7. Conclusion and recommendations

7.1 Preface

In this chapter, the final conclusions of the research are represented in a bulleted manner to make the conclusions and contributions clear and concise. The conclusions are grouped into sections dealing with measurement, signal analysis and modelling issues. The conclusions are measured against the specific objectives, listed in Section 1.5. After the conclusions, some recommendations for future research in this area are made. The recommendations are specifically aimed to continue the current success with employing NNs for TCM in industry. Recommendations are also made on the broad scope of hardware and software issues related to this work.

7.2 Conclusions

7.2.1 Summary of conclusions

A new AI approach for TCM is proposed. It was shown that the method:

- can monitor two wear modes accurately during hard turning with inclusion of machining parameters,
- monitor flank wear in interrupted cutting of Aluminium on a shop floor with varying feed rate.
- utilises the advantages of AI, using a combination of NNs that estimates the wear values based on basic knowledge (static networks), past knowledge (dynamic networks) and present knowledge (on-line sensors) and can be used with cost-effective hardware instead of expensive laboratory equipment
- is the first industrial implementation of an AI approach to TCM, and provides a useful solution to industry,
- provides significant new knowledge as to how to solve the problem of TCM.

When measured against the general objectives in Section 1.5.1, it can be stated that the objectives were met adequately.

7.2.2 Signal measurement

In this research, several sensor approaches were investigated. An exhaustive survey of research and industrial developments was also included and the following conclusions are made:

- Sensors for TCM in industry must be cost-effective, robust and reliable. A measurement as close as possible to the point of metal removal is absolutely essential for continuous tool wear estimation.
- AE sensors can be used on a shop floor situation because they are robust, small and easy to install. However, they are not reliable for continuous wear estimation due to a lack of physical in-

terpretation of the obtained signal and their sensitivity towards unrelated process noise. AE sensors are however very efficient for tool breakage detection and other applications in machining process monitoring.

- Vibration monitoring assist in collecting the dynamic behaviour of the machine tool and if vibration signals are processed by an expert a continuous wear estimation can be achieved. A difficulty still lies with appropriate interpretation of vibration signals and some basic ways of analysing the vibration signals were presented in this work. An advantage is that wideband accelerometers specifically for machine tools are available although they are somewhat expensive.
- It was shown that measuring a parameter related to the cutting force can achieve cost-effective and reliable TCM in industry. This was accomplished using strain gauges. The strain gauge approach has several advantages:
    - low cost
    - robust
    - small
    - measurement close to point of metal removal
    - wireless signal transmission possible
    - does not change dynamic properties of machine
    - 3-D cutting force can be determined with reasonable accuracy
    - wideband frequency analysis possible
- Thus, the strain gauge combines the advantages of force and vibration sensors in one simple package. The optimal position of strain gauges on the tool holder was determined using the FEM. Furthermore, static and dynamic testing procedures were presented to calibrate the strain gauge system to reconstruct the cutting forces. The measurements were insensitive to clamping conditions, materials and other vibrational effects.
- It was shown how an automated data logger can be built cost-effectively. The data logger utilises an overload protection device, amplifiers, filters, A/D conversion and a computer with C++ software. Drift (due to temperature effects) compensation is provided and the system could be monitored though the Internet.
- Another advantage of the data logger approach is that the tool wear is recorded under realistic conditions (hence not an accelerated tool life test).
- Care must be taken to avoid electrical disturbances when applying sensors on machine tools. Proper earthing and cable shielding are essential.
- Other methods besides force and vibration based approaches have yet to show that they can provide an acceptable solution for continuous wear estimation in industry.

Measured against the signal measurement objectives in Section 1.5.2, these conclusions exceed the expectations set in the objectives. All objectives were met adequately.

7.2.3 Signal processing

Another important step for successful TCM is the signal processing that is employed. Appropriate signal processing methods must be used to generate signal features that correlate or indicate tool wear.

The best features must then be selected to be used as an input to a wear model or decision-making technique. The following conclusions regarding signal processing are made:

- The type of signal processing that will generate reliable features for TCM depends on the type of operation, machine and sensors. As a general rule, the following analyses should be included (when available):
  - Static forces as features
  - Frequency analysis of force and / or vibration to identify wear sensitive frequency ranges as features
  - AErms as a feature (usefulness of AE frequency analysis is debatable)
  - Time domain features
  - Statistical features
  - Time-frequency investigation for non-stationary behaviour
- Using one or several of the techniques listed above, wear sensitive signal features can be generated. The signal features do not have to be insensitive to controllable machining conditions.
- The usefulness of wavelet analysis for TCM is debatable. Using wavelets adds to the complexity of the TCMS and using an appropriate selection of digital filters can achieve better results.
- A combination of features derived from time, frequency and statistical analyses will yield the best results. A TCMS should not be based on features from only one of the domains.
- Identifying internal and external disturbances to the signal features can assist in interpretation of the signals and features. Disturbances should be avoided, or their effect removed from the signals. It was shown how a SOM analysis could assist in data mining for data collected from machining processes. The result can be used to identify and avoid disturbances in experimental data.
- Feature selection or feature space reduction can be achieved through various automated methods. Methods that were used in this study was:
  - Correlation Coefficient Approach (CCA)
  - Statistical Overlap Factor (SOF)
  - Genetic Algorithm (GA)
  - Principal Component Analysis (PCA)
- Combining the CCA and SOF for feature selection yielded the best results and is most suitable if a quick and simple method is required. The GA is somewhat slower and requires more trial runs (a GA procedure must always be repeated several times to ensure that the global optimum was reached).
- Using only the Principal Components as features is generally not reliable for TCM. It was shown that including the 1st principal component as an additional feature can improve the result somewhat. However, the adaptability of the PCA toward small changes in the process conditions must be investigated before industrial application.
- The most important aspect of feature selection is engineering judgement. Care must be taken not take 100% linearly correlated data. However, using features that show some degree of correlation is not wrong, if the features were generated from different sensors and also using different signal processing methods. Hence, an appropriate combination representing different sensors and processing methods yields the best results. However, care must be taken not to choose too many fea-

tures. If a single sensor single feature approach works very well, adding more features will probably worsen the situation. In the case of TCM, it was found that the single feature approach is generally not reliable due to noisy conditions and therefore sensor / feature fusion is required. As a general rule 4-10 features could be used.

The objectives listed in Section 1.5.3 were met adequately.

7.2.4 Modelling and monitoring

Different techniques of modelling were investigated during the course of this research. The following conclusions are made:

- Analytical / theoretical modelling is of limited use to TCM. The models suffer from many limitations and might never reach the level of sophistication where a model is available for any process without experimentation. Furthermore, tool wear cannot be described by these methods.
- Numerical / simulation models are reaching a level of sophistication where most processes can be modelled with any combination of materials and geometry. Because the methods require a lot of expertise and time, they are not feasible for on-line implementation but can be considered as an additional tool for either treating the effect of new cutting conditions or as verification of the experimental models.
- Empirical / experimental modelling is the only remaining option. Many different approaches exist, for instance parametric or non-parametric approaches. AI modelling also has a non-parametric empirical nature. In this research, it was shown for the first time that the AI method can work effectively on shop floor conditions.
- The use of a mechanistic model proved unsuccessful due to some basic assumptions within the model that do not apply to a diverse range of turning operations.
- In this research, it was shown that the growth of tool wear is always unique and unpredictable. As a result, the sensorless approaches to the tool wear problem will not be effective enough if optimal tool use is required. The sensorless approaches yield a tool life equation that will only be an estimation of the real tool life. With sensor-based methods, the tool life is monitored.
- An AI method of monitoring is proposed based on Neural Networks (NNs). The method utilises combinations of static and dynamic NNs. The method has several advantages:
    - Excellent generalisation capabilities
    - Effective use of temporal information
    - Insensitive to noisy data
    - Machining conditions (*e.g.* feed rate and speed) can be included
    - Insensitive towards clamping conditions and other external disturbances
    - Combines the use of current and historical data as well as a knowledge basis
    - Same architecture applies to different turning operations
    - The method can follow any geometrical development of tool wear
    - The method can follow more than one wear mode (*e.g.* flank wear and crater wear)
- Several NN architectures were compared for use on the static NN level. It was found that the inclusion of time delays requires a slightly larger network with more training. The inclusion of the

time delays did not yield a further improvement. Radial Basis Function (RBF) networks, Multi-layer Perceptron (MLP), Elman type networks and FF networks with different activation functions were compared. Most yielded acceptable results. It is suggested to use the Elman or FF network with the "tansigmiod" activation function for best results.

- The methods employed in this research to ensure generalisation capabilities of the static networks were early stopping and using a small network. It was shown that a too large network or over-trained networks cause instabilities.
- Several new optimisation algorithms were investigated for training the dynamic NNs, because it was found that conventional methods are too slow for on-line implementation and do not always converge. The Particle Swarm Optimisation Algorithm (PSOA) was found to be best algorithm for on-line training. The PSOA has the following advantages:
    - Fast and reliable
    - Simple formulation and implementation
    - No gradient function evaluation required
    - Random nature of optimising ideal for NNs
    - The method outperforms other methods in unconstrained global optimisation
- The AI monitoring method was trained, validated and tested on separate data sets. It was also shown that the results are repeatable after re-initialisation and training of the static NNs. The dynamic NNs converge within a few outer steps after re-initialisation.

Measured against the signal measurement objectives in Section 1.5.4, most conclusions exceed the expectations set. In the area of numerical models more research is required, and this is explored in Section 7.2.3.

7.3 Recommendations

7.2.1 Measurement

The following suggestions can be made for future research with respect to signal measurement:

- optimise the number, size and position of strain gauges on tool holder.
- investigate the possibility of an on-board strain gauge amplifier on tool holder
- develop better mechanical protection for strain gauges
- investigate the industrial implementation of wireless data transfer
- attempt constructing a sensor-integrated tool for larger tool holders
- use mechanical amplification on tool holder (*e.g.* holes that cause stress concentrations)
- extend the Internet monitoring capabilities of the system

7.2.2 Signal processing

Many signal processing methods were investigated in this study. Future work should be directed towards feature selection or feature space reduction. Other techniques that have been mentioned in the literature but not considered in this work are for example octave analysis and bispectrum analysis. These might prove useful for future research. It is however suggested that other types of machining operations be investigated. The type of operation also determines which signal processing technique will be most effective. It might require the development of a custom technique.

7.2.3 Modelling

A significant improvement in the use of the on-line AI method would be to minimise the amount of training data required for successful implementation. Future work should be mainly directed towards this topic. The disadvantage of NNs (and many other experimental) models is that they require training / calibration data for the range of conditions they are expected to operate on. A NN cannot be expected to yield accurate results for previously unseen machining conditions (although it might perform to satisfaction, it cannot be expected *a priori*). Thus, methods of normalising data with respect to machining conditions should be the main focus of future work. Consequently the NNs do not need to be trained for every condition. The use of numerical models to achieve this is one attractive option and should be investigated in future, such as a simulation model described by Weinert and Zabel [244]. The use of any kind of experimental model will basically have the same influence as including the machining conditions in the AI approach, as was done in this research. The advantage of a numerical model would be that no experimental data is required, and therefore no adjustments to the TCMS would be required when a machining condition change. Present analytical models will not provide a solution to this problem.

Future work can of course also include the integration of the current system into the CNC machine, instead of a separate stand-alone device. Additionally, the exact machining parameters and machining profile could be provided to the TCMS in this way, and the machine can be automatically shut down when excessive wear is detected.

7.4 Contribution

Despite exhaustive investigations, conversations and communications with researchers and industrial representatives worldwide, the author could not find a single example of a TCMS using AI that was proved to work on industrial data (also refer to Section 1.5.6). Thus, this research has overcome the difficulties involved with a real implementation of the AI method for TCM. This was achieved by designing, developing, and building the system from start to finish (hardware and software). This required insight into many different disciplines, *e.g.* electronics, structural dynamics, NNs, mathematics (optimisation and statistics), manufacturing, signal processing, data acquisition and computer programming. A suitable combination of knowledge from the different disciplines enabled a unique solution to the TCM problem, and is claimed to be the first practical implementation of a TCMS using AI. The formulation and application of the AI tool wear monitoring method proposed is unique in terms of its formulation and application, and was shown to outperform other AI approaches. This contribution provides a significant improvement towards more cost-effective, reliable and accurate tool wear monitoring.

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