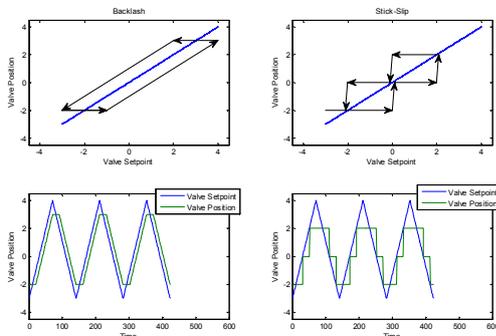


Figure 2. Illustration of backlash (left) and stick-slip motion(right).

Usually, the process dynamics of typical process industry controls are well modeled using simple linear transfer functions. However, control valves with pneumatic actuators don't show such an ideal behavior. For example, valve positioners typically have a hysteresis specification of 0.5 % and a dead-band specification (defined as how much valve setpoint can change before we can expect valve movement) of 0.2 % (Valmet Flow Control, 2024). Hence, PID tuning recommendations based on ideal linear transfer functions, are not necessarily optimal, not even for well-performing control valves.

4 Criteria for Oscillations

A fundamental question is: does backlash or stick-slip in the valve cause control loop oscillations?

For the stick-slip case the answer is quite straightforward: yes, the loop will oscillate with an amplitude and period that depends on the amount of stick-slip, the PID controller tuning parameters, and process dynamics.

For the backlash case, the situation depends on the PID controller tuning parameters and process dynamics: we may see oscillations in the loop, or we may get a stable loop. Hence, with proper tuning we can minimize oscillations, decrease control error, and reduce valve wear.

To predict limit cycle oscillations due to stick-slip or backlash in the valve, we use describing function analysis (Atherton, 1982). With describing function analysis, we get the amplification and phase angle of the valve, assuming sinusoidal inputs. This assumption means that the analysis is approximative, but it usually predicts oscillations quite well. For backlash, the describing function $N(A)$ depends on backlash d input and amplitude $A>d$ as (Johansson et al. 2012)

$$N(A) = a + bi, \text{ where} \quad \text{Eq. (1)}$$

$$a = \frac{1}{\pi} \left[\frac{\pi}{2} + \text{asin} \left(1 - \frac{2d}{A} \right) + 2 \left(1 - \frac{2d}{A} \right) \sqrt{\frac{d}{A} \left(1 - \frac{d}{A} \right)} \right]$$

$$b = -\frac{4d}{\pi A} \left(1 - \frac{d}{A} \right)$$

With stick-slip d , we have (with input amplitude $A>d$) as

$$N(A) = a + bi, \text{ where} \quad \text{Eq. (2)}$$

$$a = \frac{2d}{\pi A^2} \sqrt{4A^2 - 4d^2}$$

$$b = \frac{-4d^2}{\pi A^2}$$

For a known input amplitude A , the describing function N returns a complex value where $|N(A)| = (a^2+b^2)^{0.5}$ is the amplification and $\angle(N(A)) = \text{atan}(b/a)$ is the phase angle of the valve.

Assuming known transfer functions of process $G_P(s)$ and controller $G_{PI}(s)$, we can predict the existence and details of oscillations. To enter limit cycle oscillations, the following two criteria of the control loop must hold: 1) net amplification of process, controller, and valve equals unity, and 2) net phase angle of process,

controller, and valve is -180° . Mathematically this is expressed as

$$G_P(s)G_{PI}(s)N(A) = -1 \quad \text{Eq. (3)}$$

To investigate oscillations using Eq. (3), we plot $-1/(G_P(s)G_{PI}(s))$ vs. $N(A)$ (with $s=j\omega$, $\omega=2\pi/P$) in the complex plane and look for possible intersections of the curves. The intersection gives the oscillation amplitude A and frequency ω , as illustrated in Figure 3 below. With no intersection of the curves, we can assume a stable loop.

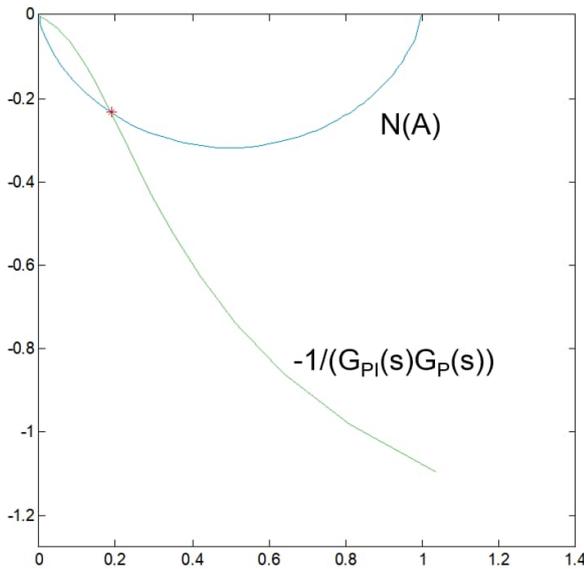


Figure 3. Intersection of backlash describing function $N(A)$ and $-1/(G_P(s)G_{PI}(s))$ predicts limit cycle oscillations.

5 Controller Tuning

To investigate impact of tuning on control performance for control loops with valve problems we simplify the analysis as follows

- We assume first-order-plus-deadtime process models.

$$G_P(s) = \frac{K \exp(-Ls)}{T_S s + 1} \quad \text{Eq. (4)}$$

- We assume that PI control is used and employ Skogestad IMC tuning with tuning parameter $T_{CL} = 1.5L$ (called nominal tuning)

$$G_{PI}(s) = \frac{K_c(T_i s + 1)}{T_i s} \quad \text{Eq. (5)}$$

- The amount of backlash/stick-slip d is not important to investigate, as it does not affect the existence of oscillations. Instead, oscillation amplitudes are proportional to the amount of backlash/stick-slip.

- Process gain is also irrelevant because nominal controller gain times process gain is an invariant with fixed tuning recommendations.

Without loss of generality, it is hence enough to investigate various process time constant / dead time ratios T/L to get a good overview of PI tuning impact on control performance. Here we chose two cases: 1) $T/L = 2$, which we named "Flow loop", and 2) $T/L=200$, named a "Level loop".

For each 4 cases (Flow & Level loops, backlash & stick-slip), we investigated various PI tuning parameters and used Eq. (1)-(5) to check the existence of oscillations and to calculate oscillation amplitudes and periods. To evaluate the goodness of tuning for oscillating loops, we calculated valve travel (control output amplitude / oscillation period) for each tuning setting.

Figure 4 below illustrates tuning impact on valve travel for the Flow loop with backlash case. This loop works well and remains stable with nominal tuning settings but will oscillate if integral time T_i is chosen too small, as illustrated by the red area in Figure 4.

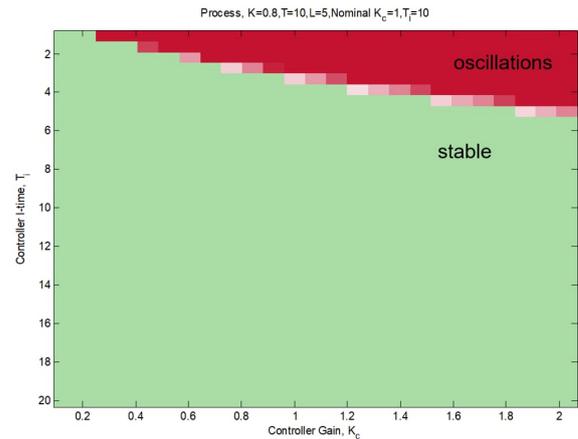


Figure 4. Tuning impact of Flow Loop with backlash case. Color indicates amount of valve travel (control output amplitude divided by oscillation period). This loop is stable with ideal tuning but if a too small T_i is selected, it starts oscillating.

Figure 5 illustrates the Level loop with a backlash case. Here, the loop is oscillating with nominal tuning settings, but we see that increasing T_i reduces valve travel (white color in Figure 5), and that the loop stabilizes with a large enough T_i (green color). Impact of controller gain is small.

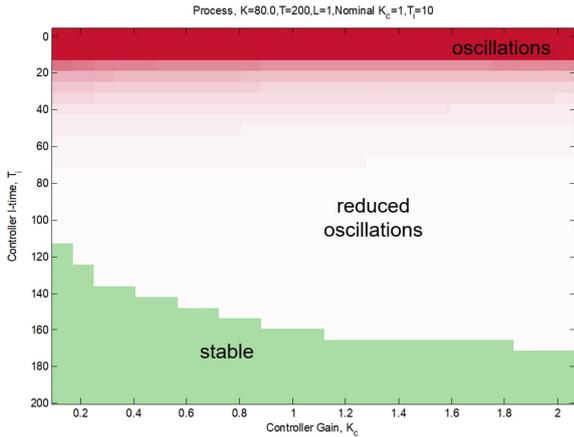


Figure 5. Tuning impact on Level loop with backlash. For this loop valve travel decreases clearly with increased T_i , and it is even possible to stabilize the loop. The impact of controller gain on oscillations is marginal.

For the backlash case we further investigated the impact of integral time T_i on oscillations. As illustrated in Figure 6, integral time must be large enough to avoid oscillations. A good rule of thumb is to have at least at the same level as time constant

$$T_i \geq T \quad \text{Eq. (6)}$$

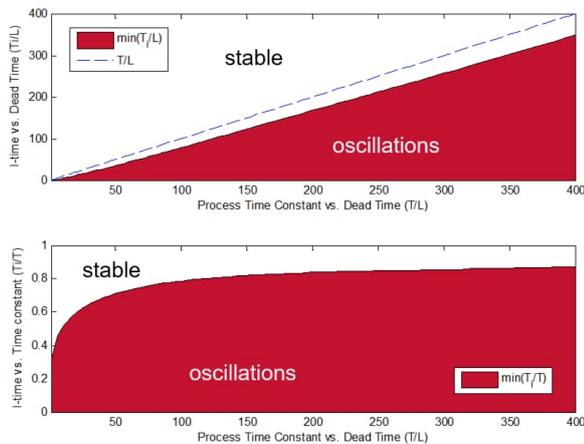


Figure 6. The selection of integral time is important to avoid oscillations for valves with backlash.

Figure 7 shows tuning impact for the Flow loop with stick-slip. Here it is impossible to stabilize the loop by tuning the controller, but we can reduce valve travel by selecting a smaller gain and a larger integral time. For the Level loop with stick-slip (not shown) the results are quite similar, except that the impact of controller integral time T_i is marginal.

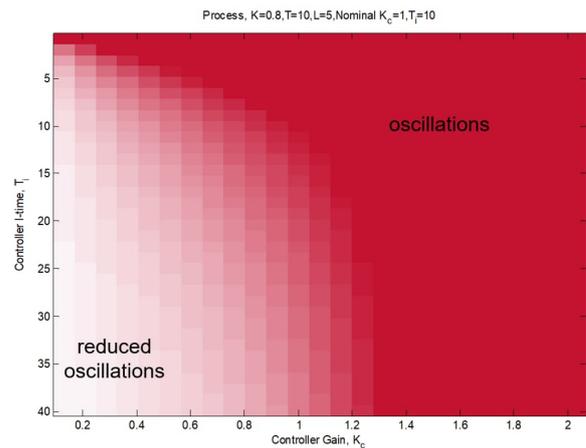


Figure 7. Tuning impact on the Flow loop with stick-slip. Here we can reduce valve travel by decreasing gain and increasing integral time.

6 Controller Tuning Potential and Targets

According to our experience, PID controller tuning usually means finding a good compromise between various performance and economic targets. With improved performance we mean assessments like average control error, variability, and oscillation significance. Cost variables are for example valve travel, valve wear and air consumption.

Typically, it is not possible to obtain improved performance and decreased costs at the same time. With tight aggressive tuning, we can commonly push control error down, with a cost of increased valve travel. On the contrary, selecting a modest tuning setting, we can reduce valve wear, usually with a cost of increased control error.

However, for loops oscillating due to valve problems, the good news is that we can usually expect both increased performance and reduced costs when tuning such loops. These relations are illustrated in Figure 8.

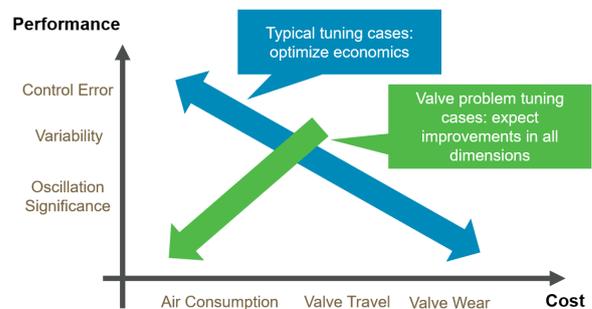


Figure 8. Overview of PID tuning targets.

7 Case Study

To test our idea of tuning loops with valve problems, we performed an industrial case study in a Finnish Pulp Mill. The plant uses PlantTriage (Valmet Automation, 2025) to continuously monitor and analyze 1500 control loops. To find loops that are oscillating due to valve problems, we used Problem Solver “Oscillating Loops” (illustrated in Figure 9) where the most interesting columns are Oscillation Significance (larger value, large influence of oscillations on process) and Osc-Valve (confidence in % that root cause of oscillations is valve). With PlantTriage, we identified around 10 loops, with a good possibility to improve control because of valves that were not performing optimally.

All these loops were classified as having backlash in the valve. Estimated backlash and process parameters (gain, time constant, dead time) were identified from trends (method not discussed in this paper) and new tuning recommendations were implemented on 5 level and 2 temperature control loops.

Loop	Description	Oscillation significance	Oscillating (%)	Osc-Valve (%)	Osc-Tuning (%)	Osc-Load (%)
15100014	Stabilizer Systems	22.91*	100*	100*	0	0
15100015	Preheat Temperature	22.91*	100*	100*	0	0
15100016	Condensate Drum	22.91*	100*	100*	0	0
15100017	Preheat Temperature	22.91*	100*	100*	0	0
15100018	Cont. Blowdown Drum	22.91*	100*	100*	0	0
15100019	Flash vapor to Compressor	13.82*	100*	100*	0	0
15100020	A18 Feed Preheat	8.797*	100*	100*	0	0
15100021	Clear solvent to Mfg	4.851*	100*	100*	0	0
15100022	HP Superheat to A	4.851*	100*	100*	0	0
15100023	HP Superheat to B	4.851*	100*	100*	0	0
15100024	Drum Outlet Temp	5.742*	100*	100*	0	0.001
15100025	Solvent to Stripper	4.851*	100*	100*	0	0.001
15100026	Superheater Outlet Temp	4.851*	100*	100*	0	0.001
15100027	HP Superheat Out B	5.1511*	80	0	0	0.01
15100028	Condensate Return	3.647*	60	0	0	0.01
15100029	Solter Feedwater C	5.829*	100*	100*	0	0
15100030	A18 Reboiler Steam Flow	16.581*	100*	30	0	0.001
15100031	Effluent PH	16.581*	100*	20	0	0.01

Figure 9. Example screenshot from Problem Solver “Oscillating Loops” of PlantTriage (loops are not from example case).

Figure 10 shows an example loop, where we see a clear improvement in loop performance.

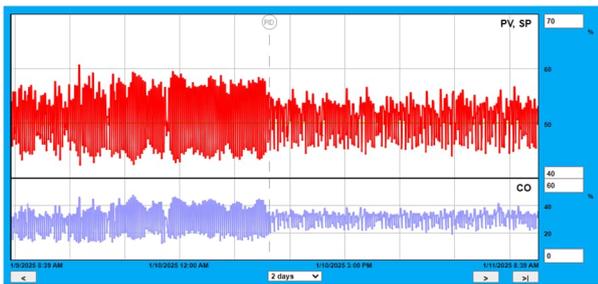


Figure 10. Example loop trends of a tuned control loop.

To estimate the impact of tuning changes, PlantTriage continuously calculates 80 assessments for each loop. Here we studied four PlantTriage assessments one week before, and one week after tuning changes: 1) Average Absolute Error, 2) Valve Travel, 3) Oscillation Significance, and 4) Variability, as shown in an example report in Figure 11 below.

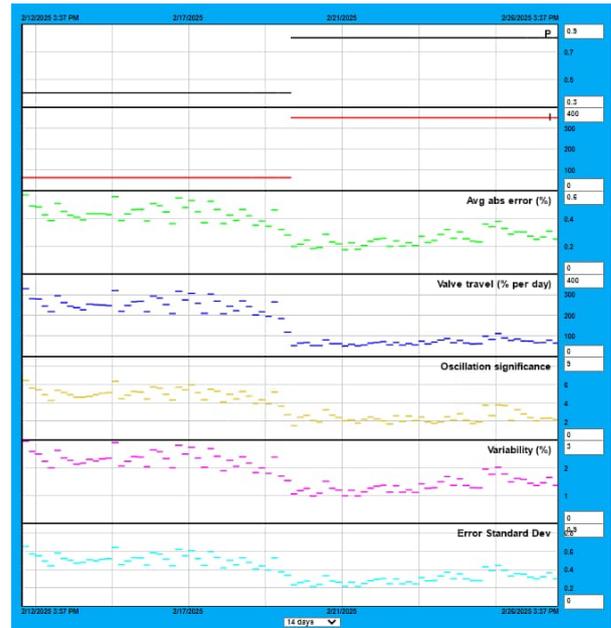


Figure 11. Example PlantTriage Tuning Report showing impact of tuning change on control loops assessments.

The results for the studied control loops are illustrated in Figure 12. We notice that, for most cases, we were able to improve performance in all assessments, except for loop 1, where changes were modest, and loop 3, where only valve travel was improved. For loop 3 we later noticed that the root cause of the oscillations was not in the valve, but in a neighbor loop.

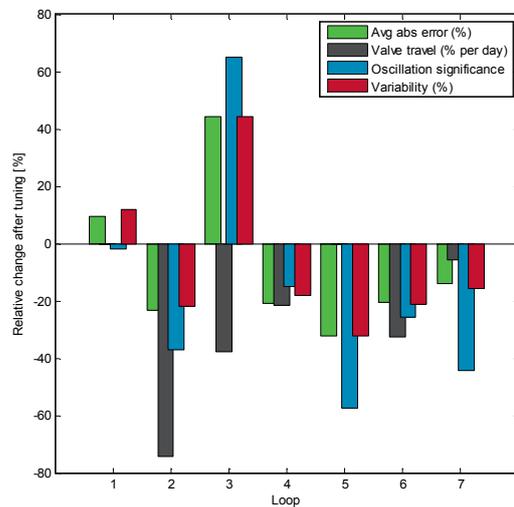


Figure 12. Results of tuning showing change of assessment for each loop after tuning.

These examples demonstrate that with problematic valves, there is usually a great potential to simultaneously reduce oscillations, control errors, and valve wear, as summarized in Figure 13 below.

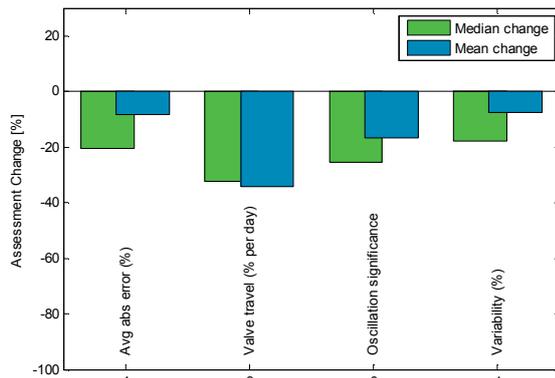


Figure 13. Average control performance change for all tuned loops.

8 Conclusions

We have studied impact of PI controller tuning on control loops with backlash or stick-slip in the valve.

For the stick-slip case, the results suggest that we should decrease controller gain, and increase integral time to reduce valve travel, and extend valve lifetime.

For the backlash case, the tuning rules (Eq. (6)) are very simple: it is important to ensure that integral time is large enough, and there is usually no need to detune gain despite of oscillations.

For loops with backlash, there is a huge potential to reduce oscillations and interactions, and to extend valve lifetime with proper tuning, primarily for loops with large time constants, typically level, pressure, and temperature control loops.

With simple tuning recommendations it is usually easy to improve control performance and reduce valve wear for loops with non-ideal valves. However, it might be difficult to find loops with valve problems if there are thousands of control loop to monitor in the plant. In such cases, good control loop performance monitoring tools that can pick oscillating control loops and determine root cause of oscillations to the valve, are crucial (Valmet Automation, 2025).

An industrial case study demonstrates that we were able to simultaneously minimize oscillations, variability, and to reduce valve travel for loops with valve backlash. In the case study we used PlantTriage, which made it is easy to find loops and valves that needed attention.

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Vjatscheslav Kekshin*, Artjom Kurapov*, Vladimir Kuts*

Integration of Beekeeping with the Concept of Smart Manufacturing

Abstract: Smart manufacturing encompasses various industries, including honey production on beekeeping farms. Modern technologies enable the resolution of complex and critical tasks in this field. This scientific article presents a method for integrating smart manufacturing into beekeeping. It describes the concept of digital control over processes inside hives, automation of hive management processes, monitoring, and problem forecasting. This, in turn, simplifies traditional beekeeping methods and improves both the vitality of bees and the productivity of honey production. Beekeepers of various levels, from amateurs to professionals managing large apiaries, are in great need of technologies that can enhance their efficiency. However, modern mass markets for beekeeping equipment, unfortunately, lack affordable solutions. Therefore, this problem remains relevant and requires attention in this field.

Keywords: Digitalisation, Automation, Smart manufacturing

***Corresponding Author:** Early Stage Researcher. Tallinn University of Technology, School of Engineering, Department of Mechanical and Industrial Engineering, E-mail: vjatscheslav.kekshin@mail.ee

Second Author: Founding engineer, Gratheon OÜ, E-mail: artkurapov@gmail.com

Third Author: Assistant Professor. Tallinn University of Technology, School of Engineering, Department of Mechanical and Industrial Engineering, E-mail: vladimir.kuts@taltech.ee

Introduction

Honey production is a complex and meticulous process that requires a high level of knowledge in this field and involves solving numerous complex tasks, such as: monitoring the condition of the bee colony includes necessary regular (weekly) inspections, fighting varroa mite infestations, predicting swarming, tracking queen presence, controlling colony growth/efficiency, and

preventing starvation. The generalization capacity in condition monitoring is therefore more preferable when compared with conventional methods [1]. The appliance of automated control procedures and targeted interventions against critical beehive conditions is the beekeeper's main concern and is carried out through periodic control checks of the entire apiary [2]. Beekeepers have to be there more often [3]. Human labor becomes more efficient with the use of smart manufacturing in beekeeping. Smart manufacturing is a general concept representing the deep integration of information technologies and advanced manufacturing technologies [4].

Physical labor is reduced, and with an increase in the number of beehives, human labor does not increase. Additionally, the time for visual inspection and diagnostics of hives on-site is shortened.

Materials and methods

The methodology involves selecting a combination of hardware and software and establishing a connection between automated tasks and the operator.

For data analysis in beekeeping, we use a SaaS (Figure 1) application that includes AI detections of frame photos, bee counts, queen and queen cups, varroa mites, frame cells, management of apiaries, hives, frames, and photos, an AI advisor, a mobile app, manual inspections, an inspection timeline, and re-training on user data. Therefore, to accurately analyze the impact of the environment on the state of the bee colony, it is necessary to use sensor devices with sufficient accuracy [5].

IoT sensors for beehives are integrated with hardware for transmitting infrequent telemetry data and are used to measure internal hive temperature, Figure 2. Enabling digital technologies (e.g., sensors and networks) are increasingly available, and with numerous digital products on the market (e.g., hive monitoring systems), beekeepers have started embracing digital beekeeping tools [6].

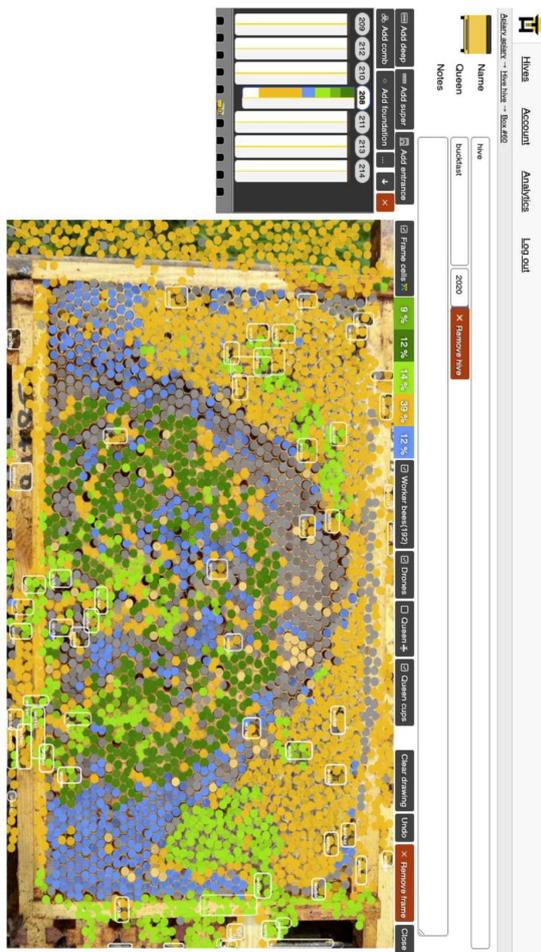


Figure 1. Data analytics SaaS app for beekeepers

In Figure 2, a web application for monitoring the temperature inside a beehive is shown. This application allows real-time temperature tracking as well as viewing recorded temperature data from previous days. The data is obtained from a temperature sensor installed inside the hive.

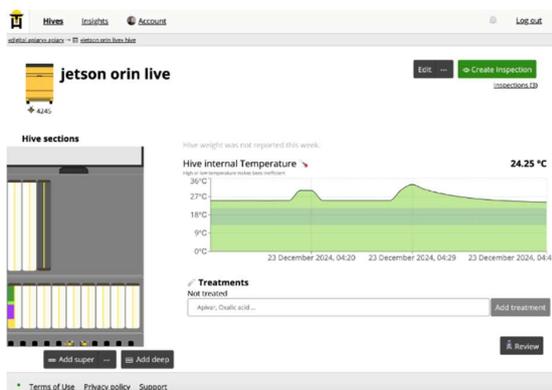


Figure 2: A Web Application for Monitoring the Temperature Inside a Beehive

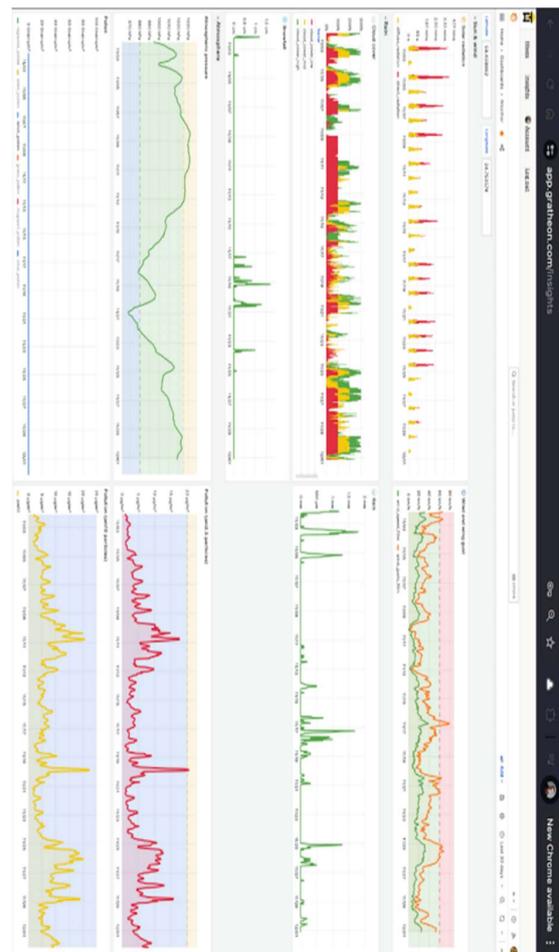


Figure 3: Weather Monitoring Display on the Web Application Page.

The temperature inside a beehive is a crucial factor for the bees' habitat. Extreme cold during winter, as well as excessively high or warm temperatures inside the hive, can significantly impact the bees. These temperature fluctuations may cause them to either perish or become ill, which in turn affects the honey yield.

With timely alerts about unfavorable temperature conditions inside the hive, provided through the web application, a beekeeper can promptly react to the situation and prevent excessive temperature increases or drops. This method is also highly convenient because temperature data collection occurs remotely.

The temperature is a very important parameter for bee colonies, as its detection can be used to identify different conditions in the hive, such as brood development, the pre-swarming condition, and, in general, the health status of the hive [7]. IoT sensors, also are used to measure humidity, atmospheric pressure, hive weight, CO₂ levels inside the hive, PM₂

pollution outside the hive, wind speed, and audio. Under this condition, how to improve the condition monitoring performance still needs to be studied [8].

In the web application displaying graphs (Figure 3) with information about the surrounding environment, various types of data are available, such as Sun & Wind, Wind and Wind Gust, Cloud Cover, Rain, Snowfall, Atmospheric Pressure, Pollution, and Pollen. Weather charts depend on the location.

Numerous algorithms can be used for feature extraction and analysis of bees' acoustic [9]. Putting a sensor inside a beehive to gather data from a colony is an advantage over being outside [10]. Due to various conditions, inspecting beehives using traditional manual and visual methods is highly limited. As a result, diagnosing the internal state of a hive with these methods is not as accurate or reliable compared to using technical devices and processing their data. Therefore, in an automated mode, we obtain crucial information through the identification, visualization, and signaling of the internal state and environmental conditions inside the beehive.

The web application enables plotting time series data in Grafana, performing analytics through graphs for identifying correlations and anomalies, and generating notifications. In that case, a web application will have the advantage of offering technical guidance without the need to establish a simulation environment [11].

Monitoring the entrance of a beehive is comprehensively performed using the Vision application and an IoT device (Figure 4). Camera used in the experiment: Mokose 4K with a resolution of 640×480 for logical output and for recording/streaming video to the cloud. Additionally, NVIDIA GStreamer API acceleration is used in the KV2 framework to reduce CPU load.

The Internet of Things (IoT) is an emerging technology to connect a myriad of devices to a data fusion center [12]. It includes video streaming and playback (Figure 5), counting incoming/outgoing bees, varroa mite detection, detecting seizures caused by pesticide exposure, monitoring pollen foraging activity, ant infestations, queen mating flights, theft alerts, and hornet attack notifications. To estimate the health status of a honey bee colony, beekeepers currently still largely rely on physical interventions, consisting of manually opening the hives and visually inspecting the colony for anomalies, such as, e.g., the presence of parasites or viruses, symptoms of diseases, and colony traits like queen and brood presence and status, colony and brood size, and honey and pollen storage [6].

The experiment using IoT was conducted on a private beekeeping apiary during the summer season when bees are in an active phase for collecting pollen. A camera was installed above the entrance of the beehive, allowing for data collection, which serves as the basis for analysis and the diagnostic model. The aforementioned results suggested that the diagnostic model had high degree of credibility and potent classification ability [13].



Figure 4. Hive entrance video monitoring / IoT device



Figure 5. Video streaming & playback

In addition, smart beehives can include a frame extraction mechanism (Figure 6). This allows for the automatic extraction of a frame filled with honey, and in place of the removed frame, a new empty frame is inserted, which will later be filled with honey by the bees, just like the previous one.

After automatic extraction, the filled frame is also automatically directed to a device that extracts honey from the frames using a centrifugation method.

This method of honey frame extraction is effective because it subjects the bees to less stress compared to traditional frame removal. In the traditional, or manual, method, beekeepers disturb the entire hive and use

smoke throughout the beehive, affecting all the bees inside.

2 cameras to take photos of the frame for uploading to a web app, frame extraction for honey harvesting, frame movement across hives, and initially, a robot for a single colony. It moves on rails and also contains sensors for temperature, humidity, weight, and audio monitoring, as well as ventilation, automatic feeding, and anti-varroa mite treatment. The varroa mite disease is one of the most common causes of bee mortality [2].

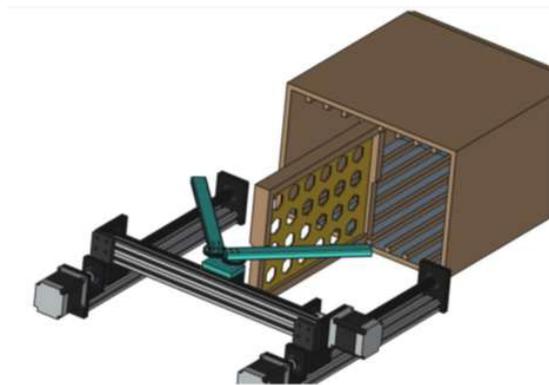


Figure 6. Frame extraction mechanism

In the future, it is possible to develop honey production using Smart manufactory on a larger scale, thanks to specialized containers in which the above-mentioned method will be used.

Conclusion

In the course of the study, a methodology was developed for the implementation and use of smart manufacturing technologies in beekeeping. Smart manufacturing necessitates a profound fusion of cutting-edge manufacturing technologies with sophisticated digitalization solutions [14]. The technology, consisting of data collection devices, software, and data transmission peripherals, has proven its suitability and efficiency in use. This enables the simplification of tasks in beekeeping while improving the quality and productivity of honey production. The future development of automated beekeeping management will simplify and improve traditional honey production on apiaries, taking into account the biological behavior of bees and the impact of the technical devices used on them.

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Juho Pirttilahti, Sakari Pollari, Janne Kapela

Safety system delay measurement and implementation to VR- simulation

Keywords: delay, stopping time measurement, virtual reality, safety validation, digital twin

Pirttilahti, Juho: Seinäjoki University of Applied Sciences, juho.pirttilahti@seamk.fi

Pollari, Sakari: Seinäjoki University of Applied Sciences, sakari.pollari@seamk.fi

Kapela, Janne: Seinäjoki University of Applied Sciences, janne.kapela@seamk.fi

Abstract

This paper examines the distinctions between virtual and real-world environments in the assessment of machine safety applications. The high-speed camera was employed for the actual configuration for measurement of a single DC motor stop time, which represents part of the real machine architecture. The delay between the activation of the safety laser scanner and the cessation of the motor was measured. Additionally, the delay from the safety laser scanner to the contactor shut down operation was measured. The result serves to establish a benchmark for comparison with a virtual model developed in Unity.

The virtual environment is constructed in such a way as to replicate the real-world system, with the objective of implementing real-world measured delay and safety performance under controlled conditions. By simulating different scenarios, researchers can assess the system's response and identify critical weaknesses without the inherent risks associated with physical machinery.

Latency is a critical factor in the context of safety. It is defined as the time interval between the triggering of a safety condition and the corresponding system action. The reduction of latency is of paramount importance for the implementation of effective safety responses. In the virtual setup, computational latency is analyzed in conjunction with real-world mechanical delays to ascertain the viability of utilizing virtual simulations for safety-critical assessments.

Moreover, the study assesses compliance with ISO 13849-1, a foundational safety standard that delineates the specifications for control system design. Verification of adherence to these criteria in both the virtual and physical setups serves to validate the robustness of simulations for machine safety systems. The integration of high-speed camera data improves the accuracy of the virtual model, enabling a comprehensive analysis of system behavior under dynamic conditions.

Introduction

In machine safeguarding, time delay in a safety system's response can be the difference between a near miss and severe injury. ISO 13849-1 standard [1] highlights that the safety function design must consider the machine's stopping performance. The delay is a crucial factor when a person or object approach dangerous parts of the machine. From this view, the B1-type standard ISO 13855 [2] is constructed to include the calculation of safety distances. The standard introduces Formula 1 for separation distance.

$$S = K \times T + D_{DS} + Z$$

Formula 1: Separation distance calculation according to ISO 13855

Here K is the assumed approach speed of the body or body part, T is the overall system response time, D_{DS} is the reaching distance associated with the protective device and Z is the additional distance constant determined by the application, which is more commonly referred to as safety margin [2]. From this formula, because S scales with T , even small increases in delay can demand significantly large safety distances. If we assume that quick movement of the hand could be done with the speed of 2000 mm/s, the additional delay of one second would require about 2000mm more separation distance to the dangerous parts of the machine. This translates to 2 mm more separation distance for every millisecond of additional delay introduced by the safety system.

Integrating virtual reality into machine system development offers a transformative methodology for system evaluation and verification, particularly in relation to safety and operational efficacy. By employing VR technology, comprehensive testing of both functionality and safety features can be conducted prior to physical deployment, thereby mitigating risks, and reducing development costs [3]. In VR, designers can simulate real-world conditions with high precision. For instance, VR can replicate the dynamics of machine tools, such as lathes and milling machines, allowing designers to evaluate various scenarios, including different speeds and separation distances, to identify potential hazards [4][5]. This capability is particularly useful for evaluating the safety of automatically controlled machine tools, where human-machine interaction is critical [4]. However, while VR offers substantial benefits for safety validation, there is a risk of learning false information if simulations do not adequately cover all safety aspects or reflect real-world parameters [6].

Methodology

To replicate key aspects of the actual machine architecture, a real-world experimental setup was constructed. The test environment was intended to serve as a reference for the virtual model to be created and to utilize the measurement data obtained from it to create the most accurate digital twin possible.

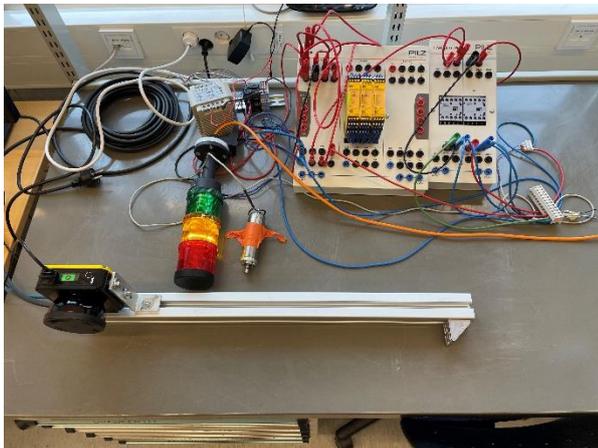


Figure 1: Test setup consisting of the components for safety architecture.

In the wiring of the safety laser scanner, the example provided in the Pilz PNOZ S4 operating instructions [7] for connecting the OSSD outputs to the safety relay was used. The test setup is shown in Figure 1. The safety laser scanner’s OSSD1 and OSSD2 outputs are connected to the Pilz PNOZ S4 safety relay’s S12 and S22 connectors. The safety relay’s outputs, terminals 13–14 and 23–24, control the motor’s front contactors

K1 and K2. The supply voltage to the motor passes through terminals 13–14 of the K1 and K2 contactors, forming a series connection for the motor’s supply. This configuration creates a category 0 stop by disconnecting the motor’s power supply. More detailed electrical drawings are shown in Figure 2.

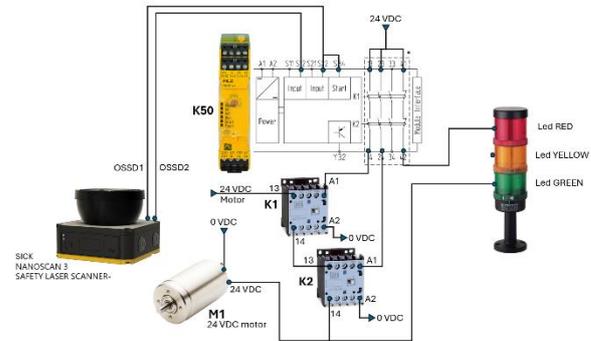


Figure 2: Electrical schematics of test setup.

Delay measurements were performed using a Citius Imaging C100 high-speed camera in conjunction with Citius Imaging 1.48 software, which was configured to capture images at intervals of 2.306 milliseconds. The safety laser scanner (Sick nanoScan3), configured with a 20 mm finger detection resolution, was mounted vertically on an aluminum profile bar, and aligned with the camera to ensure reliable observation of the safety field activation [8]. The verification report, which shows the area of the laser scanner is shown in Figure 3.

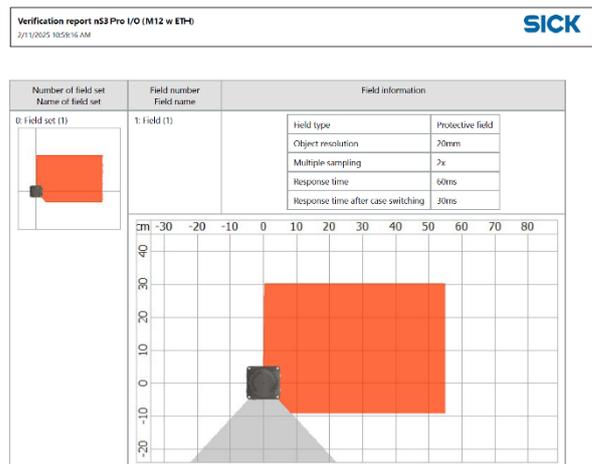


Figure 3: Verification report of protective field information.

The camera’s field of view also encompassed a small DC motor equipped with a mechanical rotation indicator and signal lights. These lights indicated the activation of the safety relay (Pilz PNOZ s4) and the switching of the contactor. For the experiment, an operator’s hand was employed to trigger the safety light curtain, and the subsequent video recordings were analyzed—using the

known frame rate—to calculate the delay from safety field activation to motor cessation. The visualisation of the high-speed camera picture is shown in Figure 4.



Figure 4: Screenshot from highspeed camera video taken from test setup.

According to manufacturers' datasheets, the configuration introduces a minimum switching delay of 70 ms for the Sick nanoScan3 [8]. The Pilz PNOZ S4 safety relay exhibits a switch-off time of 10 ms [7]. The WEG CWC016 motor contactor has a contact opening time ranging from 7 to 12 ms when operated by a 24 VDC coil [9]. Together, these components result in a total stopping time ranging from 87 ms to 92 ms. The motor itself does not have a defined nominal stopping value, and significant variation was observed during testing.

After the real-world measurements, a virtual reality (VR) model of the test setup machine and its safety control system was developed in Unity. This VR model replicated the stopping architecture of the physical system, with delays for each component (safety light curtain, safety relay, contactor, and motor) parameterized based on the high-speed camera data. The Unity object code was modified to incorporate the motor's ramp-down time, and parameters encompassed an error margin ranging from 1 millisecond to 1 second. This was included in the test using a random generator to emulate a similar standard deviation effect observed in real-world tests.

Constructing the VR Environment

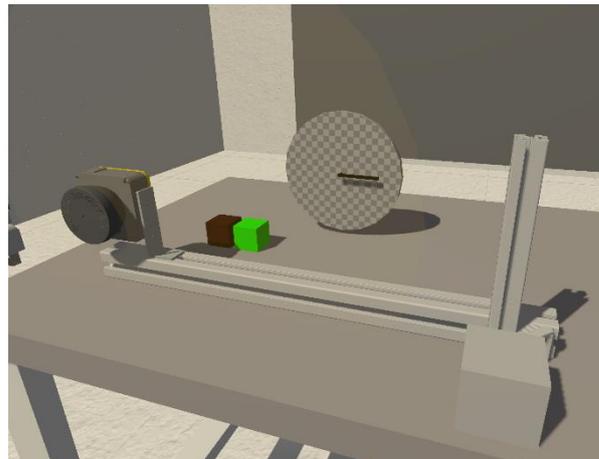


Figure 5: Test setup replicated in VR.

The VR simulation was built to mirror the real machine's safety system, including a virtual curtain, relays, and the motor stop sequence. The test setup is visualized in Figure 5. The light curtain in VR is represented by an invisible sensor zone that detects intrusions just like a physical light curtain would. In the real system, breaking a light curtain's beams immediately triggers a safety response: the light curtain's outputs turn off and the safety relay cuts power to the motor, bringing hazardous motion to a stop [10]. The VR model replicates this chain of events. When the user (or any object) crosses the virtual light curtain's plane, the simulation initiates an emergency-stop routine that sequentially emulates the relay activation and motor braking, just as the real hardware would. By reproducing each component's function and interaction, the VR setup acts as a digital twin of the safety system, ensuring that the virtual machinery responds to safety breaches exactly like the real machinery.

The simulation does not immediately stop the machine upon intrusion to reflect real safety system timing. Instead, it introduces staged delays that correspond to each component's reaction time. This was accomplished in Unity by using sequential timed events to represent the delay at each step of the safety chain. For example, when the virtual light curtain is breached, an initial trigger fires and starts a short countdown representing the light curtain's detection and processing time. Once this delay elapses, the next step simulates the safety relay's response – after its own configured delay, it “opens” the circuit in the simulation.

Finally, after the relay delay, the motor stop sequence is executed: the VR motor begins decelerating or

halting over an additional brief period to imitate the motor's coast-down time. Each timed step in the simulation is governed by an adjustable response parameter, allowing the delay between stages to be fine-tuned to match the exact milliseconds observed in real-world measurements. In addition, an adjustable error margin parameter is incorporated to simulate the inherent measurement errors and natural variability seen during physical testing. This dual-parameter approach effectively strings together the sequential delayed reactions—from sensor activation, through relay switching to motor stopping—recreating the cascade of events in an actual emergency stop. By calibrating both the nominal delays and their associated error margins, it is ensured that the overall stop time in VR not only aligns closely with reality but also reflects its dynamic variability. The setup values are introduced in Figure 6.

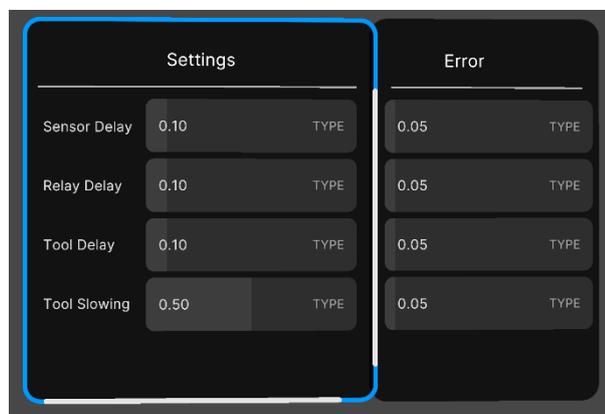


Figure 6: Delay parameters and error parameters for deviation.

Why parameterize these delays? In a real safety circuit, each device introduces a known reaction time. Manufacturers of safety components specify how quickly their device responds – for instance, a light curtain might have a response time of tens of milliseconds, and a safety relay might add its own small delay (often in the 10–40 ms range) [11]. In the VR model, these times are not hard coded as fixed values; instead, they are exposed as parameters that can be configured. This approach allows users to plug in the exact timings from the device datasheets (or from empirical measurements) for each component. It also makes the simulation flexible: if a different sensor or relay is used in the future (with a different spec), or if the real system's performance is re-measured, the virtual model can be updated by simply changing the delay parameters. In short, parameterizing the delays ties the simulation's behavior directly to manufacturer-specified values, which is essential for realism [11]. According to safety standards, the response time of the presence-sensing device as stated by the manufacturer or measured by the employer must be accounted for in

safety calculations – the VR follows this principle by using those same values in the model. The VR- setting with test scoreboard is illustrated in Figure 7.

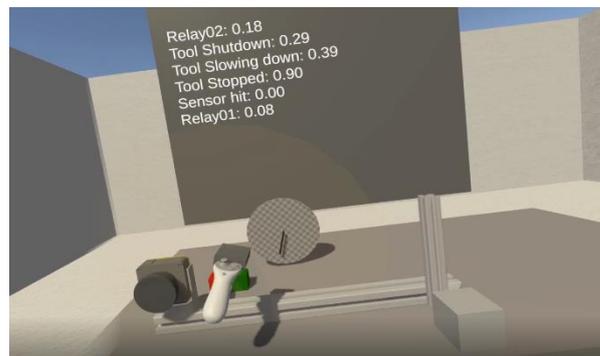


Figure 7: VR- test setting with delay time scoreboard.

Results and Discussion

The high-speed camera system was employed to conduct two distinct measurement configurations. In the first measurement, the delay from the activation of the safety scanner to the cessation of the motor was evaluated. This test was repeated ten times, yielding a mean delay of 1404.79 ms with a standard deviation of 50.12 ms.

In the second configuration, indicator lights were incorporated into the circuit following the safety relay and motor contactor. These lights visually indicated the activation of the respective components, which were captured by the high-speed camera. The results from this setup revealed a mean delay of 14.87 ms with a standard deviation of 16.08 ms for the time between the activation of the safety sensor and the triggering of the safety relay. Additionally, the mean delay from safety scanner activation to the state change of the contactor was found to be 26.20 ms, with a standard deviation of 16.63 ms. This was found to be significantly faster than the delay calculated from the components' datasheets including the deviation. The total delay from the activation of the safety laser scanner to the cessation of the motor in this second setup was 1388.74 ms, with a standard deviation of 66.68 ms. When combining the results from all 20 trials, the total mean delay from the activation of the safety scanner to the cessation of the motor was 1396.77 ms, with an overall standard deviation of 61.10 ms.

The largest portion of the delay arises from mechanical deceleration of the motor rather than from the electronic or sensing components. The brief intervals measured between the scanner activation and the safety relay (~15 ms) or contactor off (~26 ms) are minimal in comparison. This is consistent with typical small motor inertia and the absence of an electronic brake in the test setup.

The short delays (e.g., scanner-to-relay or scanner-to-contactor) exhibit higher standard deviations (about 16 ms) compared to their mean values. This reflects the frame-based measurement resolution of the high-speed camera and potential jitter in signal switching. While the camera provides accurate timing over the full 1.40 s window, sub-30 ms intervals are proportionally more affected by each frame's ~2.36 ms increment.

Conclusions

The experimental results indicate that the high-speed camera reliably detected the laser light emitted by the safety scanner, thereby facilitating precise alignment during testing. However, further investigation is required to refine the accuracy of motor cessation event timestamp extraction from the video frames, as the software-based frame measurements exhibit a non-negligible tolerance.

In developing the virtual reality (VR) model, it was essential to parameterize two key factors: the nominal delay associated with each component and the additional delay introduced by measurement tolerance. This approach enables simulation of safety responses under various conditions, providing a robust framework for analyzing system behavior. Moreover, the VR environment allows for rapid testing and optimization of safety measures without the inherent risks and costs of physical trials.

The high-speed camera proved to be an effective tool for validating total delay times—from safety scanner activation to motor cessation—under conditions where safety tolerance is critical. Nonetheless, its precision diminishes when capturing noticeably short time intervals, such as those between the activation of the safety scanner and subsequent events like safety relay or contactor switching. Furthermore, while manufacturers typically provide component reaction times and delay values that incorporate built-in safety factors for practical applications, additional optimization may be necessary to reflect the dynamic performance of the system more accurately under test. However, based on the test, it is more feasible to inspect the stopping time of mechanical systems rather than electrical control systems.

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European Union. The logo is represented in Figure 8.



Figure 8 8: Funder logo.

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Heikki Saha*, TKE Oy

An improved IoT gateway and configuration approach for mobile mining machine applications

Abstract: Typical IoT systems have been based on dedicated sensor networks. Gateways (GW) have been designed to route to server the entire communication message by message, without any processing. Further, automatic discovery of sensors has often been used. Data buffering has been used to cope with temporary communication failures only. Modern mining equipment contain electronic control systems, which provide various kinds of data for monitoring. In each site there may be numerous kinds of equipment, each providing different data as different sets. Especially in underground mines, there are areas without any communication network available due to a harsh conditions. This paper presents a new GW concept, which has intentionally been designed to provide a flexible connectivity to various equipment, networks and servers. Intentionally selected data will be extracted into a source independent format. Data buffered by the GW may be sent to the remote server, when a connection exists. Configurability requires well defined management processes to result reliable operation. This paper presents process examples for three major alternative connections, J1939 fleet management, CAN-based superstructure network and a CANopen sensor network. Field tests proved, that the presented GW concept reached the defined targets. The presented configuration processes improved getting the GWs configured without errors.

Keywords: IoT, IIoT, gateway, configuration, mining

***Corresponding Author: Heikki Saha:** Dr., E-mail: heikki.saha@tke.fi

1 Background

A set of physical objects – “things” – that send data and communicate with a network was called first time as a term of the Internet of Things (IoT) in 1999 by the MIT [1]. Industrial IoT (IIoT) may be defined integration of internal and external data, which means typically collecting process data from the actual control system and supplemental extra sensors and combing the data in the server [2] [3]. Different

requirements apply to IoT and IIoT by means of environmental protection and interfacing [2]. Modern distributed control systems use embedded networks, “fieldbuses” for sharing the control system internal data inside the systems [4]. Similar networks are also in use in mobile assets, but may be called differently, e.g. “automotive networks” [5]. Typical use cases for IIoT data include production process, asset usage and service monitoring and optimization as well as invoicing [2] [4] [6].

Mining operations consist of multiple tasks – drilling, charging, exploding, secondary breaking, scaling, loading, hauling and reinforcing following each other and dedicated equipment are required in each task [7]. Typically such means the use of different kinds of equipment from multiple vendors, which leads into further challenges regarding fleet wide production process and condition monitoring systems.

Modern equipment contain distributed electronic onboard control system, e.g. trucks [5], with a standardized network interface for fleet management [8], which is a typical interface to obtain various kinds of remote monitoring data. In addition to the mandatory FMS (fleet management system) data, equipment vendors may provide optional data [9] as vendor specific sets. Some truck vendors provide similar communication also by so called BBM (body builder module) interface, which is intended for superstructure integration. Additionally, there may be one or more control networks dedicated for superstructure, which may need to be connected. Reliable installation of supplemental sensors has been found to be challenging [2].

Depending on mining method, production areas may vary and be in use for short periods. Thus it does not make any sense to build communication infrastructure covering the entire production areas [7]. There is typically an excellent infrastructure in the fixed areas of the mine, in which the data may be sent to the network. The networks available in the mines are company specific, from which a managed Internet

connection is available through firewall. The networks contain business critical data, why communication is strictly constrained due to security and privacy reasons. Thus, the companies prefer to keep the server's master database strictly under their own control. As a result, each company may use different server framework and further use different application programming interface (API) for interfacing.

In underground mines, cellular networks are typically provided in very limited areas such as service areas, offices and lounges. Main underground communication medium is a WiFi. Cellular networks exist underground, but are more widely used for IIoT in surface mines. However, there may exist random blind spots.

Direct internet connection of an individual sensor is difficult to implemented in a proper way, especially with constrained resources [10]. A gateway (GW) is a device integrating sensors with heterogenous interfaces to a cloud platform over an available network connection [11] [4] [12]. In addition to the data routing, a GW may filter, preprocess and buffer the data [13] [12]. Due to the central role of the GW and its configuration in the IIoT systems, GW behavior and related configuration management are in the main scope of this paper.

This paper has been organized as follows. Section 2 contains a review of the major existing GW concepts. An analysis of the adaptability of the existing concepts into mining IIoT GW is shown and improvement objectives set in section 3. Section 4 describes the details of a new concept as three asset connection scenarios. Test experience is summarized in section 5. Discussion on the results is in section 6 and conclusions set in section 7.

2 State-of-the-art

In IoT domain it is typical to have many systems operating in the same area but owned and operated by different parties [6] [14] [15], which also applies to the IIoT domain, including mining. The systems may provide concurrent application using same sensor and actuator data up to some extent [15]. The systems may serve the same master process but each system may provide business value primarily to a single company [6]. Such scenario requires managed data sharing among the systems [15] [6] [14]. In many application domains the sharing is not only a technical problem – data is business critical and shall be available for the owner only or the trusted parties by means of e-commerce or comparable mechanisms

[16]. Privacy may also be an issue [6], because e.g. several subcontracting companies competing with each other may operate in the same areas. There is also variation across the applications in data timeliness, which has effect on, how to share the data [14] [11]. Requesting data by multiple consumers [14] is less efficient. Therefore, sharing is typically used instead. Together with the asset operator company silos, data sharing problems apply to the infrastructure after a GW [17]. However, GWs of different parties may need to use the same networks without conflicts.

Performance of GW is one of the critical criteria together with asset specific investment cost [2]. Processing power and data flow analyses are documented approaches to identify application specific performance requirements [13]. Due to a heterogenous selection of source interfaces [13] [10], also the used interfaces, protocols and data structures have effect on the performance demand. In larger systems the performance requirements have been managed by hierarchy, limiting the number of data flows through a single GW [18] [19]. Literature has also identified the significance of communication cost and server data storage and processing cost [20], which may be reduced by moving processing closer to the field and thus reducing the data to be sent to server domain for storage and processing.

Same GW components may be used by different companies and with different assets and servers in order to reduce the GW unit cost. Such kind of sharing leads into the use different server APIs and communication networks [2] [12]. There are server framework specific interface libraries in the market [2]. Such will shorten development time but may degrade re-usability by dependency to the server framework.

GWs are categorized in the literature according their configuration approach.

Basic	A basic GW just forwards all messages sent by the IoT devices upwards to the remote server [12].
Smart	A smart gateway handles data efficiently by preprocessing, filtering, analyzing the data, and delivering only the related or necessary data to the cloud platform [12].
passive	Passive GW needs to configured manually [12]. IoT devices need to

be configured manually in order to get them registered to the network and communicating with a GW [21] [10].

semi-automated Like passive one but auto registration of devices to the network and configuring devices through an interface [12] [21] [10].

automated Fully automated device discovery, registering, configuring and release [12]. still under research [19] [21]. due to lack of relevant processes [18].

Variable protocols and data structuring are well known topics that increase the complexity of GWs [13] [10]. Networks may be wired [2] or wireless, in which there is a limited lifetime due to the use of batteries [2] [21]. Furthermore, sensor configuration management is challenging, especially assignment of unique identifiers for the sensors [22]. An idea of a generic device description exists [23]. It is dedicated to IoT-oriented sensors and is not compatible with existing field buses. Dedicated sensor networks serve also retrofitting of old assets by IoT connectivity [2]. Extracting sensor data into a generic format in the GW has been found to solve the problems of heterogenous sensor interfaces and protocols [11].

Field buses are used as a sensor networks in industrial applications [4]. The most commonly used field buses in machinery applications, such as CANopen, typically support standardized system design and configuration management process improving the efficiency of configuration data management [24]. A comparable system design process for e.g. J1939 looks different [25].

3 Required improvements to the GW concept

Objectives for the concept are set in this section based on the identified requirements. When an existing in-vehicle control network is used as a data source, the GW concepts presented in the literature do not fully apply. Most essential is, that control over the source network design and maintenance is managed by the asset vendor. Nodes, messages and signals may be added, modified and removed based on the vendor's decision. A concept of an automated, smart GW would route the entire in-vehicle communication without any control to a remote server and is thus totally out of

sense. Automatic integration of nodes will introduce a significant attack surface, which cannot be accepted in the industrial applications. Communication network to the server has always constrained bandwidth and such automation may overload the entire network infrastructure in the worst case. Thus, instead of the fully automated behavior, a proper process for configuration management shall be used.

O1: Smart and passive kind behavior

In-vehicle communication is heterogenous from communication details point of view, too. E.g. in J1939, there may be different source addresses used by different vendors for same messages. All signals of a message may not be supported by the all vendors. Practically same information may be transmitted as different signals packed into different messages among the vendors. Transmission rate of the messages is designed for in-vehicle controls and is thus too high to be forwarded as is to the server, without downsampling.

O2: Fully configurable data reception for each supported protocol

O3: Interface and protocol agnostic internal data model

The level of heterogeneity increases when superstructures or work hydraulics are considered. Depending on the asset type, there may be one or more 3rd party control networks using arbitrary protocols to be connected to the GW. From GW point of view, dedicated sensor networks and retrofit deployments are the simplest ones, because in such cases the entire network designs are in own control and dedicated to the IoT needs only.

O4: Configuration data management for each supported protocol

Storage capacity for buffering the data in a GW needs to be highly configurable, because part of the assets' typical working areas are outside the range of communication networks. Out-of-area times are relatively short during normal operation, but may be much longer in process exceptions or for certain process phases.

O5: Flexible local data buffering

Different organizations may use different cloud services or other kind of server frameworks. Thus, the use of a same GW product by various organizations

expects a flexible support of various data formats and mechanisms for communication with the server environment. Over-the-air (OTA) update of a GW from server has been found to be challenging [20] and a support of multiple server frameworks increase the challenge. Therefore, a support OTA updates by means of modularity and configurability will be considered in this paper.

O6: Server- and network agnostic, plugin-based uplink

Test assets include trucks, wheel loaders and a secondary breaking machine. Interfacing for each network type shall be solved separately, because of the process differences between the networks. Therefore, configuration management mechanism for J1939, CANopen and raw CAN networks are in the scope of this paper and thus covered by the example scenarios.

4 A new GW concept

A modular, plugin-based structure illustrated in Figure 1 has been designed to cope with arbitrary number and kind of data sources, source networks and communication protocols [11]. Due to heterogenous assets, a highly configurable implementation is needed – connectivity may be expanded by adding supplemental plugins, without any effect on the existing ones.

Modular structure of SW and configuration also helps bandwidth optimization of updates. Each update may cover all or selected items, depending on a need.

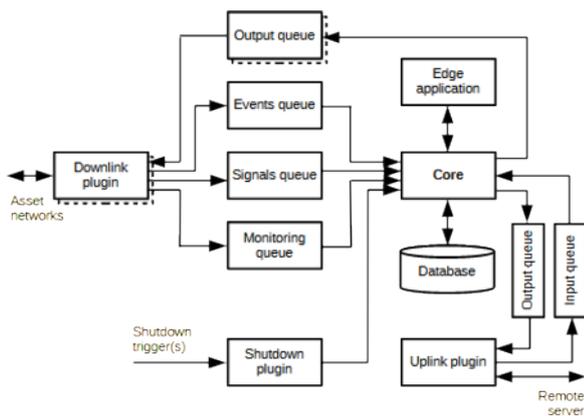


Figure 1: Modular structure of the GW

Instead of manual writing, configurations are intended to be generated from source network descriptions.

Typical source network has been designed by asset vendor. Such means that there may be partial documentation available, in the best case a standard description file, e.g. DBC-file for J1939 network. Supplemental sensor networks are intentionally designed for the IoT implementation. The self designed networks are easier, because the entire network projects with the GW included are available, e.g. standardized nodelist and DCF files in a case of CANopen.

Workflow introduced in this paper expects the use of a standard CANopen and J1939 design processes. Thus, format of the results is well known and may be used as a source for automated workflow. When the 3rd party designs are used, there is messaging of the entire network included. When only a written documentation is available, a formal communication description needs to be manually created as a DBC file.

When the communication description is in a standard DBC format, such may be validated by testing and fixed until correct. In addition to the CAN design tools, most CAN analyzer applications use DBC format for exchanging communication decoding rules, which makes the use of such files very practical. After validation with a real asset one can ensure, that the description is correct and all required signals are included.

Conversion from a validated source projects to GW specific JSON module is performed for each interface. Then the all modules are joined into a single downlink configuration file. Port assignment shall be checked while joining the modules to avoid port mismatches or overlaps, because such cannot be validated with CAN analyzer applications.

GW uses a uniform internal data model based on source agnostic signal samples and events as shown in Figure 2 and Figure 3. Signals and events use separate databases in order to prevent one override another. All signals and events are timestamped by the GW, enabling variable and configurable data buffering.

```
{
  'ts': '<timestamp>' # Receive timestamp
  'sname': '<name>' # Signal name
  'sval': 0.1, # Value
  'sunit': 'm', # Unit
  'sstat': 0 # Signal status
}
```

Figure 2: Internal signal sample data structure

Existing systems have already defined names.

Therefore, such names are re-used to keep the overall namespace consistent. As a result, the use of the same, application specific namespace everywhere results intrinsic linking of signal data to other data without any supplemental concepts.

Signal unit is included to keep decoding straightforward. Configuration may vary from time to time and possible changes in scaling are easy to handle, when signal value is supplemented by unit information.

Signal status is a way to identify signal sample timeliness. A signal value in process image may be valid but updated last time too long time ago and thus be outdated.

Events are also timestamped as signal samples. Each event is identified as a numeric event code to provide use-case and language agnostic identification. A signal sample value may be attached to each event in order to provide supporting data for consumers.

```
{  
  'ts': '<timestamp>' # Receive timestamp  
  'ecode': <code> # Event code  
  'esval': 0.0, # Signal value  
  'enrof': 1, # Burst size  
  'sstat': 0 # Signal status  
}
```

Figure 3: Internal event data structure

Events may be generated by the GW itself, its edge application or read by a downlink plugin directly from another device. Events generated locally by the GW itself are typically single ones. Events generated by edge application or read from another device may be combined so, that a number of occurrences since the last read is given in “enrof” attribute. Such enables efficient transfer of event bursts with a reduced processing power and communication overhead. There is also a smaller risk of overriding less often occurred events by event bursts.

Event status may be used for e.g. to indicate whether an exception has been asserted or negated.

From processing point of view a GW may generate many kinds of events, but the constraints are set by the typical configuration processes. The typical available metadata consists of minimum and maximum values only, enabling only out-of-range events. More details are provided in the case scenarios explained further.

4.1. Scenario 1, connection to an existing J1939 network

Typically trucks support FMS or BBM providing subset of J1939 signals and messages. Other kinds of machines have J1939 at least for engine and transmission integration.

J1939 allows the use of a “real” J1939 GW interface, which is easy to configure based on source address, priority, suspected parameter and parameter group numbers instead of raw CAN-IDs. The supported signals and messages may be imported from a standard J1939 communication database (DBC) in order to avoid manual typing and human mistakes [25].

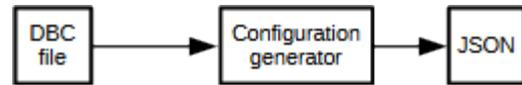


Figure 4: J1939 configuration generated from DBC-file

The asset specific DBC may then be tested by analyzer and fixed if required before generating a GW interface configuration from it according to Figure 4. Such testing is essential, because the messages and signals may exist in the network but marked as “not supported” by a dedicated signal value.

The DBC may contain both standard and custom attributes for data, but typically the standard attributes are commonly used across the tools. CAN-ID, name and cycle time are commonly supported for messages and name, data type, scaling, unit, minimum and maximum values for signals. There does not exist any generic method to control a use of a signal or message for certain purpose, e.g. IoT-connection. Thus, a conversion covers all included messages and signals.

4.2. Scenario 2: supplemental CANopen sensor network

Supplemental sensor networks are typically full, self designed CANopen networks with a GW intentionally included as an integral part of the network. GW acts as an NMT-master, taking care of the network start-up. There are also heartbeat and receiving process data monitoring services available providing status information for each signal. Status may indicate signal invalidity due to e.g. configuration problem or a damaged cable or sensor.

Thus, a complete CANopen project with nodelist and device configuration files (DCF) is available as a result of the standard design process [24]. Figure 5 illustrates, that the interface configuration for a GW may be generated from the CANopen project. CANopen system tools create a DBC file from the project, but it does not contain as much information as the entire project.

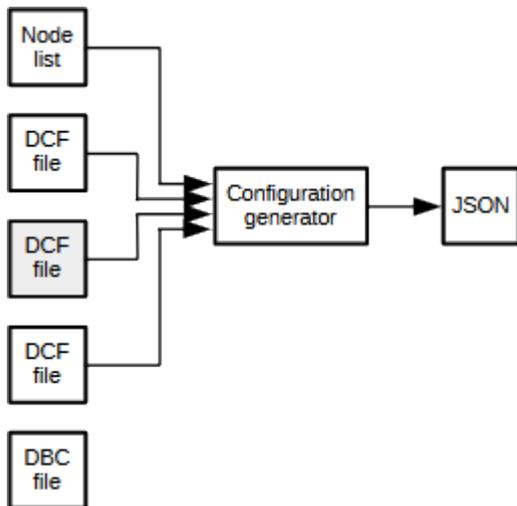


Figure 5: CANopen configuration generated from a CANopen project

Commonly supported message and signal attributes are as constrained as with DBC-files. DCF-files enable the use of custom attributes, but the tools in the market typically support the standard attributes only. A GW is intentionally designed in this scenario, which enables managed exports by relying on the common design practices.

4.3. Scenario 3: connection to an existing CANopen network

When machine control or truck superstructure control networks need to be connected, a 3rd party GW cannot be included into the subsystem network project. Instead, it shall be invisible to the subsystem and just consume specified data from the network. It is assumed that CANopen is used in this scenario.

When a GW cannot actively produce and consume CANopen services, it may only consume the data. Thus, CANopen management services are not fully accessible because of the constrained configuration data available in a DBC-file format. According to Figure 6 the DBC-file is in this scenario the main source for GW configuration. Machine or superstructure vendors

do not typically provide such data and the DBC-file shall be reverse engineered.

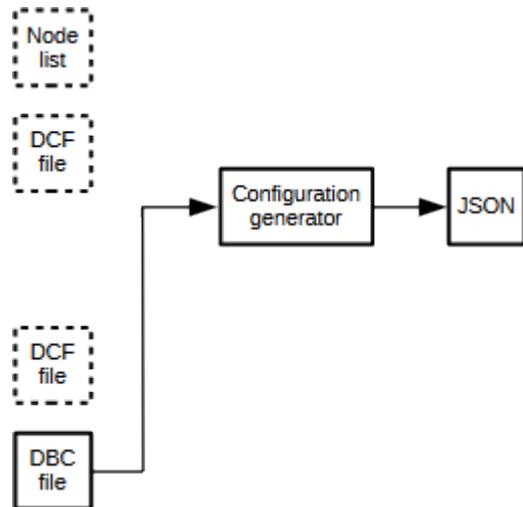


Figure 6: CAN configuration generated from a DBC-file

As in a case of J1939, also in this case a GW configuration DBC may be exported from the covering the entire network. Then, the exported file may be validated by an analyzer application and finally exported to a GW specific JSON.

This scenario is applicable to any CAN protocol, only the source of a system-wide DBC-file may vary from protocol to protocol.

5 Test experience

A GW with smart and passive kind behavior (O1) has been deployed. The major advantage is, that such enabled abstraction of the asset differences by providing harmonized data sets to the server, independent on the asset specific deviations. Uniform data sets improved e.g. efficient re-use of the business logic.

Fully configurable data reception for each supported protocol (O2) was found a major tool to manage the constrained bandwidth of network between GW and server. Sample rates of even with a small subset of the available signals had to be adjusted to avoid overloading the networks.

Interface and protocol agnostic internal data model (O3) enables flexible adaptations and supplementing missing data by dedicated sensing networks but still keeping uplink constant. The use of a high-level, signal oriented internal data model enabled the use of

practically any network type and protocol inside the downlink plugins.

Configuration data management follows the same scheme for each supported type of interface (O4), enabling easy but interface specific configurations. Standardized and commonly used configuration workflows were used. The basic setups were working well, but some standard improvements would help adoption of additional edge processing features.

Lossless data forwarding (O5) has been achieved by flexible local data buffering. Due to a finite buffer capacity, the oldest data may be overwritten, when the designed capacity will be exceeded. The maximum configurable buffer capacity depends on the available capacity of a target HW.

Server- and network agnostic, plugin-based uplink (O6) supports modern way of working. On one hand such enables easy testing of various cloud platforms and in the another hand such keeps it simple to change the cloud platform, if needed. It also provides a freedom to optimize the data structure to optimize data storage and processing in the cloud. Core application functionality is independent of the server connection.

Table 1: Tested target operating systems and processor architectures

Operating system	x86	ARM
Debian Linux		X
macOS	X	
Raspberry Pi OS (Linux)		X
Ubuntu Linux	X	X
Windows 7	X	
Windows 8	X	
Windows 10	X	
Windows 11	X	
Yocto Linux		X
Ångström Linux		X

Operating systems (OS) and processor architectures, in which the GW with the presented scenarios has been tested, are summarized in Table 1.

HW agnostic SW is easy to scale by just changing the HW, which is often essential due to a tight HW budget [2]. It was found typical to start with an entry-level HW, which had to be replaced with a higher capacity one

during testing. Adaptations in in-asset GWs are natural due to increasing knowledge during the deployment projects. The use of a flexible GW enabled making the changes locally, without changes in the cloud and business intelligence (BI).

Truck vendors offer warranty only when FMS and BBM interfaces are used and not directly power train or body networks. FMS/BBM data may need to be activated by a vendor’s service tool. Description of available data was well documented. There were not documents available for superstructure control networks and control networks of other machines. Thus, these presented configuration processes with support for reverse engineering and verification by measurement were essential.

Reliable mechanical installation of supplemental sensors was found difficult. In almost each asset there were missing usable process attachments, cable routing paths and free space for the supplemental installations.

6 Discussion

CAN or J1939 configuration needs to be defined as a dedicated DBC-file containing exactly the required messages and signals to enable validation by an analyzer. DBC format would allow custom attributes to control e.g. usage by a GW, but e.g. CAN analyzers do not support data visibility control based on such signal attributes. This may be a point to be generally improved in the future by the tool vendors.

A generic configuration data model covers, but is not limited to CAN, J1939 and CANopen. The data model may be expanded in the future to cover at least DDS, Modbus, NMEA0183 and general-purpose I/O.

Support of supplemental sensor network also applies to retrofitting of older assets. Together with the generic internal data model a retrofitted asset does not necessarily differ from a modern asset from server point of view.

There exist generalized data set specifications for BI layer in the industry, e.g. [26], why it is a good idea to provide data sets supporting such already by the in-asset GWs. Such enables the use of harmonized data streams and APIs in the IT-domain and deployment freedom in the assets – in the OT-domain.

Flexible configurability enables easy adoption of various assets. However, the dominating constraint is uplink bandwidth. Thus, specification of any

deployment shall be started from the throughput constraints between a GW and a server. Then it makes sense to prioritize the selection of signals to be sampled and their sample rates.

Configurability enables scaling the concept usage vertically to other application areas. It is not mandatory to use buffering capability. The GW operates as well between the continuously available networks. It also works with much larger buffering capacity, supporting operation out of uplink up to several days or weeks, if required.

The challenge becomes more significant, when assets operate partially outside the network coverage. Then the question is, how fast the buffered data may be sent to the server? Or do we have sufficient online time to get the data sent and avoid buffer overflow? The answers will vary from application to application and will be found by data flow based analysis.

7 Concluding remarks

Based on tests, the presented modular and HW-agnostic GW implementation solves most of the current challenges in IIoT deployments, especially in mining applications. Loose coupling to the HW, OS and communication network technologies enables efficient updates according to the changes in the related technologies and application requirements.

It was found a significant improvement to export configurations from existing, machine understandable sources instead of writing such manually. Both efficiency and quality were improved.

The identified main area for future development will be data availability from the assets. Standardized FMS and BBM interfaces are commonly available in trucks. Similar kind of open, standardized interfaces will be needed also in other kinds of machines.

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