Development of a wireless data transmission system for a uniaxial dynamometer

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Abstract

Wireless dynamometers are an adequate solution to measure mechanical loads where the use of cables is not practicable. Proprietary solutions are applied in most of the cases found out in the literature on wireless dynamometers. However, these solutions have a high market price, and they are black-box systems, which limit their application in customized conditions. In this context, this study presents the development of a wireless dynamometer based on low market price components and with an open-source technology for real-time monitoring with a suitable sampling rate of 400 Hz (or 32.8 kbps). The proposed dynamometer used a complete Wheatstone bridge configuration and an amplifier circuit with a static gain of 99.8 V/V. Calibration tests and analysis of the performance were carried out according to ISO 376 standard. The proposed wireless dynamometer presented performance indicators of 0.76% for hysteresis, 1.34% for linearity, 4.83 mV/N for sensitivity, and 5.22% for repeatability. These results show that the low market price components and open-source technology can be used to build reliable wireless dynamometers able to comply with customized industrial demands.

Keywords Wireless data transmission · Dynamometer · Calibration · Force measurement · Data processing

1 Introduction

Dynamometers are devices employed to measure static or dynamic mechanical loads. These devices can be instrumented with different types of transducers, such as resistive, capacitive, inductive, optoelectronic or electromagnetic [1]. The design of resistive dynamometers is based on the use of one or more mechanical components referred to as sensing elements. Thus, strains caused by the application of mechanical loads are concentrated in specific regions of the sensing elements and measured with the

aid of transducers that provide a response as an electrical voltage. In the design of stationary dynamometers, strain gauges are widely applied since they are resistive transducers that balance low market price and high measurement sensibility [2, 3].

Since the electric signal produced by strain gauges transducers is in mV, an adequate way of measuring this signal is to associate strain gauges in an electrical circuit referred to as Wheatstone bridge [1]. The signal produced by this bridge is analogical and needs to be amplified before being discretized. Also, the data

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transmission from the measurement point up to the data logging device can be carried out via cables or wireless. Even though in most cases this communication is done via cables, there are circumstances in which this option cannot be appropriate, such as in the case of mechanical systems installed in insalubrious or difficult-to-access environments and rotary systems. In such cases, the application of wireless data transmission technology becomes mandatory. According to Santos and Volante [4], in the context of Industry 4.0, the wireless connectivity provides flexibility to the systems by connecting different devices to a network. This type of communication enables a real-time data update and a procedure of decision making based on algorithms that does not require human intervention. For that, the transmitted data need to be reliable and accurate [5].

IEEE 802.3ck (implemented in 2018) is the latest protocol for wired data transmission which allows a maximum transfer rate of 400 Gbps [6]. However, for wireless transmission, the latest protocol is IEEE 802.11ad (implemented in 2012) which allows a maximum transfer rate of around 862.5 Mbps [7]. Therefore, one of the current challenges for wireless data transmission technology is the transfer rate, which is lower as compared to cable transmission. The telemetric system proposed by Milani [8] presented a sampling rate of 120 Hz, consisted of a Bluetooth BlueSMIRF Gold used as a transmitter module and a Bluetooth USB WRL-09434 used as the receiver module. However, most researchers do not present any information regarding the data transfer rate of their devices; they only present the maximum transfer rate of the transmission module, available in the datasheets of these components. As the cases of Wu et al. [9] and WangWang et al. [10], that developed devices with transfer rates of 0.92 Mbps and 1 Mbps, respectively. The first one obtained a sampling rate of 1 kHz, with a device composed of a RAK433 as a transmitter module, associated with a C8051F 206 microcontroller (Silicon Laboratories Inc.[®]), and an analog–digital converter (ADC) of 12-bit resolution. As a receiver, the authors claimed to have used a computer. The second one did not provide its sampling rate of the device. The transmitter system was built using a CRM2400 module connected to an ATmega16 microcontroller (Atmel[®]), and a 10-bit resolution ADC. The receiver system was composed of the same electronic components. WangWang et al. [10] do not inform the company that produces the transmission modules used. Indeed, the point is that the maximum transfer rate presented in the datasheet is not always possible to be verified in operating conditions. This is due to the fact that there are demands from electronic components that compose the telemetric system itself which limit this rate, in addition to the influence that the environment has on the device operation [11].

Proprietary solutions systems have been applied to rotary devices in order to allow wireless data transfer in machining processes. Totis et al. [12] and Rizal et al. [13] developed rotary dynamometers to be mounted directly into the spindle of vertical machining centers. The device designed by Totis et al. [12] was equipped with a high-performance telemetry system for data transmission. In this case, the analog signals were digitized at a resolution of 12-bit allowing a sampling rate of 13 kHz. However, the authors did not refer to the company that produced the telemetry system. Rizal et al. [13] developed a dynamometer to measure resultant force in milling operation. In this case an acquisition and transmission module (MT32-STG) with a 12-bit resolution for analog–digital conversion associated with a receiver module (MT32-DEC8) and a storage module (DT9836) were used. The components of the resultant force were measured using a wireless telemetry system at a sampling rate of 5 kHz. The transmission and receive modules were developed by KTM Telemetry Company[®] and the storage module was produced by Data Translation[®]. It should be noted that in machining processes the sampling and transfer rate must be high enough to reach the cutting edge excitation frequency. This fact implies on the use of high-performance commercial telemetric systems with high market prices. Also, proprietary solutions work as black-box systems, not allowing data transfer to customized systems.

In this sense, the main objective of this work was to develop a wireless data transmission system for a uniaxial dynamometer able to measure forces from 0 to 100 N based on an open-source technology. To achieve this aim, some specific points were previously defined: (i) definition of an instrumentation procedure; (ii) construction of a signal amplifier and a wireless data transmission system; and (iii) development of the computer codes aimed at the step of calibration.

2 Methodology

Figure 1 shows the six phases followed to develop the telemetric system proposed in this study. It should be noted that the design of the uniaxial dynamometer was based on a commercial model, with a measurement range from 0 to 100 N.

As illustrated in Fig. 1, the first phase involved the instrumentation of the uniaxial dynamometer, which was divided into the following steps: (1a) strain analysis, to identify the best points on the sensing element to stick the strain gauges; (1b) surface preparation to apply the strain gauges. In order to find out the best points to stick the strain gauges on the sensing element, the module for Finite Element Analysis (FEA), from PTC Creo Parametric™

Fig. 1 Phases followed for the telemetric system development

software, was used for the strain analysis. Before sticking the transducers at these points, the surface of the sensing element was sanded aiming to obtain a surface roughness with a random texture and a grade number between N5 and N6. After that, the surfaces were cleaned off using acetone PA and cellulose papers. In order to better identify the places where the strain gauges should be stuck, a Mitutoyo HDS-H12 height gage was used to produce visual markings. Rapid adhesive Z70-HBM was used to stick the strain gauges on the surfaces. The application of this adhesive followed the instructions provided by HBM [14]. Afterward, copper wires (diameter of 0.3 mm) and the connection terminals of the strain gauges were welded together and covered with a PU140-HBM lacquer, according to HBM [15] and procedures adopted by Ribeiro [16], Lourenço [17], and de Oliveira [18], who performed instrumentation of the dynamometers to measure the multiple components of the resultant force in machining.

The second phase consisted in constructing a signal conditioning module able to meet the following requirements: (2a) having a power supply capable to provide energy to the transducers and other electronic components; (2b) having a reference voltage circuit able to ensure a stable and appropriate power supply for the Wheatstone bridge; (2c) reading the Wheatstone bridge output signals; (2d) having an amplifier circuit able to provide a static gain of around 100 V/V; (2e) having an offset adjustment circuit to adjust the Wheatstone bridge output signal.

The telemetric system was developed in the third phase, and its requirements were: (3a) converting the analogical signal coming from the transducers into a digital signal; (3b) creating a routine for data transfer; (3c) allowing the data transmission for a distance at least 2 m, and at a sampling rate from 120 Hz to 1 kHz, which are values commonly found in the literature when studies that applied proprietary solutions are disregarded; and (3d) being space saving. Microcontrollers and commercial radio frequency transmission modules were employed to balance such requirements at a low market price. Copper wires were used to connect these components to the

signal conditioning circuit. It is important to emphasize that the connections between pins and the copper wires should be properly protected to prevent the occurrence of electrical damage.

The fourth phase was the design and manufacture of cases to protect the signal conditioning and the telemetric systems. In this case, the requirements were: (4a) being able to electrically insulate the systems; (4b) having locks for attachment of lids; (4c) apply proper materials to avoid the occurrence of electrical damage or failures in the electronic components; (4d) providing appropriate attachments of the electronic components; and (4e) having holes for passing the wires and cables.

The fifth phase consisted in elaborating the data acquisition and processing computer codes, which must be used in the device calibration. These computer codes need to be capable of (5a) reading the electrical signals generated by the receiver system, and enabling their real-time visualization; (5b) allowing the user to save the data from a temporal window; (5c) evaluating the device calibration curve and its coefficient of determination; (5d) enabling the real-time visualization of the force data; and (5e) comparing the measured force values with the experimental applied standard loads. These computer codes were created using the software LabVIEW™ (2011 version). The data acquisition system used functions provided by the VISA Serial library. The software temporal window tool was used to allow the user to define an appropriate range of interest from the raw signal. The linear regression coefficients and the coefficient of determination were evaluated with function Linear Fit VI and Goodness of Fit VI, respectively.

The device calibration was carried out in the sixth development phase. There were used a rod of 6.67 N (as a support device) and 10 loads of 9.8 N, which were applied using standard masses. Three cycles of loading and unloading were applied varying the loads in a range from 0 to 104.7 N. Before each cycle, the device was subjected to preloads to accommodate it. This procedure was based on ISO 376 [19], which addresses the calibration of force-proving instruments used for the verification of uniaxial

testing machines. Performance analysis of the dynamometer was carried out considering the following indicators: sensitivity, hysteresis, linearity, and repeatability. Performance indicators were determined according to the equations described in Zhao et al. [20].

The phases 1, 2, 3, 4 and 5 were carried out in the Manufacturing Lab and phase 6 was carried out in the Metrology Lab at the Federal University of Rio Grande do Norte (UFRN).

3 Results and discussion

The results are presented and discussed according to the steps defined in Fig. 1. Therefore, the first result is related to the device instrumentation. The engineering analysis, instrumentation of the sensing element and dynamometer with all mechanical components mounted are illustrated in Fig. 2.

Figure 2a shows the strain analysis in the sensing element, which indicates the locations where the maximum strains are concentrated when an external load of 104.7 N was applied, considering as material the aluminum alloy 7075-T6. For such load, the maximum strain was 1.357×10^{-3} mm/mm. Figure 2b illustrates the

manufactured sensing element and the strain gauges placed on the locations with high strain concentration. Strain gauges, model HBM 1-LY43-3/350, were associated in a full Wheatstone bridge configuration. This model of strain gauge is specific for aluminum alloys and enables the measurement of unidirectional strains. Besides, it presents a length of 10.9 mm, a width of 5.9 mm, a maximum supply voltage of 19.53 V, and a resistance of 350Ω [21]. Figure 2c exhibits the device with all support components assembled on it. A lid was used to organize the power supply wires which connect the strain gauges. This lid was manufactured of an Acrylonitrile Butadiene Styrene (ABS) filament by Fused Deposition Modeling (FDM), an additive manufacturing technique. The support components were bolted to the sensing element in order to support the measurement system. The force 'F' represents the external load applied to the dynamometer. The characteristics mentioned above fulfill the requirements described as 1a and 1b.

With the mechanical system and instrumentation defined for the uniaxial dynamometer, the next step is processing the data provided by the Wheatstone bridge. Figure 3 shows the data flowchart diagram defined herein to facilitate the understanding.

Fig. 2 Instrumentation and assembly of the uniaxial dynamometer: **a** strain analysis; **b** instrumentation; and **c** dynamometer characteristics

Fig. 3 Data flowchart diagram for the wireless transmission system

Figure 3 shows that, after the voltage difference to be emitted by the Wheatstone bridge, the data chain follows the steps: (a) signal conditioning; (b) signal transfer aided by telemetric system; and (c) processing data by computer codes to define the calibration procedure. As shown in Fig. 3, the second phase is related to the construction of a signal conditioning circuit. The electrical diagram is schematized in Fig. 4.

According to Fig. 4, the voltage provided by the power supply system (1) is adjusted in the reference voltage system (2) in order to continuously supply the suitable power to the Wheatstone bridge (3) and, also, avoid the undesirable effects from the batteries discharge. The electrical signal provided by Wheatstone bridge is acquired (4), processed in the amplification system (5), and so, adjusted in the offset setting system (6). Then, the conditioned output signal (7) is routed to the telemetric system, which is connected to the board. This circuit was prototyped in a phenolic board.

The power supply system is composed of two 9 V batteries connected in series, capable of supplying a continuous and symmetric electrical power. A L7805CV linear voltage regulator was associated with a 10 μ F capacitor and a 100 nF capacitor in the reference voltage system, allowing the stabilization of the electrical voltage at 5 V. The amplification system consists of an AD620 instrumentation amplifier (Analog Devices, IncTM); two 10 nF capacitors; and a 500 Ω resistor. As a recommendation of the amplifier manufacturer, a symmetric power supply was used [22]. Two capacitors were employed to stabilize and reduce the noise of the power supply voltage, and the resistor was used to define the required gain (signal amplification). As a result of this step, a static gain of 99.8 V/V was achieved.

The offset setting system consists of a 3296 W potentiometer associated with a 100 Ω resistor. Also, it was built in a voltage divider configuration, which enables the setup of the electrical signal from 0 to 5 V. This configuration

allowed to set the output unloaded dynamometer voltage at 2.5 V and correlate the values from 0 to 2.49 V to tensile loads, and the signals from 2.51 to 5 V to compression loads. Therefore, the described features satisfied the requirements 2a, 2b, 2c, 2d and 2e.

The configuration of the electrical circuit developed in this research is similar to that reported by Wu et al. [9]. In that case, the conditioning circuit developed was composed of three subsystems: the amplification system (gain of 1000 V/V); the reference voltage system for the Wheatstone bridge (3.3 V); and the power supply system with lithium batteries in 3.7 V. However, the current study presents the reference at 2.5 V to allow a better split of the opposite signals (tensile and compression), required for supply the system with voltages greater than 5 V. The choice of 9 V batteries associated with 5 V linear voltage regulator was done to reach a longer operating time for the system before discharge. A similar voltage divider configuration was proposed by Milani [8].

The development of the telemetric system was carried out in the third phase. It was built with two Arduino[®] Nano microcontrollers (which has an ATmega328P), with a 10-bit resolution for analog–digital conversion, with a clock speed of 16 MHz [23], and two nRF24L01 + 2.4 GHz radio frequency transmission modules (manufactured by Nordic Semiconductor[®]). One of the microcontrollers associated with a transmission module was configured to be the emitter and carried out the conversion of the analog electrical signal to digital-based on the discrete values from 0 to 1023, fulfilling the requirement 3a. The other microcontroller connected to the second module was programmed to be the receiver.

The computer code acquires the signal provided by the amplifier, temporarily stores this signal as an object composed by integer variables, and lastly, the signal is transmitted. Also, it allows the user to retransmit the data if the first transmission did not succeed. However, this security

Fig. 4 Electric diagram applied to signal amplification and conditioning

process could result in high delays, reducing the data transfer rate and its interpretation. Thus, this function was usually disabled to allow an effective data sampling rate of 400 Hz and data transfer at a rate of 32.8 kbps over a distance of 2 m, aiming to fulfill the requirements 3b and 3c. The described computer code is available in Batista [24].

The wires used for connecting the electronic components have a diameter of 0.405 mm (26 AWG). The connections between pins and wires were covered by heat-shrinkable tubes (produced by Rontek®), preventing short circuits between the components.

The fourth step of the development involved the manufacturing of the protective cases. The protecting cases were manufactured by the FDM process, using ABS filament, and fulfilled the requirements 4a, 4b, 4c, 4d and 4e. Figure 5 shows the pair of protective cases with all electronic components arranged inside.

According to Fig. 5a, the emitter system and the signal conditioning circuit are arranged in the same case. It is also possible to identify the two batteries employed for power supply, the prototyped board used for the signal conditioning system, the wires used to power the Wheatstone bridge and to read its output signal and the emitter system (the microcontroller and the transmission module). On the other side of the system, Fig. 5b shows the receiver system, which is composed of a microcontroller, a transmission module and a cable to transmit the output data to the computer.

The protective cases have a wall thickness of 2 mm. The case for the signal conditioning and emission systems has external dimensions of $131.3 \times 8.5 \times 36$ mm. The case for the receiver system has external dimensions: $57.3 \times 52.5 \times 35$ mm. Besides that, as shown in Fig. 5, all wires used to connect the electronic components are flexible enough to be bent, allowing them to be adjusted to the locations. The microcontroller used herein presents some similarity with the ATmega2560 Arduino®, used by Milani [8], as the same ADC resolution (10-bit) and clock speed (16 MHz). However, the one used by

Milani [8] would not be appropriate for the current study, because it provides an excessive number of pins for this application. Also, the Arduino® Nano is small and has an affordable technology.

The results of the fifth step refer to the data acquisition and processing computer codes. It should be noted that this step describes the features of each computer code, and their operation will be shown in the next step. Four computer codes were developed for the entire process (two for the transducer characterization and the other two for the device calibration). The first computer code (for the data acquisition of system characterization) allows the user to visualize in real-time and acquire electrical signal data, to select the data temporal window and to store these data as a text file ('.txt' extension). In the second one (for the data processing of the system characterization) is possible to open the files saved by the previous computer code; calculate the average values of the temporal window (for each applied load value); evaluate the coefficients of a linear regression that relates these average values to the applied load values; display, in the graph form, curves representing the loading and unloading processes and values predicted by the linear regression; and, of course, evaluate the coefficient of determination between the applied load and the output voltage. These two computer codes were necessary to create a reference curve in such a way that it could be used in the further calibration tests.

Therefore, to carry out the calibration test, the third computer code allowed the real-time force data acquisition and visualization based on the linear regression obtained in the previous phase and stores these data also as a text file ('.txt' extension). Lastly, the fourth computer code processes these files; evaluated the average values in a temporal window (for each value of applied force); and compares them with the experimental applied loads through their relative error evaluation. Thus, the requirements 5a, 5b, 5c, 5d and 5e were fulfilled. These four computer codes also are available in Batista [24].

Fig. 5 Protective cases and electronic components arranged: **a** emitter and signal conditioning systems and **b** receiver system

The following results are related to the calibration procedures for the uniaxial dynamometer, which belong to the sixth phase of this development. Before the device characterization and calibration, the offset value was set up to 2.558 V. The system for the calibration procedures is presented in Fig. 6.

According to Fig. 6, the uniaxial dynamometer is connected to rod in which the standard masses are assembled. The signal conditioning and the emitter systems are connected to the dynamometer. The receiver system is connected to the computer using a USB cable. As can be seen in Fig. 6, the data are displayed in the graphical interface, which makes the data interpretation an easier activity by the operator. In order to facilitate the understanding, the computer codes graphical interfaces for the calibration process are shown in Fig. 7.

Figure 7a shows three curves (indicated as 1): blue represents the loading process, red represents the unloading

process and green is the values estimated by means of the linear regression. It should be noted that the curves are practically overlapped. Also, in Fig. 7a it is possible to note the linear regression equation and the coefficient of determination R^2 (indicated as 2 and 3, respectively). On the other side, Fig. 7b shows the real-time signal acquisition, in terms of the applied force (4); the temporal window (5); the field to insert the linear regression file (6); the average force for a temporal window selected (7); the command button that allows the user to save the signal in a text file format (8); and, lastly, the stop button (9). For reference only, Fig. 7b illustrates that the data are correlated to an experimental load of 55.72 N applied to the axial dynamometer.

In this study, a coefficient of determination of 0.9996 was obtained. This value indicates that, in the calculated linear regression model, 99.96% of the voltage variation is due to the applied loads and 0.04% of the voltage variation is related to other factors [25]. This result suggests a suitable accordance between the real value of the load and the one presented by the system proposed in this work. The performance indicators were 4.83 mV/N for sensitivity, 0.76% for hysteresis error, 1.34% for linearity error, and 5.22% for repeatability error. These values are within the performance range of wireless force measurement devices available in the literature [9, 18].

This study presented the entire development chain; a wireless communication system proper to transmit at a data transfer rate of 32.8 kbps; and a data processing computer codes in which it is possible to calibrate the device and carry out functional tests. The application of

Fig. 6 System setup for calibration process

Fig. 7 Computer codes graphical interfaces for the calibration process: **a** characterization data processing routine and **b** calibration data acquisition routine

wireless dynamometer for mechanical load monitoring is an increasing demand for safety and optimized industrial procedures. In the literature, academic studies on the development of wireless systems for mechanical loads monitoring have mostly presented sampling rates in the range from 120 Hz to 1 kHz. In this last case, the device is composed of expensive electronic components, similar to CC-WMX6-KIT (US\$ 389.00—DIGI) as a transmitter module associated with SLWSTK6021A microcontroller (US\$ 99.00—Silicon Labs Inc.®). Furthermore, proprietary and specific solutions are applied in wireless transmissions, such as NI WLS-9191 WIFI DAQ (US\$ 463.00—National Instruments). These commercial solutions have a high market price, besides being black-box systems, which limit their application in customized conditions. The current proposal has a low-cost wireless system solution (total price lower than US\$ 100.00) based on open-source technology for real-time monitoring with a sampling rate at 400 Hz. Also, it presented all the steps to create a suitable communication between the hardware and the software, besides the computer codes to calibrate the device. Performance indicators showed that the dynamometer can be applied in a wide range of applications. Finally, it should be noted that the technology described in this proposal is open-source, which allows its adaptation to different areas, such as automotive (torque measurement in transmission shafts) and aeronautics (strain measurement in rotor turbines).

3.1 Future work

The most relevant challenges in the development of a wireless data transmission with a suitable sampling rate for real-time monitoring are related to the limitation of electronics components, computer processing, and scheduling algorithms. To improve the developed system some optimizations could be done: (a) testing other low-cost electronic components models in order to increase the sampling rate; (b) combining the amplification and conditioning circuits with the acquisition system (A/D converter and microprocessor) on a single board in order to reduce electricity consumption; (c) optimizing the dimension of the printed circuit; and evaluating other microcontrollers aiming to operate with multithreading feature.

4 Conclusions

This study presented the development chain of a telemetric system for a uniaxial dynamometer. Based on the six proposed development steps, the following conclusions can be stated:

- (a) the dynamometer instrumentation was successfully developed with the aid of engineering analysis to define the location where the maximum strains are concentrated in order to stick the four strain gauges (connected in a full Wheatstone bridge);
- (b) the signal conditioning circuit enabled the amplification of the Wheatstone bridge output voltage, with a static gain of 99.8 V/V;
- (c) the amplified voltage was adjusted to a range from 0 to 5 V, considering the interval from 0 to 2.49 V for tensile loads; and from 2.51 to 5 V for compression loads;
- (d) the application of pairs of microcontrollers and transmission modules allowed a wireless data transmission greater than 2 m and at a transfer rate of 32.8 kbps;
- (e) the calibration tests indicated a suitable uniaxial dynamometer for the proposed application range and a coefficient of determination of 0.9996 was evaluated in the interval from 0 to 104.7 N.

Availability of data and materials 'Not applicable' for that section.

Code availability 'Not applicable' for that section.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

1. Stefanescu DM (2011) Handbook of force transducers: principles and components, 1st edn. Springer, Berlin
2. Killedar JS (2012) Dynamometer: theory and application to engine testing. Xlibris Corporation, Bloomington
3. Klika V (ed) (2011) Theoretical biomechanics. InTech, Rijeka
4. Santos DRG, Volante CR (2018) The importance of wireless technology in industry 4.0. Technol Interface 15:245–254. <https://doi.org/10.31510/inf.v15i2.487>

5. Gilchrist A (2016) Industry 4.0: the industrial internet of things, 1st edn. Apress Publisher, New York
6. IEEE Std 802.3™ (2018) IEEE Standard for Ethernet
7. IEEE Std 802.11ad™ (2012) IEEE Standard for Information technology—Telecommunications and information exchange between systems. Local and metropolitan area networks—Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 3: Enhancements for very high throughput in the 60 GHz band
8. Milani C (2014) Instrumented training platform and wireless data acquisition, storage, and transmission system to cycling applied force platform. Monograph in Electrical Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil (**in Portuguese**)
9. Wu F, Li Y, Guo B et al (2018) The design of force measuring tool holder system based on wireless transmission. IEEE Access 6:38556–38566. <https://doi.org/10.1109/ACCESS.2018.2853735>
10. WangWang Y, Zhang R, Li D et al (2009) Study on wireless data transmission for dynamometer walker system. In: Proceedings of the IEEE international conference on virtual environments, human-computer interfaces and measurements systems (VECIMS), Hong Kong, China, 11–13 May 2009. IEEE Instrumentation and Measurement Society, 232–235.
11. Dugaev D, Siemens E (2014) A wireless mesh network NS-3 simulation model: implementation and performance comparison with a real test-bed. In: Proceedings of the 2nd international conference on applied innovations in IT (ICAIIT), vol 2. Kothen, Germany, 27 March 2014. Hochschule Anhalt, 1–5.
12. Totis G, Wirtz G, Sortino M et al (2010) Development of a dynamometer for measuring individual cutting edge forces in face milling. Mech Syst Signal Process 24:1844–1857. <https://doi.org/10.1016/j.ymssp.2010.02.010>
13. Rizal M, Ghani JA, Nuawi MZ et al (2014) Development and testing of an integrated rotating dynamometer on tool holder for milling process. Mech Syst Signal Process 52–53:559–576. <https://doi.org/10.1016/j.ymssp.2014.07.017>
14. HBM (2020) Z70: Cold Curing Superglue for Experimental Tests, and for Sensors Without High Accuracy Requirements—Instructions for use. <https://www.hbm.com/en/2962/z70-a-single-component-cold-curing-adhesive/>. Accessed 27 June 2020
15. HBM (2020) PU140: Covering Material for Strain Gauges—Polyurethane Lacquer—Instructions for use. <https://www.hbm.com/en/3081/strain-gauge-protective-coatings-pu140/>. Accessed 27 June 2020
16. Ribeiro KSB (2014) Manufacturing of dynamometer for loads assessment in oil and gas industry. Monograph in Mechanical Engineering, Federal University of Rio Grande do Norte, Natal, Brazil (**in Portuguese**)
17. Lourenço MAM (2018) Design and manufacturing of triaxial dynamometer with multiple sensing elements. Monograph in Mechanical Engineering, Federal University of Rio Grande do Norte, Natal, Brazil (**in Portuguese**)
18. de Oliveira AJ, Silva DML, da Silva JID et al (2020) Design and experimental set-up of a hybrid dynamometer applied to a fourth axis of the vertical machining center. Int J Adv Manuf Technol 110:2155–2168. <https://doi.org/10.1007/s00170-020-06005-2>
19. ISO 376 (2011) Metallic materials—Calibration of force—proving instruments used for the verification of uniaxial testing machines
20. Zhao Y, Zhao Y, Ge X (2018) The development of a triaxial cutting force sensor based on a MEMS strain gauge. Micromachines 9:1–11. <https://doi.org/10.3390/mi9010030>
21. HBM (2020) Strain Gauges: First Choice for Strain Measurements—Strain Gauges—Catalogue. <https://www.hbm.com/en/0014/strain-gauges/>. Accessed 27 June 2020
22. Analog Devices (2020) AD620 – Datasheet. <https://www.analog.com/en/products/ad620.html#product-overview>. Accessed 27 June 2020
23. Atmel® (2020) ATmega328P – Datasheet. http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P_Datasheet.pdf. Accessed 27 June 2020
24. Batista LDA (2020) Routines. <https://github.com/lucasdamascenobatista/Routines>. Accessed 27 June 2020
25. Montgomery DC, Runger GC (2018) Applied statistics and probability for engineers, 7th edn. Wiley, Hoboken

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