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Final Report

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Project coordinator name: Dr. Ramesh Raghavendra E: rraghavendra@wit.ie
Final Report author: Dr. Denis O'Sullivan E:dhosullivan@wit.ie

Project coordinator organisation name: WATERFORD INSTITUTE OF TECHNOLOGY

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1 Executive Summary

The machining of hard wearing metals may result in pronounced in-process tool wear and catastrophic tool failure (CTF). Ideally tool wear should be monitored by stopping the process intermittently and completing a visual inspection of the tip, but this is not always possible in a real time production facility. Experienced CNC operators may use "tell-tale" signs of enhanced tool wear including; visual analysis of the cutting chip, changes in sound, the monitoring of motor power consumption, but inexperienced operators may not always recognise same. Enhanced tool wear and tool failure may cause substantial damage to the tool, the workpiece and/or the machine tool.

There has been considerable research from both an academic and industrial perspective into the monitoring and control of CNC machining processes. This work has been continued by the consortium engaged in the REALISM project, an EU-FP7 funded project which investigated the use of sensor fusion in a real time production environment, to monitor CNC tool wear and catastrophic tool failure (CTF) through the use of three sensor technologies - Force, Acoustic Emission and Vibration.

Intelligent data analysis using a neural network approach was used to analyse the results of the sensor data, to correlate the degree of tool wear, as a means of future wear predication. The sensor signal features are analysed in real-time to detect catastrophic tool failure (CTF) and to allow corrective actions to be put in place. A Human Machine Interface (HMI), for an Artificial Neural Network (ANN)-based machine tool process monitoring system, was developed allowing user interaction for closed loop ANN machine learning. The operator initially teaches the ANN by identifying when a pre-determined number of tools are worn. From this teaching, the ANN compares the learned results against process conditions, gathered from the sensors, allowing the system to make decisions around the degree of tool wear present on the cutting tool.

A Tool Condition Monitoring (TCM) working prototype was integrated onto a Mazak 200 lathe and testing on in real time production in the Schivo Precision engineering (Waterford, Ireland) facility. Since installation of the TCM system, scrap rates due to tool wear have reduced, with over 64% savings on scrap value over a 6-week period. The visual element of the HMI has enhanced operator engagement and new operator training performance in their understanding machine performance, which has resulted in decrease in new operator training time by over 20%. The HMI feedback is being used to optimize feeds and speeds for tool/material configurations. An unforeseen impact has been operator feedback in terms of cutting tool performance. The TCM has shown that there was significant difference in cutting insert degradation over their lifetime from

different suppliers. As a result of this, the facility has moved to a single source supplier which has resulted in prolonged cutting insert lifetime.

Interest from the dissemination activities has resulted in the development of a business plan by Schivo to investigate the feasibility of in-house production of a bolt-on TCM system targeting CNC machine users. Early calculations suggest that the manufacture of 100 systems per year would lead to the creation of 7 new assembly operator jobs, 1 process/manufacturing engineer and 1 quality control personnel.

The TCM has been demonstrated to large aerospace customers at Schivo and Tulino CTM (Naples, Italy) for hard-to-machine titanium alloys, which are commonly used for component manufacture for this industrial sector. Implementation of the TCM will help achieve the quality management systems requirements under the ISO EN 9100:2003 (E) aerospace guidelines for machining operations which will drive business growth. Tulino CTM expects to hire 2 new employees in order to satisfy the production demands for the aerospace industry in 2016. IDT foresees the performance benefits with the adaption of the TCM across a number of its manufacturing techniques including friction stir welding and automated robotic swing cells.

2 Summary description of project context and objectives

In precision engineering, tool wear has a large effect on the accuracy and surface finish of machined parts and is the single greatest contributor to scrap in the industry. In the surgical products' market, cosmetic finish requirements placed on parts continues to be raised to new levels. Similarly, in the aerospace industry, parts need to be increasingly accurate (to increase energy efficiency). Through the development of CNC technology, tolerances of 1µm are now possible. However, SMEs involved in this project see significant failures in the current technology. Austenitic stainless steels and titanium and its alloys have been widely used for biomaterials such as artificial hip joints and dental implants and in aerospace industry. These materials are considered to be very difficult to machine. One of the most often used: Ti–6Al–4V is notorious for poor machinability due to its low thermal conductivity that causes high temperature on the tool face and strong chemical affinity with most tool materials, thereby leading to premature tool failure. Furthermore, its inhomogeneous deformation makes the cutting force fluctuate and aggravates tool-wear. This poor machinability has limited cutting speed to less than 60 m/min in industrial practice. The quality and performance of a product is directly related to surface integrity achieved by final machining. When the tool wear increases, the hardness of such material increases as well, due to the work hardening process while machining.

Currently, errors associated with tool wear remain uncompensated for and are usually only detected at the end of the machine cycle, by which time the product is usually of scrap value. Scrap at the Schivo facility is 2% of turnover and costs the company €300,000 per year. Analysis of this figure has shown that over 50% of the scrap generated is attributed to worn or broken tooling. These are comparable figure in both IDT's facility and Tulino's facilities. If real time, accurate monitoring were available, machining parameters could be adjusted to compensate for tool wear, tools could be replaced in proper time when they approach their tool life, not prematurely as they are now, machines could be scheduled for down-time and surface finish and dimensional stability would be increased. Such advances would have a strong impact on the efficiency of processes and increase competitive advantage of European precision engineering firms. The specific aim of the project is to develop a robust 'smart' sensor-based system to provide accurate, real-time analysis of the process performance and alter the machining process to optimal conditions, resulting in better control of the process and reducing scrap rates.

This project is collaboration between research leaders in the areas of CNC process monitoring and leading SMEs in the CNC machining industry. The REALISM project is a two-year project and includes three small-medium size enterprises (SMEs) and four research and technological development (RTD) providers from four countries, working together to overcome issues relating high scrap rates caused by tool wear in the precision engineering sector.

The project objectives include strategic, technical and scientific objectives:

Strategic objectives:

- Improvement of the competitive advantage of the SMEs involved in project-Lean Manufacturing.

- Improvement of the competitive advantage of the SMEs involved in the project- process predictability and reduction of waste.
- Enhancement of the SMEs usage of consumables-furthering competitive advantage.
- Improvement of the environmental impact of the SMEs involved-energy consumption.

Technical objectives:

- Development of an in depth understanding among the SMEs of the dynamics of the cutting processes involved in CNC machining.
- Development of sensoring technologies capable of effectively monitoring the processes.

Scientific objectives:

- Development of a Neural Network for the analysis of signals from multiple sensors in a previously unmapped process.
- Development of an understanding of the physics of the cutting operation and how this can influence the resultant product.
- Development of specific neural network algorithms that can be applied on a process specific basis – the specific application here is medical devices and pharmaceuticals.

3 Description of main S & T results/foregrounds

The general structure of tool and process condition monitoring system is presented in Figure 1. In the cutting zone there are many process variables (cutting forces, vibration, Acoustic Emission, noise, temperature, surface finish, *etc*.) influenced by tool and process condition. Those which are potentially useful for Tool Condition Monitoring (TCM) can be measured by appropriate sensors. Signals acquired from these sensors are then subject to signal processing, the aim of which is the generation of useful signal features, correlated with tool or process condition. Signal features are then integrated into final diagnosis, which can be presented to the operator and/or sent to the Numerical controller (NC), executing the appropriate action. All elements of the tool/process control monitoring (T/PCM) system presented in Figure 2 are addressed in this section.

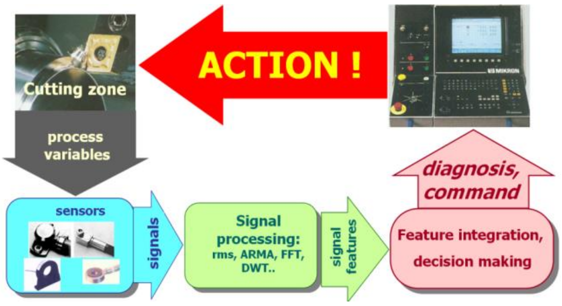


Figure 1. Structure of Tool/Process Condition Monitoring System.

There are several phenomena, which can be used for extracting indicators of the state of a machining process:

- Acoustic emission.
- Cutting forces and torque
- Temperature
- Motor power and current.
- Vibrations
- Machine vision

This project has developed a sensor fusion system, whereby multiple process parameters are sensed and combined to provide accurate feedback on the operation performance. The ability to monitor the performance of the operation allows the user to prevent wasteful manufacturing cycles by allowing intervention in a non-ideal cycle to correct the situation, such as by making offsets to allow for tool wear or adjusting spindle speeds to correct cutting conditions, thus giving predictable surface finishes and product dimensions.

3.1 Realism TCM 1.0 Working Prototype

The following section details the Realism TCM working prototype Version 1.0 as developed in Schivo. It consists of 3 main elements which includes the hardware components, software components and human machine interface.

3.1.1 Hardware components

The hardware components include the sensors, sensor processors and amplifiers, data acquisition hardware and PLC controller (Figure 2).

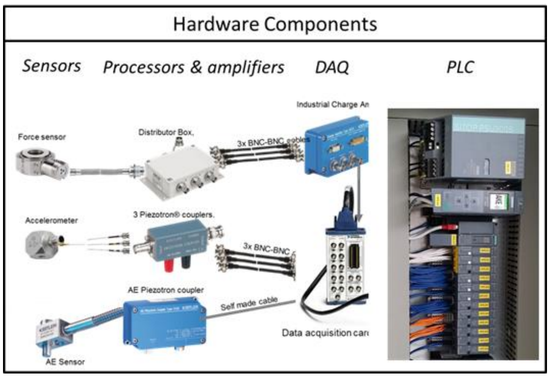


Figure 2. Hardware components of Realism TCM system.

The sensors are integrated into the machine tool to allow for optimized sensing. Figure 3 shows the accelerometer and acoustic emission sensor integrated onto the machine turret in a Mazak Quickturn Nexus 200 lathe.

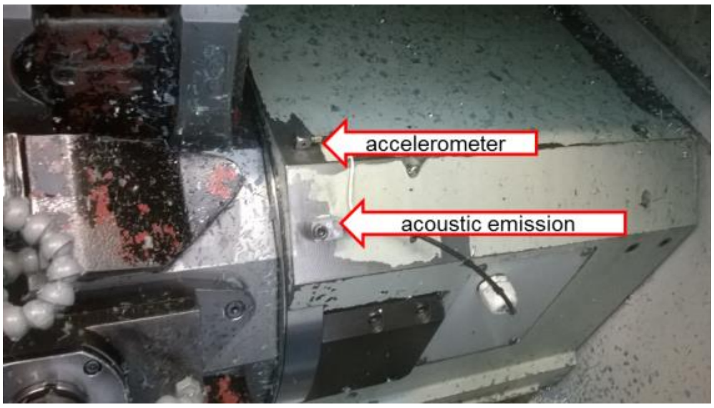


Figure 3. Position of installation sites of AE & Vibration sensors.

A force sensor was integrated into the turret sliding head as shown in Figure 4.

Figure 4**.** Location of force sensor in drilled pocket

3.1.1.1 PLC controller

All sensor analogue signals are collected through a data acquisition system based on an industrial portable computer installed with a National Instruments card and data logging software developed in LabView as a VI. The diagnostic system processes the data in real-time. The frequency contents of the signals generated during machining do not exceed or are limited to 2-3 kHz. Therefore the applied sampling rate was 10kS/s per channel.

As the entire data acquisition system operates in an automatic mode, it is necessary to continuously monitor the status of the machine tool such as the tool holder position of the actual working tool, a digital trigger (start/stop) of operation and indication (start/stop) of working feed. These signals are created by the machine controller as digital signals (logic 1 or 0). Each start of a new operation (high level, logic 1 of appropriate digital signal) activates data recording to a new file – all digital and analogue signals are sampled simultaneously and saved to the same file. The end of operation (low level, logic 0 digital signal) stops the data recording and closes the file.

In addition to the above outlined sensor and operational information, there is other information that can be taken from the CNC machine in terms of the operational parameters, such as the spindle speed , program block number and similar data. It is important to note at this point that a PROFIBUS or LAN standard communication connection is required to include this information in the analysis; however, inclusion of these data variables at this stage is outside the scope of the deliverable. Figure 5 shows the analogue and digital communication between CNC controller and PLC.

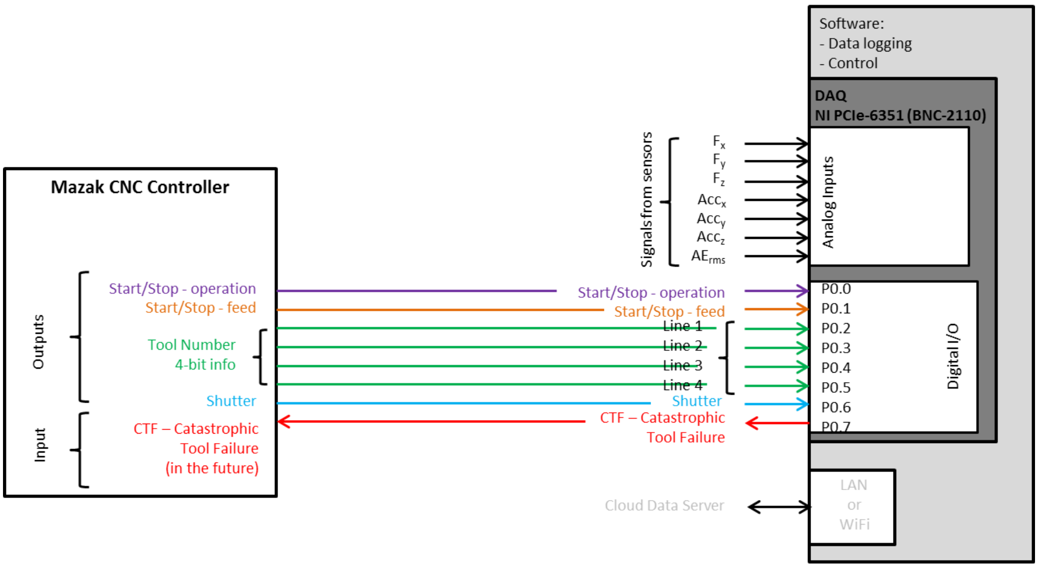


Figure 5. Diagram of communication between CNC controller and PLC.

3.1.2 Software components

The software allows for both manual and automatic recording of analogue and digital signals, connected to the industrial PC equipped with a data acquisition card. As the data analysis was being undertaken in a different country to the data collection the files were synchronized to the cloud file server. This allowed for very quick verification of the accuracy of recorded data by all the project participants (Figure 6.).

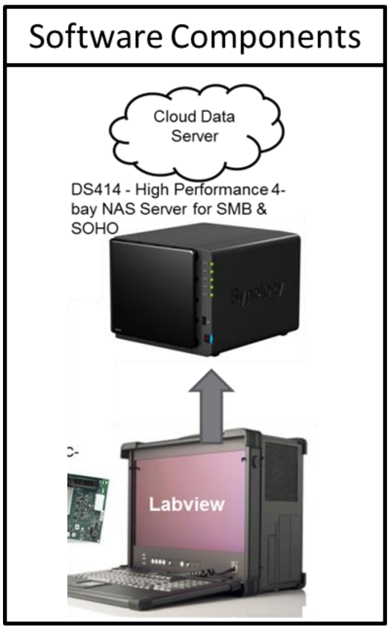


Figure 6. Industrial PC hosting LabView and cloud server.

3.1.2.1 Signal Processing

All signals acquired during machining can vary due to the changes of feed value or direction, changes of depth of cut or other disturbances of cutting conditions. Therefore only stable parts of the signals should be selected for tool wear monitoring.

During long cutting cycles, large amounts of raw data are generated which requires large computing power and memory which can impact on data processing time. As tool wear is a continuous process, representative fragments (segments) of the signals are sufficient enough for analysis therefore representative parts of the signals have to be identified.

For data segment identification, signals are divided into segments lasting 1 second each. The effective value (RMS) of each segment are compared with the RMS of adjacent segments to determine if the signal is relatively stable using a stability index ST [EQN 1] as shown in Figure 7.

$$\boldsymbol{St}[\mathbf{B}] = \left|\frac{\boldsymbol{RMS}[\boldsymbol{A}]}{\boldsymbol{RMS}[\boldsymbol{B}]} - \mathbf{1}\right| + \left|\frac{\boldsymbol{RMS}[\boldsymbol{C}]}{\boldsymbol{RMS}[\boldsymbol{B}]} - \mathbf{1}\right| \quad \text{[EQN 1]}$$

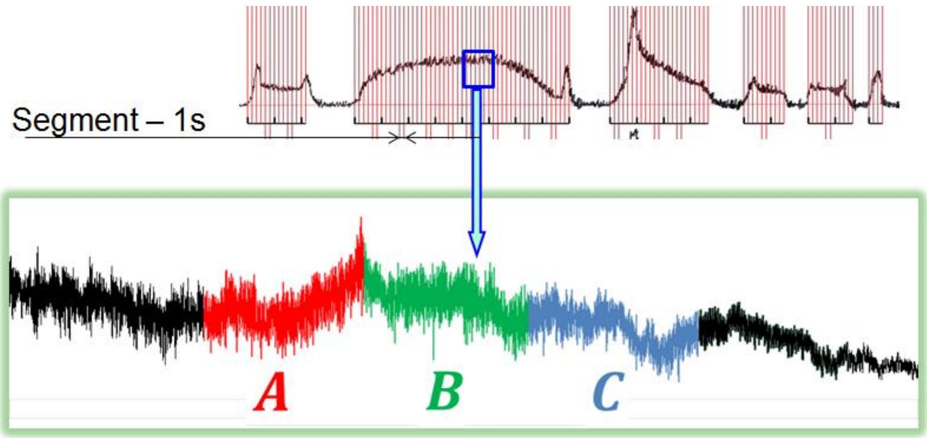


Figure 7. Segmentation and segment assessment

The lower the value of the *St*, the more stable the signal and more useful for data processing. All *St* values obtained from all signals for a particular segment, are averaged to produce the segment stability evaluation.

3.1.2.2 Signal Feature Extraction

Selected segments of signals from all applied sensors are subject of signal feature (SF) extraction. The signal feature extraction applied here is based on the wavelet transform. The Discrete Wavelet Transform (DWT) decomposes a signal into the scaling coefficients (approximations *A*) and the wavelet coefficients (details *D*) by the convolution of the signal and the impulse response of the low-pass and high-pass filters. The filter's outputs are sub-sampled by [EQN 2] and [EQN 3]. At the first level the original signal is decomposed into A_1 and D_1 then approximation A_1 can be decomposed again into A_2 and D_2. Generally the approximations (A_{j+1}) and details (D_{j+1}) at level j+1 can be expressed by convolutions:

$$A_{j+1}[n] = \sum_{k=-\infty}^{\infty} h[2n-k] A_j[k] \quad \text{[EQN 2]}$$

$$D_{j+1}[n] = \sum_{k=-\infty}^{\infty} g[2n-k] A_j[k] \quad \text{[EQN 3]}$$

where *h* and *g* are the impulse responses of the low-pass and high-pass filters, respectively, which are discrete equivalents to the scaling function and wavelet.

Another type of wavelet transform is the Wavelet Packet Transform (WPT) where approximations and details are both decomposed, providing much more frequency bands (Figure 8). This provides more opportunities to find useful signal features, so it is used in this research. From a mathematical point of view, the structure of computations in a WPT is exactly an octave-band filter band, thus approximations and details are band pass signals. Whilst several wavelet basis function types are available in the literature db02 wavelet and 3-level decomposition WPT was applied here as the most informative.

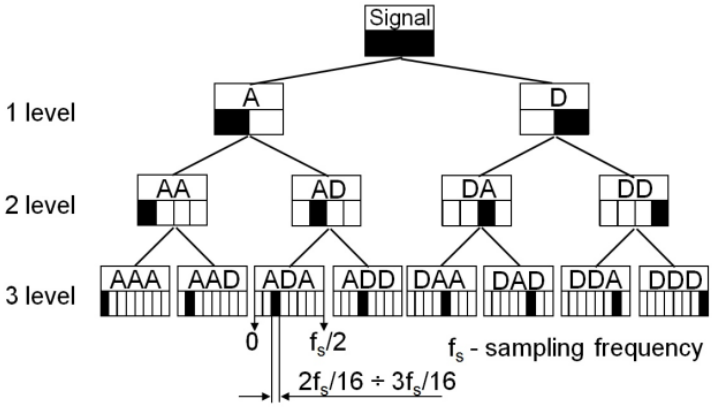


Figure 8. Three level Wavelet Packet Transform (WPT) decomposition, blackened fields indicate frequency band of the original signal.

For each of the band signals obtained from the WP the following signal features (SFs) are calculated: average value (mean), standard deviation (st_dev), power (pow), energy (E), skewness (skew), kurtosis (kurt), effective value (root mean square - RMS), mode - the value that appears most often in a set of data (mode), peak value-to-peak (PP), crest factor (CF) & 90% percentile (Perc90). So for each band, including raw signal, 11 SFs are calculated. As there are 15 band signals (including a raw signal), altogether there are 165 SFs for each signal segment. Additionally the energy of power spectral density of the raw signal is determined. This gives a total number of 166 signal features for each segment of the signal.

Algorithms for signal preprocessing are programmed in LabView environment and tested using signals which were previously obtained by WUT. Figure 9 shows the results of a turning operation consisting of five cuts performed by 3 tools, designated by separate colors. Upper part of the diagram shows Boolean variable values, meaning (from the bottom to top), FEED – working feed, Cut – cutting, Seg – one second long segment selected for tool wear monitoring, COSeg – segment selected for tool wear monitoring in subsequent operations.

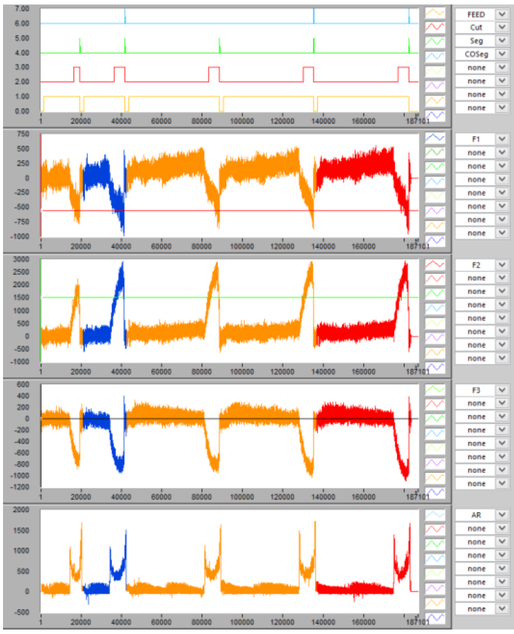


Figure 9. Digital and analogue data from a turning operation.

3.1.2.3 Development of cognitive methods for decision-making

The outcome of sensor signal feature extraction is a set of six relevant features correlated to a specific output for tool wear characterization, i.e. the percentage of consumed tool life. Sensor acquisition and, consequently, signal feature (SF) calculation is stopped whenever the tool wear of the insert reaches the maximum, meaning that the tool life has reached its end. Using these signal features, a Neural Network (NN) decision-making system for tool wear prediction was developed in LabView.

The NN approach is based on training the built NN architecture with a chosen training set made of known instances identified by the couples constituted by one input feature vector (signal features) and one output quality value (consumed tool life) for later testing of the output instances containing only the input feature vector. The elements of the input feature vector are represented by the features extracted from the sensor signals, and the corresponding tool wear level (e.g. expressed as tool life percentage) represents the output quality value. The testing is performed to assess the trained NN performance, in order to decide whether that specific NN architecture is reliable in the prediction of the output quality value and then employ it for decision-making regime.

The basic NN architecture is characterised by three layers: the input layer constituting the input nodes consisting of the extracted SFs, the hidden layer made up of a number of hidden nodes related to the number of input nodes. The output layer contains only one output node, providing the consumed tool life. The maximum number of epochs or iterations that the NN can perform during the training iterations to achieve convergence is initially set. If convergence occurs before reaching the maximum number of epochs, the training of the NN is stopped.

The NN training and testing procedure was carried out as follows: the input SFs vectors and the corresponding consumed tool life percentages for tool life 1 were used for NN training, while the input SFs vectors for tool life 2 were used for NN testing. Next, the input SFs vectors and the corresponding consumed tool life percentages for tool lives 1 and 2 were used for NN training while the input SFs vectors for the tool life 3 were used for NN testing. Finally, the input SFs vectors and the corresponding consumed tool life percentages for tool lives 1, 2 and 3 were used for NN training and, one at a time, tool lives 4, 5, 6 and 7 were used for NN testing.

3.1.2.4 Implementation of the NN decision-making approach in LabView

The add-on library Machine Learning was used for training and testing of the NN architectures implemented in LabView. Two VIs were used: back-propagation learn (BP Learn: training VI) and back-propagation evaluate (BP Evaluate: testing VI). For each VI, the input needs to be identified. The inputs and outputs datasets are saved as text files: train input, train output, test input, test output.

The output of the BP Learn VI is connected as input to the BP Evaluate VI. The output of the BP evaluate is a 1D vector with the predicted outputs. The number of hidden neurons is specified in the BP Learn VI. The training algorithm is the Levenberg-Marquardt.

3.1.2.5 General scope and setup of the NN based decision-making system

The NN based decision-making system requires the creation of a training database through an experimental campaign. After the creation of the training database, the NN based decision-making system can be set up. As mentioned earlier, the dataset is composed of three sets of tool lives, i.e. three sets of sensorial features coupled with the corresponding consumed tool life values.

For the proper implementation of the system, a computer where the developed NN based decision-making system is installed needs to be connected to the CNC turning machine is required. Figure 10 summarizes the NN based decision-making procedure throughout the machining process. The CNC controller sends via Wi-Fi or Ethernet cable the machining process code to the NN based decision-making system running on the computer (Figure 10). The system uses this machining process code to identify the machining process which is necessary to identify. As mentioned in the preceding section, the identified NN was trained with the process relevant set of sensorial features and related output quality values.

Consequently, when the turning process is started, the relevant NN is identified through the process code, and the sensor signal data acquisition commences. A sensorial data acquisition time window of 1 second has been considered sufficient for subsequent sensor signal feature extraction and, finally, these features are tested with the trained NN to obtain the predicted consumed tool life (Figure 10).

Once the predicted consumed tool life is obtained, it is compared to 1, the end of tool life i.e. the need to change cutting insert. If the predicted consumed tool life is less than 1, another 1 second of machining is carried out. For each 1 second of machining, the sensorial features are extracted and are coupled with the predicted consumed tool life that is obtained by testing the trained NN. The data represented by sensor signal features and predicted consumed tool life couples are stored sequentially in a buffer.

This process is repeated till the predicted consumed tool life reaches 1, i.e. the maximum tool wear is reached and the insert should be changed. Once the predicted consumed tool life reaches 1, the computer program sends a STOP command output to the CNC controller in order to interrupt the turning process and indicates an alert alarm on the CNC controller screen, warning the operator to change the insert.

Meanwhile, the initial dataset used for training the initial NN is modified. The first tool life set composed of sensorial features and predicted consumed tool life couples is eliminated The new tool life set is included in the dataset and the NN is trained again using the new modified training set. After changing the cutting insert, the retrained NN is used to predict the consumed to tool life of the new cutting insert.

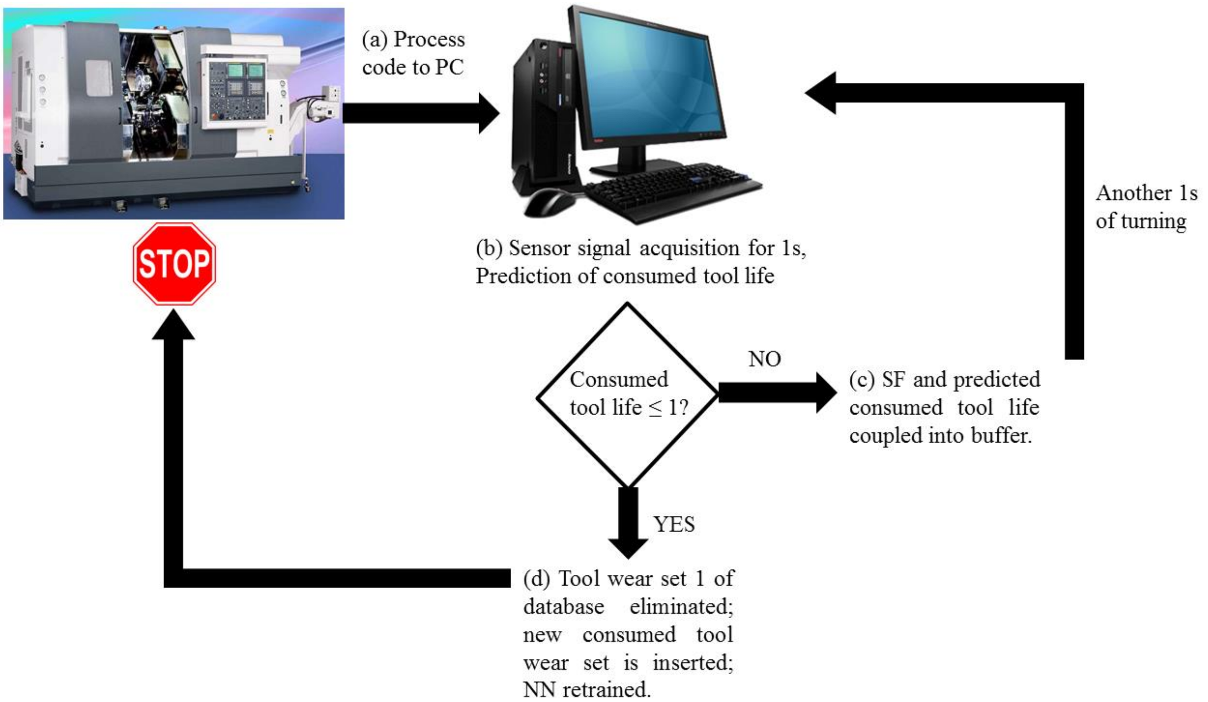
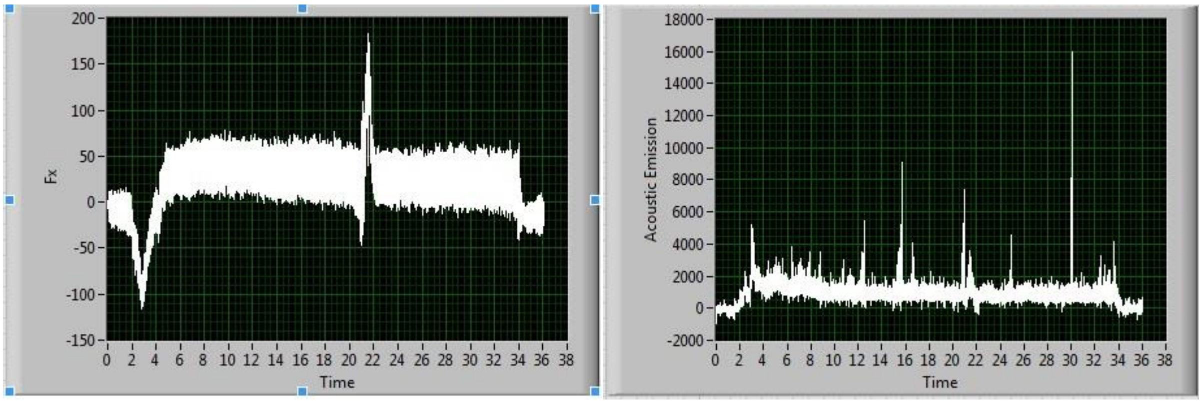


Figure 10. The NN based decision-making procedure throughout the machining process.

3.1.2.6 Signal processing and feature extraction for Catastrophic Tool Failures

The methodology used to detect the CTF occurrence was developed using two kinds of signals: one characterized by CTF occurrence and the other without CTF occurrence. Example signals corresponding to the above two kinds, from cutting operations were initially monitored with two sensors: one for the acquisition of the three components of the cutting force and the other one for the acquisition of the acoustic emission RMS were utilized for the development of the CTF detection method. The three components of the cutting force are measured simultaneously by one sensor type (3D force sensor) while another sensor detects the acoustic emission RMS during the machining process. The method for CTF detection starts by plotting the cutting force signals and acoustic emission RMS signal vs time. The visual examination of CTF is relatively simple because it is characterized by a large variation of the trend of the signals. In particular, this variation is more evident in the cutting force components signals rather than in the acoustic emission signals. This may be due to the critical influence of the noise of the machining process on the acoustic emission signal (Figure 11).



(a) F_x signal vs time (b) Acoustic Emission RMS signal vs time

Figure 11. Example signals for CTF detection (a) Cutting force component F_x vs time; (b) Acoustic Emission RMS vs time.

In the methodology, the CTF detection is realized by using the statistical features (signal mean, variance, etc.) from the sig extracted signal features. For this methodology of CTF detection, the algorithm starts by considering the mobile mean with fixed number of samplings and identifies the value of the mean that it is greater than zero. From this value, a comparison is carried out between each element of the recorded signals and the successive ten elements. The comparison is done by searching when this difference is greater than a threshold value; once this value is identified, the algorithm doesn't stop but continues until the last value for which this is true is obtained.

Preliminary results showed that the CTF detection based on analysis of the cutting force signals was more efficient way than using AE_{RMS} signals. Based on these results it was decided that only the force sensor would be utilised for CTF detection and developed algorithms were used the CTF subVI which was integrated into the TCM main LabView program. Upon CTF occurrence, a digital signal is sent to the CNC controller to stop the working feed and a Boolean alarm is signalled on the GUI.

3.1.3 GUI Development

Previous investigation shows that typically an interface for such types of monitoring system is developed either without knowledge of interpreted physical processes or without considering usability requirements. Therefore, in the REALISM project the development of human-machine interface (HMI) is performed considering both general physical processes and users' needs. Special attention is paid to difference in users' experience, which requires different access levels to different types of information presented on the interface. Another important aspect of the monitoring system is that it should allow for continuous improvement in the future. From this perspective, all information should be recorded and easily accessible. This is caused by the needs to modify and improve monitoring system based on the analysis of the data earlier obtained from the process, and improvement of users' skills becomes possible.

3.1.3.1 HMI prototype development

3.1.3.1.1 Interpretation of data requirements to HMI

Data requirements should describe type of data, size of data, etc. Based on the needs to create an interface using LabView software, data requirements are presented in Table 1with a focus on a specific type of data used during software requirements.

Table 1. Input data requirements for sensors.

Name	Type of data	User access group
Signal name (f_x, f_y, f_z, V_x, AE_{rms})	Unsigned word [integer]	Administrator
Maximum value of signal	16-bit integer	Administrator
Physical unit	& String	Administrator
Signal range	Unsigned word [integer]	Administrator
Collision detection (on/off)	Boolean	Administrator
Threshold of collision detection	16-bit integer	Administrator
Signal feature for cutting detection (average, rms, off)	Unsigned word [integer]	Administrator
Threshold of signal feature	16-bit integer	Administrator

3.1.3.1.2 Interpretation of user requirements to HMI

User requirements clarify user groups with detailed information regarding access levels to the monitoring system. The first analysis of the accessibility was performed based on the documentation from an interview that took place in Schivo, and programming code description as well. The result of this analysis is presented in Table 2.

Table 2. Information regarding accessibility for different user groups.

Administrator	Supervisor	Operator
Installation monitoring system	Configuration of workpiece	Start/stop machine
Manage sensor (installation and input information)	System learning (training a neural network)	Tool change
Manage hardware and software	Product changeover	Observes (native HMI)
Data management (in case of database presence)	Observes (external HMI system) with representation more specific information	Shift closure (Operator1 – Operator2), exchange information between operators in different shifts
Create/manage user account	Requesting for ANN design	Reporting errors in process and monitoring system
Monitoring system modification	Exchange of information between all participants	Requesting for re-teaching or maintenance needs
Training personnel with using historical data earlier stored during monitoring	Organizing meeting regarding innovation, modification and improvements of the monitoring system	Communication with supervisor regarding system performance
Learning process (development/acquiring new skills and knowledge)		

However, users from different access groups should communicate between each other. Even though, supervisor is responsible for organizing this exchange of information between users, better clarification of how it can be organized is provided in Figure 12.

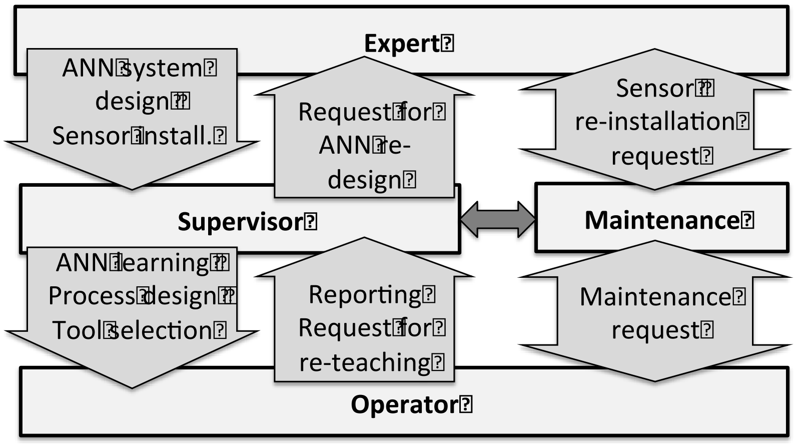


Figure 12. Interactions between the main human roles in an ANN based machine tool process monitoring system

To comply to the needs of the different roles (after proposed changes) and the interactions between them the HMI could have the following features:

- *Expert:* The HMI must cover the needs for sensor installation, ANN design, and redesign, testing and diagnostics, as well as cover the needs for easy basic training. The expert might direct event alarm in the case of a sensor malfunction etc.
- *Maintenance:* The HMI will be mainly the output of statistics from the machine tool, vibration measurements etc.
- *Supervisor:* The supervisor needs to fill in the process and product data, as well as manage the ANN learning process. The HMI should also allow good communication with the operators, viewing shift/ event logs.
- *Operators:* The operators need output on the tool condition from the HMI, and a signal /alarm when to change the tool and a second alarm for CTF. Moreover will there be inputs such as changing tool, workpiece changeover and any other events and anomalies worth reporting. The operator needs to communicate with the Supervisor(s) and other operators and the HMI should aid this.

3.1.3.2 Process monitoring learning loop

Learning is a feature of practice that might be present in all sorts of activities, not just in clear cases of training and apprenticeship, and a process monitoring system can be a tool for learning and knowledge creation. Firstly the operator and the supervisor must be knowledgeable about the process and how different variables within the process interact, both in a practical and an abstract theoretical sense. Secondly they need to make correct decisions based on analysis, knowledge, experience and skills. The ability through interaction with the process and the process monitoring system to decide for example that a tool needs to be replaced, is a single loop learning process. The second outcome is to move into a process of double loop learning about the process and the monitoring system in itself. How can the machining process and the process monitoring system be further improved? This requires the ability to analyze the process outputs and monitoring measurements over time, and the HMI of the monitoring system should aid this.

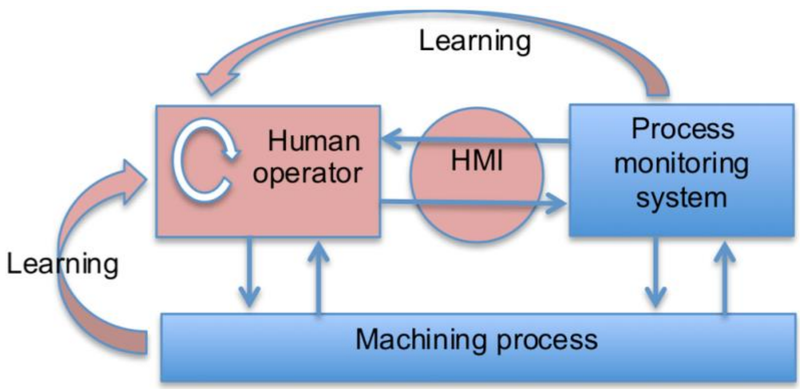


Figure 13. Control Loop and Knowledge creation loop.

Figure 13 illustrates how the human operator (in this case more or less all the roles mentioned previously) interacts with both the process monitoring system and the machining process engaging a double loop learning from both. The HMI of the process monitoring system should aid this and allow the human operator to reflect in action.

3.1.3.3 TCM GUI construction

LabView software is used to create prototype of human-machine interface in accordance with REALISM project requirements. Interface development was started with a creation of the main window for user interface on the front panel. This window consists of 4 tabs, which are **Service**, **Configuration**, **Monitoring** and **Event Log** (Figure 14). Each tab describes specific information, but before getting access to main window user needs to input his personal data into empty fields placed on log in pop-up window.

Figure 14. Example of different tabs final version of TCM GUI.

Development of the tabs on main window was performed one-by-one. The first tab is **Service**, and it consists of two subtabs: **Account Manager** (to manage account profiles) and **Sensor (**updating information regarding sensors supplemented to the machine equipment).

The next tab on main window is **Configuration** that should be accessible mainly by supervisor, but administrator should also has access for its testing (after monitoring system is installed). From the main window, supervisor should choose which type of configuration should be done (workpiece configuration or system training).

The next tab – **Monitoring** tab is created for actual monitoring. All users must have access to this tab. When user logs into the system, his username will be shown on the screen. Information about workpiece, machine and cutting tools will be imported from the configuration files (filled in before).

The last tab is **Event log** depicted on **Error! Reference source not found.**. This window is created to represent he actions, which are performed during using monitoring system. This information is very important for further usage. Since events can be analyzed, especially in case of wrong system performance or not good enough system performance, improvement and modification can be done based on this information.

Additional information about TCM system can be found in the separate document **"Training manual"**, where procedure of using TCM system is described with more details and for different access groups.

3.1.3.4 Evaluation

One of the main functions of the TCM is its use in training unskilled operators in CNC machine tools. An important element of the GUI was ease of use to keep GUI training time to a minimum so not to distract from machine tool learning. During GUI development, user experience was utilized in the simplification of tis construction. Users of different abilities, skill levels and access rights were assessed and amendments were made to the GUI accordingly. The feedback from users is presented in Table 3 and Table 4.

Table 3. Evaluation of TCM system by users from Schivo.

TCM Version	User	Ability (1-5) 1 = unskilled 5 = skilled	GUI Tab	Comments	Actions
1.0	Operator no. 01	5	All	"Information about logged in user on each tab separately can lead to ambiguities"	Information is placed on the area visible from any tab
	Operator no. 02	1	Monitoring	"screen too small" "buttons too small"	Increased screen resolution and button size
	Operator no. 03	3	Monitoring	"graph needs some mesh to see values"	Mesh was added to graph
	Supervisor no.01	4	Signal reviews	"Consists of useless information"	Tab is deleted
	Supervisor no. 02	3	Configuration	"behaviour of the system is not clear during system training"	Additional window for system training is created
	Maintenance no.01	5	Monitoring	"'*Stop Monitoring*' button doesn't work each time"	Changes in the code are made '*Stop monitoring'* button is functional
2.0	Operator no. 01	5	Monitoring	"Difficult to understand info on graphs"	Graphs are changed with buttons
	Operator no. 02	1	Monitoring	"Difficult to see a number of cutting tools on the buttons"	Increased text size of numbers on the buttons
	Operator no. 03	3	Login	"Bulb 'Logged' is not necessary"	Bulb 'Logged' is deleted
	Supervisor no.01	4	Monitoring	"Not enough information about cutting tools"	Under each button more information about cutting tools is added
	Supervisor no. 02	3	Configuration	"Difficult to changes data which is already in the system"	A new form is created with more functions
	Maintenance no.01	5	Event log	"Information which tool was changed and by whom is missed"	Changes in code are made
3.0	Operator no. 01	5	Message about broken tool	"not clear what should be done after clicking on 'OK' button"	Buttons "Changed tool" for each cutting tool is added and message text is changed
	Operator no. 02	1	Monitoring	"'CTF' indicator button unclear"	Increased indicator button, colour changes are added
	Operator no. 03	3	Monitoring	"Some objects are over another "	Objects are moved
	Supervisor no.01	4	Monitoring	"During monitoring there is no info about status of the system"	'Status of Monitoring' object is added
	Supervisor no. 02	3	System training	" All objects are too small"	Increased size of objects
	Maintenance no.01	5		No Comments	

Table 4. Evaluation of TCM system by users from IDT.

TCM Version	User	Ability (1-5) 1 = unskilled 5 = skilled	GUI Tab	Comments	Actions
1.0	Operator no. 01	5	Monitoring	"How to scroll back on graph to check previous values?"	This function was added
	Operator no. 02	1	Monitoring	"Impossible to zoom in/out on graphs"	This function was added
	Operator no. 03	3	Monitoring	"Difficult to switch between cutting tools"	All cutting tools are placed as separate buttons visible simultaneously
	Supervisor no.01	4	Log in	"what to do if user forgot his password"	"Forgot password" button was added
	Supervisor no. 02	3	Configuration	"'Serial Production' button is useless"	'Serial Production' button is deleted
	Maintenance no.01	5	Message about broken tool	"needs for additional bulb for broken tool"	Bulb for broken tool is added
2.0	Operator no. 01	5	Monitoring	"Difficult to see values of tool life on the 'Tool life' bar"	Table with tool number and tool life % is added
	Operator no. 02	1	All	"Text about logged in user is too formal, more stress"	Text was changed to more friendly form
	Operator no. 03	3	All	"Buttons 'Log out' and 'exit' are placed on each tab on different area make its usage uncomfortable"	Buttons 'Log out' and 'exit' are placed on general area visible from any tab
	Supervisor no.01	4	Configuration	"Is it possible to save data from the table to another place?"	A new form is created with more functions
	Supervisor no. 02	3	Monitoring	"Graphs do not show any important information"	Cutting tool buttons created instead of graphs
	Maintenance no.01	5	Message about broken tool	"'Cutting tool' bulb not always are red when tool is broken "	Code is changed
3.0	Operator no. 01	5	Signal reviews	"Represents the same info as 'Monitoring' tab"	Review of represented data
	Operator no. 02	1	Monitoring	"Bulbs are too small"	Bulbs are increased
	Operator no. 03	3	Monitoring	"TCM Results" is over another object	Table is moved, form is increased
	Supervisor no.01	4	System training	"If the button 'changed tool' is pressed mistakably, how let system know about it?"	Additional button to confirm about changed tool are added
	Supervisor no. 02	3	Workpiece configuration	" After some information from table was deleted, mistakably pressed on exit button and form was closed without saving the changes"	Added message that reminds that information is not saved, so user can come back and save or close the form without changes
	Maintenance no.01	5		No comments	

3.1.4 Testing of the TCM system

Figure 15 shows a simplified block diagram of the system which will be used to explain the testing of the TCM system which was carried out at three different stages of the system development. The neural network tool wear and CTF LabView developed VI's were tested at all stages of development.

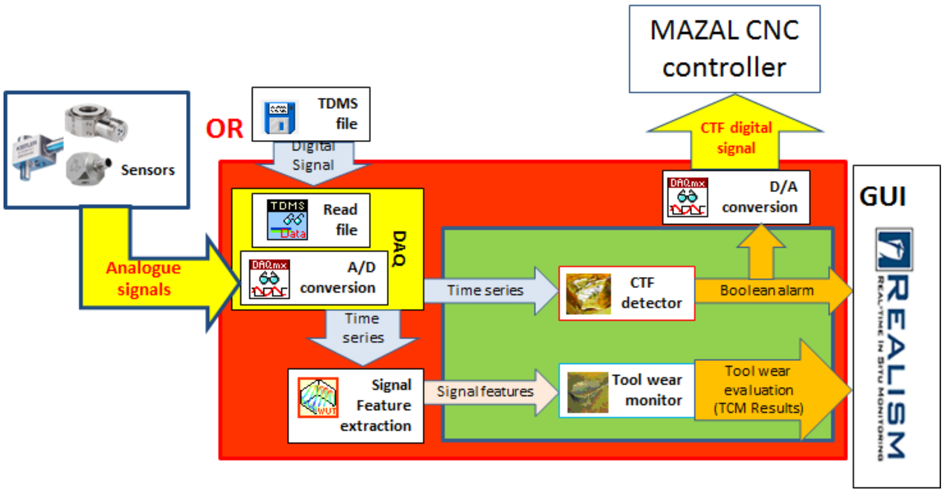


Figure 15. Block diagram of TCM system.

3.1.4.1 Stage 1: Development of the diagnostic algorithms

Inputs to diagnostic algorithms of the system – "CTF detector" and "Tool wear monitor" are time series and signal features respectively. Outputs are Boolean alarm and Tool wear evaluation, TCM results in the form of array of percentage usage of the tool life. So during development and testing of these algorithms (green field in the above figure) the input data from past data files were used to test the algorithms.

3.1.4.2 Stage 2: Integration of the software

After integrating the diagnostic algorithms into the core part of the system (red field in the figure), the system performance was tested in quasi real time conditions. This time the inputs are real sensor signals recorded previously in TDMS files and signal processing was carried. The outputs of the system are the same as in the first stage. There are only three differences between such testing and real time application-

a) computer can take as much time as it needs,

b) exactly the same experiment can be repeated as many times as needed, allowing for detecting any program errors, tuning the system configuration etc.;

c) the CTF alarm is not passed to the CNC controller

3.1.4.3 Stage 3: Real time testing of the system

Final testing was completed under a simulated industrial application. Now the source of the signals is sensor data in TDMS file format in real time (Figure 16). All elements of the system, including the capability of performing all necessary calculation are tested. Natural disturbances and randomness of the machining process were also assessed to determine effect on results.

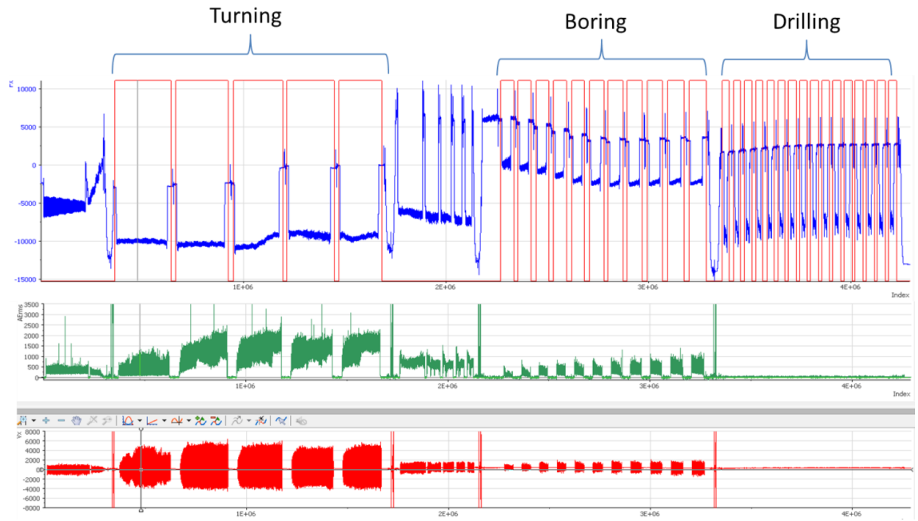


Figure 16. Sensor data in TDMS file type.

3.2 Validation and Results

In applying validation to the REALISM project, several aspects are taken into account. The TCM consists of a 3-axis force sensor, an acoustic emission (AE) sensor, a 3-axis accelerometer, a data acquisition system, an industrial portable computer, custom data logging software and custom control software linked back to a HMI. While systems may be rule or knowledge based in their decision making, here the control software incorporates an artificial neural network (ANN) which requires the operator to initially teach the TCM by identifying when a pre-determined number of tools are worn. From this teaching, the TCM will compare the learned results against process conditions, gathered from the sensors, allowing the system to make decisions around the degree of tool wear present on the cutting tool. Validation of the NN system establishes whether an individual test case has been solved correctly through benchmarking against learned information acquired from operator expectation. Two basic parameters are used, the Result Acceptability Criteria (RAC), and the System Validity Criteria (SVC). The RAC serves to determine whether an individual test case has been solved correctly by the ANN system. It is the distance between the system solution and the benchmark standard that are then measured.

3.2.1 Tool Wear Vi Validation

3.2.1.1 Installation & Operational Testing

The IOQ test criteria are set out in Deliverable 7.1 (Validation & Evaluation Report). The IOQ testing took place in Schivo's manufacturing facility in Waterford between the 14th December 2015 and 18th December 2015 with all DRF's (Deviation Report Forms) and other documentation closed on the 18th December 2015. Both installation and operational testing qualification *passed* with the test results reported in appendices 1.

3.2.1.2 Performance Qualification (PQ)

The PQ testing took place in Schivo's manufacturing facility in Waterford between the 4th January 2016 and 26th February 2016 with all DRF's and other documentation closed on the 26th February 2016.

Test 1 – Prerequisites Verification
Test Result: PASS
To verify that all required pre-requisite activities for the PV testing on the TCM have been completed and approved before beginning the PV activities.
DRFs Generated: N/A
Comments: N/A

Test 2 – Critical Measuring Instrumentation Calibration
Test Result: PASS
This test assures all test instruments used during the performance testing, to record data, are calibrated.
DRFs Generated: N/A
Comments: N/A

Test 3 – Performance Testing
Test Result: Passed with Deviation
Performance testing involves running trials to ensure that the system produces outputs of a predetermined quality when operated under normal operating conditions.
DRFs Generated: DRF-001
Comments: Two versions of the TCM software were tested as part of the PQ. Predetermined values based on in-house machine performance statistics were used for result verification. Values with a calculated probability P-value < 0.05 and R-Sq > 70% passed the PQ.

Version 2 of the software yielded significantly better results than version 1. Boring was deemed to be operating effectively with 100% pass rate, while Turning (66%) and drilling (33%) were passed based upon conditional deviations. DRF-001 states that the turning operations will be re-tested using unused cutting tips, as tip (Tool4_Tip1_V1) had been used in a previous operation under different cutting conditions that may have affected the integrity of the cutting tip resulting in a fail. DRF-001 states that the drilling operations will be re-tested with a more precise technique for wear measurement because of previous difficulties in accurate tool wear measurement resulting in large variabilities in cutting time determination. Detailed results are outlined in Table 6,Table 7 and appendices 1.2.

Table 6. Performance Qualification (Version 1)

Tool Wear vi (Version 1)		**R-Sq**	**P**	**Result**
Turning	Tool4_Tip1_V1	88.9	0.005	Pass
	Tool4_Tip2_V1	65.1	0.052	Fail
	Tool4_Tip3_V1	63.3	0.058	Fail
Boring	Tool8_Tip1_V1	71.4	0.017	Pass
	Tool8_Tip2_V1	55.9	0.087	Fail
	Tool8_Tip3_V1	70.2	0.077	Pass
Drilling	Tool8_Tip1_V1	18.9	0.33	Fail
	Tool8_Tip2_V1	0.3	0.908	Fail
	Tool8_Tip3_V1	1.2	0.889	Fail

Table 7. Performance Qualification (Version 2)

Tool Wear vi (Version 2)		**R-Sq**	**P**	**Result**
Turning	Tool4_Tip1_V2	87	0.007	Pass
	Tool4_Tip2_V2	71.2	0.035	Pass
	Tool4_Tip3_V2	28.2	0.278	Fail
Boring	Tool8_Tip1_V2	98.7	0	Pass
	Tool8_Tip2_V2	98.8	0	Pass
	Tool8_Tip3_V2	93.3	0	Pass
Drilling	Tool8_Tip1_V2	92.9	0	Pass
	Tool8_Tip2_V2	56.3	0.052	Fail
	Tool8_Tip3_V2	9.8	0.687	Fail

3.2.2 CTF vi Validation

3.2.2.1 Installation & Operational Testing

The IOQ test criteria are set out in Deliverable 7.1 (Validation & Evaluation Report). The IOQ testing took place in Schivo's manufacturing facility in Waterford between the 14th December 2015 and 18th December 2015 with all DRF's (Deviation Report Forms) and other documentation closed on the 18th December 2015. The test results are reports in appendices 2.

3.2.2.2 Performance Qualification (PQ)

The PQ testing took place in Schivo's manufacturing facility in Waterford between the 4th January 2016 and 26th February 2016 with all DRF's and other documentation closed on the 26th February 2016.

Test 1 – Prerequisites Verification

Test Result: PASS

To verify that all required pre-requisite activities for the PV testing on the TCM have been completed and approved before beginning the PV activities.

DRFs Generated: N/A

Comments: N/A

Test 2 – Critical Measuring Instrumentation Calibration

Test Result: PASS

This test assures all test instruments used during the performance testing, to record data, are calibrated.

DRFs Generated: N/A

Comments: N/A

Test 3 – Performance Testing

Test Result: PASS

Performance testing involves running trials to ensure that the system produces outputs of a predetermined quality when operated under normal operating conditions.

DRFs Generated: N/A

Comments: CTF validation was completed on two versions of the developed CTF vi and is presented in Table 8. Validation was completed over 39 machining operations. Version 1 of the CTF vi was found to have an 80% accuracy while version 2 was found to have a 100% accuracy. Given the accuracy of version 2, it was concluded that no further development was necessary.

Table 8. CTF vi version 1 & 2 validation.

Op no.	Turning (T) Boring (B) Drilling (D)	Consumed tool life (ΔT)	CTF		Op no.	(T) (B) (D)	Consumed tool life (ΔT)	CTF		Op no.	(T) (B) (D)	Consumed tool life (ΔT)	CTF		Op no.	(T) (B) (D)	Consumed tool life (ΔT)	CTF	
			Ver 1	Ver 2				Ver 1	Ver 2				Ver 1	Ver 2				Ver 1	Ver 2
	T	17%	0	0		T	90%	0	0		T	51%	0	0		T	17%	0	0
1	B	14%	0	0	11	B	68%	0	0	21	B	51%	0	0	31	B	17%	0	0
	D	14%	0	0		D	56%	0	0		D	42%	0	0		D	84%	0	0
	T	34%	0	0		T	**CTF**	☑	☑		T	68%	0	0		T	34%	0	0
2	B	29%	0	0	12	B	85%	0		22	B	68%	0	0	32	B	34%	0	0
	D	28%	0	0		D	70%	0	0		D	56%	0	0		D	**98%**	1	0
	T	51%	0	0		T	18%	0			T	85%	0	0		T	51%	0	0
3	B	43%	0	0	13	B	**CTF**	☑	☑	23	B	85%	0	0	33	B	51%	0	0
	D	42%	0	0		D	84%	0	0		D	70%	0	0		D	14%	0	0
	T	68%	0	0		T	36%	0	0		T	**102%**	0	0		T	68%	0	0
4	B	57%	0	0	14	B	17%	0	0	24	B	**102%**	0	0	34	B	68%	0	0
	D	56%	0	0		D	98%	0	0		D	**84%**	0	0		D	28%	0	0
	T	85%	0	0		T	54%	0	0		T	17%	0	0		T	85%	0	0
5	B	71%	☒	0	15	B	34%	0	0	25	B	17%	0	0	35	B	85%	0	0
	D	70%	0	0		D	33%	0	0		D	**98%**	0	0		D	42%	0	0
	T	**102%**	0	0		T	72%	0	0		T	34%	0	0		T	**102%**	0	0
6	B	**86%**	0	0	16	B	51%	0	0	26	B	34%	0	0	36	B	**102%**	0	0
	D	84%	0	0		D	66%	0	0		D	14%	0	0		D	56%	0	0
	T	18%	0	0		T	90%	0	0		T	51%	0	0		T	17%	0	0
7	B	**100%**	0	0	17	B	68%	0	0	27	B	51%	0	0	37	B	17%	0	0
	D	**98%**	0	0		D	99%	0	0		D	28%	0	0		D	70%	0	0
	T	36%	0	0		T	**CTF**	☑	☑		T	68%	0	0		T	34%	0	0
8	B	17%	0	0	18	B	85%	0	0	28	B	68%	0	0	38	B	34%	0	0
	D	14%	0	0		D	**CTF**	☑	☑		D	42%	0	0		D	84%	0	0
	T	54%	0	0		T	17%	0	0		T	85%	0	0		T	51%	0	0
9	B	34%	0	0	19	B	17%	0	0	29	B	85%	0	0	39	B	51%	0	0
	D	28%	0	0		D	14%	0	0		D	56%	0	0		D	**98%**	0	0
	T	72%	0	0		T	34%	0	0		T	**102%**	0	0					
10	B	51%	0	0	20	B	34%	0	0	30	B	**102%**	0	0					
	D	42%	0	0		D	28%	0	0		D	70%	0	0					

3.3 System Integration

In the working prototype, the functional components of the system, i.e. the DAQ, industrial PC and cloud server were placed behind the machining center (Figure 17).

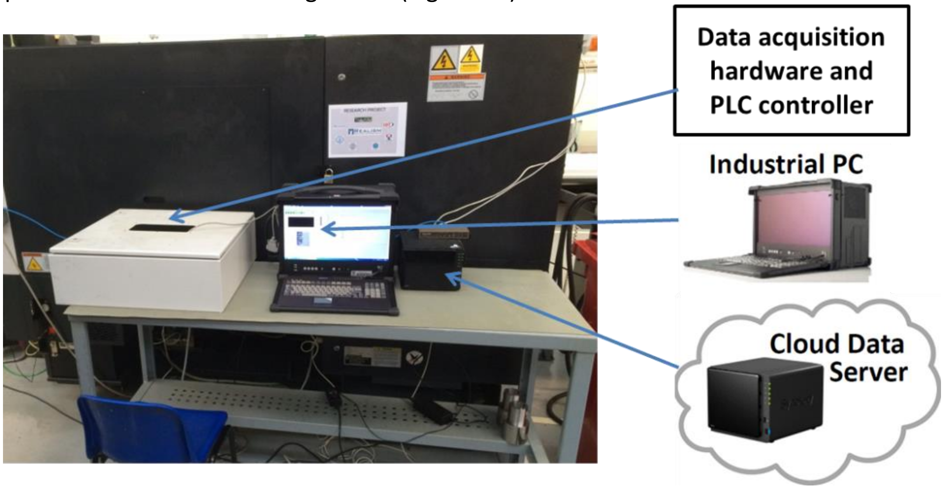


Figure 17. Functional components of TCM behind machining centre.

The TCM screen which displays GUI and allows for supervisor/operator interaction is located beside the machining centre allowing ease of access and interpretation of results by the user (Figure 18).

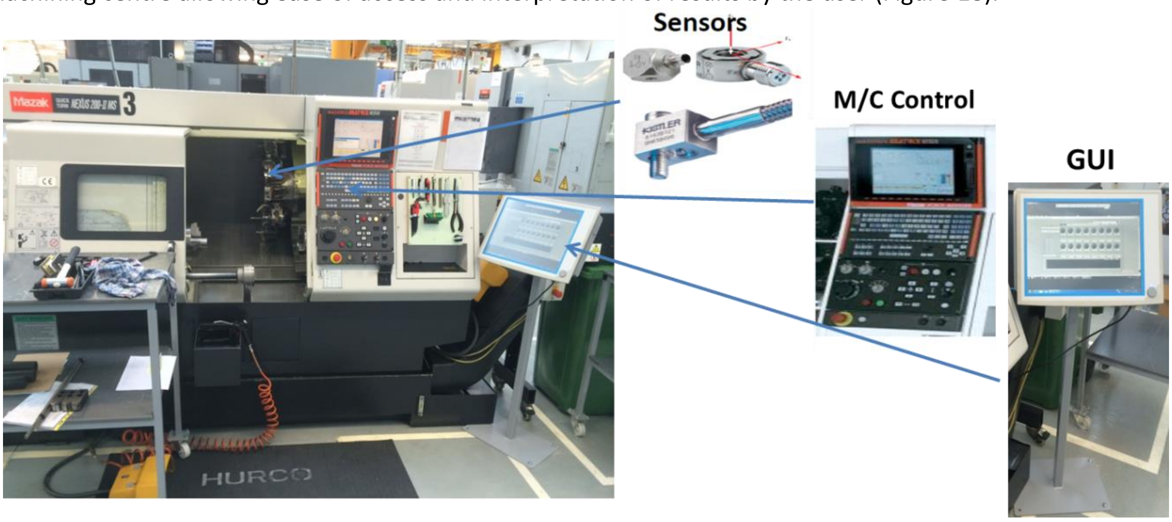


Figure 18. Components of TCM at the front of the machining centre.

3.4 TCM Version 2.0

Realism successfully developed a working prototype which fulfils the objectives laid out in the DOW. This is a 'ready to use' system and could be integrated onto any machining centre on a manufacturing floor. To determine the next development stage for the TCM system, the limitations of the current system must be understood.

3.4.1 Version 1.0 System Limitations

1. The current version of the TCM has the functional hardware components on the exterior of the machine tool which creates issues in a GMP manufacturing environment as well having health and safety implications.
2. Current processing power allows for real-time CTF detection but that tool wear prediction calculations can only be processed post machining of each workpiece. Hence if there was significant wear during a cutting operation, this would not be signalled to the machine operator until after the cutting operations for that workpiece had been completed. Significant tool wear mid process could potentially result in unrecoverable damage to the workpiece. This was not an issue for the Realism project as the workpiece operation times were relatively short to replicate typical machining times for workpieces at Schivo.

3.4.2 TCM Development

For TCM version 2.0, it is envisaged that the functional components at the front and back of the machine could be integrated into the machining centre using a National Instruments CompactRio (Figure 19). The CompactRIO controller includes a processor and reconfigurable FPGA. The processor is used for network communication, data logging, control, and processing with the deterministic and reliable NI Linux Real-Time OS. With the user-programmable FPGA, you can implement custom hardware for high-speed control, inline data processing, or complex timing and triggering. These processing abilities could allow for real-time tool wear calculations hence overcoming the limitation of the current system.

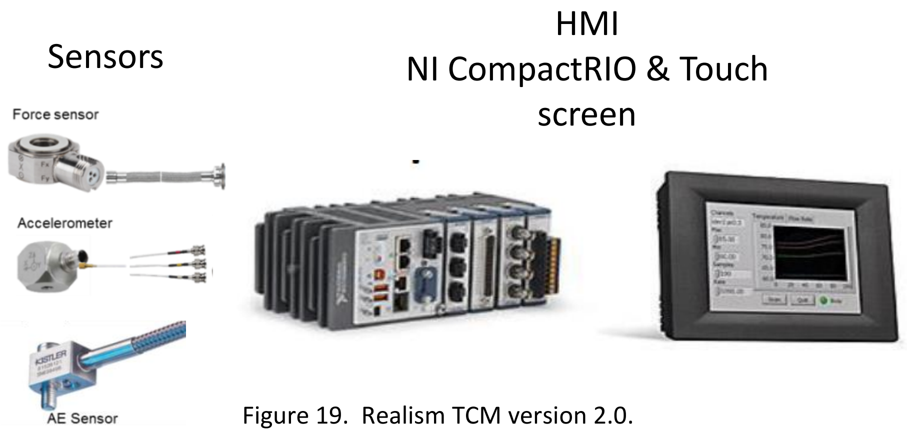


Figure 19. Realism TCM version 2.0.

Some additional feature which can be integrated into the Realism TCM 2.0 include Remote access control, Supervisory control and data acquisition (SCADA), Maintenance planning and control systems, Manufacturing execution system (MES) and Enterprise resource planning (ERP).

3.5 Experimental activities completed at Tulino CTM

Within the activities of the EC FP7 Project “REALISM”, an experimental turning campaign was carried out by Tulino CTM Srl, Naples, Italy. A Daewoo Puma L400 CNC lathe was employed for turning operations on TI6AL4V titanium alloy bars with multiple sensor monitoring of tool conditions (Figure 20.).

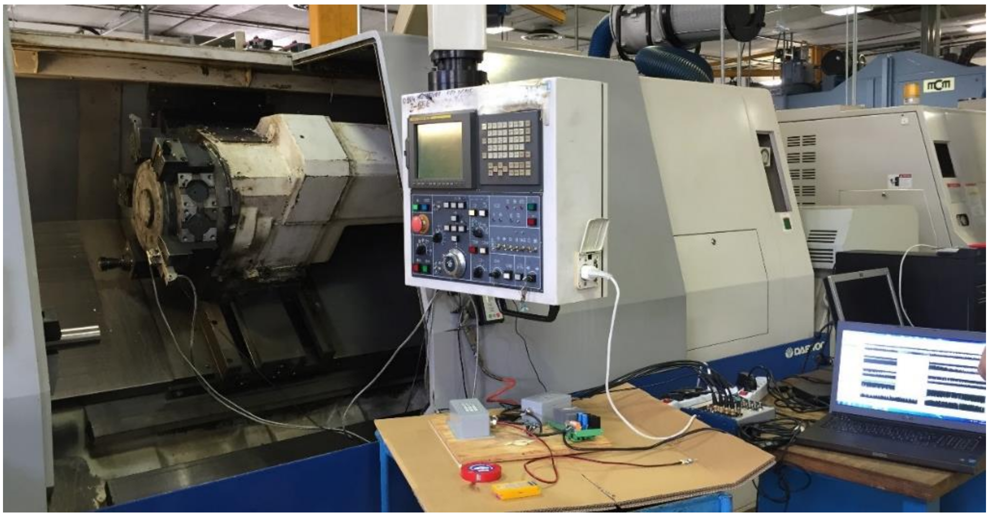


Figure 20. Daewoo Puma L400 CNC lathe.

3.5.1 Multiple Sensor Monitoring System Set-Up

Sesnors were mounted as close as possible to the cutting tool as shown in Figure 21.

1. Wireless 3D vibration sensor (Montronix Spectra Pulse)
2. 3D cutting force sensor (Montronix FS1xCXK-x-ICA)
3. Acoustic emission sensor (Montronix BV100)

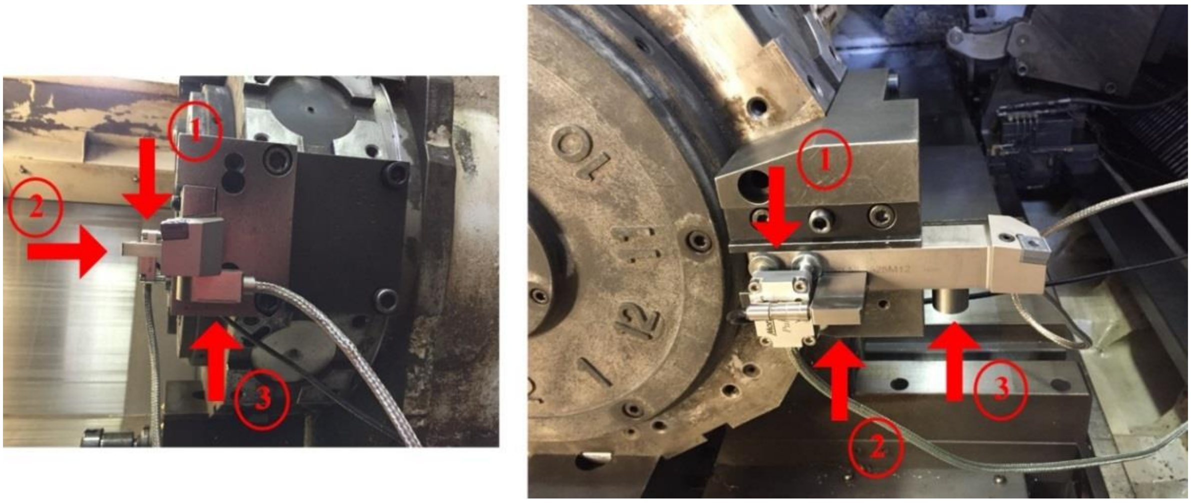


Figure 21. Multiple sensor monitoring system mounted on the tool holder.

3.5.2 Cutting Inserts for Turning Operations

The cutting inserts used for the experimental campaign are Mitsubishi uncoated WC inserts type CNMG120404-MS MT9015 (Figure 22).


Figure 22. Uncoated WC cutting inserts CNMG120404-MS MT9015.

3.5.3 Digital Signal Acquisition

A correspondence between analogue sensor signals and acquisition channels on the digitizing board (Figure 23) was set up as follows:

Dev3_ai0: cutting force component F_x
Dev3_ai1: cutting force component F_y
Dev3_ai2: cutting force component F_z
Dev3_ai3: AE RMS
Dev3_ai4: Vibration acceleration RMS
Dev3_ai7: receiving a constant signal value of 5 V from the CNC machine control when the feed starts to trigger the Signal Express software for start/stop signal recording.

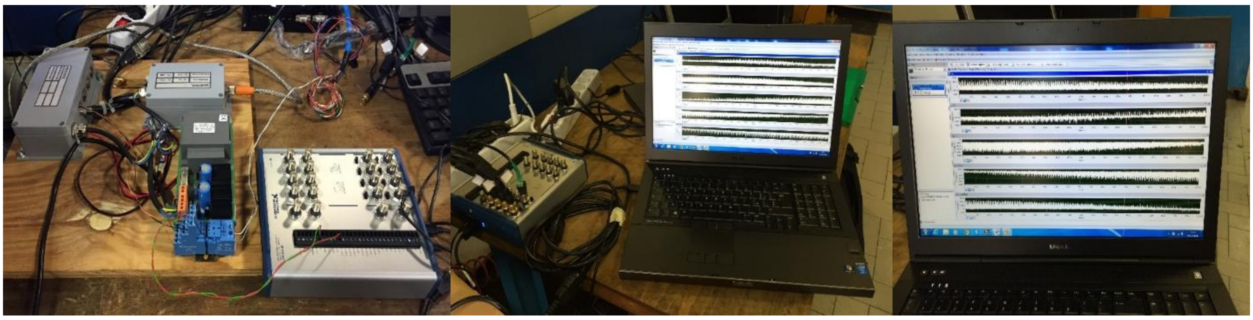


Figure 23. The digital signal acquisition system and an example of the PC screen during turning tests and sensor signal data acquisition.

3.5.4 Experimental turning tests

The cutting parameters used during testing are listed in Table 9. The experimental test highlighted in yellow was interrupted due to catastrophic failure of the cutting insert. Using a specific set of cutting, cutting was stopped after 1 minute and the cutting insert flank and rake face were photographed in order to measure tool wear. If maximum tool wear is not reached, the cutting is continued for another minute. Otherwise, the cutting test is considered finished and another cutting insert or the same cutting insert is rotated in order to have a fresh cutting insert for the successive cutting test.

Table 9. Cutting parameters for each cutting test. Each rhombic cutting insert has two usable tool tips, called S 1 and S 2, on the opposite tool sides.

DoC [mm]	f [mm/round]	V_c [m/min]	Tool number	Tool tip	# of Operations
0.50	0.20	60	1	S 1	39
0.50	0.20	80	1	S 2	16
0.50	0.20	100	2	S 1	8
0.50	0.30	80	2	S 2	7
0.50	0.25	80	3	S 1	11
0.50	0.30	60	3	S 2	31
1.00	0.20	80	4	S 1	11
1.00	0.20	80	4	S 2	8
0.50	0.25	80	5	S 1	6
0.50	0.30	60	5	S 2	25
1.00	0.30	80	6	S 1	2
1.00	0.25	80	6	S 2	4
1.00	0.20	100	7	S 1	2
0.50	0.25	60	7	S 2	31
1.00	0.25	60	8	S 1	10
1.00	0.30	60	8	S 2	10
1.50	0.30	60	9	S 1	6
1.50	0.25	60	9	S 2	5
1.00	0.20	60	10	S 1	10
0.50	0.20	70	10	S 2	13
1.50	0.20	60	11	S 1	15

The turning tests shown in Table 10 were repeated 4 times with the same cutting conditions to generate sensorial data for 4 complete tool lives to be used in the neural network decision-making paradigm for tool life prediction.

Table 10. Cutting parameters for the 4 repeated cutting tests.

DoC [mm]	f [mm/round]	V_c [m/min]	Tool number	Tool tip	# of Operations
1	0.2	60	11	S 2	8
1	0.2	60	12	S 1	15
1	0.2	60	12	S 2	13
1	0.2	60	13	S 1	16

3.5.5 Tool Wear Measurement

A portable microscope was utilized to measure the tool wear every 1 minute of cutting without dismounting the cutting insert from the tool holder (Figure 24).

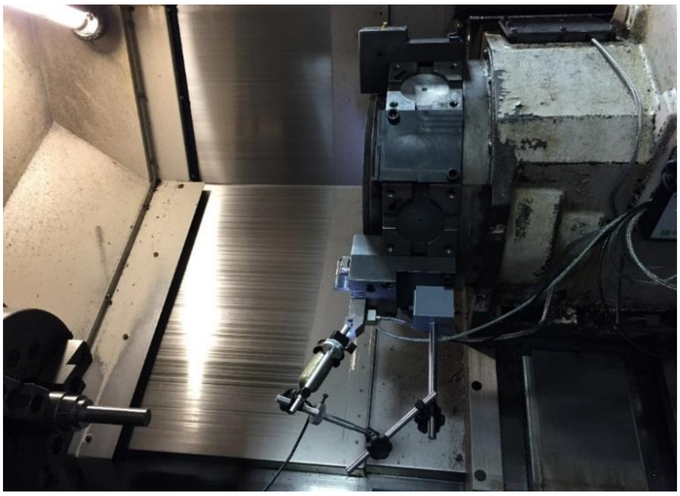


Figure 24. Portable microscope mounted on the tool holder

Tool wear was measured by comparison with a known electric wire diameter (Figure 25).

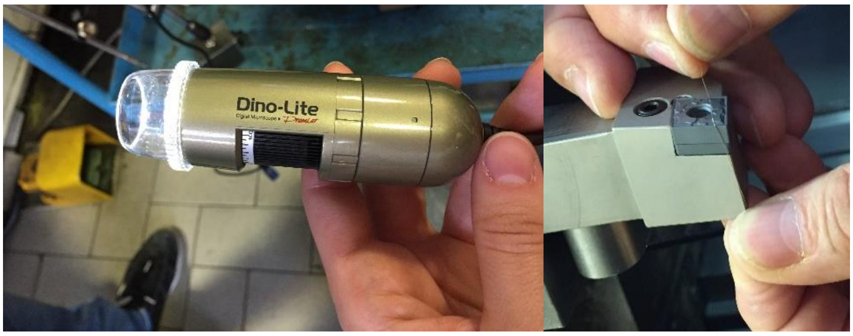


Figure 25. Tool wear measurement procedure

Using the software package Photoshop, the flank and crater wear of the cutting tool was measured by comparison with the known electrical wire diameter (Figure 26).

Figure 26**.** Measurement of the flank and crater wear of the cutting tool using the known electrical wire diameter as reference.

3.5.6 TCM Implementation

Hardware and software components of the TCM have been successfully installed and tested in the Tulino facility. Implementation of the data processing and HMI elements of the system is currently being completed and it is envisaged that complete system testing will being in Q3 2016.

3.6 Experimental activities completed at IDT

At the beginning of this project, the intention was to use a Mazak CNC lathe/turning center at Protomek, a company specialized in prototype making and precision machining. At that point Protomek was partly owned by IDT. Before testing could start, IDT sold its shares in Protomek along with the Mazak CNC Lathe. It was then decided to test the system on a CNC milling machine located at IDT's production facilities. The consequence being that the sensor setup intended for the turning centre, had to be changed and adapted to a milling machine (Figure 27).

Figure 27. First CNC milling machine.

3.7.1 Multiple sensors setup

In collaboration with WUT and GUC these 3 sensors were chosen to be installed:

- Kistler acoustic emission sensor, type 8152C0050020
- Kistler force sensor, type 9017C
- Kistler vibration sensor, type 8763B050AB

The process of sensor installation differed from the other partners. The sensors cannot be installed to the cutting tool as it was done at Tulino CTM and Schivo LTD, and therefore the machine table was used instead. However, installation of sensors directly to the machine table was not possible so an additional plate (see Figure 8) was created for these purposes. The WUT team proposed to place force sensor in the middle of the additional plate (1 on Figure 8), acoustic emission sensor in the top right corner (2 on Figure 8), and acceleration sensor is connected to the left side of the plate (3 on Figure 29 and Figure 30).

As a consequence of initial trails, it was apparent that the force sensor could be damaged so a cover plate was used for protection. Many trials were performed to find the best solution on how to cover force sensor, and the latest one is presented on Figure 29 and Figure 30.

From the figures, it can be summarized that the main plate is screwed to the piece of metal (Plate 2), and that Plate 2 is mounted to CNC machine table with 4 big screws. Also, between Plate 1 and Plate 2 is placed aluminum cover (28). This set-up was tested and the results not of all sensors were acceptable. Signal from the force sensor was not correct.

It was assumed that signals measured by force sensor are not correct because of:

- Bad screwing between Plate1 and Plate2, which can lead to their movements. They should be screwed as one plate so sensor will measure signal from the machining only.
- Additional screwing (Plate1 fastened with Plate2, and then Plate2 is screwed with CNC table – but was planned to fasten just Plate1 to CNC table) influences sensor with additional force even before actual machining is started.

These issues could lead to incorrect force sensor performance, and therefore improvements of the set-up wad done by connecting two plates closer via additional screws on the corners. This solution was successful and signal from force sensor was acceptable. However, compering signal from force sensor at IDT to signal from Tulino CTM or Schivo LTD, it was not the same quality. To achieve the same quality of data, customized solution from Kistler Holding AG is necessary. By the reason of additional costs and lack of time, this solution cannot be performed in this project. However should be considered as an option for future.

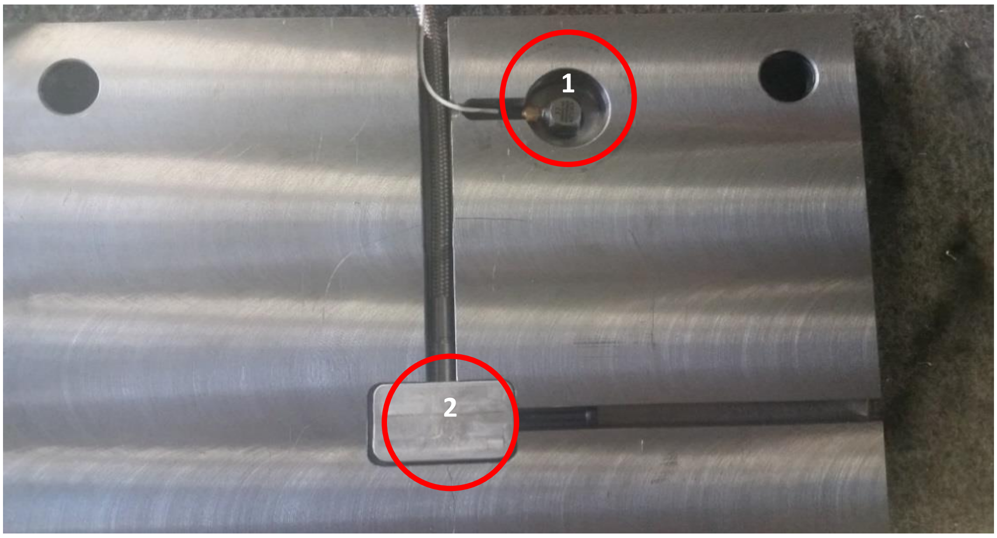


Figure 28. First cover for force sensor in the additional plate.

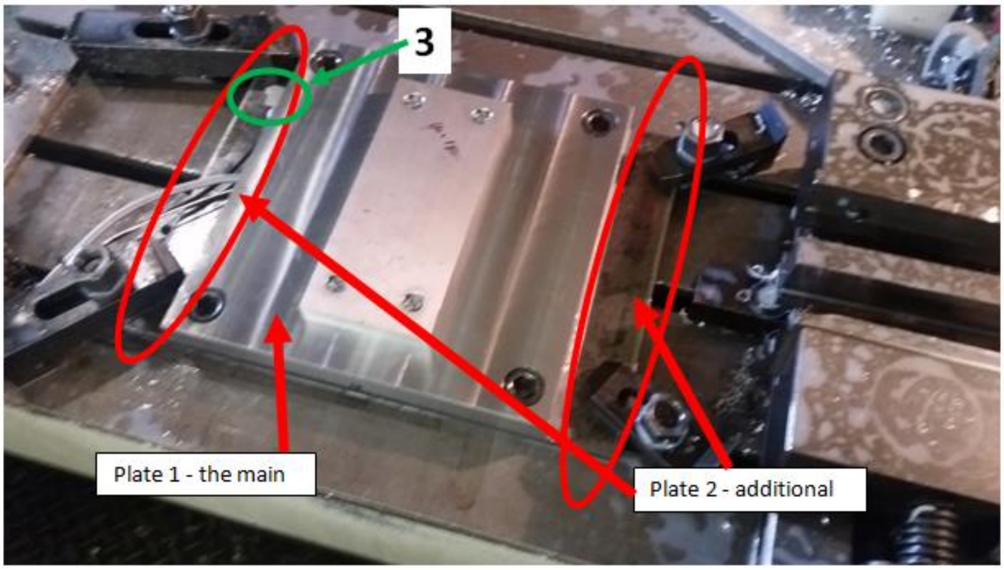


Figure 29. Additional metal plate to cover sensors from a tableside.

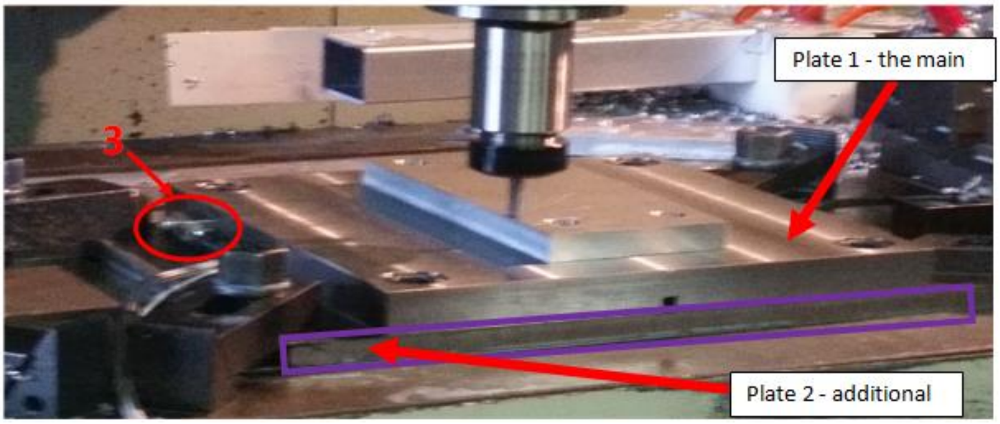


Figure 30. Additional metal plate to cover sensors from a tableside (another angle)

The final set-up of integrated sensors into the additional plane and placed it on the CNC machine table is shown on Figure 31 and Figure 32.


Figure 31. Set-Up fixed on the CNC machine table

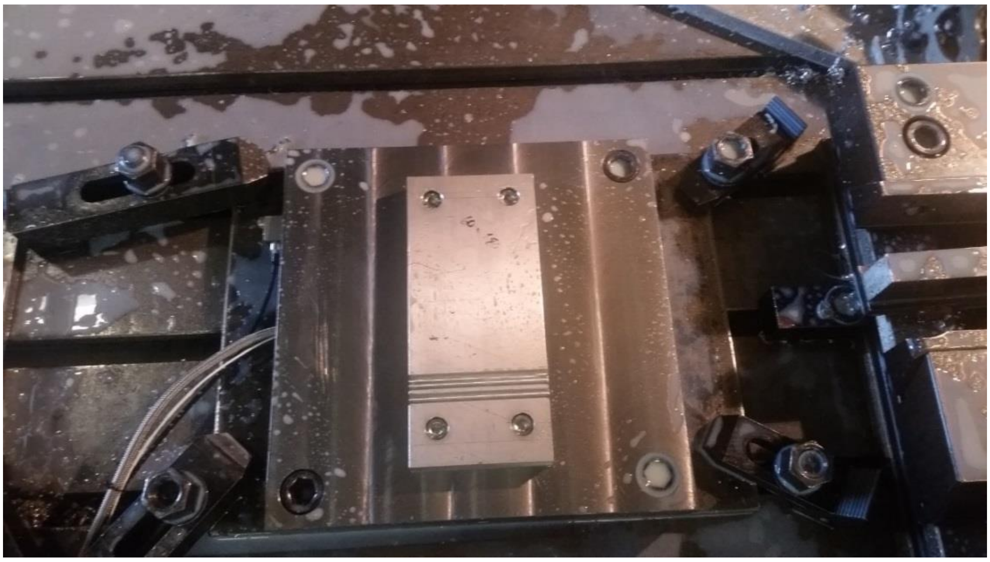


Figure 32. Set-Up with a piece of material for testing on top

3.7.2 Milling Tool description

A 4 mm 3 flute end mill (see Figure 33) was used for the testing and data acquisition. The first signal test was done with a 6061 aluminium workpiece. The data acquisition was performed with standard S235JR steel.

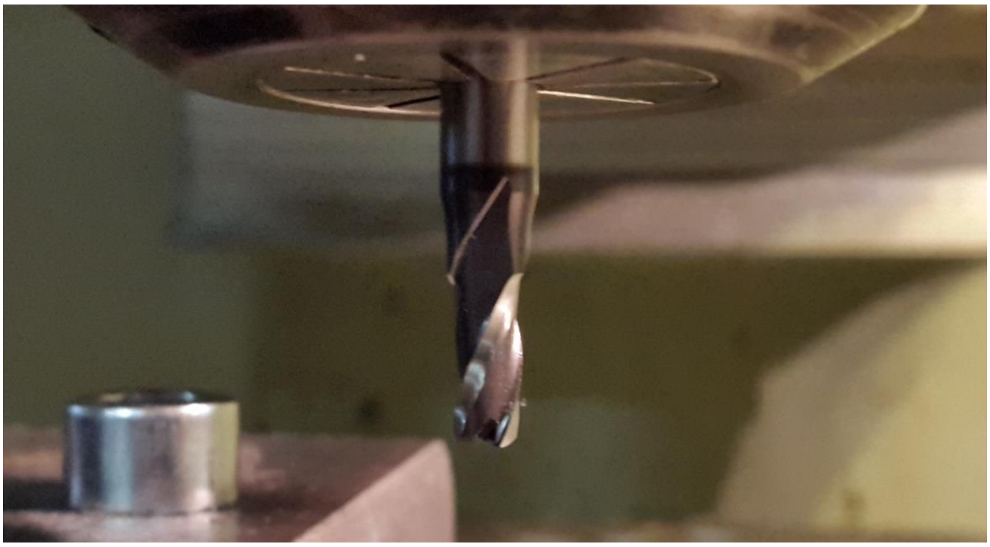


Figure 33. Example of a milling tool used for experimental testing

3.7.3 Digital Signal Acquisition

A correspondence between analogue sensor signals and acquisition channels is the same it was described before by Tulino TCM. The digital signal acquisition system at IDT is presented on Figure 34.

Figure 34. The digital signal acquisition system

3.7.4 Experimental milling tests

During the experimental milling tests, the following parameters were varied:

- Depth of cut [mm]
- Feed rate [mm/rev]

The cutting parameters for each cutting test are depicted at Table 13. The first test is highlighted due to appearance of catastrophic tool failure, which appeared by the reason of too high feed value. Since feed value was too high, two trials with decreased feed values was performed. After each cutting, machine was stopped to check tool and quality of cutting, since a quality of surface is one of the most important factors for milling machine.

Table 13. Cutting parameters for each cutting test

Testing tool N	D (mm)	a_p (mm)	f(mm/rev)	S(rev/min)	Number of operations
1	5	2	585	2786	1
2	5	2	230	2786	10
2	5	2	130	2786	25
2	5	3	130	2786	16
2	5	4	130	2786	10

The milling tests were repeated 4 times with the same cutting conditions to generate sensorial data for 4 complete tool lives. The cutting parameters for these 4 repeating cutting sets are presented at Table 14.

Table 14. Cutting process parameters for 4 repeating cutting tests

Testing tool N	D (mm)	a_p (mm)	f(mm/rev)	S(rev/min)	Number of operations
5	5	4	130	2786	9
11	5	4	130	2786	6
12	5	4	130	2786	8
16	5	4	130	2786	13

3.7.5 Plan for utlisiation of REALISM Results

The main plan for IDT is to utilize the knowledge gained from the REALSIM project in their own development of machine tools where process monitoring and control can be utilized. The plan is to develop the concept further and commercialize a solution for milling and friction stir welding. Tool condition monitoring system development plan is shown in table 15.

Table 15. TCM development Gantt chart

	2016				2017				2018			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
TCM milling cutting trails	■	■	■									
Concept development	■	■	■	■	■	■						
Negotiations on IPR					■	■						
Feasibility study					■	■	■	■				
Business development (national funding application)							■	■	■	■		
Commercial prototype development					■	■	■	■	■	■	■	■
Pilot production									■	■	■	■
Product Launch												■

3.7.6 Project update

Milling trials have confirmed the successful operation of the TCM system in IDT. Due to the one-of-a-kind production operations that are scheduled to be carried out on this process, it has been decided to implement the system on special purpose friction stir welding machines built by IDT. IDT believe that offering features that were developed in the REALISM project on their process, such as catastrophic tool failure detection and tool wear prediction, that this will give them a competitive advantage over their competitors. Full system integration and cutting trials are due to begin in Q4 2016.

3.7.6.1 Update: TCM (Version 2.0)

Demo activities started with TCM (version 1). However we quickly noticed few short comings (see below table-column 'User observations') and it became necessary to go back to the drawing board to address these short comings. Subsequent reworked version of the TCM (Version 2) developed by the RTD partners which reflects the stakeholders observations as a consequence of TCM demonstration at Schivo, Waterford and Tulino, Italy are clearly laid out in the table. This change has been approved and implemented on SME sites. The cost of the work carried out by the RTD partners for this TCM development is taken from the DEMO allocated budget thus reflecting the lower demo costs in the Form Cs. The table below details the project partners, tasks and the upgrades completed on the TCM (Version 2).

Table 16. TCM Version 2 upgrades.

User	GUI Tab	User observations	Actions	Project Partners & Tasks
Operator	Monitoring	"screen and buttons are still too small even after the latest upgrade"	Increased screen resolution and button size	GUC: Reworked GUI main screen to resize buttons and screen. WIT/Schivo: Trailed and validated updated GUI
Operator	Monitoring	"'CTF' indicator button unclear"	Increased indicator button, colour changes are added	GUC: Reworked GUI main screen to resize buttons. WIT/Schivo: Trailed and validated updated GUI
Operator	Monitoring	"CTF audio warning would be useful"	Add speaker to GUI interface	GUC: Included code to activate audio signal when CTF WIT/Schivo: Integrated, tested and validated new speaker including dB level.
Maintenance	Message about broken tool	"Tool no. should be shown in bulb when tool is broken	Tool no. added to broken tool button	GUC: Reworked GUI main screen to include tool no. in button. WIT/Schivo: Trailed and validated updated GUI
Supervisor	Monitoring	"CFT didn't not alarm upon tool breaking in IDT"	Investigate tool breakage sensitivity levels	WUT: CTF sensitivity changed in program. GUC: Trailed and validated updated TCM.
Supervisor	Monitoring	"30% error in tool wear prediction in Tulino"	Investigate neural network algorithms and operator training.	WUT: Neutral network algorithms updated. Unina: On-site training in Tulino

4 TCM Impacts

4.1 Schivo feedback

4.1.1 Current Impacts

- Since the installation of the TCM system, scrap rates due to tool wear (as trended on the BEAS manufacturing control system) have reduced. Figure 26 compares the Mazak scrap value for a 6-week period, with and without the TCM in place. It was found that there was an over 64% savings on workpiece scrap value for similar product with the TCM in place.

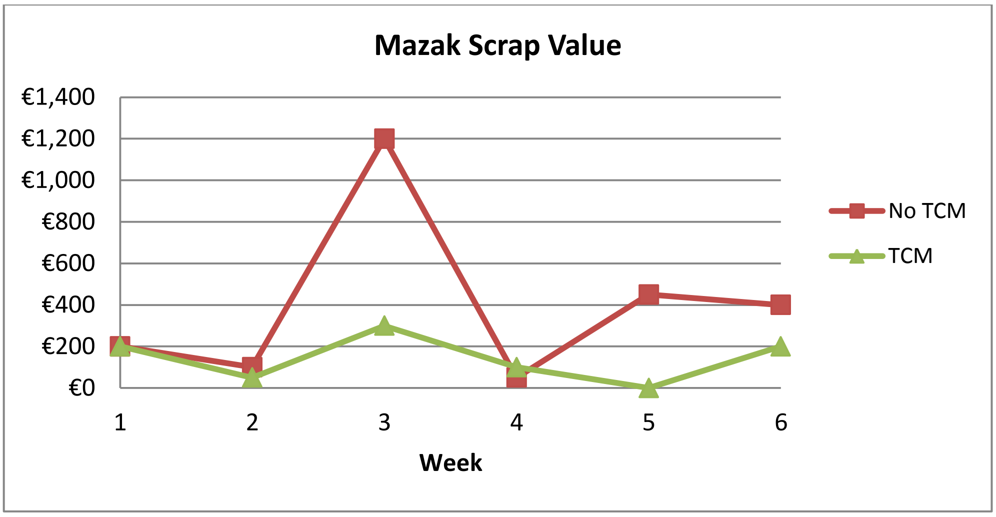


Figure 35. Mazak scrap value for month 11 (2015) to month 2 (2016).

- New operator training performance has also been greatly improved as a result of the TCM. We have found that the visual element of the HMI has enhanced operator engagement in their understanding machine performance. We estimate that there could be a *20% savings* in new operator training time based on initial testing.
- Experienced operators have HMI feedback to optimize feeds and speeds for tool/material configurations. Prolonged tool life has resulted in increased machine operation time by approx 20%.
- Detection of early stage catastrophic tool failure has resulted in reduced machine downtime, as workpiece and tool holder damage has been minimized. Initial indications suggest that the downtime savings could be *upto 20%.*
- An unforeseen impact has been operator feedback in terms of cutting tool performance. The TCM has shown that there was significant difference in cutting insert degradation over their lifetime from different suppliers. As a result of this, the facility has moved to a single source supplier which has resulted in prolonged cutting insert lifetime.

4.1.2 Potential Impacts

- The TCM has been demonstrated to a large aerospace customer as a potential application for some of their products. It has been agreed with the customer that products will be machined with TCM to monitor tool wear and workpiece scrap value. Implementation of the TCM will help Schivo achieve the quality management systems requirements under the ISO EN 9100:2003 (E) aerospace guidelines for machining operations which has the potential to drive business growth in this sector.
- Interest from the dissemination activities has resulted in the development of a business plan to investigate the feasibility in-house production of a bolt-on TCM system targeting CNC machine users. Early calculations suggest that the manufacture of 100 systems per year would lead to the creation of 7 new assembly operator jobs, 1 process/manufacturing engineer and 1 quality control personnel.
- The revenue stream from the possibility to license the technology to CNC machine manufacturers is being investigated.
- We are also now starting an internal project to use the sensors and the system to monitor the actual time that the machinery is productive, as this system provides information on actual cutting time, rather than the spindle's rotating time. This will allow production time optimization which will reduce manufacturing costs.

4.2 Tulino feedback

The aim of the EC FP7 "REALISM" project was to develop a robust 'smart' sensor-based system to provide accurate, real-time analysis of the process performance in order to attain the optimal machining conditions, achieve better control of the process and reduce the scrap rate.

- <u>Know-how Acquisition</u> - Through the EC FP7 REALISM Project, Tulino CTM has gained know-how on machining of titanium alloys that the SME did not possess. Titanium alloys are hard-to-machine materials, where the machining difficulties originate from high cutting temperatures, chemical reactivity with the tools and the relatively low elastic modulus of the material. Titanium, also, generates a thin chip, which is moving at high speed above the tool surface of a small area of contact. The high contact pressure and the low thermal conductivity result in an unusually high temperature at the end of the tool. The high reactivity of titanium leads to severe damage by friction and wear of the tool itself. The relatively low elastic modulus of titanium can induce large deformations in the slender parts in the processing component, causing difficulty in maintaining tolerances and problems due the friction with the tool. A significant number of these problems were faced and addressed during the experimental testing campaign, helping Tulino CTM in gaining experience, knowledge and confidence in titanium alloys machining.

- Production Improvement - Capability in monitoring of machining processes has led to product quality improvements through increased process monitoring applications. In addition, through adaption of the monitoring system on the machine tools, there is also an increase in production throughput and yield. Several advantages are noted: reduction of scrap, reduction of quality control costs, and reduction of tooling costs.
- Economical Turnover - Titanium alloys are considered very important in the aerospace industry. In the Campania region, where Tulino CTM is located and acts as an SME supplier to large industries, the aerospace industry is a very important industrial division, considered a fundamental column for the economy of the region. Gaining knowledge and experience in machining of titanium alloys is critical and of great help for Tulino CTM in order to add a new range of parts they can machine and produce for their present and prospective clients. This is crucial for Tulino CTM in order to present itself as a reliable manufacturing supplier to the aerospace industrial sector of the Campania region.
- Socio-economic Impact - Increasing the capability in executing advanced machining processes leads to increasing the number of clients, the production capacity as well as the economic profit. In order to be able to satisfy the increase in orders demand, new job opportunities will emerge at Tulino CTM that is expected to hire 2 new employees in order to satisfy the production demand.
- Tulino has formed relationships with several companies who have expressed their interest in the EC FP7 REALISM. Successful implementation of the system will potentialy lead to business growth.

  - Magnaghi Aeronautica SpA, Naples, Italy, which is an aerospace company in the Naples area. It is part of the INVESCO Group, which also includes “Salver” (development and production of components in composite materials), and “Metal Sud” (supplier of a wide range of surface finishing’s). The company is involved in all aspects of landing gear fabrication, starting from design to industrial development, right through the manufacture of fully integrated systems of several types of aircraft and helicopter landing gear.
  - Avio Aero S.p.a., Pomigliano d’Arco, Italy, which is a GE Aviation company which designs, manufactures and maintains components and systems for civil and military aeroengines. Today, the company provides its clients with innovative technological solutions to respond quickly to constant changes demanded by the market.
  - Alenia Aermacchi S.p.a., Pomigliano d’Arco, Italy, which is a large industry with an extensive range of know-how in design, development, manufacturing and maintenance of military and civil aircraft fuselage, training systems, and aerostructures.

4.3 IDT feedback

IDT is seeing the advantages of the TCM integrated in the milling machine in terms of new operator training and their understanding of process optimisation and tool wear identification. The system is being used for CTF detection in the machining of large complex aluminium parts, where in the past, undetected tool breakages have led to costly workpiece scrappage. IDT see applications for this system for its friction stir welding process which experiences high tool wear rates and CTF thus allowing for cheaper production costs making IDT more competitive in the market place.

Another possible use could be in automated robotic sawing cells (Figure 36) to detect blade imbalance caused by cracked or chipped blade tooth. It is IDT’s intention to adapt the system for this process during the quarter 3 of this year. Figure 9 Example of a robot in automated sawing cells.

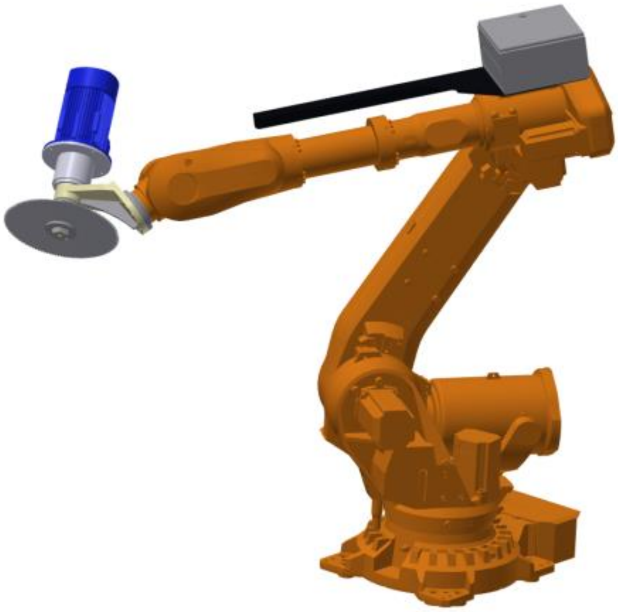


Figure 36. Example of a robot in automated sawing cells

IDT foresees that with TCM adaptation across a number of manufacturing techniques, could allow the company to achieve the quality management systems requirements under the ISO EN 9100:2003 thus opening new market opportunities and job creation.

5 Dissemination Activities

5.1 Contributions to standards

The consortium members are familiar with the published ISO standards that relate to REALISM (Table 17).

Table 17. Published standards that are relevant to the REALISM project

ISO 13372:2012: Condition monitoring and diagnostics of machines -- Vocabulary
ISO 13374-1:2003: Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 1: General guidelines
ISO 13374-2:2007: Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 2: Data processing
ISO 13374-3:2012: Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 3: Communication
ISO 13374-4:2015: Condition monitoring and diagnostics of machine systems -- Data processing, communication and presentation -- Part 4: Presentation
ISO 13379-1:2012: Condition monitoring and diagnostics of machines -- Data interpretation and diagnostics techniques -- Part 1: General guidelines
ISO 13379-2:2015: Condition monitoring and diagnostics of machines -- Data interpretation and diagnostics techniques -- Part 2: Data-driven applications
ISO 13381-1:2015: Condition monitoring and diagnostics of machines -- Prognostics -- Part 1: General guidelines
ISO 17359:2011: Condition monitoring and diagnostics of machines -- General guidelines
ISO 18129:2015: Condition monitoring and diagnostics of machines -- Approaches for performance diagnosis
ISO 18436-1:2012: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 1: Requirements for assessment bodies and the assessment process
ISO 18436-2:2014: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 2: Vibration condition monitoring and diagnostics
ISO 18436-3:2012: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 3: Requirements for training bodies and the training process
ISO 18436-4:2014: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 4: Field lubricant analysis
ISO 18436-5:2012: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 5: Lubricant laboratory technician/analyst

ISO 18436-6:2014: Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 6: Acoustic emission
ISO 22096:2007: Condition monitoring and diagnostics of machines -- Acoustic emission
ISO 21289:2008: Mechanical vibration and shock -- Parameters to be specified for the acquisition of vibration data
ISO 18431-2:2004: Mechanical vibration and shock -- Signal processing -- Part 2: Time domain windows for Fourier Transform analysis
ISO 18431-1:2005: Mechanical vibration and shock -- Signal processing -- Part 1: General introduction
ISO 18431-3:2014: Mechanical vibration and shock -- Signal processing -- Part 3: Methods of time-frequency analysis

The REALISM consortium are aware of the Technical Committee (*ISO/TC 108 Mechanical vibration, shock and condition monitoring)* involved in the development of standards which are relevant to the work completed in this project. ISO/TC 108 is developing standardisation in the fields of mechanical vibration and shock and the effects of vibration and shock on humans, machines, vehicles (air, sea, land and rail) and stationary structures, and of the condition monitoring of machines and structures, using multidisciplinary approaches. The standards and projects under development, which are of interest to the consortium are under the direct responsibility of the secretariat *ISO/TC 108/SC 5 - Condition monitoring and diagnostics of machine systems.* Specifically ISO/WD 13379-3 Condition monitoring and diagnostics of machines -- Data interpretation and diagnostics techniques -- Part 3: Knowledge-based applications presents the standardisation of the procedures, processes and equipment requirement, uniquely related to the technical activity of condition monitoring and diagnostics of machine systems, in which selected physical parameters associated with an operating machine system are periodically or continuously sensed, measured and recorded for the interim purpose of reducing, analysing, comparing and displaying the data and information so obtained and for the ultimate purpose of using this interim result to support decisions related to the operation and maintenance of the machine system. This standard is at stage 20:20 (Working draft (WD) study initiated). The National Standards Authority of Ireland (NSAI) and Standards Norway (SN) are participating in the standards development, while UNIM (Italy) are observing. The NSAI have invited members of the Irish consortium to participate in the standards and be present at the next meeting to be held in Sydney, Australia in March but the resources for such participation are unavailable. However, members of the REALISM consortium will participate in an observational role and have access to all draft working documents through the NSAI. The consortium believes that careful observation of these working documents will allow for the robust development of TCM. The consortium may decide to participate in the technical committee if it will benefit prototype development.

5.2 Contribution to policy developments

Whilst government agencies (e.g. Enterprise Ireland) are interested in the success of the project from a job creation standpoint, it is envisaged that the project will not have any significant impact on research-based policy development at regional, national or European level. If any policy developments take place, it will be relayed to the relevant authorities, e.g. for manufacturing policy if there is a perceived lack of skilled CNC programmers, it will be raised with Forfás, which is Ireland's policy advisory board for enterprise, trade, science, technology and innovation.

5.3 Other relevant (EU) projects for collaboration/exchange/knowledge

A number of funded EU projects have been identified. These projects are trying to develop systems to better monitor and control manufacturing systems, particularly those concerned with the cutting of metal. The partners in the REALISM consortium are engaged in a number of other relevant projects (e.g. ADACOM, IFACOM) and there have been a number of meetings, whereby cross collaborative efforts in the projects has been discussed.

Members are aware of a number of proposals that have been submitted to the H2020 programme that relate to the area of investigation of this project and continue to keep a close eye on developments within these proposals and the potential collaboration that could be liked to these if the proposals are successful.

A joint workshop hosting representatives of the REALISM and IfaCOM FP7 European projects was held in Tulino CTM on 15th January 2015 (Table 18). The purpose of this workshop was to further the knowledge of industry stakeholders, the scientific community and civil society of the technology advances in Tool Condition Monitoring. Discussions also took place in relation to potential Horizon 2020 collaborations.

Table 18. Details of the IFaCOM EU funded project.

Project Title & Acronym	Reference no.	Relevant Partner	Date of Completion
IFaCOM – Intelligent Fault Correction and self-Optimizing Manufacturing systems.	285489	Unina	April 2015
The vision of IFaCOM is to achieve zero defect level of manufacturing for all kinds of manufacturing, with emphasis no production of high value parts, on large variety custom design manufacturing and on high performance products.			

5.4 Project Dissemination Event

A REALISM project dissemination event was organised with the purpose of dissemination project information to SME project partners and for industry stakeholders which included representation from a number of SME engineering industries, machine shop engineers, operators, machine tool manufactures and suppliers. The dissemination event included morning presentations from RDT and SME partners detailing the work completed on developing the tool condition monitoring system and its benefits to SME's. This was followed by a live prototype demonstration on a Mazak 200 lathe in Schivo. The demonstration was completed on two stainless steel 316l workpieces showing tool wear prediction and catastrophic tool failure. The running order of event is shown in presented in Deliverable 8.3. A press release in relation to this event can be viewed https://www.wit.ie/news/research/seam-hosts-eu-project-dissemination-event.

5.5 Training Manual

A formal training manual pertaining to correct implementation and operation of the developed technologies is presented in Deliverable 8.3. Standard operating procedures are being developed in accordance to Schivo GMP practices.

5.6 User training

Machine tool operators from all participating SMEs were formally trained on the TCM the day after the dissemination event (Table 19). A further training webinar is scheduled to take place in March 2016 to go through system integration and training manuals.

Table19. Project dissemination details.

Type of activities	Main leader	Title	Date	Place	Type of audience	Size	Countries addressed
Oral presentation to a wider public	WATERFORD INSTITUTE OF TECHNOLOGY	FP7-SME Realism Project Dissemination Event	10/12/2015	Waterford Institute of Technology, Waterford	Scientific community	40	European
Organisation of Workshops	SCHIVO PRECISION LIMITED	Demonstration of Realism Tool Condition Monitoring System	10/12/2016	Schivo Precision Engineering, Waterford	Scientific community		European
Press releases	WATERFORD INSTITUTE OF TECHNOLOGY	SEAM HOSTS EU PROJECT DISSEMINATION EVENT	11/12/2015	Waterford Today Newspaper	Scientific community		European
Organisation of Workshops	SCHIVO PRECISION LIMITED	Realism TCM training workshop	11/01/2016	Schivo Precision Engineering, Waterford	Industry	15	Republic of Ireland

Organisation of Workshops	UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II.	Realism/Ifacom joint workshop for the purpose of furthering knowledge of technological advances in Tool Condition Monitoring	15/01/2015	Tulino CTM, Naples, Italy	Scientific community	European
Organisation of Workshops	SCHIVO PRECISION LIMITED	Realism TCM training workshop webinar	March 2016	Webinar	Industry	

6 REALISM Exploitation

A detailed market report has been completed to gain an understanding of REALISM exploitation opportunities. A summary of the report is given below.

6.1 CNC Machine and Cutting Tools Market

The European CNC Machine tools market accounts for $10.85 billion in revenue and is expected to grow at 15.3% CAGR and is forecasted to surpass $22.11 billion in 2015. CNC metal-cutting machine tools account for over 70% of the market with CNC metal-forming machine tools making up the rest. Almost two-thirds of the total CNC revenue belongs to GE Fanuc Intelligent Platforms (Fanuc), Siemens, AG (Siemens) and Hedenhain Corporation. [Strategic Analysis of the European Computerized Numerical Control (CNC) Machine Tools Market, Just-In-Time Products Requirement Drives the CNC Machine Tool Market Growth, Frost & Sullivan, 26th Jan 2012]

The global cutting tools market is expected to grow at 6.2% CAGR during 2012-2017 and generate $21.18 billion in revenue at the end of the forecast period. Three manufacturers account for over 50% of the cutting tools market; Sandvik Coromant, Kennametal Inc, and Iscar IMC. Revenue growth is fuelled by the demand for machine tools and cutting tools due to increased investment in automobile, O&G and infrastructure sectors. [Global Machine Tools and Cutting Tools Market Increased Investment in Infrastructure Development in China and India is Expected to Bolster Growth, M925-01, Frost & Sullivan, Guru Mahesh, 26 Mar 2013]

The global condition monitoring equipment market which includes vibration condition monitoring equipment is expected to grow at a CAGR of 4.9% generating a revenue of $1.905.3 million by 2019. The price of online vibration condition monitoring equipment can vary between $3,000 and $3 million. The average price of permanently installed systems is about $150,000, which includes the cost of hardware, software, and installation. Hardware components include vibration sensors, accelerometers, transducers, signal conditioner, cables and monitors. Leading companies in this market include; GE Bentley, Meggitt Sensing systems, SKF Condition Monitoring, Rockwell Automation Inc. and Emerson CSI. [Analysis of the Global Condition Monitoring Equipment Market Cautious Optimism Despite Strong Headwinds, NDAD-30, Frost & Sullivan, Vijay Mathew, 7 Apr 2015]

6.2 Exploitation Options and Actions

A summation of the exploitation options based on project foreground IP and relevant actions are detailed. Table 20 shows the REALISM Tool Condition Monitoring system 1.0 which comprises of all the hardware and software elements, and the sensor 'fusion' system. Table 21 details the Data acquisition and PLC 'feedback' system, and the two possible exploitation options for the Data Processing which includes the Signal Feature extraction toolbox and the Neural Network Prediction toolbox. Table 22 details the Human Machine Interface and Knowledge.

Table 20. Exploitation of REALISM foreground.

No.	Item	Description	Lead Users	Targeted Messages	Dissemination
1	**Realism** Tool Condition Monitoring system 1.0	A robust 'smart' sensor-based system providing process feedback loop to both the machine tool and the operator for **tool**	1. Machine Tool Manufacturers 2. Tool Monitoring specialists 3. Process and/or	"reduced scrap" "reduced downtime" "reduced training" "optimised	Conference participation/ LinkedIn groups/ Brochure/ Direct sales/ Distributors/

		wear prediction and **catastrophic tool failure detection**.	Manufacturing Engineers 4. Machine Tool Operators 5. Quality Managers	machining”	Sales representatives & online purchases
2	**Sensor 'fusion' system** for machine tools	Configuration and set-up of sensor 'fusion' system consisting of force, acoustic emission and accelerometer sensing elements on a machine tool.	1. Machine Tool Manufacturers 2. Tool Monitoring specialists	"optimised tool condition sensing" "optimised sensor integration"	Conference participation/ LinkedIn groups/ Brochure/ Direct Sales

Table 21**.** Exploitation of REALISM foreground.

No.	Item	Description	Lead Users	Targeted Messages	Dissemination
3	**Data acquisition and PLC 'feedback' system**	Configuration and set-up of data acquisition and PLC hardware elements providing a continuous process feedback loop to the machine tool and operator.	1. Machine Tool Manufacturers2. Tool Monitoring specialists	"optimised data acquisition""machine tool feedback system"	Conference participation/ LinkedIn groups/ Brochure/ Direct Sales
4	**Data Processing Toolbox** - Signal Feature extraction	Extraction of usable, meaningful signal features which adequately describe the tool and/or process condition.	1. Machine Tool Manufacturers 2. Tool Monitoring specialists	"real-time accurate data processing"	Conference participation/ LinkedIn groups/ Brochure/ Direct Sales
5	**Data Processing toolbox -** Neural Network Prediction	Cognitive decision making toolbox for tool wear prediction and catastrophic tool failure detection.	1. Machine Tool Manufacturers 2. Tool Monitoring specialists	"real-time tool wear prediction" "Catastrophic tool failure detection"	Conference participation/ LinkedIn groups/ Brochure/ Direct Sales

Table 22. Exploitation of REALISM foreground.

No.	Item	Description	Lead Users	Targeted Messages	Dissemination
6	**Human Machine Interface**	Closed loop feedback graphical user interface for tool condition monitoring.	1. Machine Tool Manufacturers 2. Tool Monitoring specialists	"easy to use GUI" "multi-access user level"	Conference participation/ LinkedIn groups/ Brochure/ Direct Sales

7	**Knowledge**	Associated knowledge from project	College students/ PhD and Post doc projects/ Research collaborations	"experts in the field"	Cordis Partner search/ Euraxess/ Conference participation

7 REALISM Partner Contacts

Contact		Address	E-mail	Phone number
RTD Partner				
Ramesh Raghavendra, Denis O'Sullivan	**WIT**	SEAM Research Centre, Waterford Institute of Technology, Cork Rd, Waterford	rraghavendra@wit.ie dhosullivan@wit.ie	Tel: +353 (0) 51 845 648 Tel: +353 (0) 51 302489
Krzysztof Jemielniak	**WUT**	Politechnika Warszawska (WUT***)***, Plac Politechniki 1, Warszawa, 00-661, Poland	k.jemielniak@wa.home.pl	Tel (+48 22) 234 8656
Prof. Roberto Teti	**UNINA**	Universita Degli Studi Di Napoli Federico II (UNINA),Corso Umberto I 40, Napoli, 80138, Italy	roberto.teti@unina.it	Tel. +39 081 7682371
Kristian Martensen	**GUC**	Gjøvik University College, Hogskolen I Gjovik (GUC), Teknologivegen 22, Gjovik, 2802, Norway	kristian.martinsen@hig.no	Tel: +4799521849
SME Partner				
Jonathan Downey	**Schivo**	Schivo Precision Limited, Cork Road, IDA Industrial Park, Waterford, Ireland	jdowney@schivogroup.com	Tel +353 (0) 51 337392
Sten Oderud	**IDT**	IDT Solutions AS, Lenagata 131, Lena, 2850, Norway (an hour ahead of us)	sten@idt.no	Tel: +47 918 34 650
Alberto Tulino	**Tulino**	Tulino CTM SRL, Via Vittoria Aganoor 8, Napoli, 80145, Italy	albertotulino@tiscali.it	

8 Realism Website Address

http://realism-fp7.eu/

9 Appendices

9.1 Appendices 1

Installation & Operational Testing

The IOQ testing criteria are set out in Deliverable 7.1 (Validation & Evaluation Report). The IOQ testing took place in Schivo's manufacturing facility in Waterford between the 14th December 2015 and 18th December 2015 with all DRF's (Deviation Report Forms) and other documentation closed on the 18th December 2015. The test results are reports in appendices 1.1?

1.1. Test 1 – Personnel Identification

Test Result: PASS

All personnel involved in the execution and review of this protocol shall enter their name and signature on the Signature Log.

DRFs Generated: N/A

Comments: N/A

1.2. Test 2 – Validation Test Equipment Verification

Test Result: PASS

All equipment/instrumentation used during the execution of this protocol must be calibrated and be in current calibration when the testing is conducted. A copy of all calibration certificates should be attached to this IOQ protocol.

DRFs Generated: N/A

Comments: N/A

1.3. Test 3 – Validation Materials Verification

Test Result: PASS

All test materials used during the execution of this protocol must be recorded on the validation tests material test sheet. Each entry should be signed and dated.

DRFs Generated: N/A
Comments: N/A

1.4. Test 4 – Software Disaster Recovery
Test Result: PASS
Testing shall verify that the correct software is installed and that a disc image of the software can be loaded on to the machine.
DRFs Generated: N/A
Comments: N/A

1.5. Test 5 – Software Verification
Test Result: PASS
The control system type and software version for the REALISM TCM shall be verified.
DRFs Generated: N/A
Comments: N/A

1.6. Test 6 – Equipment Installation Verification
Test Result: PASS
Testing shall verify that a documented walk down of the Mechanical and Electrical system has been completed.
DRFs Generated: N/A
Comments: N/A

1.7. Test 7 – Documentation Verification
Test Result: PASS
Testing shall verify that all the relevant documentation is available and reviewed. In some cases this documentation will be attached to the relevant datasheet and will form a permanent part of this protocol, alternatively its permanent stored location will be recorded on the Documentation Verification Checklist for future reference.
DRFs Generated: N/A
Comments: N/A

1.8. Test 8 – Drawing Verification
Test Result: PASS
The drawings shall be inspected, to ensure that they accurately reflect the actual equipment layout. Any drawings, which have been redlined to accurately reflect the installed equipment, should be signed, dated and the original red-lined, marked-up drawings should be attached to the protocol.
DRFs Generated: N/A
Comments: N/A

1.9. Test 9 – SOP Verification
Test Result: PASS
Testing shall identify whether a revision is required as a result of validation, and also if the latest revision of SOP's are available at the time of execution.
DRFs Generated: N/A
Comments: N/A

1.10. Test 10 –Verification of Utility Supply and Installation
Test Result: PASS
Utilities that are required for the continuous operation of equipment are considered support utilities. Without them the system would not operate properly. This test verifies that required support utilities are correctly installed.
DRFs Generated: N/A
Comments: N/A

1.11. Test 11 –Safety Features Verification
Test Result: PASS

Process quality, equipment and operator safety are ensured through the proper operation of alarms and interlocks. Alarm triggers, interlocks shall be tested here.
DRFs Generated: N/A
Comments: N/A

1.12. Test 12 –Startup/Shutdown/Loss of Power
Test Result: PASS
Testing shall verify that the REALISM TCM starts up and shuts down as per design intent and there are no adverse side effects during a power loss.
DRFs Generated: N/A
Comments: N/A

1.13. Test 13 –PLC Input/Output Testing
Test Result: PASS
Testing shall verify that the PLC controller software, in the DAQ panel, is operating per design intent.
DRFs Generated: N/A
Comments: N/A

1.14. Test 14 – Diagnostic Algorithm Testing
Test Result: PASS
Testing shall verify that the Diagnostic Algorithm portion of the REALISM TCM software is operating per design intent.
DRFs Generated: N/A
Comments: N/A

1.15. Test 15 – Integrated Software Testing
Test Result: PASS
Testing shall verify that the integrated REALISM TCM software package is operating per design intent.
DRFs Generated: N/A
Comments: N/A

9.2 Appendices 2

Regression Analysis: Tool4_Tip1_R1 versus Tool4_Tip1_Meas

The regression equation is
Tool4_Tip1_R1 = 21.7 + 0.831 Tool4_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	21.667	9.621	2.25	0.087
Tool4_Tip1_Meas	0.8310	0.1465	5.67	0.005

S = 10.2422 R-Sq = 88.9% R-Sq(adj) = 86.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3377.2	3377.2	32.19	0.005
Residual Error	4	419.6	104.9		
Total	5	3796.8			

Regression Analysis: Tool4_Tip1_R2 versus Tool4_Tip1_Meas

The regression equation is
Tool4_Tip1_R2 = 15.8 + 0.839 Tool4_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	15.85	10.64	1.49	0.211
Tool4_Tip1_Meas	0.8392	0.1619	5.18	0.007

S = 11.3237 R-Sq = 87.0% R-Sq(adj) = 83.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3444.6	3444.6	26.86	0.007
Residual Error	4	512.9	128.2		
Total	5	3957.5			

Regression Analysis: Tool4_Tip2_R1 versus Tool4_Tip2_Meas

The regression equation is
Tool4_Tip2_R1 = 15.8 + 0.633 Tool4_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	15.81	15.68	1.01	0.370
Tool4_Tip2_Meas	0.6325	0.2315	2.73	0.052

S = 16.5105 R-Sq = 65.1% R-Sq(adj) = 56.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2035.1	2035.1	7.47	0.052
Residual Error	4	1090.4	272.6		
Total	5	3125.5			

Regression Analysis: Tool4_Tip2_R2 versus Tool4_Tip2_Meas

The regression equation is
Tool4_Tip2_R2 = 15.6 + 0.716 Tool4_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	15.57	15.41	1.01	0.370
Tool4_Tip2_Meas	0.7155	0.2275	3.15	0.035

S = 16.2259 R-Sq = 71.2% R-Sq(adj) = 64.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2604.2	2604.2	9.89	0.035
Residual Error	4	1053.1	263.3		
Total	5	3657.3			

Regression Analysis: Tool4_Tip3_R1 versus Tool4_Tip3_Meas

The regression equation is
Tool4_Tip3_R1 = 40.5 + 0.439 Tool4_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	40.50	11.32	3.58	0.023
Tool4_Tip3_Meas	0.4387	0.1671	2.63	0.058

S = 11.9192 R-Sq = 63.3% R-Sq(adj) = 54.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	979.1	979.1	6.89	0.058
Residual Error	4	568.3	142.1		
Total	5	1547.3			

Regression Analysis: Tool4_Tip3_R2 versus Tool4_Tip3_Meas

The regression equation is
Tool4_Tip3_R2 = 36.5 + 0.346 Tool4_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	36.49	18.69	1.95	0.123
Tool4_Tip3_Meas	0.3463	0.2760	1.25	0.278

S = 19.6816 R-Sq = 28.2% R-Sq(adj) = 10.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	609.9	609.9	1.57	0.278
Residual Error	4	1549.5	387.4		
Total	5	2159.3			

Regression Analysis: Tool8_Tip1_R1 versus Tool8_Tip1_Meas

The regression equation is
Tool8_Tip1_R1 = - 22.2 + 0.840 Tool8_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	-22.16	15.18	-1.46	0.204
Tool8_Tip1_Meas	0.8399	0.2379	3.53	0.017

S = 18.0749 R-Sq = 71.4% R-Sq(adj) = 65.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4071.9	4071.9	12.46	0.017
Residual Error	5	1633.5	326.7		
Total	6	5705.4			

Regression Analysis: Tool8_Tip1_R2 versus Tool8_Tip1_Meas

The regression equation is
Tool8_Tip1_R2 = 0.90 + 1.02 Tool8_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	0.903	3.403	0.27	0.801
Tool8_Tip1_Meas	1.02426	0.05331	19.21	0.000

S = 4.05050 R-Sq = 98.7% R-Sq(adj) = 98.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	6055.4	6055.4	369.08	0.000
Residual Error	5	82.0	16.4		
Total	6	6137.4			

Regression Analysis: Tool8_Tip2_R1 versus Tool8_Tip2_Meas

The regression equation is
Tool8_Tip2_R1 = - 12.0 + 0.457 Tool8_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	-12.05	13.33	-0.90	0.417
Tool8_Tip2_Meas	0.4572	0.2029	2.25	0.087

S = 14.1928 R-Sq = 55.9% R-Sq(adj) = 44.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1022.3	1022.3	5.07	0.087
Residual Error	4	805.7	201.4		
Total	5	1828.0			

Regression Analysis: Tool8_Tip2_R2 versus Tool8_Tip2_Meas

The regression equation is
Tool8_Tip2_R2 = 3.17 + 0.884 Tool8_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	3.172	3.254	0.98	0.385
Tool8_Tip2_Meas	0.88441	0.04953	17.86	0.000

S = 3.46360 R-Sq = 98.8% R-Sq(adj) = 98.5%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3825.5	3825.5	318.88	0.000
Residual Error	4	48.0	12.0		
Total	5	3873.5			

Regression Analysis: Tool8_Tip3_R1 versus Tool8_Tip3_Meas

The regression equation is

Tool8_Tip3_R1 = - 5.20 + 0.376 Tool8_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	-5.200	7.997	-0.65	0.562
Tool8_Tip3_Meas	0.3765	0.1418	2.65	0.077

S = 7.62452 R-Sq = 70.1% R-Sq(adj) = 60.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	409.60	409.60	7.05	0.077
Residual Error	3	174.40	58.13		
Total	4	584.00			

Regression Analysis: Tool8_Tip3_R2 versus Tool8_Tip3_Meas

The regression equation is

Tool8_Tip3_R2 = 0.30 + 0.971 Tool8_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	0.300	2.590	0.12	0.915
Tool8_Tip3_Meas	0.97059	0.04594	21.13	0.000

S = 2.46982 R-Sq = 99.3% R-Sq(adj) = 99.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2722.5	2722.5	446.31	0.000
Residual Error	3	18.3	6.1		
Total	4	2740.8			

Regression Analysis: Tool12_Tip1_R1 versus Tool12_Tip1_Meas

The regression equation is

Tool12_Tip1_R1 = 100 + 0.000000 Tool12_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	100.000	0.000	*	*
Tool12_Tip1_Meas	0.00000000	0.00000000	*	*

S = 0 R-Sq = *% R-Sq(adj) = *%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.000000000	0.000000000	*	*
Residual Error	5	0.000000000	0.000000000		
Total	6	0.000000000			

Regression Analysis: Tool12_Tip1_R2 versus Tool12_Tip1_Meas

The regression equation is

Tool12_Tip1_R2 = 13.7 + 0.528 Tool12_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	13.71	30.68	0.45	0.674
Tool12_Tip1_Meas	0.5281	0.4900	1.08	0.330

S = 36.2963 R-Sq = 18.9% R-Sq(adj) = 2.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1530	1530	1.16	0.330
Residual Error	5	6587	1317		
Total	6	8117			

Regression Analysis: Tool12_Tip1_R3 versus Tool12_Tip1_Meas

The regression equation is
Tool12_Tip1_R3 = - 3.57 + 1.03 Tool12_Tip1_Meas

Predictor	Coef	SE Coef	T	P
Constant	-3.571	7.922	-0.45	0.671
Tool12_Tip1_Meas	1.0255	0.1265	8.11	0.000

S = 9.37321 R-Sq = 92.9% R-Sq(adj) = 91.5%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5771.6	5771.6	65.69	0.000
Residual Error	5	439.3	87.9		
Total	6	6210.9			

Regression Analysis: Tool12_Tip2_R1 versus Tool12_Tip2_Meas

The regression equation is
Tool12_Tip2_R1 = 52.0 + 0.643 Tool12_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	52.00	23.24	2.24	0.075
Tool12_Tip2_Meas	0.6429	0.3712	1.73	0.144

S = 27.4955 R-Sq = 37.5% R-Sq(adj) = 25.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2268.0	2268.0	3.00	0.144
Residual Error	5	3780.0	756.0		
Total	6	6048.0			

Unusual Observations

Obs	Tool12_Tip2_Meas	Tool12_Tip2_R1	Fit	SE Fit	Residual	St Resid
1	14.0	16.0	61.0	18.7	-45.0	-2.24R

R denotes an observation with a large standardized residual.

Regression Analysis: Tool12_Tip2_R2 versus Tool12_Tip2_Meas

The regression equation is
Tool12_Tip2_R2 = 61.6 - 0.059 Tool12_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	61.57	30.07	2.05	0.096
Tool12_Tip2_Meas	-0.0587	0.4803	-0.12	0.908

S = 35.5824 R-Sq = 0.3% R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	19	19	0.01	0.908
Residual Error	5	6331	1266		
Total	6	6349			

Regression Analysis: Tool12_Tip2_R3 versus Tool12_Tip2_Meas

The regression equation is
Tool12_Tip2_R3 = 34.3 + 0.393 Tool12_Tip2_Meas

Predictor	Coef	SE Coef	T	P
Constant	34.286	9.684	3.54	0.017
Tool12_Tip2_Meas	0.3929	0.1547	2.54	0.052

S = 11.4580   R-Sq = 56.3%   R-Sq(adj) = 47.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	847.0	847.0	6.45	0.052
Residual Error	5	656.4	131.3		
Total	6	1503.4			

Regression Analysis: Tool12_Tip3_R1 versus Tool12_Tip3_Meas

The regression equation is
Tool12_Tip3_R1 = 131 - 0.703 Tool12_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	131.41	62.63	2.10	0.171
Tool12_Tip3_Meas	-0.7034	0.7884	-0.89	0.466

S = 43.5041   R-Sq = 28.5%   R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1507	1507	0.80	0.466
Residual Error	2	3785	1893		
Total	3	5292			

Regression Analysis: Tool12_Tip3_R2 versus Tool12_Tip3_Meas

The regression equation is
Tool12_Tip3_R2 = 46.3 + 0.144 Tool12_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	46.26	72.61	0.64	0.589
Tool12_Tip3_Meas	0.1442	0.9139	0.16	0.889

S = 50.4317   R-Sq = 1.2%   R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	63	63	0.02	0.889
Residual Error	2	5087	2543		
Total	3	5150			

Regression Analysis: Tool12_Tip3_R3 versus Tool12_Tip3_Meas

The regression equation is
Tool12_Tip3_R3 = 25.5 + 0.298 Tool12_Tip3_Meas

Predictor	Coef	SE Coef	T	P
Constant	25.52	50.94	0.50	0.666
Tool12_Tip3_Meas	0.2984	0.6412	0.47	0.687

S = 35.3814   R-Sq = 9.8%   R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	271	271	0.22	0.687
Residual Error	2	2504	1252		
Total	3	2775			