Real-time Machinery Monitoring Applications in Shop Floor

Tanel Aruvali, Taavi Reinson, Risto Serg

Abstract—**Monitoring in shop floor is of great importance to achieve better quality and save the environment. Embedded computers are used in wireless sensor network (WSN) monitoring systems to process data and provide quick feedback. A method for detecting working modes based on vibrations in CNC lathe is introduced. Optimization of nodes energy usage has also been taken into account as an essential parameter in WSN. In addition, a sample WSN production monitoring system was positively tested and suggestions for raising its accuracy were proposed.**

Index Terms—**Production environment monitoring, tool wear, vibration, WSN nodes**

I. INTRODUCTION

MANAGING operators and controlling a work of machineries are of great importance in shop floor. For managing efficiently machinery operators, feedback from working process is needed. For controlling and operating machinery efficiently, feedback concerning machinery, tools and working piece is essential.

Classical feedback methods like visual estimation, machinery noise comparison and collection of information touching work piece are not reliable and measurable. In modern and competitive manufacturing company machinery monitoring system should be utilized to achieve the highest quality, to reduce perversion of material and to prevent damages of machinery and tool failures. The last two damages are especially harmful for production, causing unplanned breaks in production and delays in fulfilling customer orders.

In modern factory it is essential to employ wireless sensors for monitoring. Wireless measurement and monitoring systems provide an opportunity to reduce installation and system costs, increase flexibility, simplify system deployments, and address a new set of applications that were previously challenging or impossible with a wired approach. Attaching embedded computers with a wireless communication interface which form a wireless sensor network (WSN) onto machinery for monitoring machinery condition keeps the price of the solution reasonable but provides extra safety to existing process. The installation cost of cable in industrial plant can vary greatly based on the type of plant and physical configurations. According to studies the average cable installation cost lies between 10 $ and 100 $ per foot [1], in nuclear plants as high as 2000 $ per foot.

Turning operation is a common metal working process in modern manufacturing industry. Due to its wide utilization, many researchers have analyzed this process in detail. The main research areas have been influenced by cutting forces [2], vibrations [3], temperature [4], acoustic [5], chip formation [6], and tool wear [7] in accordance with improving surface roughness. The main goals of these researches have been to achieve better work piece surface quality by changing cutting parameters as feed rate, cutting speed, and depth of cut and work piece material.

Optimum cutting parameters help to improve cutting quality, but they are not always applied. It is often complicated to use them, since they are floating parameters depending on the level of tool wear. Considering this, it can be concluded that being aware of optimum parameters does not ensure their usage. Consequently, the most suitable working mode is not always applied.

Besides using optimum cutting parameters it is important to change tool insert on time to maintain the cutting quality. Every tool insert has a limited lifespan. In case the time outlasts, a turning result is poor, irrespective of cutting parameters.

Every tool has an average lifespan in minutes, but depending on the way of usage, it may vary considerably. In order to avoid poor quality in turning it is not sufficient to count working minutes. It does not always provide a reliable result according to working mode used. Also visual detection of tool wear level is inaccurate and may depend on operator. For tool wear level identification there is a great need for automatic indicator.

It has been found that tool lifespan is in correlation with the amount of vibrations [8]. Vibration also signals differently in a fault situation [9]. Deeper investigation of vibrations gives the possibility to predict the tool lifespan.

Smart tool is a target for many researches. Sensor fusion system is utilized for monitoring tool wear level in turning. Fusion system includes a force sensor, a sound sensor, an accelerometer sensor and an acoustic emission sensor [10, 11].

The aim of the article is to analyze WSN network tool kit to estimate its stability and reliability in production environment. Additionally, turning machinery working modes have been investigated in vibration section to create a

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smart turning tool that can indicate its wear level.

II. Sample WSN Production Environment Monitoring System Test

Measurement method

Real time monitoring system has to be wireless to enable easy installation and quick adjustment for utilization.

A sample tool kit system for production environment monitoring was created. Sensor system bases on Wireless Sensor Network (WSN) technology produced by National Instruments. The sample system consists of three WSN nodes, one gateway, a user interface with processor (touch-screen computer with environment analyzing program in LabViw environment) and three sensors for measuring temperature, relative humidity and force (Fig. 1). This monitoring system was created in order to test stability and reliability of WSN nodes in production environment and to evaluate nodes compatibility with different type of sensors.

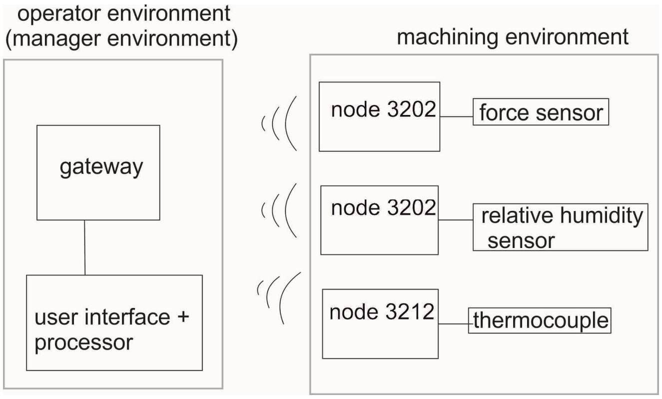

Fig. 1. WSN monitoring system architecture

Gateway is a device that creates Ethernet type wireless network between nodes and computer. It uses a standard IEEE 802.15.4.

All the sensors attached to the nodes were powered using the node's internal sensor power output terminal SEN PWR. The correct supply voltage of the sensors was secured by voltage regulator connected between the power terminal of the node and the input terminal of the sensor. The supply voltage of the sensors varied between 5 V to 10 V. All sensors used within the system had a voltage output which the nodes were able to measure. The output signals of the sensors were calculated into their expected shapes using formulas provided by sensor producers.

In sample monitoring device, total duration of measurement and cycle length has to be entered to start monitoring. As a result, user interface software displays all the measured values on the screen both numerically and graphically. All the results are also saved in log files. This method allows the measurement data to be analyzed later in more detail if necessary. The software of this measurement system contains also an analyzing tool which enables the user to get a quick overview of measurement results.

The measured parameters were chosen based on the capability of the nodes. The maximum cycle rate at which WSN-3202 node can measure voltage is 10 Hz. Since this cycle rate is rather slow, it limits the choice of parameters measurable by the nodes. Therefore, parameters used in the system fluctuate at low frequencies.

The test contained measurements of temperature, force and relative humidity. Measurement of temperature was one part of achieving the result of relative humidity.

All the measurements taken with nodes were compared with a reference result measured at the same time with a device of higher accuracy. This comparison provided a sufficient overview about the accuracy of the developed WSN monitoring system. All the measurements were taken simultaneously with the reference device in order to get a direct comparison between different nodes.

Measurement process of relative humidity

Relative humidity test was performed in a CTS C40/1000 climate chamber. All the measured values were compared with a reference result taken with Hygroclip HC-2SH humidity and temperature measurement probe. The accuracy of the reference probe is ±0.01 °C and ±0.5% RH, which exceeds the accuracy of nodes by several times.

The test was performed using a WSN-3202 node and a humidity sensor produced by Honeywell. All the relative humidity measurements were taken at 20 °C. During relative humidity tests, measurements of temperature were simultaneously utilized. The output signal of relative humidity sensor is affected by the temperature of the measuring environment. WSN-3212 node with J-type thermocouple was utilized for temperature measurement. The relative humidity levels used for the test were 20%RH, 40%RH, 60%RH, 80%RH and 90%RH.

Relative humidity was measured with sensor of Honeywell HIH-4000-003, with accuracy ±3.5% RH. As the supply voltage was 5 V and output voltage was 12 V, a voltage regulator had to be connected before the sensor. For holding stability of supply voltage also two capacitors (3.33 μF and 0.1 μF) were connected. Output voltage of sensor was measured between terminals SEN OUT and GND. Terminal GND was used for grounding the supply voltage. MC7805 is a voltage regulator. The circuit diagram is presented in Fig 2.

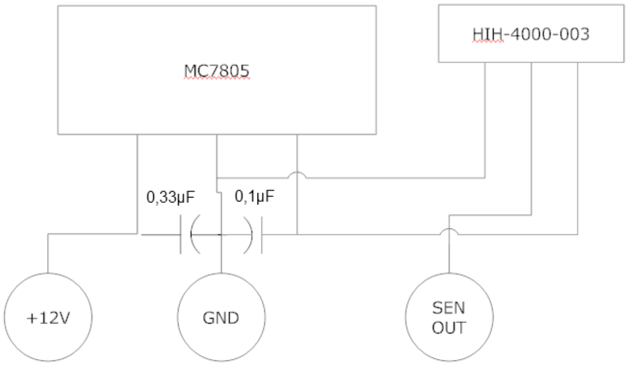

Fig. 2. The circuit diagram of measurement of relative humidity.

A program was created in LabVIEW programming environment to measure the voltage input of WSN-3202 node and relative humidity is calculated by the use of voltage. Sensor 0-point has been taken off from the voltage and the result is divided with the sensitivity of the sensor. As a result, the relative humidity sensor is subject to temperature, also temperature coefficient has been taken off.

After the first test the sensitivity of the sensor output was recalculated according to test results.

Measurement process of force

Force of the unit was measured using WSN-3202 node and Honeywell force measuring sensor FSG15N1A. Specification of the sensor is presented in Table I. Results were compared with calibrated weights.

TABLE I
HONEYWELL FORCE SENSOR FSG15N1A SPECIFICATION

supply voltage	measurement range	accuracy	consumption of current	output voltage
10 V	1500 gram	±1 gram	1.5 mA	0-360 mV

The sensor sensing element is piezoelectric resistor that changes its nominal value subject to force affected. The sensor output voltage is linearly subject to force. Sensitivity of the sensor output is 0.24 mV for 1 gram when measured at room temperature.

After the first test the sensitivity of the sensor output was recalculated subject to test results.

Results and discussion

Relative humidity test demonstrated stable accuracy in WSN monitoring system up to 60% RH. On higher level it loses its linearity and inaccuracy grows (Fig. 3). It means that the sensor accuracy ±3.5 was exceeded.

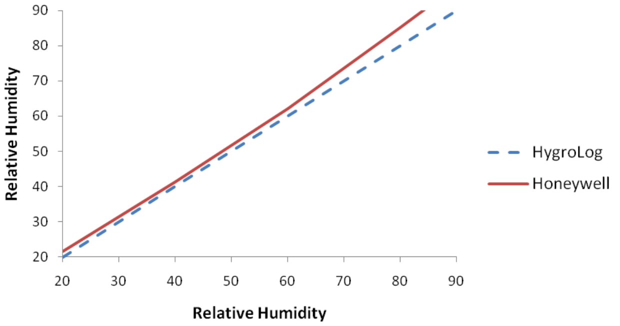

Fig. 3. Comparison of relative humidity measured using WSN monitoring system with Honeywell sensor and Hygroclip HC-2SH probe.

After analyzing the test results it was obvious that the majority of varied results were caused by sensor rather than nodes. To ensure the reliability of the monitoring system, voltage and humidity ratio constant was changed. The new constant was midrange of signal/expected value ratio. Original constant 0.031 was changed to 0.0328 and a new test was utilized with the new constant. After constant change the results were within accuracy limits. Relative humidity test results are presented in Table II.

TABLE II
THE RESULTS OF RELATIVE HUMIDITY TEST

expected value (%RH)	node value (RH%)	signal (mV)	signal/ expected value ratio	new expected value (%RH)	new node value (%RH)	signal noise
20	21.5	0.6665	0.033325	20.3	20.6	15
40	41.4	1.2834	0.032085	39.1	38.9	20
50	51.8	1.6058	0.032116	48.9	49.2	21
60	62.1	1.9251	0.032085	58.7	58.5	23
80	85.3	2.6443	0.033054	80.6	80.6	26
90	97.4	3.0194	0.033549	92.0	91.8	30

Force measurements difference between measuring instruments outputs was maximum 10% in low values, in higher levels about 7%. WSN force monitoring system exceeded its accuracy limits ±1 gram. Maximum difference was 14.9 grams at the highest force level (Table III).

Similarly to humidity test, output value calculation constant was changed. New constant was midrange of signal/expected value ratio. New constant 0.259 increased the reliability of measurements. Force sensor accuracy comparison at different load level is presented in Fig. 4.

It can be concluded that all nodes used in the tests performed as expected. The performance of the nodes was stable and all the nodes acted equally in comparison with each other. It can also be concluded that when using external sensors, the accuracy of measurements depends mostly on the accuracy of the sensor rather than the accuracy of the node. Before using nodes with sensors it is strongly recommended to compare the results with instruments of higher accuracy. Based on test results adjustment of output value calculation constants has to be carried out to achieve the highest accuracy.

TABLE III
THE RESULTS OF FORCE TEST

expected value (gram)	node value (gram)	signal (mV)	signal/load (mV)
0	0	0	
5	5.5	1.32	0.264
10	11	2.64	0.264
20	21.5	5.16	0.258
50	53	12.72	0.2544
100	106.7	25.608	0.25608
200	214.9	51.576	0.25788

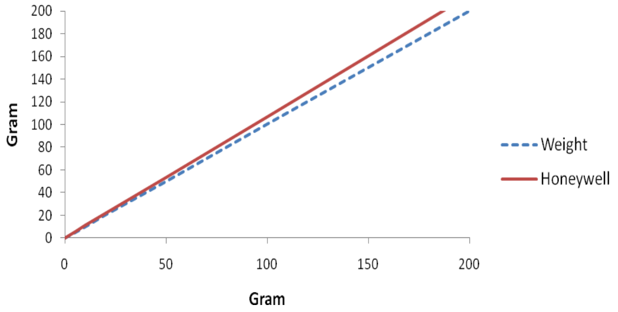

Fig. 4. Force measurement WSN monitoring system accuracy comparison using calibrated weights

WSN monitoring system is a practical tool in production environment helping to collect information for better machining results.

III. VIBRATION TESTS ON CNC LATHE

Measurement method

Vibration of the unit was measured with a solid-state micro electromechanical system (MEMS) accelerometer LIS3LV02DQ. This device can measure acceleration in three directions in the range of ±2g at 12 bit resolution. The Earth gravity was included in measurement values. This sensor type was selected as it has a suitable measurement range and accuracy, small footprint (7×7×2 mm), internal digital conversion unit with built-in noise filtering, suitable electrical interface and is readily available in prototyping form. The same sensor can be used in the final and optimized WSN as it possesses a suitable electrical interface (SPI) and very low power requirements (0.8mA@3.3V). The sensor was interfaced to a computer during the experiments via the low-voltage SPI bus. An additional data acquisition/interface board was installed between the sensor and the main data acquisition computer as the computer was not equipped with the SPI interface. The data acquisition board was a WSN node prototype, based on the Atmel AVR XMEGA microcontroller. As the data acquisition board is essentially a fully fledged WSN node, it can read sensor data, buffer it and forward to the computer in serial (RS232) format.

Measurements were carried out in all 3 axes. Sampling frequency was changed during the tests from 160-2560 samples/s. For keeping WSN battery lifespan as long as possible it is recommended to take as few samples as possible. On the other hand, the number of samples has to be sufficient for analysis and decision making.

In the final and optimized WSN the serial (RS232) data link will be replaced with a wireless communication module that is already present on the prototype board. Depending on the analysis results and firmware, it is possible to transmit measurement information continuously or just monitor the identified state of machinery.

Measurement process

All measurements were carried out on a CNC turning machine Okuma OSP 2200. The acceleration sensor was bolted to aluminum L-profile and fastened with cutting tool to CNC lathe magazine and 7 sets of data acquisition experiments were conducted. Accelerometer also measures gravity of Earth and its influence is unequal in all 3 axes. Sensor output values are in units 10-3 m/s^2. These units are not changed, since every calculation uses limited energy when applying WSN as proposed.

All 7 test pieces were of the same shape and diameter 224 mm. Steel S335 was used as test piece material. New tool insert was used in test no 1. All tests were carried out with the same tool insert. Mitsubishi tool insert UE 6020 recommended linear velocity 150-250 m/min. Coolant was not used during the turning.

During the tests 3 parameters were changed (sampling frequency, feed and spindle speed that also changed linear velocity). Cut of depth was held 2 mm during the tests. Tests 1-3 were all measured in normal turning mode, thus keeping the tool insert lifespan at maximum. Linear velocity was 155 m/min which is close to lower velocity limit. The only difference between these was sampling frequency measured by accelerometer. Tests 4-6 were measured in hard working mode. Linear velocity was 380 m/min and the feed was raised to 0.4 mm/rev. Again, the only difference was sampling frequency rate. Test number 7 was carried out with empty spindle turning to recognize turning without tool usage (Table IV).

TABLE IV
CUTTING PARAMETERS IN VIBRATION TESTS

TEST NO	SPINDLE SPEED (MIN^{-1})	FEED (MM/REV)	DEPTH OF CUT (MM)	LINEAR VELOCITY (M/MIN)	SAMPLING FREQUENCY (SAMPLES/S)
1	220	0.25	2	155	160
2	220	0.25	2	155	640
3	220	0.25	2	155	2560
4	540	0.4	2	380	160
5	540	0.4	2	380	640
6	540	0.4	2	380	2560
7	540	-	-	-	640

Analysis of the results

Before carrying out the tests 4 problems were raised:

1. Is it possible to recognize normal working mode, hard working mode and turning without working based on acceleration results?
2. Which sampling frequency gives an optimum result?
3. How many successive samples are needed for analysis on optimum sampling frequency level to define the working mode running?
4. Which axis gives the best results?

Maximum range value of every test was found in all 3 axes (Table V). Comparison of range values indicates that only results measured by the same sampling frequency are comparable. Comparison can be carried out only between tests 1 and 4; 2, 5 and 7; 3 and 6. Investigating sampling frequency 640 samples/s, it can be stated that vibration level is minimum in idle running, higher in normal working mode and the highest in hard working mode. These range values are presented in Table VI in percentage. Every axis has been examined separately. The biggest difference between turning modes is in x-axis, next z-axis and the smallest in y-axis, Difference is sufficient in every axis to determine a working mode based on range values.

TABLE V
ACCELERATION RANGE VALUES ALONG DIFFERENT AXIS DURING THE MEASURING PERIOD

test no	x-axis	y-axis	z-axis
1	40	22	44
2	379	130	223
3	1397	2335	1045
4	152	290	97
5	594	394	442
6	2199	3507	1839
7	59	82	75

TABLE VI
ACCELERATION RANGE VALUES IN PERCENTAGE ALONG DIFFERENT AXIS DURING THE MEASURING PERIOD

working mode	test no	x-axis	y-axis	z-axis
idle	7	100%	100%	100%
normal	2	642%	159%	297%
hard	5	1007%	480%	589%

According to comparison of vibration graphics of different axis, x- and z-axis graphics are symmetrical, whereas y-axis is asymmetrical (Fig. 5). Y-axis has many especially high values in one direction that can distort the result when analyzing smaller sections. Based on this notice, y-axis is eliminated from further analysis.

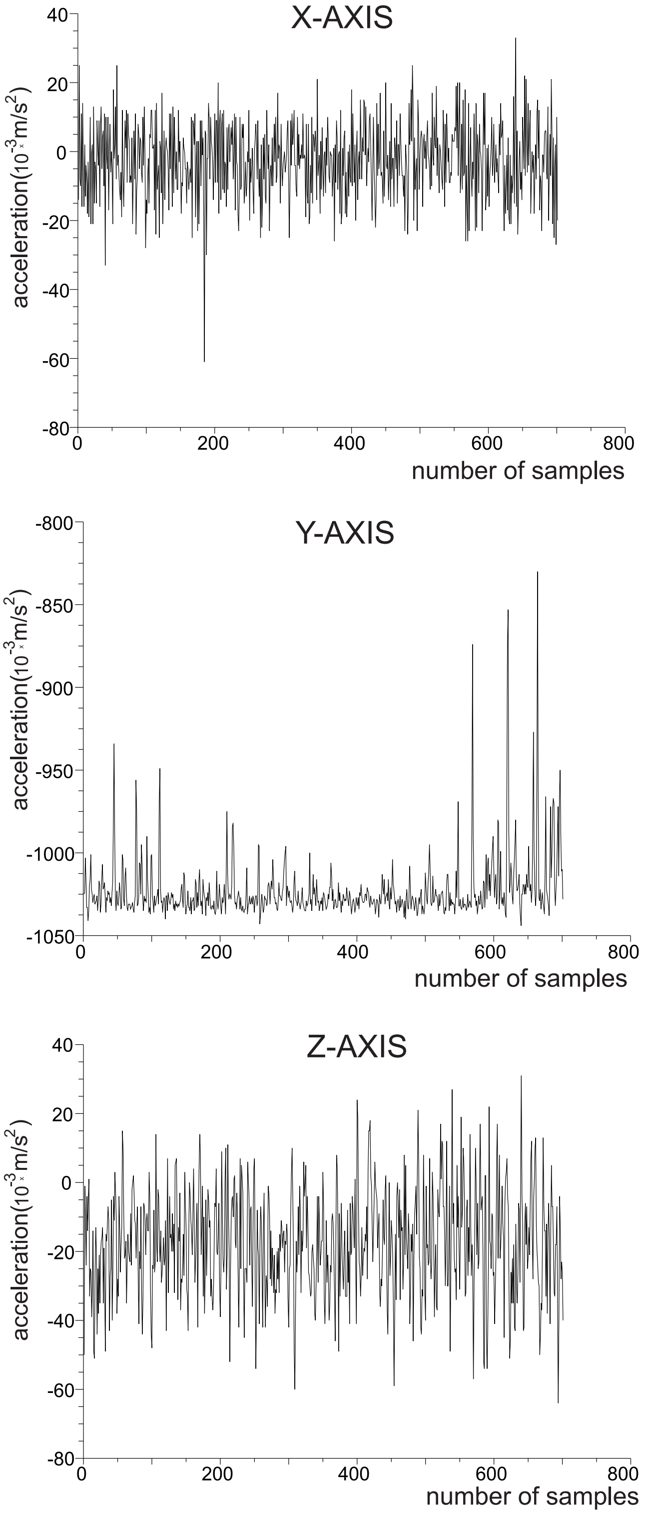

Fig. 5. Comparison of symmetry and existence of especially high values between different axes in test no 4.

Next, z-axis values have been investigated in test 1 and 2 by taking 10 random sections from every test in x- and z-axis. All sections contain consecutive measurement values. Quantity of measurement values (q) has been changed in sections to find the optimal sampling size. Range value of every section (R), as well as arithmetic mean value of these range values (X(R)) have been found. Minimum and maximum number in ranges and range value of range values (R(R)) in samplings (Table VII) have been elaborated.

For selecting the optimum section size and comparable axis the following criteria have to be considered:

1. Arithmetic mean value must be higher than the average of mean values.
2. R_{max} has to be at least 90% of whole test range value in particular axis.
3. Sections range value (R(R1-R10)) has to be lower than the average of sections range values.

The first and third points keep the values compact and limit their divergence. The second point guarantees that the calculated range stays close to the working mode in whole range value.

TABLE VII
TEST 1 X- AND Z-AXIS AND TEST 2 Z-AXIS SECTIONS COMPARISON ON THE BASIS OF NUMBER OF VALUES IN SECTIONS AND THEIR RANGE VALUES

test no	axis	q	X(R1-R10)	R_{min}-R_{max}	R(R1-R10)
2	z	130	136	104-193	89
2	z	260	152.4	111-193	82
2	z	520	167.5	128-193	65
2	z	640	171.7	135-201	66
1	z	60	25.6	19-31	12
1	z	100	31.5	21-39	18
1	z	130	31.9	28-39	11
1	z	160	31.4	27-39	12
1	x	60	29.6	24-34	10
1	x	100	31.2	27.38	11
1	x	130	32.6	27-40	13
1	x	160	32.5	30-40	10

Test 1 range was 44 and test 2 range was 223. All suitable cells in table VII have been marked with grey background. In test 2 (z-axis), using sampling rate 640 samples all compared parameters were accepted for analysis. In test 1 (z-axis) sampling rate, 130 samples meet all the requirements. In test 2 sampling rate, 640 samples fit within 1 second, in test 1, 130 samples fit within 0.8 seconds. The number of seconds indicates the time of delay in monitoring. According to previous comparison sample frequency 160 samples/s are preferred as measured in test 1. Since test 2 (sample frequency 640 samples/s) parameters were weaker, test 3 with highest sample frequency were discarded without comparison.

Finally, x- and z-axis were compared to choose the most reliable axis. The whole test range value in x-axis was 40 and in z-axis 44. All suitable cells in Table VII are marked with grey background. In x-axis the suitable sample rate was 160 samples. Above the mentioned z-axis 130 samples are also suitable and even better for collecting information in less time and using less WSN node power for wireless connection and processing the data.

Conclusions and discussion

1. Based on information of vibrations it is possible to recognize idle operation, normal working mode and hard working mode in CNC lathe.
2. The lowest sampling frequency possible in used accelerometer (160 samples/s) is fast enough for collecting reliable information to determine working

modes in real-time monitoring. Low frequency also prolongs the time of battery life in WSN mode.

3. Section of 130 samples is optimum for determining the running working mode. It takes about 0.8 seconds to get feedback from monitoring device.
4. According to the tests, z-axis provides the most reliable result. But using different cutting parameters, also z-axis can be useful for monitoring.

IV. WSN/ SMART DUST APPLICATIONS IN MONITORING

The vibration tests described in the paper were performed using wired sensors. For real applications in the manufacturing floor it is essential to employ wireless sensors integrated in an e-manufacturing system [12]. Wireless sensors or smart dust motes can be used in monitoring applications in addition to the wide range of other smart dust potential applications [13]. Smart dust motes can be equipped with a wide range of sensors, thus, depending on the application the properties of a smart dust mote can vary substantially as the processing unit of the mote may also be different, to be able to process the data collected by the sensors.

So far the manufacturing reports are generally created through manual triggering by the user. However, especially for standard reports, the option of using automatic, timed report creation should be preferred. The proactive distribution of important information through the manufacturing execution system is especially useful in mobile end devices [14]. Motes can be included in this report chain, as proved in the current research.

The biggest challenge for WSN is to achieve noiseless data transmission in the manufacturing environment. Electromagnetic interferences can be decreased to minimum by increasing the number of motes and placing them closer.

V. CONCLUSION

WSN production monitoring device testing proved it necessary to test the accuracy of the system before utilization. Modification of constants given by producers of sensors and nodes can provide a more accurate result in production environment.

Based on vibration tests on CNC lathe, different working modes can be defined. Optimal sampling frequency of 160 samples/s and optimal number of samples for data analysis were found.

Vibration tests were carried out with cabled sensor, nevertheless, the idea of smart network and intelligent tool requires wireless connection.

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