Accuracy in Detecting Failure in Ballscrew Assessment towards Machine Tool Servitization

Nurudeen Alegeh, Abubaker Shagluf, Andrew P. Longstaff, and Simon Fletcher
Centre for Precision Technologies, University of Huddersfield, Huddersfield, UK
Email: Nurudeen.Alegeh@hud.ac.uk, a.Shagluf@mtt.uk.com, a.p.longstaff@hud.ac.uk, s.fletcher@hud.ac.uk

***Abstract*—Many manufacturers, in particular machine tool builders, aim for service innovation in order to improve their market competitiveness. Machine tool trading companies expect to create a value-added process through shifting from just selling product i.e. machine tools to selling an integrated combination of product and services, so called product-service system (PSS) which in turn competes with other developing companies. This is the process of servitization. The purpose of this work is to explore the benefits of servitizing machine tool industry and identify the effect of such an approach on the performance of engineering companies. As important, is to evaluate the accuracy of components as part of predictive maintenance, to support machine tool sevitization. This paper proposed a case study of ballscrew performance assessment. The purpose was monitoring the degradation of two parallel ball screws in a 5-Axis gantry machine tool, based on data from an acoustic emission sensor and machine learning technology. The significance of this work is that ballscrew performance as part of machine tool accuracy is critical for high value manufacturing. Machine tool users would prefer their machines to be maintained to the required tolerance by the predictive maintenance service warranty offered by the machine trader and keep their machines up to date to reduce unnecessary downtime.**

***Index Terms*—Servitization, Ballscrew, machine tools, manufacturing, sensors, machine learning, temperature**

I. Introduction

Recently, the growing role of PSS in developed economies has been the focus of much trading company's debate. Yet manufacturers can offer services; in fact, they are aiming to provide a cradle-to-grave service. If this is to happen within machine tool traders, this requires commitment, flexibility, and a will to collaborate across the whole machine tool organization. As part of machine tool sevitization, this work aims to explore the threats, rewards and the commercial benefits of the development and the delivery of such advanced ball screw performance assessment service approach.

II. Industrial Need For Market Competitiveness Approach

The term servitization was first mentioned by Vandermerwe in 1988 [1]. Since then, there is a growing amount of research interest in the role of services in sustaining the competitiveness of manufacturers and the term become known as servitization of manufacturing [2]. There has been some work that attempted to discuss the approach of product-service. In 2009 Baines [3] claimed that the most highly cited papers for such a subject have come from the United States of America followed by contributions from the UK and Western Europe. This means that manufacturing servitization is the focus of the industrial research in the UK for the past decade. All this industrial research work seeks to give reasonable answers of the assumptions behind the process of servitization. It also seeks to address the balance in terms of how integrated combination of product-service is viewed in relation to technological innovation in machine tool industry especially with the fast growing of new machine calibration technologies and the support of metrology science. This has enabled the industries with such a strategy to undergird their competitive advantage. Where the long-term goal of introducing innovation is to increase manufacturing productivity, "Sevitization has at least one weakness. While it is used worldwide also in economies with lower production costs, services in manufacturing are slowly becoming commoditized and will become a necessary, though not sufficient, condition for reaching an above average competitive advantage" [4].

III. Service And Innovation

Nowadays, manufacturing companies could hardly continue as pure manufacturing businesses in industrialized economics. Alternatively, they have to shift beyond just manufacturing and provide their customers with solutions and services, which are delivered through their products [5]. Mei [5] claimed that Industrial servitization has been adopted by machine tool builders in developed countries to improve their market competitiveness by offering more service in order to add value to their products. Also, to improve product's precision and reliability.

Hence, machine tool builders and traders adopting servitization need to investigate the technical aspects of machine tools related to accuracy and productivity. The development of a cost/benefit algorithm for machine tools accuracy maintenance to support the process of servitization is crucial because it can help the manufacturers in evaluating the effectiveness of the amount of money they spend to improve their

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productivity and selecting optimal machine accuracy error mapping opportunities. The investment towards 'zero-defect' components should not be based on faith, and should be assessed by the measures of machine tool accuracy as one of the critical factors in determining the quality of these components. Therefore, what is needed is a way of measuring the impact of industrial maintenance programs and a mechanism for predicting the return on an investment in these methodologies to benefit from introducing Servitization [6]

If a cost algorithm was to be developed in order to adopt sevitization it would be innovative in that it utilizes maintenance cost and machine tool quality assessment to make it feasible to implement a much wider sustainable service while further reducing its environmental impact is valuable. Full Life-Cycle-Cost (LCC), Cradle-to-Grave of machine tools accuracy-related cost is suggested that covers CNC machine tool's life from installation to disposal. Disposing the machine tool could be a burden at the end-of-life. Storing it would require space and may encounter rent cost. Scrapping it maybe an environmental burden and might be either cost benefit or cost loss. Significant resources and information are required to investigate to provide evidence of scale of investment return. Suggesting a Life Cycle Cost (LCC) is for more environmental benefits by reducing production waste, scraped parts and non-functioning machines for greener design and improved manufacturing sustainability. LCC has been the subject of machine tool users. The costs of the machine life cycle could be seen differently by the purchaser and the customer as in the table below.

TABLE I. IMPORTANT COST OF THE MACHINE TOOL LIFE CYCLE

Important cost of the machine tool life cycle		
Purchaser	Acquisition costs	• Product price • Installation cost • Shipping cost
	Ownership costs	• Operating cost • Maintenance cost
	Disposal costs	• Scraping cost • Environmental burden
Customer	Guaranteed performance	• Reliability • Accuracy • Repeatability • Steady and stable performance
	Competitive life	• Long life

Product oriented services could become a necessary especially with the software giants have started providing products to complement their services and obtain even more data [4]. Here, servitization might be accepted as a positive shift from just buying goods to purchasing a product-service integration. Therefore, understanding the risks associated with adopting such an approach especially if the provider is not an indigenous is highly desirable [7]. Baines et al [7] said that as the work of researchers and practitioners in service innovation continues five areas need urgent attention:

- Identifying the effect of servitization on the performance of firms.
- Defining unified and foundational concept of advanced services.
- Mapping the process of servitization.
- Exploring the mechanisms of reverse servitization.
- Understanding the threats associated with servitization.

Baines and Lightfood [2] analysed the output of the research on servitization since 1988. They claimed that the paper reviewed in their work originate in the USA (40%), UK (20%), Switzerland (15%) and the rest of the Western Europe (25%). This shows the amount of work has been done in the research and the development on the road to servitization. The Authors claimed that the biggest challenge for such a research in this area is not the specific topic to explore rather than which organisations it will be the most productive to study. Moreover, the authors believe that another challenge is the organisational constraints, as information such as quality failure and no-documented operator quick tweaks, maintenance activities are usually very difficult to obtain from research target firms like Lean, Toyota etc. to support the process of servitization. However, lessons could be learned from smaller industries that are rising sharply in terms of innovation and revenues.

Howells 2000 [8], claimed that innovation expenditure within a number of service sectors has grown over recent years. The author presented some interesting figures for research and development expenditure. As mentioned earlier, there has been rapid growth in research and development activity by service, with the service share of total business expenditure on research and development between 1980 and 1997 risen sharply for most countries (except Germany and Japan), from less than 5% in 1980 to15% in 1997. Another survey showed a high proportion (76.5%) of German companies claimed to have introduced innovation of any type between 1993 and 1995 [8]. Here, more surveys are needed to identify and explore the possibilities of such innovation in the UK's leading companies.

There are some leading examples of manufacturing companies that add service to their product. Rolls Royce came up with Power-by-the-hour package, where customers of the package pay for their product a fixed warranty and operational fee for the effective run time of jet engines [5]. The adoption of servitization is based on the design of service and is significantly different from a company to another due to the challenges to the nature and culture of the organisation. One of these challenges is the strategic arrangement and the supplier relationships while shifting from a product oriented to a product-service oriented organisation. Companies are likely to meet resistance within the organisation where the service approach is not clearly understood due to the fear of infra-structural change. Therefore the service culture is specific and different from traditional manufacturing culture [2].

Moreover, in order to sustain growth and strengthen competitive advantages, machine tool traders wanting to adopt servitization have to realise deficiency and competitors' capabilities [5]. Servitization tends to improve profitability particularly in machine industry sectors where is high base of manufacturing could be seen as a positive transition. However, lower cost economy and the demands of customers are two factors need to be studied and surveyed before adopting it. Therefore, benefits of implementing servitization in manufacturing companies from different points of view should be distinguished.

TABLE II. POTENTIAL BENEFITS FROM ADOPTING A SERVITIZATION

Entity	Benefit
Service provider	Strategic, financial and marketing benefits. A long term increased revenue which in turn reduces competition
Customers	Maximise performance and lower the cost of ownership
Consumer	Better products and service
Society	Better sustainability and environmental performance.

IV. THE GUIDANCE FOR MANUFACTURERS SEEKING TO ADOPT SERVITIZATION

Machine tool manufacturers have been providing partial service along with their machines. These companies have to look at the value chain through the customer's eyes, examining all the activities the customer performs in using and maintaining a product through its life cycle [5]. Hence, there should be a clear analysis to adopt such an approach to provide full product-service system. This might be guided by some important research questions such as:

- Who is the owner of the product through the product life cycle?
- What are the customers' demands?
- What are the Key performance indices (KPI's) and the customer measuring values?
- How could this service be benchmarked to support the approach?
- What are the available technologies supporting the approach?
- What is the available infrastructure to deliver the performance? What to add?
- What are the deficiencies and issues noticed from other companies' experience?

This could be expressed in a form of SWOT analysis as follows:

TABLE III. SERVITIZATION SWOT ANALYSIS

SWOT Analysis			
Strengths	Weakness	Opportunities	Threats
Advantage Maintain manufacturer's competitive advantage in the face of competitive pressure arising from globalisation Create value for customers.	Compatibility? Cost? Manufacturing managers have to assess the individual value of the technologies available to support the approach, as a service system component, in order to ensure long-term service competitiveness. This assessment is particularly important as the adoption of many technologies is dependent on lengthy organisational transformation.	What makes the different from other competitor? Changes in the technology and market and the influence of the GPS or Geo-spatial technologies Could you do anything better? RFID and barcodes	Obstacles Time Culture risk and infra-structural change.
Improvements Generating new revenue stream Maintenance efficiency and effectiveness Product performance Increasing data gathering (volume, quality and data types) Improving access to information.	What to avoid? What makes problems and complaints? Manufacturing companies need to align their products, technologies, operations and supply chain to provide a new service. This takes time and so it is therefore essential to identify the right technologies, and incorporate these early in the service design process, in order to progress towards the provision of more advanced services.	Changes in policy? Environmental burden? Government bodies should technically favour the widespread promotion and adoption of Servitization.	What needs researching further? Manufacturing companies lagging in their adoption to technologies. Automated production control. Service automation.

While servitization is an attractive approach for manufacturing companies, it also raises significant challenges. Teunebrink [9] stated multiple different forms of risk in adopting the product-service strategy including: operational risk, partner risk, financial exposure, performance risk, incentive distortion risk, systemic risk and dynamic risk. Neely [10] stressed that the transformation to services still needs to be understood, especially in terms of business models that best enable manufacturers to create and capture value through the delivery of services. The author analysed a considerable number of companies in 25 countries. The author also identified 820 UK manufacturing companies, 209 of them are servitized. This shows about 25% of these firms is servitized.

Baines [3] stated that "The design of services is significantly different to the design products since, by their nature, services are fuzzy and difficult to define. This may discourage companies from expanding the service dimension, particularly because they need to take account of competition outside the usual domain from unexpected rivals including their own suppliers, distributors, and customers". The author added "marginal risk incurred might outweigh the benefits of increased profit potential". However, adapting the necessary organisational structures and processes is the main step to get the benefit out of such an approach.

Some critical findings are that in smaller firms servitization appears to pay off while in larger firms it proves more problematic [10]. This is maybe due to that extended service business leads to increased service offering and higher costs, but not to correspondingly higher returns [9]. Moreover, servitization seems to be non-trivial to implement and the implementation difficulties could decrease overall financial performance of the bigger companies.

V. Technology and Servitization

While technology is growing the interest in servitization continues to gain more attraction. Advanced services delivery in the right way just-in-time is a key for this approach to compete with other manufacturers. Baines et al [11] mentioned important key findings for the delivery of advanced service which ensures healthy communication and leads to improved understanding of how products are used and performed.

- Localised facilities enable faster fault diagnostics and rectification. Largely because staff are physically closer and more likely to be available when a failure occurs, possibly witnessing an incident, and taking corrective actions more quickly and precisely.
- Localised facilities sustain strong relationships between the manufacturer and customers at the level of day-to-day operations.

Information and communication technologies (ICT) are used in production systems. For instance, they manufacturing suppliers to place orders on their own supply chain for components and raw materials [11]. Baines established a common architecture for such ICT systems as illustrated in Fig. 1.

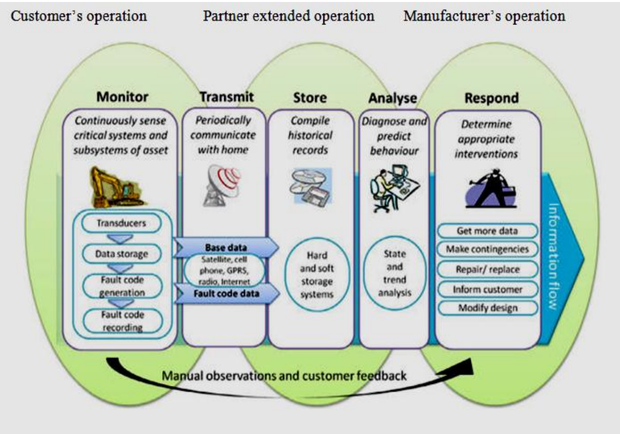

Figure 1. Common architecture for ICTs. Source Baines [11]

Dinges et al [12] ranked the top five technologies to support the approach of product-service system as follows:-

1- Predictive Analytics; used to predict specific failure modes

2- Remote communications; remotely adjust, fix, or send software updates to Machines/Products.

3- GPS or Geo-spatial technologies used to track Machines/Products, People, or Components.

4- Consumption monitoring; used to create consumption driven supply chains for consumer specific offerings.

5- Mobile communication (or other mobile platforms); used to receive internal data or customer information in real time. E.g. control system data or information pushed to customers.

In addition to these, data analysis, the use of dash-boarding "to provide KPI's to make service more visible", inventory management, position tracking, RFID and sensor technology are all considered to be skills and technologies that support servitization to offer competitiveness and provide a better approach success.

VI. Case Study

In recent years, it has been demonstrated that artificial intelligence is arguably the more accurate technique in condition monitoring to predict the machines' state with high confidence level, in particular in the presence of nonlinear characteristics [13].

In this paper, Support Vector Machine (SVM) a machine learning technique is used to have a better prediction to the condition of a CNC machine. The CNC machine used in this experiment is a five-axis gantry machine in which the health condition of the ball screw on which the gantry moves, is accessed. The direction of movement of the gantry is the y-axis and the sensor used for gathering data is an Acoustic Emission (AE) sensor. For this experiment the axis speed was varied between 1000 and 10000 mm/min. The reason for using SVM [14] [15] and AE sensor [16] [17] lies in their accuracy and reliability.

VII. Support Vector Machine

SVM is a machine learning technique that constructs a hyperplane or a set of hyperplane to separate a set of data point into two or more classes and in the process generate the maximum possible margins between the classes [18].Generally, SVM transforms the set of input data point from its original finite dimensional space to several higher dimensional space (or hyperplane) and then selects the higher dimensional space with the maximum margin which then used to accurately perform classification or regression. The higher dimensional space margin is determined by a subgroup of the original input data points referred to as the support vectors. For the mathematical basis of SVM refer to the works of Dao-guang et al and Bhat et al [18, 19].

VIII. Experiment Setup

Geiss machine is a 5 –axis gantry machine at the University of Huddersfield, see Fig. 2 below. From previous work by Abdulshahed et al [20] , the machine has a healthy and a worn ball screw. Hence this provides a good source of experimental data to analyse a healthy ball screw against a worn one.

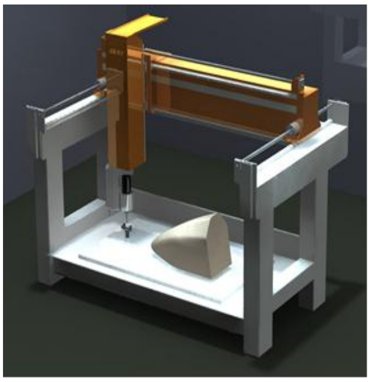

Figure 2. CAD model of the GEISS Five-axis Gantry machine tool

- AE sensors are located on both ballscrews connected to a data acquisition system.
- The experiment is applied to both ballscrews as shown in Fig. 3, in which the readings from the AE sensor will be taken during a back and forward movement (15 times each) of the ballscrew in the y-axis direction at the indicated speed.

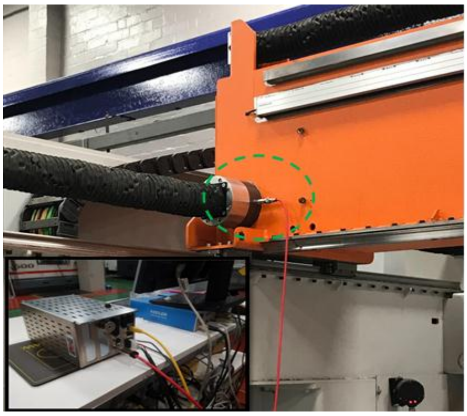

Figure 3. AE sensor on the ballscrew nut

TABLE IV. EXPERIMENT PLAN

Experiment No.	Axis speed	Axis direction	Ball screw condition
1	1000	Forward	Healthy
2	1000	Backward	Healthy
3	2500	Forward	Healthy
4	2500	Backward	Healthy
5	3000	Forward	Healthy
6	3000	Forward	Healthy
7	5000	Forward	Healthy
8	5000	Backward	Healthy
9	7500	Forward	Healthy
10	7500	Backward	Healthy
11	9000	Forward	Healthy
12	9000	Forward	Healthy
13	10000	Forward	Healthy
14	10000	Backward	Healthy
15	1000	Forward	Worn
16	1000	Backward	Worn
17	2500	Forward	Worn
18	2500	Forward	Worn
19	3000	Forward	Worn
20	3000	Forward	Worn
21	5000	Backward	Worn
22	5000	Forward	Worn
23	7500	Backward	Worn
24	7500	Forward	Worn
25	9000	Forward	Worn
26	9000	Forward	Worn
27	10000	Backward	Worn
28	10000	Forward	Worn

As shown in Fig. 4 and Fig. 5, which represent the training and prediction stages respectively, after the sensor data has collected, it undergoes a pre-processing stage using signal analyses techniques to remove any possible trends due to sensor. Then features such as mean, root mean square (r.m.s), skewness, kurtosis, single value decomposition (svd) and standard deviation (std) are extracted [21]. SVM which is a supervised machine learning approach is then applied to the extracted feature to obtain a model.

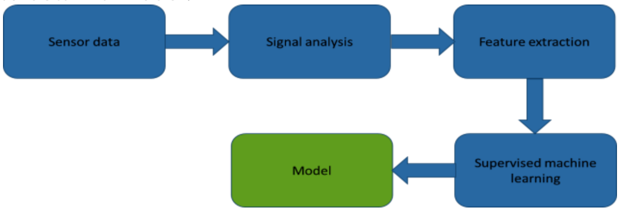

Figure 4. Training phase

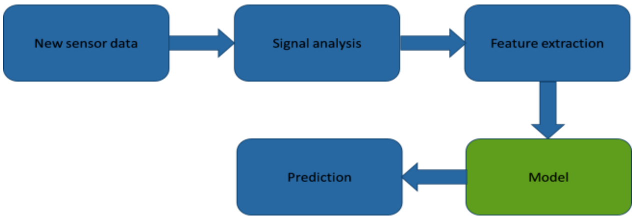

Figure 5. Prediction phase

IX. EXPERIMENT RESULT

The AE sensor was attached to the Y axis ballscrew nut of the Geiss 5-axis machine tool as shown in Fig. 3.

This could be mounted using a powerful magnet or mechanically screwed in place. It has a data acquisition box which is connected via Ethernet to a computer, which provides the requisite high-speed data acquisition without having to obtaining a separate high specification Data acquisition (DAQ) channel.

Fig. 6 and Fig. 7 show a typical plot of the obtained AE from the ball screw shown in Fig. 3, from a single run with a particular axis speed. This data can then be processed accordingly using suitable signal processing technique to produce desired result.

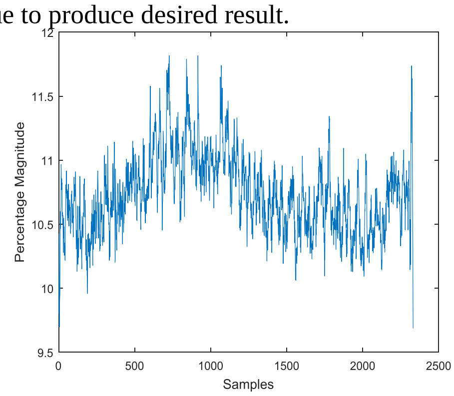

Figure 6. AE data capture during 9m/min axis traverse. Sensor on the worn ballscrew

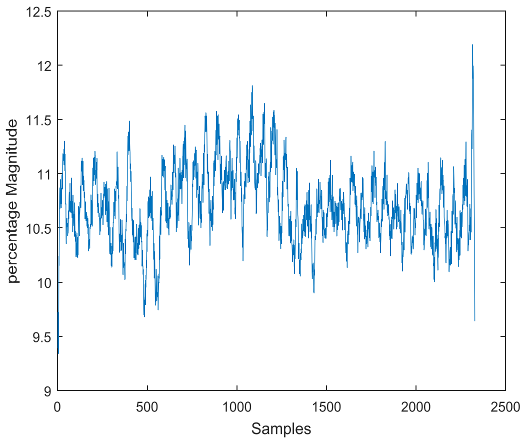

Figure 7. AE data capture during 9m/min axis traverse. Sensor on the healthy ballscrew

SVM is employed after signal processing as the machine algorithm for the prediction of the ballscrew state. The SVM uses a total of 420 observations in its prediction. The observations where individually divided into 6 predictors classes (mean, r.m.s, skewness, kurtosis, svd and std) and 1 response class (healthy or worn).

The confusion matrix in Fig. 8 shows the misclassified data, resulting in an accuracy of 88.1%. The validation strategy is a 6-fold cross validation; this is as a result of the relatively small number of observations.

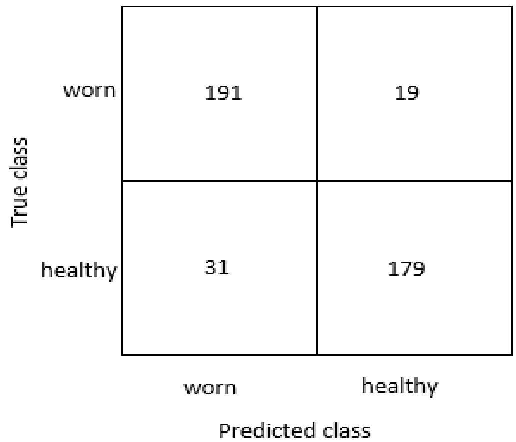

Figure 8. The confusion matrix of the SVM

X. Conclusion

Companies competing in a complex global marketplace face enormous pressure to maintain operational excellence.

Machine tool companies that traditionally offer machine trading are currently extending their business to value-adding services. In this context, Product-Service means that machine tool traders try to find an optimal combination of products and services to product income. There are several reasons or drivers for machine tool builders to servitize. These are economic, environmental and competitive strategic drivers. In this research study, the product and service integration aims to find PSS solution for servitization with a view to increase the profitability for machine traders.

Machine tool companies have become increasingly interested in environmental issues. These companies aim to limit the environmental impact by limiting scrap and waste production in order to meet government-regulated quotas. Servitization or product-service is a scheme that aims to support the existing infrastructure and continuously strive to be competitive, satisfy customer demands and have a lower environmental impact than traditional business models. The commercial benefits of servitization might be convincing. As public pressure on environmental concerns grows, government bodies should technically favour the widespread promotion and adoption of Servitization. Hence, as the environmental arguments could not be tolerated, this will have positive impact on the growing of such a strategy. In other words, the pressure of government regulations concerning the environmental effect has pushed manufacturers to strictly track their environmental impact. The success of servitization is suggesting an LCC for more environmental benefits by reducing production waste, scraped parts and non-functioning machines for greener design and improved manufacturing sustainability. Therefore, environmental legislation barriers “including political, economic, social and technological obstacles” will be a huge support for product-service system.

Ballscrew performance assessment is a case study proposed in this paper. The purpose was monitoring the degradation of two parallel ball screws in a 5-Axis gantry machine tool, based on machine learning technology and the use of acoustic emission sensor.

The lifelong aim of this study is to identify the effect of Servitization on the performance of engineering companies.

Data is collected over time to monitor the state of ballscrew. The main aim is to find patterns that could help predict and ultimately prevent failures using acoustic sensors. This is to support predictive maintenance. For a further work, machine learning with improved feature extraction strategy like wavelet analysis and deep learning methods can be considered and will be applied to look at different time series data which could be used to look back at longer periods of time to detect failure patterns of the ball screw.

The findings and analysis in this work provide a useful review of product-service system and a platform for more in-depth research based on data-driven and statistics facts.

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Nurudeen Alegeh, obtained his first degree in electrical/electronic engineering from Ambrose Alli University, Ekpoma in 2006. He also has a master's degree in engineering control systems and instrumentation from Huddersfield University, UK in 2016. He has worked as an IT SPECIALIST for three years and also as an INSTRUMENTATION AND CONTROL ENGINEER for five years. He is currently a PhD researcher in the field of artificial intelligence at the University of Huddersfield.

Dr. Abubaker Shagluf is a Research and Development Engineer at the (MTT) Machine Tool Technologies. After gaining an honours degree in Instrumentation and a Master degree in modern digital and radio frequency wireless communication from Leeds University, he joined the group of Centre for precision technologies and began research into machine tool performance and optimising calibration strategies and completed his PhD in 'Calculating the Cost of Calibration Strategies for CNC Machine Tools'. Dr Shagluf has been directly involved at various levels in nearly all the projects successfully undertaken by the group including the EPSRC Centre of Innovative Manufacture in Advanced Metrology and various European, UK government and industry projects. He is active in the area of machine tool.

Professor Andrew P. Longstaff, Has an honours degree in mathematics and a PhD in, "Methods of evaluation of the positioning capability of Cartesian and non-Cartesian machines," under the supervision of Professor Derek Ford at the University of Huddersfield. He is active in the area of industrial metrology and automation. He has worked on several successful UK Engineering and Physical Science Research Council (EPSRC) and EU-government funded projects involving the development and EU-government funded projects involving the development and evaluation of new sensors and measurement devices.

Dr. Simon Fletcher, Is a PRINCIPAL ENTERPRISE FELLOW in the Engineering Control and Machine Performance Group (ECMPG) at the University of Huddersfield. After gaining an honours degree in Computer Aided Engineering, he joined the group and began research into machine tool Performance and completed his PhD in 'Computer aided system for intelligent implementation of machine tool error reduction strategies'.
Dr Fletcher has been directly involved at various levels in nearly all the projects successfully undertaken by the group including the EPSRC Centre of Innovative Manufacture in Advanced Metrology and various European, UK government and industry projects. He is active in the area of machine tool simulation and advanced metrology.