CHALMERS
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Industry 4.0: Digital platform for grinding machines

Implementing Sensor Data Acquisition and Cloud Integration for Enhanced Manufacturing Efficiency

Master's thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

In the manufacturing industry, and for a company like SKF with facilities worldwide, it is challenging to monitor machining processes in real-time from remote locations. One method involves monitoring and visualizing machine output on a digital dashboard, updated manually at various locations. Both methods present certain challenges. For security reasons, new CNC machines do not support data transfer via USB sticks and can only store data for about a week.

Additionally, when any external sensor is connected to the machine, monitoring this data becomes even more complicated, requiring manual intervention to record, document, and store the data digitally. This makes it difficult for SKF to conduct real-time machining studies with multiple sensors connected to the machine. To address these issues, the Manufacturing Development division at SKF is conducting extensive studies and projects. This thesis, proposed in collaboration with Chalmers, aims to demonstrate the project's potential, which is to setup up a digital platform for grinding machines to capture sensor data and send it to the cloud.

Through discussions with SKF team members and several brainstorming sessions, we identified and refined possible outcomes based on SKF's feedback and expectations. We focused on data collection, storage, and real-time monitoring on the SKF Cloud platform. This was to be implemented to push machine data and any external sensors to the SKF cloud platform, which is Microsoft Azure.

The thesis project successfully demonstrated the capability and possibilities of capturing and monitoring data in real time. The project utilized hardware and software that may or may not be implemented later in the SKF MD lab. SKF is currently engaged in collaborative work with different partners who supply advanced edge devices that can be connected to machines. Currently, the thesis project serves as a demonstrator, integrating hardware components (selected by the customer) with software (to capture data from sensors). This integration is demonstrated on the Chalmers grinding machine.

Keywords: Grinding, machine tool, sensor, monitoring, edge, cloud

Foreword

The students involved in this thesis are from the Product Development Master's program and have worked as a team on various projects and courses over the past two years. We were assigned the thesis project due to our interest in the manufacturing industry and emerging technologies. Initially, we were unsure how to achieve our goals but were confident and eager to work with our professor at Chalmers, Peter Krajnik.

Thanks to our professor and our supervisor Magnus Wahlgård from SKF, we are extremely privileged to have had this opportunity. Without Peter's support, we could not have accomplished what we did. He connected us with the Chalmers team, including Phillip Hoier and Johnny Hamnesjö Olausson, and showed confidence and trust in our work, giving us the freedom to proceed. He was always available for advice when needed.

The SKF team was very welcoming, and we are grateful to Magnus for involving and encouraging us to participate in weekly meetings at SKF. We felt like part of the SKF team, not just students. Tomas Gustavsson and Martin C. Johansson were very supportive throughout the project, providing suggestions and hands-on involvement that were crucial in overcoming challenges.

In the end, we are truly grateful for the time and effort of the entire team who supported us along the way. Without their involvement, completing the project would have been a monumental task.

Acknowledgements

This project's successful completion is attributed to the combined efforts of the entire team involved. The valuable suggestions and recommendations received were instrumental in driving the project forward. Special thanks to supervisors Peter Krajnik and Magnus Wahlgård for their continuous and invaluable insights. Gratitude is also extended to Philipp Hoier and Johnny Hamnesjö Olausson for their assistance in the Chalmers lab. Appreciation goes to Martin C. Johansson and Tomas Gustavsson from the SKF team for their knowledge and practical help. Lastly, thanks to Neil Arstad and Buelent Tasdelen from Kistler for their support in resolving hardware issues.

Dominic Adamidis & Ajay Vivek Gokhale, Gothenburg, May 2024

LIST OF ACRONYMS

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AE	Acoustic Emission
AI	Artificial Intelligence
C4	Context, Container, Component, and Code
CNC	Computer Numerically Controlled
CPPS	Cyber-Physical Production Systems
DAQ	Data Acquisition Device
FREI	Factory Real-Time Edge Innovation
IoT	Internet of Things
IIoT	Industrial Internet of Things
IP	Internet Protocol
KEP-server	KEP (company)
LP	Low Pass filter
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
OPC UA	Open Platforms Communications Unified Architecture
PLC	Programmable Logic Controller
SC	Scaling factor
TS	Trust Sensitivity

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1. INTRODUCTION

The following chapter establishes the context for the thesis by providing an overview of the collaborative project involving SKF and other industry partners. It outlines the significance of integrating advanced digital connectivity in manufacturing processes, emphasizing SKF's commitment to Industry 4.0. This chapter highlights the thesis's aim to develop a comprehensive solution for real-time data collection from grinding machines, and it establishes the context, objectives, scope, and limitations of the research. Furthermore, a literature study section is included to review existing research and to align the project with current industry trends.

1.1 CONTEXTUAL BACKGROUND

A consortium comprising SKF, UVA Lidköping, Volvo Group, Tyrolit, Medius, and Chalmers is developing future Industry 4.0 solutions for machine tools. The objective of this thesis work is to provide support for the project prior to its initial phase, establishing a basic digital infrastructure for monitoring of grinding machines.

SKF is a global leader in the bearings and mechanical engineering sector and is headquartered in Sweden. This master's thesis was conducted at the Department of Industrial and Materials Science (IMS) at Chalmers and the Manufacturing Development division within SKF located in Gothenburg.

As industries worldwide strive for increased efficiency and productivity, the significance of advanced manufacturing technologies and digital transformation has never been more pronounced. SKF's mission is to leverage digital connectivity to enhance machinery performance, optimize maintenance routines, and contribute to sustainable industrial practices. In alignment with this vision, SKF recognizes the important role of Internet of Things (IoT) and cloud computing technologies in realizing these goals.

1.2 THESIS AIM

The aim of this thesis is to develop a comprehensive monitoring solution and connectivity for the grinding machine at Chalmers. This will involve connecting and integrating different machines internal and external sensors to enable real-time data collection.

This thesis will focus on the collection of usable data from acoustic emission (AE) and force sensors. This will in turn pave the way for the future connectivity of multiple sensors (i.e. sensor fusion).

A solution is proposed for a physical demonstrator that can be integrated into a digital platform for capturing, storing and analyzing data.

1.3 SCOPE AND LIMITATIONS

The project aims to demonstrate a prototype digital platform for grinding machines that integrates a physical machine and its sensors with a digital platform for data storage and analysis. This "product package" is to be designed for use in various applications across different machines and could possibly be offered as a new product by SKF in near future. While demonstrating a fully functional prototype may not be feasible at this time, the thesis demonstrates the feasibility of this concept, showcasing the potential for integrating machine connectivity and data analysis into a comprehensive product offering.

The scope of this study is limited to collecting reliable data and its manual analysis. Eventually, this data must be analyzed by advanced edge computing devices connected to the machines and linked with basic or advanced ML and AI models to get relevant output. At this moment, this is seen as a limitation, except for the capabilities of the edge devices to run ML and AI models, which will be used for our thesis.

1.4 RESEARCH QUESTIONS

This section focuses on the areas that need to be examined from the beginning to the completion of this project. Following are the questions that are considered investigating.

1. What specific goals or outcomes are expected by SKF to be addressed in this thesis?
2. What equipment, sensors and software could be used to achieve data capture and cloud integration?
3. Which communication methods can transfer data from the sensors to the cloud?

1.5 LITERATURE STUDY

This section provides a comprehensive review of the existing literature on implementing Industry 4.0 technologies, specifically focusing on integrating digital platforms for grinding machines. The primary goal is to explore how sensor data acquisition and cloud integration can enhance manufacturing efficiency.

The concept of intelligent grinding has been extensively discussed in various studies, emphasizing the integration of digital technologies into CNC (Computer Numerically Controlled) grinding machines. Recent developments highlight the importance of real-time monitoring and predictive maintenance, enabled by the Internet of Things (IoT) and cloud computing, to significantly enhance the efficiency and reliability of grinding processes. The integration of multi-sensor data is crucial for optimizing these processes, transforming traditional grinding machines into cyber-physical production systems (CPPS) (Wegener, Krajnik, & Hoffmeister, 2017) (IEC, 2020).

Further supporting the importance of digital integration, another pivotal study explores the feasibility of connecting machinery and robots to industrial control services in the cloud. This research highlights the shift from traditional hierarchical manufacturing structures to more interconnected frameworks enabled by cloud manufacturing. It emphasizes the development of connector technologies to integrate older machinery with modern cloud infrastructures. The study identifies three primary connection scenarios: programmable logic controllers (PLCs), microcontrollers, and direct machine-to-cloud connections. These scenarios align with the goals of enhancing machine monitoring through standards like OPC UA and tools like LabVIEW, both of which focus on leveraging advanced technologies for improved data communication and analysis. The insights gained from cloud-based control services and the retrofitting of existing equipment provide valuable perspectives on integrating industrial machines with contemporary digital systems (Horn & Krüger, 2016).

Another critical aspect of Industry 4.0 for grinding machines involves data acquisition (Thomas Gittler, 2018). This work is focusing on collecting data from multiple sources within a machine tool. It identifies the limitations of current data collection methods, which rely heavily on PLCs and are often restricted to components controlled by the PLC, thus excluding auxiliary machinery used during machining. The diversity of control systems used by machine tool builders further complicates data interpretation. This study advocates for a comprehensive approach to data acquisition, starting from the lower levels of enterprise, manufacturing, and component hierarchies. A multichannel Data Acquisition System (DAQ) is employed to capture the power consumption of each connected piece of equipment, which is essential for Prognosis and Health Management (PHM) applications requiring high sampling rates. The study demonstrates that effective data collection through DAQ can significantly enhance resource monitoring and consumption optimization on the shop floor, thereby improving overall manufacturing efficiency.

2. Theory

2.1 GRINDING

Grinding can be associated with the three distinct abrasive mechanisms of sliding, plowing, and chip formation (cutting) (Malkin & Guo, 2008). Initially, the cutting edge of the grit slides on the workpiece surface (Zone I), followed by a phase of elastic and plastic deformation – inducing plowing of the work material (Zone II). Only when the grit has penetrated deep enough into the workpiece, i.e. where the chip thickness h_{cu} is equal to the grit-penetration depth T_μ does actual chip formation/cutting begin (Zone III). This is schematically illustrated in the Figure 1 below.

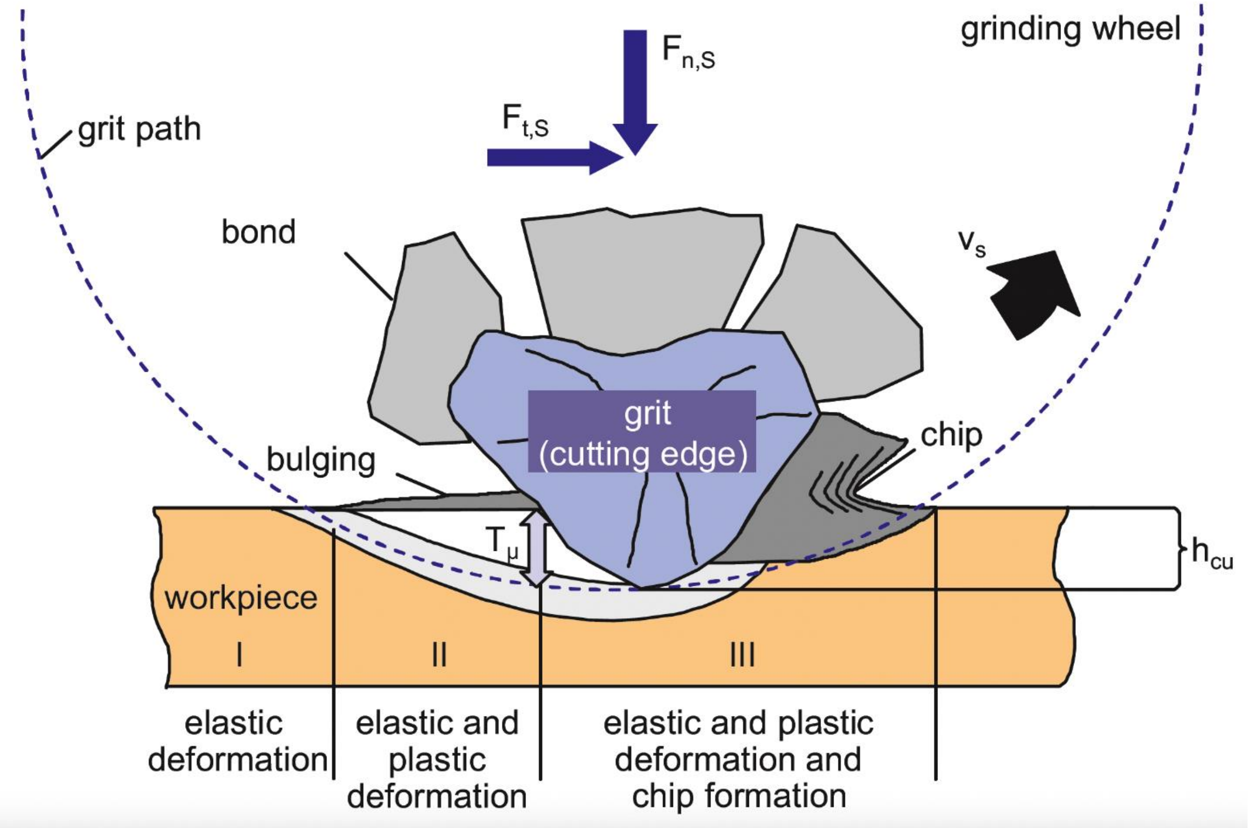


FIGURE 1 MATERIAL REMOVAL MECHANISMS FOR GRINDING (KLOCKE, 2017)

Note that not all grits on the grinding wheel surface are engaged in all three stages of material removal; some only rub or plow. The later mechanisms generate extensive heat and forces, resulting in relatively high specific energy compared to other metal-cutting processes. Larger grit-penetration depth (or chip thicknesses) in grinding typically result in a greater proportion of cutting over rubbing and plowing, lower specific energies, greater forces on the grits, greater wheel wear and a rougher surface finish (Badger, Dražumerič, & Krajnik, 2021).

2.2 PROCESS GEOMETRY AND KINEMATICS AND GRINDING FORCES

Forces developed between the grinding wheel and the workpiece during the grinding operation due to the grinding action – comprised of the sum of the forces of the three component grit-workpiece interactions: sliding, plowing, and chip formation (cutting). For surface grinding operations, as illustrated in Figure 2, the total force vector can be separated into a tangential component F_t and a normal component F_n. These two force components can be readily measured using a dynamometer. These forces largely depend on:

- Process geometry – determined by the wheel diameter d_s and the depth of cut a (which result in a certain geometric contact length l_c);
- Process kinematics – determined by the wheel speed v_s, and workpiece speed v_w.

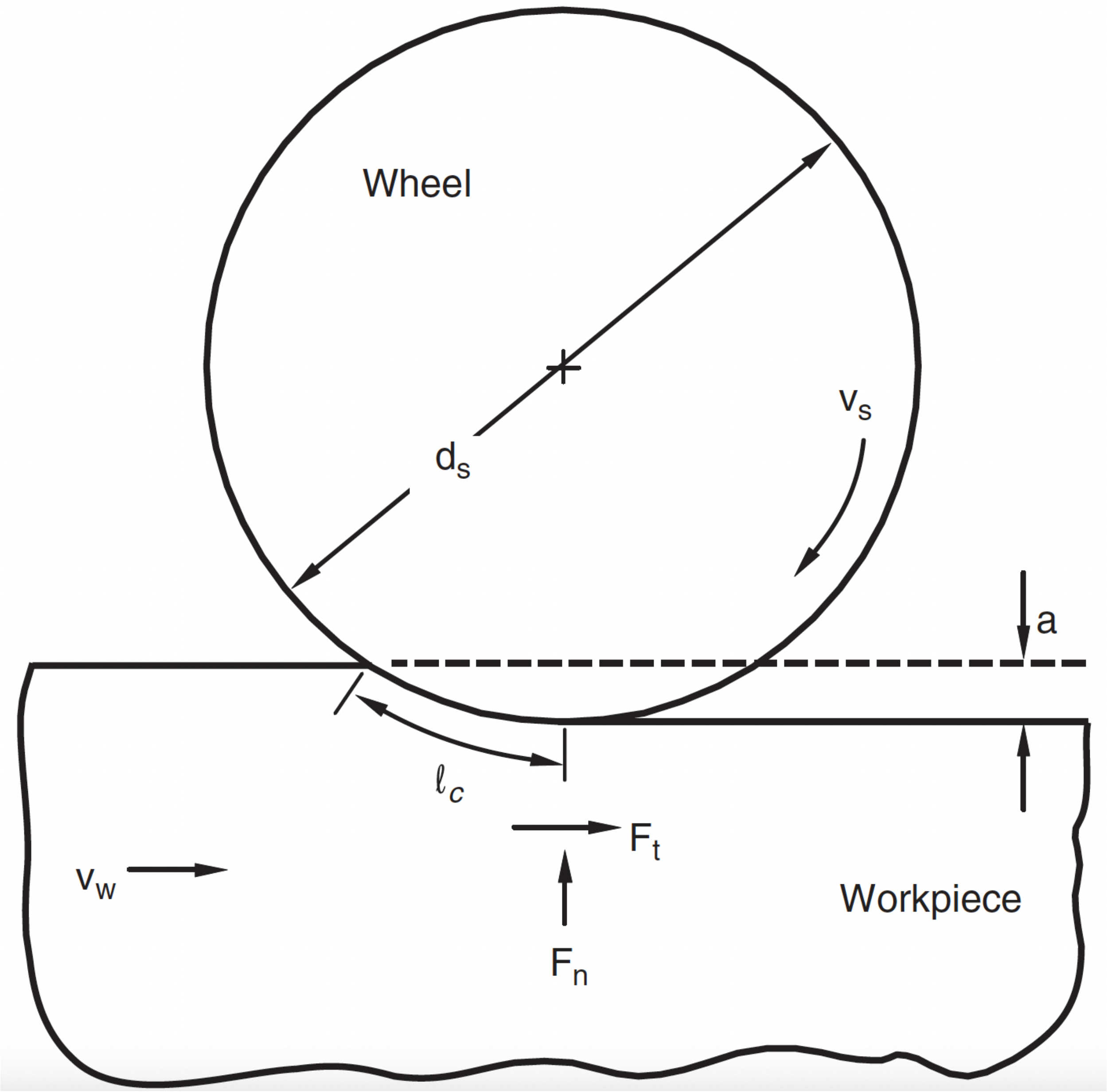


FIGURE 2 THE GEOMETRY OF SURFACE GRINDING AND ILLUSTRATION OF FORCE COMPONENTS

3. METHODOLOGY

In this chapter the methodology used will be discussed, explaining the process from understanding the thesis needs to conducting experimental work and recording grinding forces.

3.1 IMPLEMENTATION OF THESIS WORK

To get the project started, some meetings were held to better understand what is to be achieved by the end. Which means everything that needs to be done and what is to be prioritized. The first meeting at SKF headquarters was with Magnus, where the whole project was mapped out in a brainstorming manner. The potential outcomes and strategies for achieving them were discussed, even if some of the proposed actions might have been unfeasible. During this period, the FREI (Factory Real-Time Edge innovation) Project at SKF was introduced to regarding digital connectivity, and this thesis is one of the branches of this extensive FREI Project. Note that the thesis was regarded as a relatively small part of the larger project at SKF. The larger umbrella project includes a team of highly skilled professionals in the manufacturing development department at SKF, each with their area of expertise. The team consists of individuals with software backgrounds and others with mechanical and electrical engineering expertise. Collectively, they are working to connect CNC machine with sensors, enabling the display of different parameters in the cloud. This will facilitate decision-making and further AI processing and feedback (bi-directional communication).

The internal team at SKF consists of various experts, including manufacturing and processing specialists, software and digital infrastructure developers, and experts who focus on testing and implementing innovative digital technologies tailored to SKF's requirements. Data scientists in Sweden are working on developing use cases to implement on new hardware and software in collaboration with the team in Poland.

Also, weekly meetings with several suppliers and vendors support SKF in digital connectivity projects. The team consists of experts from Microsoft Azure, Edge connectivity device suppliers, the internal team involved in establishing the lab to test the new hardware and software infrastructure, and the internal SKF team members.

There was more involvement with the internal meetings than with the meetings with external vendors. Internal meetings were more focused on implementing the ideas and working with them. The external vendor meetings were to find the best possible hardware and software and test it to decide how to process based on available options or to look into new ventures.

3.2 USE CASES/DEMONSTRATORS

In the context of SKF's digital connectivity initiative, practical use cases demonstrate the potential commercial value derived from integrating sensors and data analytics in grinding machines. These use cases encompass various parameters and sensors to enhance operational efficiency, predictive maintenance, and overall process optimization.

One notable use case involves analyzing acoustic emission (AE) signals generated during grinding operations. By deploying AE sensors, SKF aims to capture and analyze subtle variations in acoustic signatures, which can serve as indicators of grinding aggressiveness, wheel dressing, wheel sharpness/tool wear, machine condition, and process anomalies (Badger, Murphy, & E. O'Donnell, 2018). This proactive monitoring approach enables early detection of potential issues, thereby minimizing downtime and maximizing machine uptime (e.g., higher overall equipment effectiveness – OEE). (Badger, 2023)

Additionally, the integration of force sensors presents another compelling use case. By monitoring the forces exerted during grinding processes, SKF can gain valuable insights into the grindability of different materials, grinding-wheel performance, and process efficiency and stability. This information enables informed decision-making regarding tool selection and machining parameters, improving surface finish quality and reducing scrap rates.

Temperature sensors represent yet another critical aspect of SKF's digital connectivity strategy. By monitoring temperature variations in crucial machine components such as bearings, spindles, and coolant systems, SKF can detect overheating events, lubrication issues, and coolant deficiencies in real-time. This proactive approach to temperature monitoring helps prevent costly equipment failures and extends the service life of critical machine components. (Ahmer, 2023)

Furthermore, SKF explores the integration of vibration sensors to monitor machine vibration levels during grinding operations. SKF can identify potential sources of machine instability, tool chatter, and imbalance by analyzing vibration signatures. This proactive approach enables corrective actions to be taken to optimize machine performance, enhance surface finish quality, and prolong tool life (Mahata, Shakya, & Babu, 2021) (Lajmert, Sikora, Bogdan, & Ostrowski, 2017).

The practical use cases for digital connectivity in grinding machines underscore SKF's commitment to leveraging sensor data and advanced analytics to drive tangible business outcomes. By harnessing the power of data-driven insights, SKF aims to empower manufacturers with the tools and technologies needed to achieve higher productivity levels, efficiency, and competitiveness in the modern manufacturing landscape.

Within a Factory

Monitoring is crucial for condition-based maintenance of machines or adaptive process control, such as predicting anomalies in machine performance, and performing dressing based on the real-time loading/wear of the wheel. Maintenance can be planned to prevent surprises such as failures of machine components that may lead to machine downtime. The workload on this machine can be decided well before planned maintenance, allowing other machines to be allocated during this activity. Thus, commitments to customers can be met without delay. (Ahmer, Marklund, Gustafsson, & Berglund, 2022)

Supporting a Factory Remotely

SKF has several factories worldwide. To support a factory with machining recommendations or to study the actual process being implemented on the shop floor, a person must visit the site and assess the situation before making any recommendations. However, with digital connectivity to monitor real-time machine and production data, it would be much easier to support multiple factories in a shorter time frame, as in-person visits could be reduced or even eliminated in most cases.

Testing The Machinability in Real-Time

The functional performance of precision components such as bearings depends on their surface integrity (including surface texture) and geometric accuracy. To achieve this high precision, bearings undergo various material-conversion and finishing processes, as shown in Figure 3 below. Here, “material conversion processes” refer to processes from raw material to machining such as turning. The hardness and microstructure of the machined component is then refined in the thermal treatment process to produce a hardened component. In the finishing process, material is removed by grinding (or hard turning) is used to produce components with specified dimensions and tolerances. In addition, the finishing process imparts the required geometrical accuracy (e.g., roundness, profile and roughness) to the component.

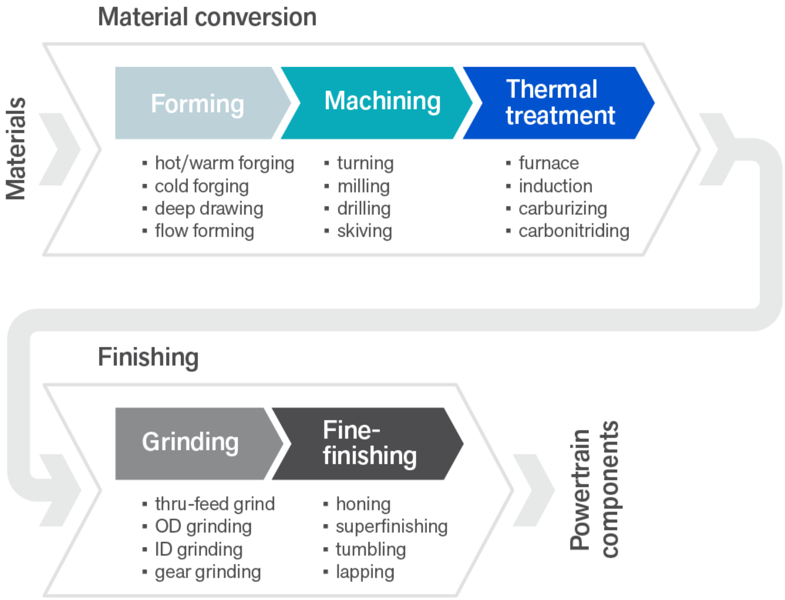


FIGURE 3 TYPICAL PRODUCTION CHAIN IN THE MANUFACTURE OF PRECISION COMPONENTS (KRAJNIK, HASHIMOTO, KARPUSCHEWSKI, JANNONE DA SILVA, & AXINTE, 2021)

With real-time grinding monitoring demonstrator at Chalmers, the mechanical (and indirectly thermal) load on the workpiece can be observed. If this results in more stable loads during grinding while achieving the required finish size and specifications, this approach can be implemented on a mass scale. Additionally, different thermal treatments can be tested, and grindability can be monitored to find the best, low-cost, and time-efficient process without sacrificing quality or performance.

3.3 ETHICAL CONSIDERATIONS

Ethical considerations are paramount in guiding the project's conduct, ensuring integrity, respect for individuals, and adherence to moral principles. The project upholds several ethical considerations:

Ensuring data privacy and confidentiality is a top priority, achieved through informed consent, anonymization of sensitive data, and secure data handling practices. Participants are provided comprehensive information about the project, risks, and benefits, obtaining informed consent before participation.

Fair treatment of all involved individuals, regardless of their role or status, is upheld. Equitable access to opportunities and benefits is ensured, with measures in place to prevent discrimination or bias.

Transparency and accountability are maintained through clear communication, documentation of project procedures, and mechanisms for addressing ethical concerns. The project operates with honesty, integrity, and accountability at all times.

By adhering to these ethical considerations, the project aims to uphold the highest standards of integrity and professionalism, safeguard the well-being of participants, and maintain the integrity of the research process.

3.4 APPROACH OF CONDUCTING THE THESIS WORK

The selected approach draws inspiration from the iterative design process commonly utilized in mechanical engineering. The methodology aligns with the acquired knowledge and skills from participation in the product development program. While the project's structure may not be tailored explicitly for design and product development, valuable insights can still be gleaned. (Rastani, Bagheri, & Ogata, 2007)

The iterative approach, involving testing, designing, and subsequent refinement, offers ample opportunities for enhancement. Initially, a comprehensive plan was devised to outline the project's objectives and execution strategy. Given the unfamiliarity with certain aspects due to their absence in the academic curriculum, referencing established engineering design processes provided invaluable guidance.

Regular Meetings with Stakeholders at Chalmers and SKF Team

Regular discussions and meetings with stakeholders from both Chalmers and the SKF team were integral to the project's progress. These sessions, held on a weekly basis, provided a platform for sharing updates, soliciting feedback, and brainstorming solutions to challenges encountered. The participation of knowledgeable individuals ensured valuable insights and constructive feedback, contributing significantly to the project's advancement.

Documentation and Collaboration of Work

Despite operating from Chalmers' campus, an efficient system was imperative to document and monitor our progress meticulously. Throughout the project, Microsoft's OneDrive was the primary platform for comprehensive documentation and collaborative efforts.

Every pertinent document, including data sheets, images, and project-related materials, found a designated space within the OneDrive repository. This centralized hub facilitated seamless access to crucial information, ensuring transparency and accessibility for all stakeholders.

Moreover, by leveraging OneDrive's collaborative features, team members could effortlessly contribute to and review project documentation in real-time. This fostered a cohesive working environment, promoting effective communication and collective decision-making.

Throughout the project, various tools were employed to streamline documentation, collaboration, and visualization processes. One such tool, Miro, proved instrumental in establishing a structured schedule and task management framework. Using Miro created a clear project roadmap and outlined key milestones, improving the project planning coherence.

Draw.io emerged as a valuable asset in the project toolkit, facilitating the creation of comprehensive visualizations and C4 diagrams to elucidate the project's architectural intricacies. C4 diagrams, renowned for their efficacy in visualizing software architecture, were leveraged to depict the essential components and interconnections necessary for realizing the digital connectivity of manufacturing machines to the cloud.

By harnessing these tools' capabilities, a conducive environment for collaboration, planning, and visualization was cultivated, thereby enhancing project efficiency and effectiveness.

3.5 EXPERIMENTAL WORK

This chapter explains how the work has been done by understanding the necessary equipment and related software. After which, small tests were conducted to capture the sensor data and check the quality of the data. Apart from this, a few intermediate tests were conducted before data can be sent to cloud, which are explained in this section in the following steps.

3.5.1 STEP 1: STUDY OF USER MANUALS FOR THE HARDWARE AND SOFTWARE

The successful execution of the project depended on the utilization of various hardware and software components to achieve digital connectivity. An extensive understanding of the hardware and software was imperative to navigate this terrain effectively. This endeavor entailed comprehensive research to gather relevant information from diverse sources, including datasheets for the piezoelectric dynamometer and charge amplifier from Kistler, the DAQ system from National Instruments, and the acoustic sensor from Accretech. Moreover, delving into the user manual for the OPC UA server embedded in the Sinumerik 840D grinding machine interface provided crucial insights into its operation and integration possibilities.

In addition to hardware comprehension, thorough studies were conducted on the software aspect, mainly focusing on LabVIEW. The exploration encompassed understanding the intricacies of LabVIEW functionality and devising methodologies to achieve the desired data acquisition capabilities for seamless communication with OPC UA, subsequently transmitting data to an MQTT broker, which is a server. Furthermore, in-depth investigations into OPC UA and MQTT protocols were undertaken to discern their operational mechanisms and compatibility with LabVIEW, facilitating informed decisions on their suitability for integration into the project framework.

Exploring LabVIEW for Data Acquisition Purposes

A thorough understanding of LabVIEW was imperative to capture sensor data from the dynamometer. This involved a comprehensive study of LabVIEW's functionalities and capabilities to ensure successful data acquisition. It began with extensive research, leveraging online resources provided by National Instruments, the creators of LabVIEW. These resources offered a wealth of tutorials, guides, and how-to articles, covering various aspects of LabVIEW usage. Additionally, YouTube proved to be a valuable source of inspiration, with numerous tutorials offering practical insights and tips for mastering LabVIEW.

LabVIEW operates on a graphical programming platform, facilitating coding through visual elements rather than traditional text-based syntax. This posed both challenges and opportunities as the exploration of LabVIEW unfolded.

The initial stages of program development were characterized by trial and error as the exploration of LabVIEW's graphical interface progressed. Through perseverance and the use of resources, a functional program tailored to the specific requirements of data acquisition from the dynamometer was eventually realized.

Subsequent iterations of the program focused on refinement and enhancement, with additional features such as the integration of communication protocols like OPC UA being incorporated. This iterative process of refinement and improvement was guided by insights gained from practical experimentation and stakeholder feedback.

Exploration and mastery of LabVIEW constituted a critical aspect of the project's methodology, enabling the development of a robust and efficient solution for sensor data acquisition. Through diligent study and hands-on experimentation, the project progressed towards harnessing LabVIEW's full potential to achieve its objectives and pave the way for further advancements in the project's development.

3.5.2 STEP 2: SETTING UP THE DEVICES

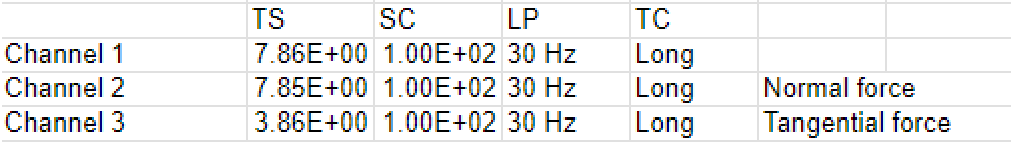
A systematic approach was undertaken to effectively capture data from external sensors that are to be connected to the machine. As stated earlier, this process began with a comprehensive understanding of the hardware and software involved in the data acquisition process. The primary hardware components included the dynamometer, charge amplifier, DAQ device, and computer running LabVIEW software.

The dynamometer, which serves as the force sensor, was connected to a charge amplifier to amplify the acquired signals. These signals were then transmitted to the DAQ device for digital conversion. LabVIEW software was employed to interpret and process the digital signals, enabling real-time monitoring and analysis.

Setting up the hardware provided by SKF was a critical step towards initiating the data acquisition process. This phase involved physical installation and ensuring proper configuration and calibration of the devices to facilitate accurate and reliable data collection.

As a heavy and sensitive device, the dynamometer required meticulous handling to prevent any damage during installation. Careful consideration was given to its placement and orientation to ensure stability and optimal performance.

The charge amplifier, which plays a crucial role in amplifying and conditioning the signals from the dynamometer, requires careful handling and configuration. Cables were connected with precision to avoid any signal degradation or interference. SKF provided configuration values for the amplifier tailored to specific applications, ensuring that the amplifier was optimized for the intended use case. The critical value to configure was the Trust Sensitivity (TS), which reflects the stability of the sensitivity setting of the charge amplifier. The Scaling factor (SC) adjusts the scaling of the output signal relative to the input charge. It essentially determines the ratio of the output signal to the input signal. The Low pass filter (LP) is a filter setting that controls the cutoff frequency below which signals are passed through and above which signals are attenuated. It helps in reducing high-frequency noise from the measured signal. Lastly, the Time constant (TC), which defines the charge amplifier's response time, is typically related to how quickly the amplifier can react to changes in the input signal. The amplifier used in this project is type 5019B and has three channels for connecting sensors. The below image displays a table of the values used for this amplifier.



	TS	SC	LP	TC		
Channel 1	7.86E+00	1.00E+02	30 Hz	Long		
Channel 2	7.85E+00	1.00E+02	30 Hz	Long	Normal force	
Channel 3	3.86E+00	1.00E+02	30 Hz	Long	Tangential force	

FIGURE 4 CONFIGURATION VALUES FOR CHARGE AMPLIFIER 5019B (KISTLER, 2024)

The DAQ (Data Acquisition) device was the interface between the sensors and the computer system running LabVIEW software. Proper placement and grounding of the DAQ device were essential to ensure the integrity of the acquired signals. Grounding considerations were critical to minimize electrical noise and ensure accurate data acquisition.

Throughout the setup process, attention to detail and adherence to best practices were paramount to ensure the successful deployment and operation of the hardware components. By meticulously addressing each aspect of the setup, from physical installation to configuration, the foundation was laid for effective data acquisition and subsequent analysis. The following images show the machine and the hardware setup at Chalmers. Figure 5 shows the picture of the Grinding machine at Chalmers, and Figure 6 shows the setup where one of the computers is used to connect to the grinding machine, and the other computer captures data from the dynamometer, before which the signal passes through the charge amplifier and DAQ.

FIGURE 5 THE SURFACE GRINDING MACHINE IN THE CHALMERS LAB

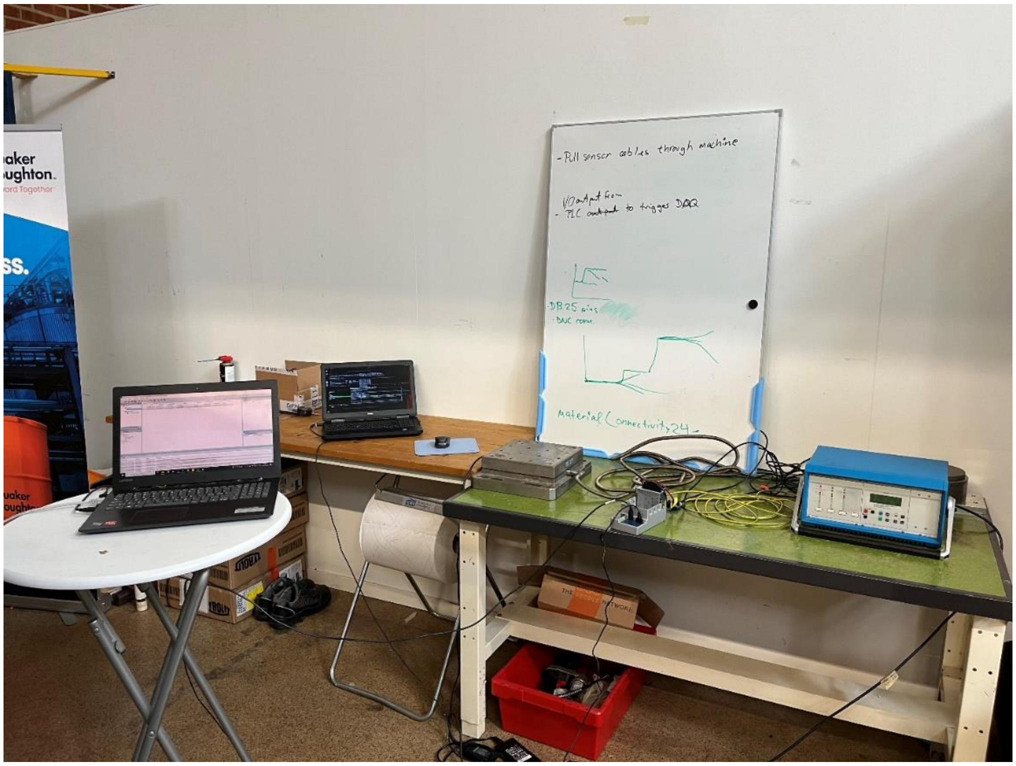


FIGURE 6 SETUP FOR THE DATA ACQUISITION FROM THE DYNAMOMETER AND THE GRINDING MACHINE

The images below illustrate the connectivity setup of multiple devices. Figure 7 shows the Ethernet cable connection at Chalmers (grinding machine), which is crucial for establishing connectivity to cloud services.

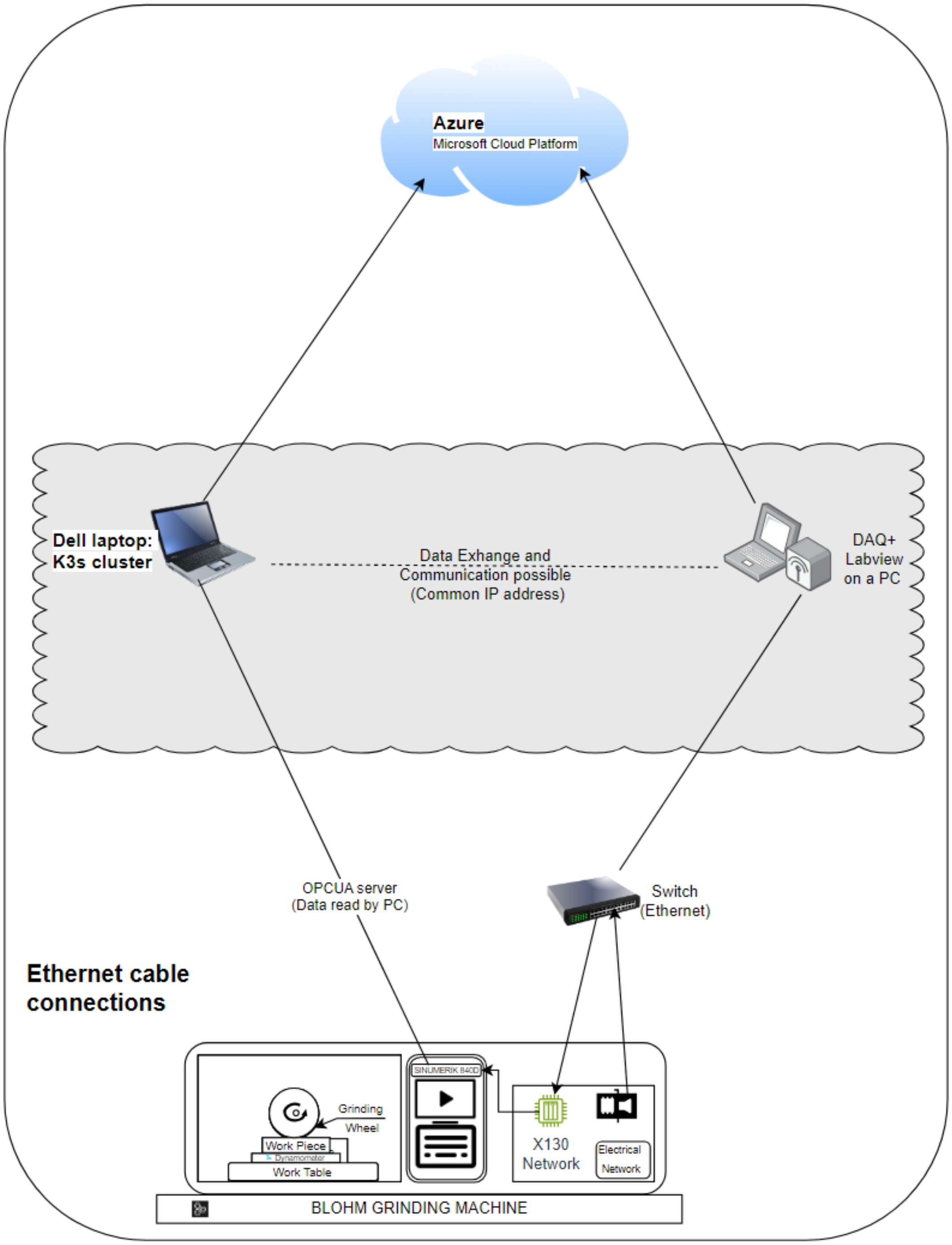


FIGURE 7 ETHERNET CABLE CONNECTION AT CHALMERS FOR ESTABLISHING CONNECTION WITH CLOUD SERVICES

The diagram in Figure 8 shows the detailed connection of Ethernet cables to and from the machine. This step is essential for enabling cloud connectivity and ensuring seamless data transfer from the grinding machine to the cloud infrastructure.

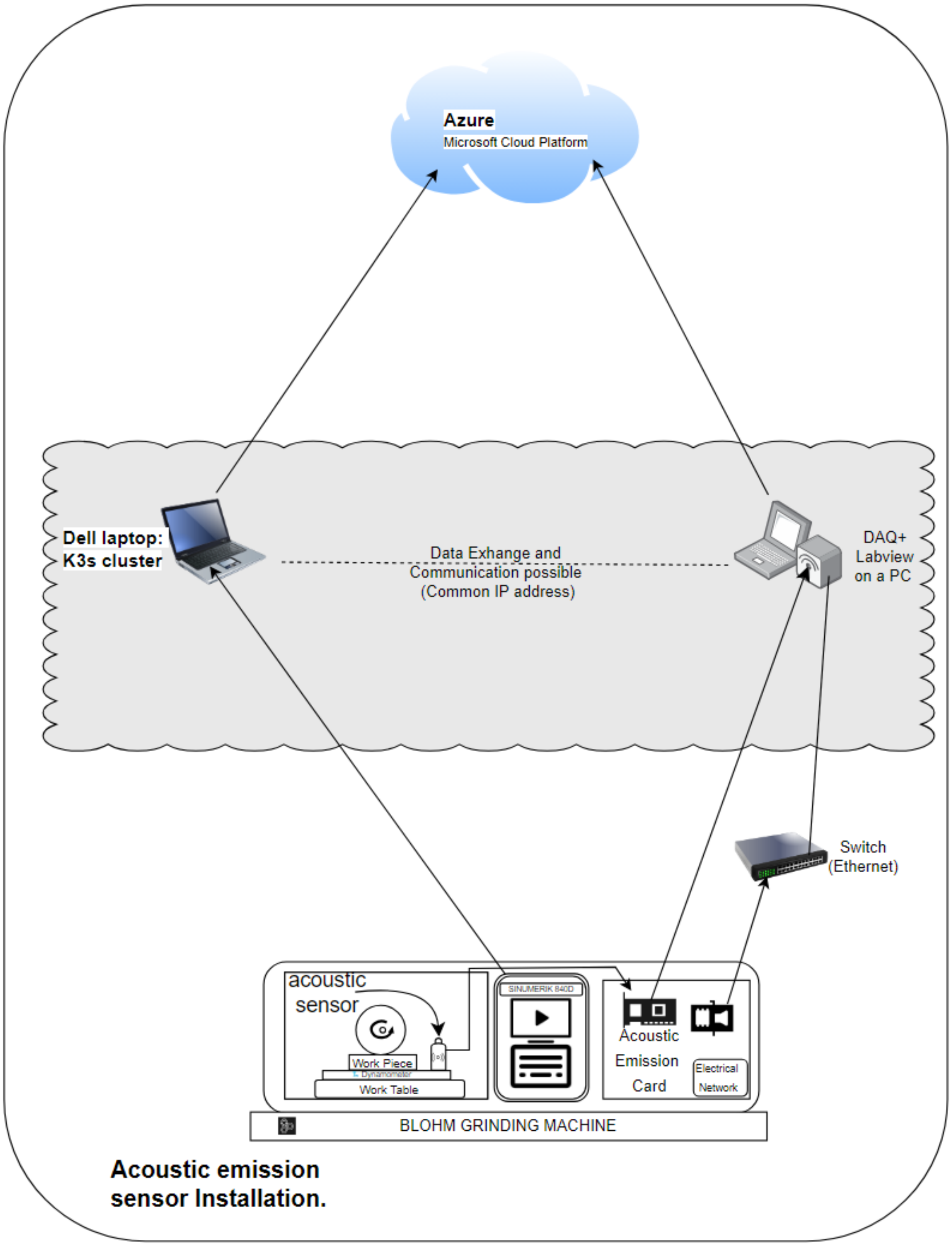


FIGURE 8 ETHERNET CABLE CONNECTION AT CHALMERS (ACOUSTIC EMISSION SENSOR) FOR ESTABLISHING CONNECTION WITH CLOUD SERVICES

Brief Introduction to Hardware and Software Components Used in the Project

The following section explains the foundations behind the hardware and software used in the thesis.

Strain Gauge and Piezoelectric Sensor

Strain gauges are widely used in engineering and scientific applications to measure the strain or deformation of a material under stress. These sensors are typically made of thin metallic foil or wire arranged in a grid pattern. When the material undergoes strain, the gauge's electrical resistance changes proportionally. This change in resistance can be measured and correlated with the amount of strain experienced by the material.

The principle behind strain gauge operation is based on the piezoresistive effect, where the electrical resistance of a material changes when subjected to mechanical strain. This change in resistance is typically minimal but can be accurately measured using sensitive instrumentation.

Strain gauges are commonly used in various applications, including structural monitoring, load testing, and stress analysis. They provide valuable insights into the behavior of materials under different conditions and help engineers optimize designs for performance and reliability. (Higson, 1964)

Piezoelectric sensors are another type widely used in engineering and scientific fields. Unlike strain gauges, which measure strain directly, piezoelectric sensors detect changes in pressure, acceleration, or force by converting mechanical energy into electrical signals.

Piezoelectric materials exhibit the piezoelectric effect, generating an electric charge in response to mechanical stress. Conversely, they also deform in response to an applied electric field. This bidirectional relationship allows piezoelectric sensors to function as both sensors and actuators.

Piezoelectric sensors are commonly used in various applications, including vibration monitoring, impact detection, and ultrasonic measurements. They offer advantages such as high sensitivity, fast response times, and wide frequency ranges, making them suitable for diverse measurement tasks. (F. Tressler, Alkoy, & E. Newnham, 1998)

One notable difference between strain gauges and piezoelectric sensors is how they measure force. While strain gauges directly measure the mechanical strain or deformation of a material, piezoelectric sensors detect changes in force indirectly by converting mechanical energy into electrical signals. In piezoelectric sensors, the applied force generates a voltage output proportional to the magnitude of the force. Unlike strain gauges, where the resistance changes, the voltage output from piezoelectric sensors eventually drops as the force is removed due to the relaxation of the piezoelectric material. (Gautschi, 2002)

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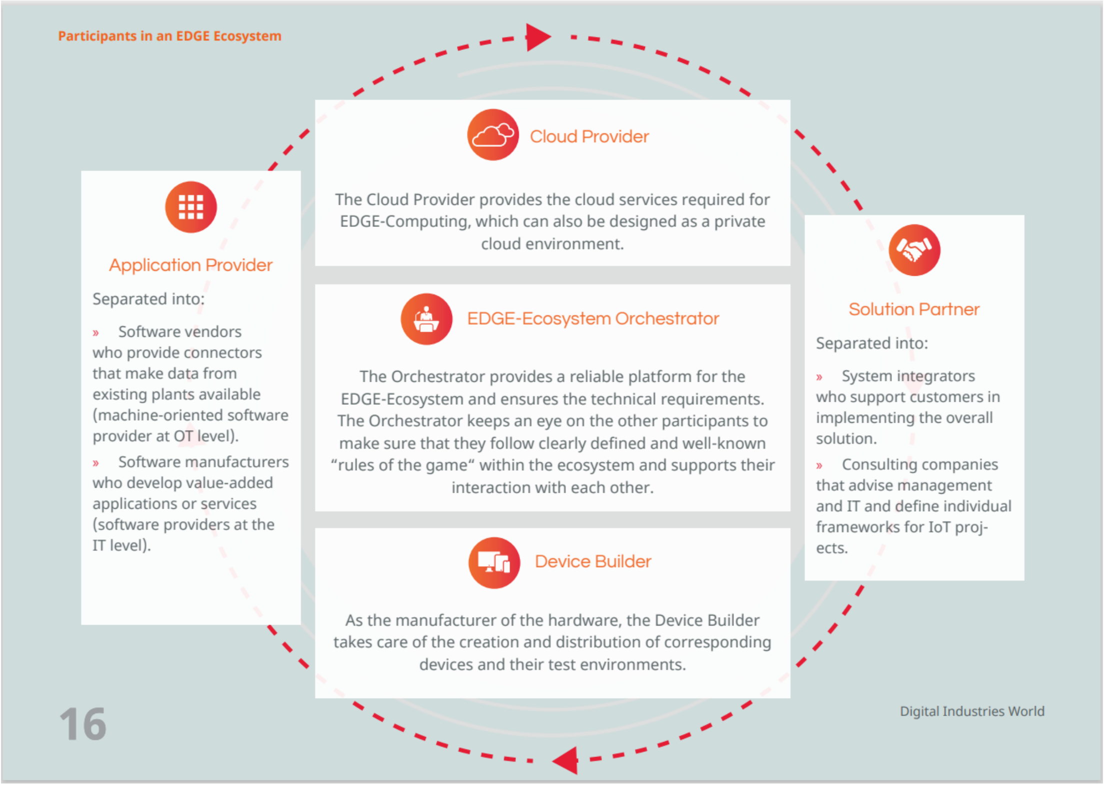
Edge Computing Device

Edge computing refers to data processing performed at or near the source of data generation rather than relying solely on a centralized data-processing warehouse. Edge devices, ranging from industrial computers and sensors to mobile devices, are equipped with computing resources to perform data processing tasks locally. This approach significantly reduces latency, minimizes bandwidth usage, and enhances data security by processing data locally on devices at the network's edge.

Edge computing is instrumental in scenarios requiring rapid decision-making based on real-time data analysis, making it ideal for applications in smart manufacturing, autonomous vehicles, and IoT implementations. By decentralizing computing resources, edge devices offer a scalable solution to manage the increasing data volumes generated by modern industrial equipment, ensuring timely and efficient operations.

Edge computing's applications are made possible through the collaboration of various stakeholders, including edge device builders, application providers, cloud providers, solution partners, and edge ecosystem orchestrators.



Participants in an EDGE Ecosystem

Cloud Provider

The Cloud Provider provides the cloud services required for EDGE-Computing, which can also be designed as a private cloud environment.

Application Provider

Separated into:

- » Software vendors who provide connectors that make data from existing plants available (machine-oriented software provider at OT level).
- » Software manufacturers who develop value-added applications or services (software providers at the IT level).

EDGE-Ecosystem Orchestrator

The Orchestrator provides a reliable platform for the EDGE-Ecosystem and ensures the technical requirements. The Orchestrator keeps an eye on the other participants to make sure that they follow clearly defined and well-known "rules of the game" within the ecosystem and supports their interaction with each other.

Solution Partner

Separated into:

- » System integrators who support customers in implementing the overall solution.
- » Consulting companies that advise management and IT and define individual frameworks for IoT proj-ects.

Device Builder

As the manufacturer of the hardware, the Device Builder takes care of the creation and distribution of corresponding devices and their test environments.

16

Digital Industries World

FIGURE 9 EDGE COMPUTING (A HITCHHIKER'S GUIDE TO EDGE-TECHONOLOGY, 2022)

Integrating edge computing in grinding machines is a critical advancement in enhancing manufacturing efficiency under Industry 4.0. Edge computing processes data near the source, reducing the need for data transfer to centralized cloud centers, thus minimizing latency, cutting costs, and improving security.

Edge computing in grinding machines, highlighted in the 2017 CIRP Keynote paper, involves transforming these machines into cyber-physical production systems (CPPS). This digital transformation enables real-time data acquisition, processing, and analysis through sensors and advanced analytics, facilitating immediate decision-making and optimization of grinding processes (Wegener, Krajnik, & Hoffmeister, 2017).

For instance, CERATIZIT/Tyrolit's ToolScope system uses edge devices to monitor machine signals and external sensors, aiding wear monitoring and adaptive feed control. Similarly, Reishauer's ARGUS monitoring system integrates edge devices with cloud applications to provide comprehensive real-time analysis and historical data evaluation, ensuring consistent quality control (Tyrolit, 2024).

Danobat's grinding machine showcases edge computing's practical application, employing a plug-and-play edge device to process data from the machine's PLC, sensors, and drives, while also connecting to the cloud for broader data analytics. This setup enhances signal processing speed and data management (Hartmann, 2020).

As edge technology relies on integrating existing setups with new technologies, robust security measures are essential for successful implementation. A business case must be identified for this product package to leverage its capabilities while also considering future scalability. Edge computing in grinding machines allows for efficient real-time data processing, leading to optimized operations and enhanced manufacturing efficiency. This technology is crucial for the future of digitalized manufacturing, aligning with the principles of Industry 4.0 (Anderson Carvalho, Krpalkova, Campbell, Walsh, & Doody, 2019).

Force Sensor (Dynamometer)

A force dynamometer is employed to capture the forces on the workpieces to determine the outcome of grinding wheel loading on different compositions. The dynamometer used in this study is a multicomponent dynamometer Type 9255B from Kistler, capable of measuring forces in the x, y, and z directions. This dynamometer consists of four built-in piezoelectric sensors that generate a voltage when an external force acts on them. (Kistler, 2024)

The output from these sensors is conditioned to a suitable scale, and the desired output, force, is recorded.

FIGURE 10 KISTLER'S DYNAMOMETER 9255B (KISTLER, 2024)

Acoustic Emission

Acoustic Emission (AE) is a powerful monitoring technique that captures the sounds generated by the deformation or fracture within materials under stress. In machining, such as grinding, AE helps understand the cutting dynamics, identify tool conditions, and detect any abnormalities in the process. By analyzing AE signals, one can differentiate between different types of tool-workpiece interactions, predict tool wear, and optimize cutting conditions for enhanced performance and longevity of the machine components. The detailed analysis of AE signals is critical to the thesis, enabling predictive maintenance and real-time monitoring to improve efficiency and reduce downtime in industrial settings. (Scruby, 1987)

Acoustic Sensors

Acoustic Emission sensors are devices designed to detect the high-frequency sound waves produced when materials undergo deformation or fracture. These sensors convert kinetic energy from sound waves into electrical signals. Positioned close to or directly on the surface of the monitored machinery, AE sensors can capture the subtle acoustic signals emitted during machining processes. The electrical signals generated by the sensors are then analyzed to identify patterns that indicate regular operation, tool wear, or potential failures, making AE sensors crucial for real-time monitoring and predictive maintenance strategies in manufacturing environments. The acoustic emission equipment used for this project was the SB-522-Q control card and the SB-3276 sensor (Accretech, 2024).

AE sensors are also instrumental in wheel balancing and reducing cycle time in grinding operations. Monitoring the AE signals makes it possible to detect imbalances in the grinding wheel at an early stage. This allows corrective measures to be taken before significant damage occurs, ensuring smoother operations and prolonging the machine's life. Additionally, AE sensors can help optimize the grinding process by identifying the most efficient grinding parameters, thereby reducing cycle time without compromising the quality of the workpiece (Dornfeld, 1992).

FIGURE 11 ACOUSTIC EMISSION SENSOR FROM ACCRETECH SB-3276 (ACCRETECH, 2024)

Charge Amplifiers

Charge amplifiers are devices that help convert very low charge signals generated by devices such as piezoelectric sensors to proportional voltage signals (in volts). The charge amplifier converts the negative charge generated by the piezoelectric sensors because of the applied pressure, and the charge generated is positive voltage proportional to the pressure acting on the sensor. (Kistler, 2024)

This project uses a Kistler multichannel charge amplifier 5019B to measure combined force and moment measurements. However the focus was solely on capturing force measurements.

FIGURE 12 MULTICHANNEL CHARGE AMPLIFIER TYPE 5019B FROM KISTLER (KISTLER, 2024)

Data Acquisition System (DAQ)

Data Acquisition, as the name indicates, is collection or measurement. It can be an electrical or physical phenomenon. In this case, it's electrical in the form of voltage acquisition. It could also be current, temperature, or sound measurements. DAQ measurement package consists of a combination of sensors, DAQ measurement hardware, and a computer with compatible software to interpret the captured data. The following image shows the DAQ device used during the project. The DAQ module used in this project is the NI-9215, equipped with sound isolation for safety and noise immunity (National Instruments, 2024).

FIGURE 13 DATA ACQUISITION DEVICE: MODULE NI-9215 BY NATIONAL INSTRUMENTS (NATIONAL INSTRUMENTS, 2024)

LabVIEW Software

LabView is a software program that has a graphical programming user interface. This software can connect with and instrument, even with manufacturer instruments other than National Instruments. It is a fast and convenient way to conduct tests in a lab environment to serve as a very helpful and productive solution to capture data, in addition to that it also has an integrated user interface in connection to programming, connectivity to any instruments. It has multiple analysis functions built into and works with programming languages such as PYTHON, C, and .NET. (National Instruments, 2024; Accretech, 2024) The images below show LabVIEW on a laptop with a data acquisition program reading signals from the dynamometer. The photo (Figure 14) below shows a graph with no load variation (normal or tangential). It can be difficult to see the graph in this figure, but the important thing to see is the changes in the graph when load is applied or not. The image (Figure 15) shows the graph again when load is applied, and there are readings in the graph.

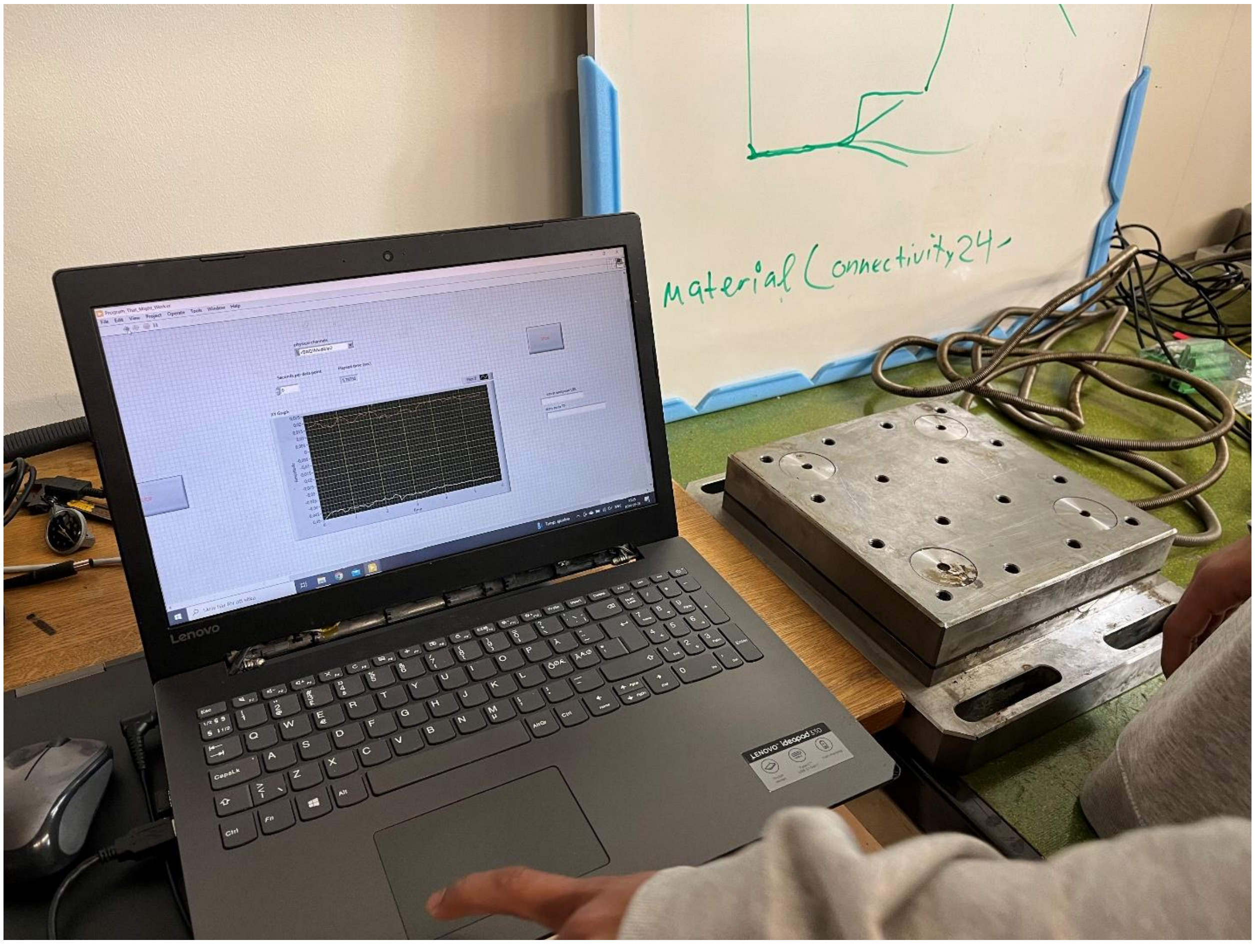


FIGURE 14 LABVIEW READING FROM THE DYNAMOMETER WITH NO LOAD APPLIED.

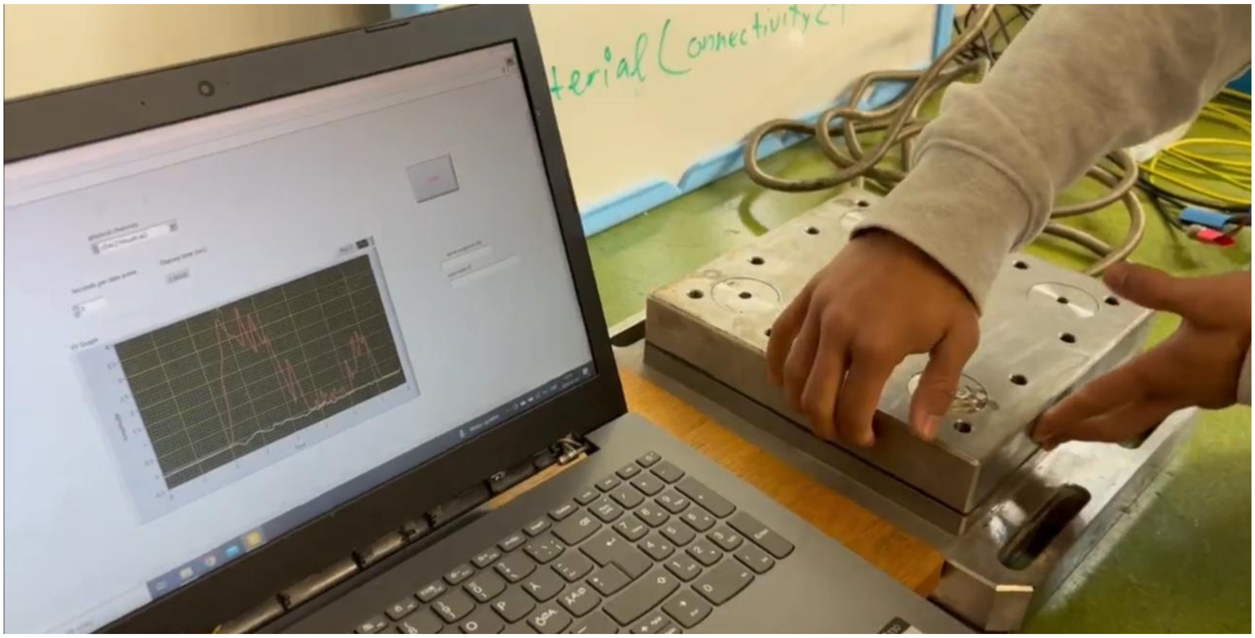


FIGURE 15 LABVIEW READING FROM THE DYNAMOMETER WITH LOAD APPLIED

OPC UA

OPC UA (Open Platform Communications Unified architecture) is a machine-to-machine (e.g., sensors to cloud) communication protocol for industrial automation (IEC, 2020). It facilitates secure and reliable data exchange in industrial environments, enabling interoperability between different hardware and software platforms. OPC UA supports complex data structures and provides a robust security framework essential for modern industrial applications. Its architecture is scalable, extending from the shop floor to the enterprise level. It enables the facilitation of real-time monitoring and optimization of industrial processes. The protocol is seen as a cornerstone in the digital transformation of manufacturing since it allows for many industry 4.0 initiatives through its ability to model complex systems and processes, such as the creation of digital twins and predictive maintenance. Its role in the thesis is essential as it allows communication between the grinding machine and cloud-based analytical tools. (Cavalieri & Cutuli, 2010)

MQTT

MQTT (Message Queuing Telemetry Transport) is a simple and lightweight messaging protocol designed for devices with limited processing power and unreliable network connections. It is commonly used in the Internet of Things (IoT) for sending data between devices. MQTT works on a publish-subscribe model, where devices can publish information on a topic or subscribe to a topic to receive information. This system allows devices to communicate efficiently without needing a direct connection (ISO/IEC20922, 2016).

In this project, MQTT sends force data from sensors to the cloud. Using MQTT, data can be transmitted reliably even if the network is unstable. This makes it possible to monitor the machining processes in real-time, improving operational efficiency and enabling predictive maintenance. MQTT’s lightweight nature and reliability make it an ideal choice for industrial applications, fitting well within the principles of Industry 4.0, which focuses on integrating digital technologies into manufacturing processes.

Both MQTT and OPC UA can be essential in transmitting data to the cloud because they complement each other’s strengths. MQTT’s lightweight and efficient messaging capabilities make it ideal for quickly sending large volumes of data from sensors to the cloud. Meanwhile, OPC UA’s robust and secure data exchange capabilities are beneficial for integrating and managing data from various industrial systems. Using both protocols together ensures efficient, reliable, and secure data transmission, enhancing the overall effectiveness of digital connectivity in industrial applications. (Dinculeană & Cheng, 2019)

Grafana & InfluxDB

Grafana and InfluxDB are critical tools for visualizing and analyzing time-series data, collected over time. InfluxDB is a database optimized for handling large amounts of time-stamped data. It’s designed to store, query, and analyze this data efficiently. This makes it ideal for storing data from sensors in an industrial setting, such as force measurements from a grinding machine.

Grafana is a visualization tool that works seamlessly with InfluxDB. It allows users to create interactive and customizable dashboards to display the data stored in InfluxDB. With Grafana, data can be monitored in real time, helping users make informed decisions based on the latest available information. (Chakraborty & Pratap Kundan, 2021)

InfluxDB stores the force data captured from sensors in this project, ensuring it is organized and accessible. Grafana visualizes this data, presenting it in clear, easy-to-understand dashboards. This combination allows for effective monitoring and analysis of the machining processes, contributing to better operational efficiency and maintenance planning. The use of these tools aligns with the principles of Industry 4.0, which emphasizes the integration of digital technologies into manufacturing to improve productivity and decision-making.

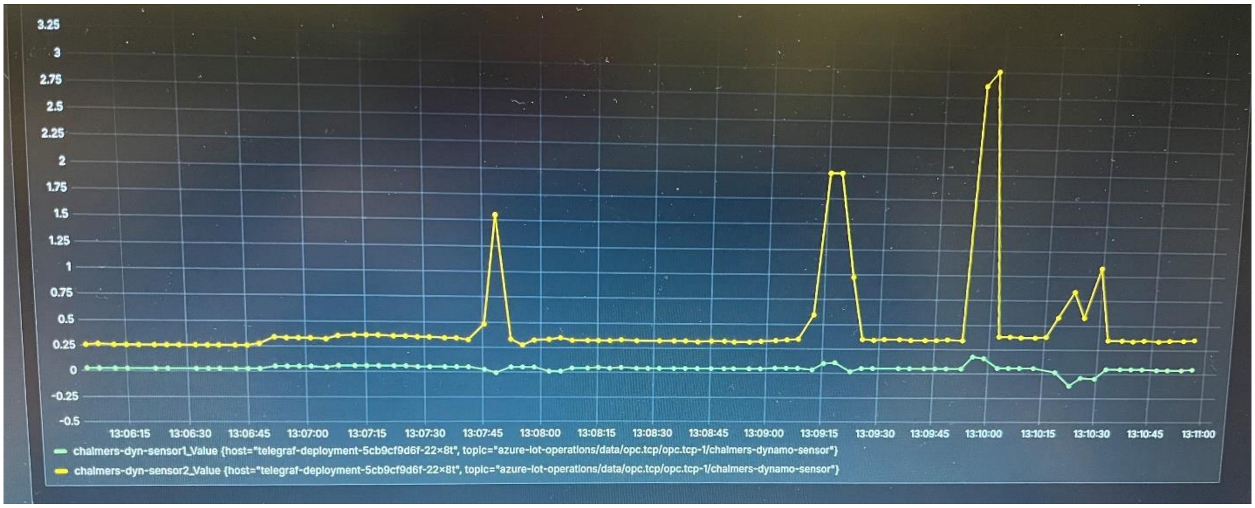


FIGURE 16 GRAFANA DASHBOARD WITH REAL-TIME VARIATIONS OF DYNAMOMETER ON SKF SERVERS. YELLOW LINE NORMAL FORCE) AND GREEN LINE (TANGENTIAL FORCE)

3.5.3 STEP 3: CONDUCTING TESTS

Data Acquisition from the Sensor

After setting up the devices and developing a custom program for signal acquisition from the dynamometer, the data-gathering process began. Initially, the signals appeared on graphs and numeric displays within LabVIEW. The captured data consisted of two primary force measurements: normal force and tangential force. As the force was applied to the dynamometer, the corresponding values were observed and recorded in LabVIEW. To enhance data management and analysis, the LabVIEW program was further developed to enable data logging. This functionality facilitated automatically recording acquired data into a spreadsheet, along with timestamp information for each data point.

The process of capturing data from external machine accessories involved a combination of hardware configuration, software development, and iterative refinement. By leveraging LabVIEW's capabilities and the underlying hardware infrastructure, the project successfully achieved the objective of capturing and recording force data from the dynamometer in real-time. However, the signals were not perfect. According to personnel at SKF, the signals still contained a lot of noise and needed to be refined.

Signal Analysis and Noise Reduction

Addressing the noise in the acquired signals was crucial to the data processing workflow, requiring careful troubleshooting and systematic problem-solving. The process started with a thorough review of user manuals and technical documentation to check for any overlooked settings or configurations that could cause signal degradation. Additionally, online resources were utilized to find troubleshooting strategies and insights from the broader community.

To further diagnose the issue, technical experts from Kistler, the manufacturer of the dynamometer and amplifier components, were consulted. During these sessions, the hardware setup was closely examined to identify potential sources of noise or interference. Kistler provided specialized equipment, including an integrated amplifier and a DAQ device, to test the signal quality under controlled conditions. This equipment significantly improved signal clarity, highlighting the importance of robust hardware configurations in signal acquisition.

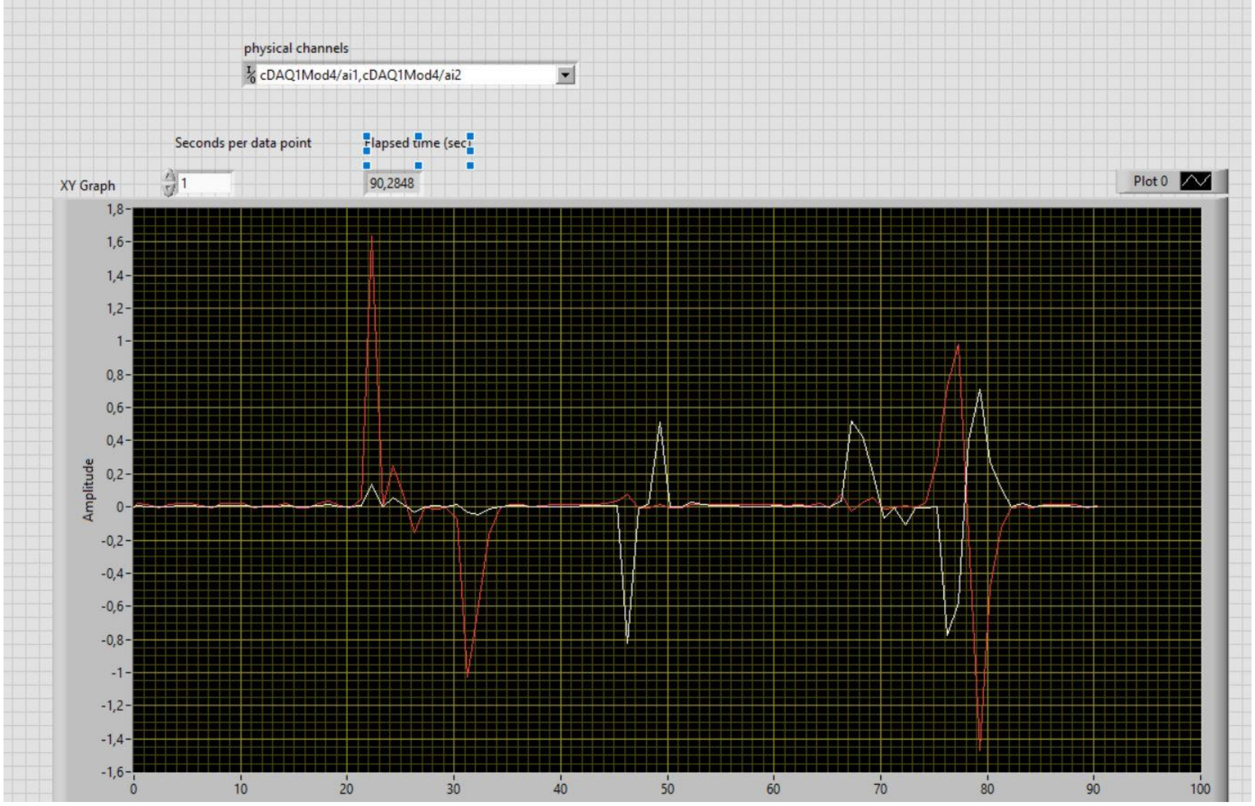
After continuous evaluation, it was found that the National Instruments DAQ device provided by SKF could contribute to signal distortion. Before drawing any conclusions, essential grounding procedures were implemented to reduce electrical noise and ensure signal fidelity. Grounding the DAQ device proved to be the crucial step in enhancing signal clarity and minimizing noise.

With the noise issue addressed, the focus shifted to validating the accuracy and reliability of the acquired signal data. A primary task was converting voltage readings to force values in Newtons, which required developing a conversion formula based on the dynamometer's sensitivity and calibration factors. After careful analysis and experimentation, the conversion formula was established, enabling the accurate translation of voltage-based signals into meaningful force measurements. The information to understand the formula lay in the configuration manual by Kistler and the configuration values provided by SKF. (Kistler, 2024)

The formula is: $Voltage * Scaling\ Factor(100) = \ Newtons$

[Example: How to calculate the load applied on a force sensor: If the voltage in the graph is 1.5, then the force would be, $1.5V \cdot 100 = 150\ N$, and the weight $150N/(9{,}82m/s^2\ ) = 15{,}3\ kg$].

The figure below illustrates the graph in LabVIEW.



physical channels: cDAQ1Mod4/ai1,cDAQ1Mod4/ai2

Seconds per data point: 1

Elapsed time (sec): 90,2848

FIGURE 17 LABVIEW GRAPH OF FORCE READINGS

The scaling factor is dimensionless and provided by the charge amplifier supplier (Kistler, 2024). Establishing this conversion protocol facilitated accurate interpretation and analysis of the acquired data, enabling correlations between force values and applied loads on the dynamometer.

Transferring Data to the Cloud

Once the dynamometer values were acquired, the next step was to transfer the data to the cloud. During a meeting with the SKF team at the Chalmers lab, the force data acquisition was demonstrated. SKF personnel connected to the grinding machine's OPC UA server to retrieve the data. It was determined that the force data should be sent to a server accessible by SKF, where it could be stored, visualized, and analyzed.

To facilitate this, a server was created. Various options were explored, and it was found that LabVIEW offers an OPC UA toolkit, which can be used to create clients and servers for data access. This required further study of LabVIEW and an understanding of how the OPC UA toolkit could be utilized for the intended application. The goal was to send the acquired dynamometer values to a server in real-time, allowing other clients to access the data.

Significant time was spent integrating the existing data acquisition program with a new program for a client to send data to the server. After overcoming various challenges, a functioning server and a client writing data to the server were established. These challenges and their solutions are detailed in the discussion chapter of the report. The following image represents how data from an external accessory is sent to the cloud with the setup at Chalmers integrated with SKF's infrastructure.

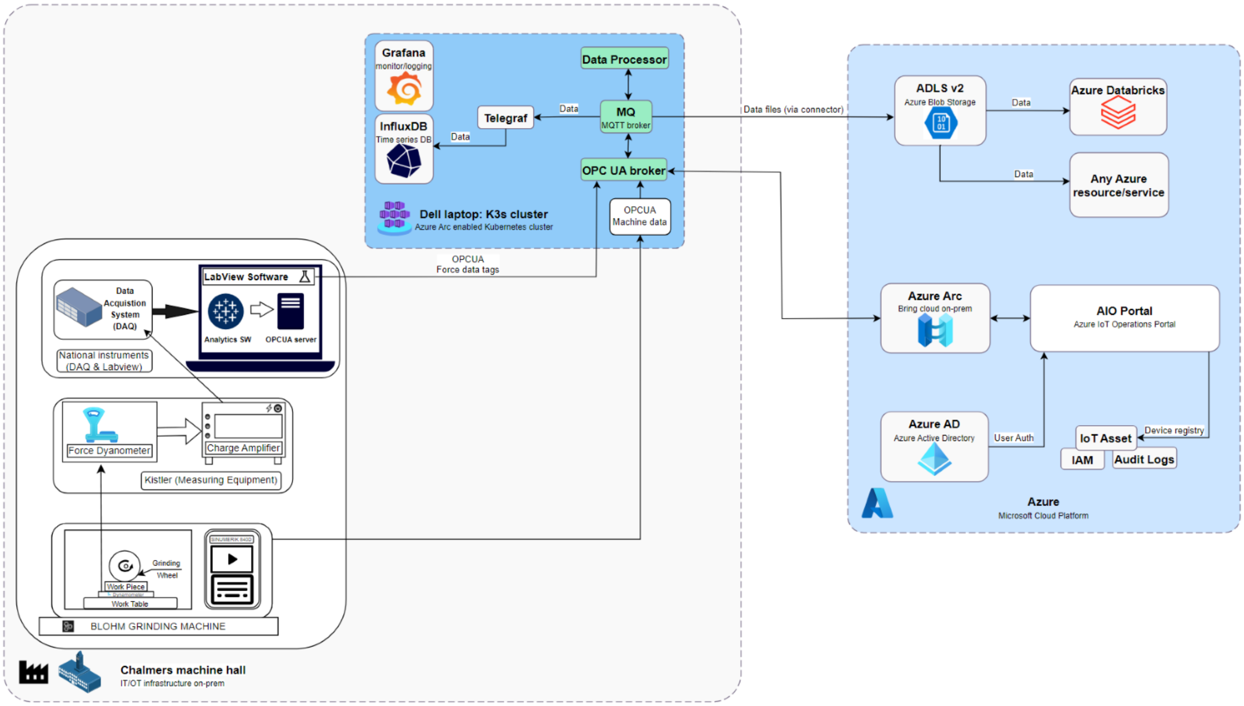


FIGURE 18 ILLUSTRATION OF DATA CAPTURE AND TRANSMISSION FROM SENSOR TO CLOUD

The part of the image on the left-hand side (Chalmers machine hall) is where the external accessory (dynamometer) and the Blohm grinding machine's data are pushed to the cloud. The part of the image on right hand side is shown for representation and an area not in our scope of thesis. This site is managed and maintained by SKF once they connect with the MQTT broker and OPC UA broker provided by the Chalmers setup.

Reading Data with External Software

After creating the server and client, it was essential to verify that the server could be accessed and that the corresponding values from the dynamometer were being read accurately. To achieve this, a third-party software, UAExpert, was downloaded to establish a client connection to the OPC UA server created in LabVIEW. Initial testing was conducted locally on the same computer.

Several challenges were encountered during this process, which will be discussed in the discussion chapter. Iterative troubleshooting revealed issues within LabVIEW's data transmission program to the OPC UA server. Once resolved, the third-party software successfully read the real-time voltage values from the dynamometer. This achievement marked a significant milestone, enabling the potential for further data transmission to the cloud.

The next step involved integrating the data with an MQTT broker (server), which is a different communication protocol needed to facilitate the final push of data to the cloud. This transition to MQTT was critical for ensuring that the data could be effectively stored, accessed, and analyzed within a cloud environment, thereby enhancing the overall utility and accessibility of the collected sensor data.

Running Practical Tests to Capture the Data and Send it to the Cloud

With successful access to data from the OPC UA server, the next step was to enable data access from an external computer. This required configuring all units involved to be on the same IP address. Ethernet cables connected the grinding machine's host network to the computers, which were then configured with mutual IP addresses to enable communication via ping.

Once connected, the SKF PC in the lab could read the data, allowing the following step: sending it to an MQTT broker and then to SKF's Azure cloud service. This step, assisted by SKF personnel Martin Johansson, involved extensive coding and posed significant challenges but was ultimately successful. This achievement meant now that the signals from the dynamometer, destined to be mounted on a grinding machine and used for capturing forces during grinding trials on workpieces, could be transmitted from the sensor through various hardware components, interpreted by software, and sent to the cloud via communication protocols.

The project's final objective was to visualize the data in the form of graphs and other displays, marking the last phase of the practical work in the thesis.

Visualizing the Stored Data on the Cloud

In the final phase, the focus shifted to visualizing the stored data. Several options were considered for the visualization tool, including Grafana with InfluxDB and Microsoft's Power BI. Power BI was initially deemed optimal due to its popularity. However, given the limited time remaining in the thesis, there was an insufficient opportunity to learn and implement Power BI and also not enough time to delve deeply into InfluxDB and Grafana.

Martin from SKF provided invaluable assistance at this juncture. During a session at the Chalmers lab, the data stored on the Azure cloud platform was successfully visualized using Grafana. This session marked a significant milestone, demonstrating the potential for real-time data visualization.

Further exploration into Grafana and InfluxDB would be necessary for a more comprehensive and tailored visualization. This would involve learning the specific coding languages and functionalities of these tools to create optimal visual representations of the data. Unfortunately, given that this was the final day of the practical phase, there was no opportunity to conduct these additional explorations within the timeframe of the thesis.

Therefore, the visualization achieved during the session with Martin represents the extent of the thesis's practical work. Future work could build on this foundation, exploring more advanced visualization techniques and tools to leverage the data collected and stored in the cloud fully. This step underscores the importance of effective data visualization in realizing the full potential of Industry 4.0 technologies in manufacturing environments.

4. RESULTS

This chapter aims to consolidate and present all the project outcomes. It will provide a comprehensive overview of the successes and milestones reached, detailing the progression from initial setup to final data visualization. This section will highlight the practical achievements, the challenges overcome, and the overall impact of the work done, ensuring a clear understanding of the project's results.

4.1 OUTCOME FROM THIS THESIS

The primary aim of this thesis is to demonstrate the digital connectivity of the CNC machine and its accessories with the remote SKF servers.

The following image shows the readings from the dynamometer installed in a grinding machine at Chalmers on the SKF's cloud platform in real-time.

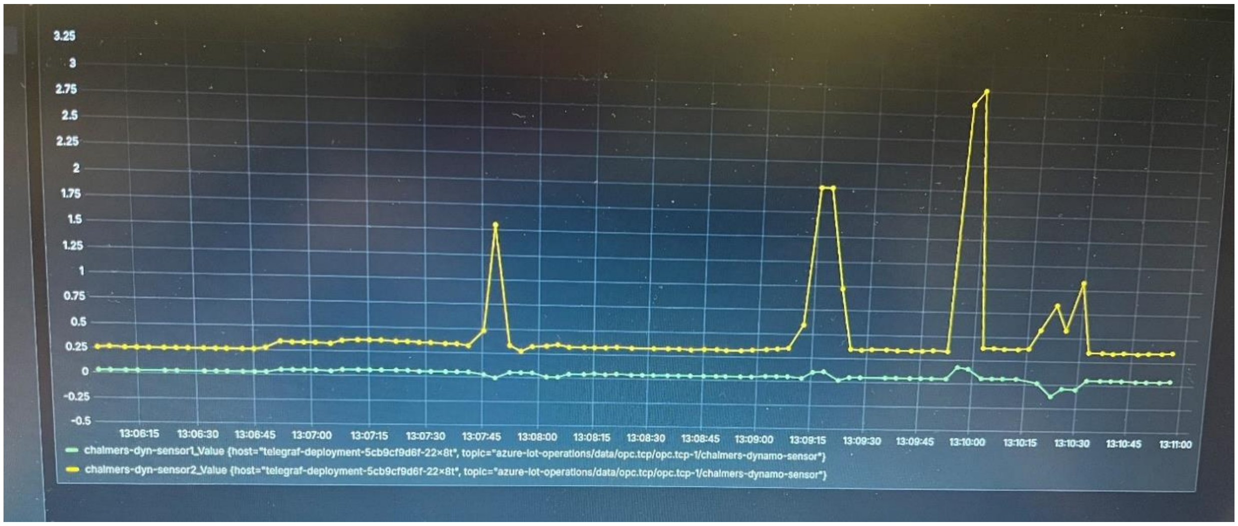


FIGURE 19 THE CONTINUOUSLY CHANGING LOAD IS RECORDED ON SKF CLOUD SERVICES IN REAL-TIME. YELLOW LINE (NORMAL FORCE) AND GREEN LINE (TANGENTIAL FORCE)

If digital connectivity is managed safely and securely, many follow-up goals can be achieved. These goals include supporting a factory to achieve optimal productivity from a remote location by studying real-time parameters and readings obtained through digital connectivity.

Although this supporting goal is still distant, the immediate objective is to monitor the machining of a particular component being machined at Chalmers using the setup established with the help of the entire Chalmers team and SKF expertise.

This thesis serves as a pilot project for SKF to demonstrate possibilities and promising results for further development. The work from this thesis will be used to run experiments in developing a new R&D setup and infrastructure for future connectivity projects at SKF, which is planned to start after summer vacation. Future digital projects will use Edge Connect devices and the Azure platform for cloud services.

4.2 THE FURTHER STEPS TO CONTINUE THE WORK USING THIS PRACTICAL SETUP

A process expert at SKF has prepared testing trials for a few samples. These samples have a new coating on their surface and are simple round-cut pieces with special coating and heat treatment. Using the setup at Chalmers, real-time monitoring and study of the forces and acoustic emission during the grinding process will be conducted. This has not been possible before because combining data from an external accessory (load and acoustic sensor) with machine parameters on a single platform in real-time (on the cloud) has not been achievable.

Although the real-time data obtained during grinding trials can be seen on the cloud, it will be monitored on location at Chalmers. Based on the data from grinding trials, informed decisions can be made to suggest changes in heat treatment and case depths on the samples. These changes could eventually be implemented in mass-produced products in the future.

Many other similar experiments can be planned, although the specifics are not certain at this moment. Ultimately, this combination of different hardware from various suppliers, machines from different suppliers, cloud services from other companies, and data collection software from another manufacturer demonstrates that integration is possible. This is achieved by having a standard protocol that can work across all these platforms to meet the company's needs.

4.3 SUPPORTING THE FOLLOWING BUSINESS CASES TO CONTINUE THE WORK IN THIS PROJECT

For any company, investing in a project or idea only makes sense if there is promising potential outcome from their investments. This is also the same with this thesis. As an academic work, SKF plans to use this as a starting point and a lead project before testing its business cases at the new R&D test rig being developed during our thesis.

The SKF team has hopefully gained valuable insights from this project, starting with identifying optimal protocols for data transfer, capturing data from the machine to the cloud, and pushing data from an external accessory connected to the machine to the cloud.

While this may not seem like a business case, the SKF team uses our thesis to make informed decisions about what they want to test and what they think can bring value to the company at this moment.

Companies working with SKF on the digital connectivity project have proven several industrial use cases profitable. However, SKF has its internal priorities and understanding of its setup and needs. They are fine-tuning key business areas worth testing and investing in the future.

4.4 SCALING UP THE PROJECT TO ADD VALUE

The SKF team works carefully with multiple players to identify the best areas and technologies to focus on. The team has devoted considerable time and effort to identifying key areas to work on, test, and invest in technology. Only after testing the identified infrastructure and technology can SKF consider implementing it on a larger scale at the R&D division and later in different factories in Europe and worldwide.

If a mistake is made after implementation in multiple factories at different locations, it will be challenging to fix and address the issue. Therefore, the SKF team working on this project focuses on identifying challenges and problems after implementing the technology and infrastructure. They also consider the availability of in-house expertise and supporting partners, consulting with them before establishing a particular area as a valuable business case to implement and test.

5. DISCUSSION

The discussion chapter addresses various critical aspects of the project, starting with the scope, which outlines the primary objectives and limitations. It evaluates how the project demonstrates practical and real-time applications in the industry, emphasizing the commercial benefits and potential cost savings. The chapter also discusses the potential for new product offerings to supplier companies and the learning outcomes from the thesis. Finally, it addresses the challenges encountered, including technical difficulties, software installations, network configurations, and collaboration with different stakeholders, providing a comprehensive analysis of the project's journey and insights gained.

5.1 SCOPE

The scope of our thesis was straightforward: to establish digital connectivity for data acquisition from an external sensor connected to the machine, monitor the required parameters from the grinding machine in real time on the Cloud, send the processed data from an external accessory to the Cloud, and finally visualize the Data on the cloud in real time as the machining is being done on a workpiece.

5.2 PROJECT AIMS TO DEMONSTRATE PRACTICAL AND REAL-TIME APPLICATION

For any industry to remain competitive, it must keep up with industry trends or even establish new trends for others to follow. SKF is a frontrunner in many areas and a key player in the industry, particularly in developing and implementing digital connectivity projects. SKF is working to develop and implement these projects in-house, utilizing its employees by retraining them or supporting those who want to work in this area for future SKF factories or digitally connected factories. As we know, data is power. With this initiative, SKF can achieve numerous possibilities in the future thanks to the infrastructure they are putting in place.

5.3 POSSIBLE COMMERCIAL BENEFIT FROM THIS PROJECT

Although SKF's current goal is to use the digital connectivity platform with its machines for internal use, it can also be used for many other applications and generate revenue by selling it to external players who use CNC machines. The demonstrated digital platform provides new insights into grinding and dressing processes and the running state of critical machine-tool components. This enables the end user to monitor and optimize processes, identify and predict maintenance issues early, and enhance the overall equipment effectiveness. The following two areas described below may be an outcome in the near future.

Cutting Down Costs

Remote monitoring of processes allows for suggesting recommendations to factories at different locations to run machines at optimal parameters based on production urgency. This saves travel time and resources. While it may not be the same as visiting a factory in person, it is possible to address a few recommendations remotely. Remote monitoring enables multiple machines connected to the cloud to be monitored and supported quickly, which is not feasible with in-person visits, especially if machines are located far apart within a factory or at different factories. Remote monitoring and support offer significant advantages.

New Product Offering to Supplier Companies

When the combination of edge devices, machines, and software works as expected at SKF and delivers the planned benefits, this setup can be sold as a package to companies that supply SKF. Supplier companies typically support the requests of their parent companies. This can create a new revenue model. After selling it to suppliers, it can also be sold to other manufacturers that use CNC machines for job production.

5.4 LEARNING OUTCOMES

The scope may seem to focus on four areas, but the reality has been different. When we started the work, we had no idea where and how to begin but were interested in working on new technologies of the future. This openness and willingness to reach out to people with related knowledge was vital for us. In addition to some literature studies in this field, we discovered that excellent results can be achieved when industry and academia work together.

We had the freedom to work at Chalmers and SKF, and we are eternally grateful to our supervisors for trusting us and giving us this privilege. Although we sometimes made no progress for 2-3 weeks during our thesis, the teams at Chalmers and SKF came to our rescue and guided us in a direction that helped us overcome the challenges at hand. Even external equipment suppliers supported us in our journey to achieving the results.

In summary, our key to success has been our openness to asking questions and receiving feedback from the team and working on the suggestions and feedback. This includes attending and participating in regular meetings at Chalmers and SKF. This approach has provided us with invaluable learning experiences.

5.5 CHALLENGES

This subchapter comprehensively examines the various challenges encountered throughout the project. Each issue faced while integrating sensor data acquisition and cloud transmission is explored in detail.

Sending the Sensor Data to the Cloud

Throughout the project, several challenges were encountered in sending data to the cloud, each requiring thoughtful troubleshooting and problem-solving strategies.

One of the initial issues was using UAExpert on a different PC to verify data transmission. The challenge was ensuring that external clients could access and read the server. Initially, connecting attempts were unsuccessful due to network configuration issues and incompatibilities between the LabVIEW OPC UA server and external clients. This was resolved by installing the necessary software on the same PC where LabVIEW was installed, allowing better control and troubleshooting of the environment.

When testing with UAExpert on the same PC, it was observed that manually entered values could be read correctly, but real-time data from the dynamometer was inconsistent. This was a significant hurdle as the main objective was to achieve real-time data visualization and analysis. Eventually, through iterative troubleshooting and adjustments to the LabVIEW program, UAExpert could successfully publish and read real-time data.

Another major challenge arose when connecting to an external, remote OPC UA server. The goal was to push data captured from LabVIEW to the OPC UA server for further transmission to the cloud. However, this attempt was not entirely successful. LabVIEW required a URL to connect to the machine's OPC UA server, but the machine only provided an IP address. This discrepancy highlighted the need for compatible addressing formats and posed a significant obstacle in ensuring seamless data transmission.

Other options were explored to overcome these issues. The use of MQTT within LabVIEW was considered, but it was deemed too complex to learn and implement within the limited timeframe. Alternative OPC UA server solutions such as Kepware KEPServerEX and open62541 were also investigated. However, these options either required significant financial investment or extensive learning time, making them impractical for immediate implementation.

The issues encountered, and their respective solutions highlight the complexities of integrating various software and hardware components to achieve a robust and reliable data acquisition and transmission system. Overcoming these challenges was crucial for ensuring the project's success and reaching the ultimate goal of real-time data visualization and cloud integration.

Challenges with Software Installations and Network Configurations

The project faced significant challenges due to the use of various PCs. SKF provided high-performance PCs, which, although excellent in performance, posed issues when downloading software and add-ons. Each installation required administrative authentication, necessitating assistance from the helpdesk, making the process time-consuming. Configuring the IP addresses to match the machine network proved problematic, as SKF PCs restricted these changes.

An alternative was using a PC from the Chalmers lab, provided by Johnny. This PC allowed unrestricted software installations but was hindered by its slow performance due to its outdated processor. This led to extensive delays and frustration, making it unsuitable for the project. Consequently, a personal laptop was used. Although it had limitations in handling LabVIEW and UAExpert efficiently, it allowed the project to proceed.

Security and permission settings on SKF laptops also presented challenges. These laptops had stringent security measures to protect SKF's digital platforms, requiring administrative authentication for minor changes. Remote support was only available when connected to SKF's network, necessitating permission to work remotely.

For instance, creating an OPC UA server on LabVIEW to push captured data from connected instruments encountered difficulties. Initially, the SKF laptop hosting the OPC UA server couldn't connect to the cloud due to the requirement for an Ethernet connection to share the same IP address as the grinding machine. This was a crucial step for connecting the OPC UA server on the SKF PC with other PCs pushing machine data to SKF's cloud.

Efforts to connect UAExpert from a personal PC to the OPC UA server on the SKF PC were unsuccessful. Eventually, the software was installed on the SKF PC, but connection issues persisted. Attempts to use Mosquitto software faced similar administrative hurdles, and efforts to utilize the C command prompt without admin access led to dead ends.

Ultimately, all software was reinstalled on personal PCs to conduct the tests. Local testing within SKF's PC environment was suggested by Martin, who provided a solution to some of the connectivity issues.

These challenges underscore the complexities of configuring and securing industrial PCs for cloud-based data acquisition and highlight the necessity for adaptable and efficient troubleshooting methods in such projects.

Collaborating with Different Actors

Collaboration with various stakeholders posed several challenges that unexpectedly prolonged the project timeline. Coordinating meetings and consultations with equipment providers from Kistler was essential to identify and resolve hardware issues. The involvement of the grinding machine manufacturer, Blohm, was crucial for integrating the acoustic emission sensor and facilitating other aspects of digital connectivity. However, their slow response time significantly hindered progress. Despite repeated follow-ups, their assistance was delayed, leading to a bottleneck in the project timeline. Eventually, as the thesis period was nearing its end, Blohm personnel were able to assist with the sensor integration. This delay underscored the importance of timely communication and efficient collaboration between all parties involved to ensure project milestones are met without compromising the project’s objectives. Additionally, navigating the different priorities and schedules of the stakeholders required persistent follow-up and adaptability to align everyone toward the common goal of achieving successful digital connectivity in the grinding machine setup.

5.6 PROJECT REFLECTION

Reflecting on the project, integrating digital connectivity in grinding machines has been challenging and rewarding. The scope was clearly defined, focusing on establishing real-time data capture from external sensors, processing this data, and visualizing it in the cloud. Achieving this required overcoming numerous technical hurdles, particularly in software installations, network configurations, and the assurance of seamless communication between various systems.

The project's practical application underscored the importance of staying ahead in the competitive industrial landscape. The learning outcomes were profound, showcasing the collaborative strength of industry and academia and the resilience required to navigate unforeseen obstacles.

Challenges such as coordinating with equipment providers and manufacturers, addressing hardware issues, and dealing with stringent security protocols were pivotal in shaping the project's progression. Despite these setbacks, the collaborative efforts and iterative problem-solving led to successfully realizing the project's goals.

The project has assisted in improving SKF's digital infrastructure and provided valuable insights into the complexities of integrating modern digital technologies into traditional manufacturing processes. This experience has laid a strong foundation for future digital connectivity and smart manufacturing endeavors.

6. CONCLUSION

This thesis successfully demonstrates the feasibility and potential of integrating digital connectivity in grinding machines to enhance manufacturing efficiency. Several vital conclusions have been drawn from the project, each highlighting a significant aspect of the work.

First, the project established a robust framework for real-time data capture from external sensors connected to the grinding machine. This included setting up and configuring the necessary hardware components such as the dynamometer, charge amplifier, and DAQ device, as well as developing a tailored LabVIEW program for data acquisition. The successful capture and interpretation of force data/signals marked a critical milestone in achieving digital connectivity.

Second, significant progress was made in transferring the acquired data to the cloud, ensuring that it could be accessed, stored, and analyzed remotely. The integration of OPC UA and MQTT protocols facilitated the seamless transmission of data from the grinding machine to SKF's Azure cloud platform. Overcoming the challenges associated with network configurations and software installations highlighted the project's resilience and adaptability.

Third, visualization of the stored data using Grafana demonstrated the practical application of the project’s outcomes. The ability to monitor machining processes in real-time through interactive dashboards enhances operational efficiency and supports predictive maintenance strategies. Although there were constraints in fully exploring all visualization tools, the groundwork laid provides a strong foundation for future enhancements.

Fourth, collaborative efforts with various stakeholders, including SKF personnel and external equipment providers, were instrumental in navigating technical challenges and ensuring the project's success. Despite some delays, the involvement of experts from Kistler and Blohm underscored the importance of effective communication and timely support in complex projects.

Finally, the learning outcomes from this thesis have been profound. The project showcased the synergy between industry and academia, emphasizing the importance of iterative problem-solving and continuous feedback. The hands-on experience gained in handling advanced digital technologies and integrating them into traditional manufacturing processes is invaluable for future endeavors.

This thesis has demonstrated the practical viability of integrating sensor data acquisition and cloud-based analysis in grinding machines. It has also paved the way for further exploration and potential commercialization of similar solutions, contributing significantly to SKF's digital transformation journey and the broader Industry 4.0 landscape.

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