System for Testing and Determining the Accuracy of a Mechanical Watch

Tsanko Karadzhov
Department of Mechanical and Precision Engineering
[1]Technical University of Gabrovo
[2]Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies
Gabrovo, Bulgaria
karadjov_s@abv.bg

Borislav Georgiev
Department of Mechanical and Precision Engineering
[1]Technical University of Gabrovo
[2]Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies
Gabrovo, Bulgaria
gborislav@gbg.bg

Abstract — **This paper presents a new system for measuring the accuracy of mechanical clocks with Swiss Movement. Mechanical watches are complex devices consisting of many miniature components. Even small deviations in accuracy can lead to significant differences in timekeeping. Testing the accuracy of mechanical watches is an important process that ensures their functionality, durability, and value. It helps maintain a high level of precision in timekeeping, which is critical in many aspects of daily life and professional activity. The developed system provides a readily applicable alternative to measure and improve the accuracy of watches using a personal computer and acoustic analyses. The proposed methodology contributes to expanding the possibilities of investigating the dynamic characteristics of mechanical watches.**

Keywords — Accuracy, Mechanical watch, Accelerometer, Measurement system.

I. INTRODUCTION

Mechanical watches are inherently less precise than quartz watches [2]. A typical modern mechanical watch exhibits a daily deviation of approximately ±10 seconds, whereas a certified chronometer-grade mechanical watch is tested to run within -4 to +6 seconds per day [7]. In practical terms, this indicates that an ordinary mechanical watch may deviate by several minutes per month, while a chronometer-grade mechanical watch maintains accuracy within 1 or 2 minutes per month [10,11]. In comparison, an average quartz watch shows a greater degree of accuracy, typically exhibiting a daily deviation of approximately ±1 second equivalent to 30 seconds per month.

Mechanical watches, despite the lower accuracy, continue to be preferred both for their complexity, yet combined with engineering precision, and for their reliability [16]. In the context of dynamic processes, the accuracy of these devices is determined by the interaction of multiple factors such as the oscillations of the balance wheel, the influence of the environment and the mechanical characteristics of the components.

II. MATERIALS AND METHODS

A. Components of a Mechanical Watch

The block diagram of a mechanical watch is structured into the following key components – fig. 1.

Power source includes mainspring and barrel. The main spring is the primary energy source of a mechanical watch. It stores mechanical energy when wound manually or automatically. The barrel houses the main spring and regulates its release of power to the gear train. It also provides a consistent force over time.

Gear train transmits the energy from the barrel to the escapement and hands of the watch. It involves a series of gears that step down the speed of the main spring's release. The gear train also drives the hands of the watch, which displays the time.

Escapement is crucial for maintaining consistent time intervals. It allows the gear train to move forward in fixed steps, thus controlling the movement of the hands. It transfers energy to the balance wheel and ensures that the gear train advances at a regulated pace.
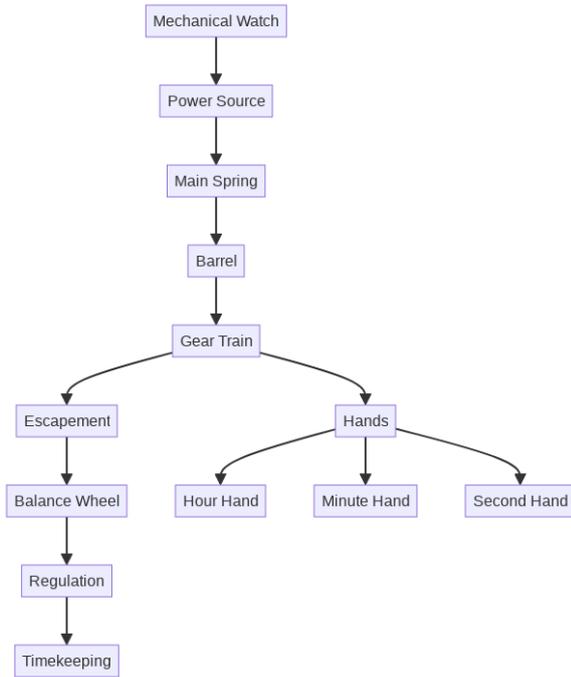
Fig. 1.   Block Diagram of the Elements of a Mechanical Watch.

Balance wheel oscillates back and forth, acting as the timekeeping element of the watch. It works alongside escapement to divide time into equal parts [5].

Regulation system adjusts the tension of the balance spring, fine-tuning the rate at which the balance wheel oscillates, thereby ensuring the watch keeps accurate time.

Timekeeping is the outcome of all these processes, displaying accurate time to the user through the watch's hands.

Each component plays a critical role in the mechanical harmony of a traditional watch, resulting in precise and reliable timekeeping.

B. Balance Spring Oscillation System. Analytical Description of the Movement of the Balance Wheel

We will focus on the balance spring oscillation system in more detail because the accuracy of the mechanical clock depends on it. The balance wheel of a mechanical watch operates on the principles of harmonic motion, driven by the interplay between the balance wheel itself and the attached hairspring also known as the balance spring.

Oscillatory motion – The balance wheel performs a periodic back-and-forth rotational movement around its pivot. This motion is akin to that of a simple harmonic oscillator, like a pendulum but rotational. The angle of rotation (θ) as a function of time (t) can be described by:

$$\theta = \theta_0 \cos(\omega t + \varphi) \qquad (1)$$

where:

θ_0 is the maximum angular displacement,

ω is the angular frequency,

ϕ is the phase constant.

The hairspring provides a restoring torque that is proportional to the angular displacement:

$$\tau = -k\theta \qquad (2)$$

where:

τ is the restoring torque,

k is the spring constant of the hairspring.

Angular frequency and period – The balance wheel's natural frequency depends on the spring constant and the moment of inertia (I) of the wheel:

$$\omega = \sqrt{\frac{k}{I}} \qquad (3)$$

The period (T) of oscillation, which is crucial for timekeeping, is given by:

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{I}{k}} \qquad (4)$$

Since the period is independent of the amplitude, the balance wheel is an effective timekeeper. During each oscillation, the escapement provides a small impulse to maintain the amplitude of the balance wheel's motion. Damping is minimal in a well-designed watch, ensuring that the amplitude remains stable over time.

Regulation of timekeeping – The balance wheel's consistent period ensures that each tick of the escapement wheel is uniform, translating to precise movement of the watch's hands. A typical mechanical watch balance wheel oscillates at a rate of 5 to 10 beats per second, often described as 18000 to 36000 beats per hour (BPH).

C. Energy Transfer Mechanism

In a mechanical watch, energy transfer and damping are critical for maintaining accurate timekeeping. The process involves the coordinated function of the mainspring, gear train, escapement, and balance wheel – fig. 2. The mainspring stores potential energy when wound. This energy is gradually released to drive the gear train. The gear train multiplier the high torque of the mainspring to a suitable level and delivers it to the escapement.
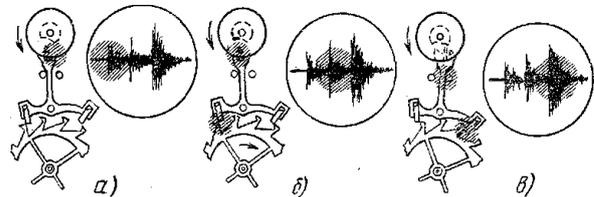

Fig. 2.   Schematics of the oscillator beats

The escapement mechanism serves two main purposes – Regulates the release of energy to the balance wheel and converts the continuous motion of the gear train into discrete impulses. The escapement transfers a small amount of energy to the balance wheel with each oscillation, maintaining its motion against damping losses.

The energy transfer can be quantified as:

$$E = \tau . \theta \qquad (5)$$

where:

E is the energy transferred,

τ is the torque applied by the escapement [22],

θ is the angular displacement of the balance wheel.

D. Damping in the Balance Wheel System

Damping is the process that dissipates energy from the oscillating system, primarily due to friction – at the pivot points of the balance wheel, air resistance – as the wheel moves through the air, internal friction in the hairspring – especially as it flexes during oscillation.

Damping introduces a resistive torque proportional to the angular velocity ω:

$$\tau_d = -b . \omega \qquad (6)$$

where:

τ_d is the damping torque.

b is the damping coefficient

ω is the angular velocity of the balance wheel.

E. Mathematical Model of the Damped Harmonic Oscillator

The balance wheel's motion under damping follows the equation [2]:

$$I \frac{d^2\theta}{dt^2} + b \frac{d\theta}{dt} + k\theta = 0 \qquad (7)$$

where:

I is the moment of inertia of the balance wheel.

k is the spring constant of the hairspring.

The solution of this equation for [11] underdamped systems is:

$$\theta(t) = \theta_0 e^{-\frac{b}{2I}t} \csc(\omega_d t + \emptyset) \qquad (8)$$

where:

θ_0 is the initial amplitude.

The exponential term represents the decay of the oscillation amplitude over time.

$$\omega_d = \sqrt{\frac{k}{I} - \left(\frac{b}{2I}\right)^2}$$ is the damped angular frequency.

F. Quality Factor (Q-Factor) of the Oscillator

The quality factor Q measures the efficiency of the oscillation and is defined by [13]:

$$Q = \frac{2\pi E}{\Delta E} \qquad (9)$$

where:

E is the energy stored per cycle,

ΔE is the energy lost per cycle due to damping.

A high Q factor indicates minimal energy loss and thus a more precise timekeeping device. Good mechanical watches often achieve Q values above 500 [14].

Insufficient energy transfer leads to a decrease in oscillation amplitude, affecting the escapement's performance. Excessive damping causes a loss of oscillatory energy, potentially stopping the balance wheel. Balanced damping ensures that the balance wheel receives just enough energy to counteract losses, maintaining consistent oscillations. The fine-tuning of energy transfer and damping is essential for the watch's consistent and accurate performance over extended periods.

III. RESULTS AND DISCUSSION

A. Factors Affecting Accuracy of Mechanical Watches

Despite careful design and certification, a mechanical watch's accuracy can be influenced by numerous factors. Some are inherent to the mechanism, while others are external influences or related to maintenance. Factors like gravity (position), temperature, magnetism, shocks, and maintenance all play a role in a mechanical watch's accuracy [16]. High-quality watches are engineered and adjusted to minimize these influences – for instance, being adjusted in multiple positions, using anti-magnetic and temperature-compensated materials, and having shock absorbers [8]. Yet even the best mechanical watch is a balance of tiny physical forces, so its rate can never be as unwavering as a quartz oscillator.

Furthermore, the accuracy of a mechanical watch can be influenced by the nonlinearity of the static characteristics of its components. In [3], methods for analyzing and correcting these errors are proposed, along with mathematical models that enable the evaluation and compensation of errors caused by nonlinearity. Together with this, the accuracy of such measurement systems is also affected by instrumental and methodical errors, especially in dynamic measurements. In [19], a method for analyzing these errors and determining their probabilistic characteristics is proposed, which is important for mechanical watch accuracy testing [19].

B. Mechanical watch accuracy measurement devices

Mechanical watch accuracy measurement devices are specialized instruments used to evaluate the performance and accuracy of mechanical watches. These devices analyze key parameters such as rate, amplitude, beat error, and positional variations [6]. Some of the commonly used devices include:

Timegrapher – A timegrapher is a professional instrument that measures the accuracy of mechanical watches by analyzing the sound of the ticking mechanism. It provides key metrics such as *rate* – the deviation in seconds per day (s/d), *amplitude* – the swing range of the balance wheel (typically 270° to 315° is ideal), *beat error* – the difference in time between ticks, indicating if the balance wheel is centered, *lift angle* – specific to the watch's design, affecting amplitude calculations.

Mechanical Watch Timing Machine – These machines measure the watch's performance in various positions (e.g., dial up, dial down, crown up). They simulate the watch's wear and help detect positional accuracy issues.

Vibrograph – A traditional device that measures the watch's vibrations to calculate its accuracy. Though older technology, it is still used in some watchmaking workshops.

Smartphone Apps – Modern smartphone apps, coupled with a microphone adapter, can provide basic accuracy measurements by analyzing the ticking sound of a mechanical watch. Apps like Watch Tuner and Tickoprint offer similar functionalities as professional devices but at a consumer level [9].

These devices cater to diverse needs, ranging from professional watchmakers who require precision instruments to enthusiasts seeking cost-effective methods to assess the accuracy of their timepieces.

C. Methods for increasing the accuracy of mechanical watch

Increasing the accuracy of a mechanical watch involves fine-tuning its components and maintaining optimal operating conditions [21]. Here are some methods for increasing the accuracy of mechanical watches:

Regulating the Balance Wheel – The regulator lever can be moved to change the effective length of the hairspring, which affects the rate of oscillation of the balance wheel. If fine tuning needs to be done, this can be done by lengthening or shortening the balance spring.

Temperature Compensation – Balance wheels and hairsprings are made of materials with low thermal expansion help maintain accuracy despite temperature changes or there is another one older method include using bimetallic balance wheels that adjust their diameter with temperature changes [20].

Shock Resistance and Incorporating shock absorbers are systems like Incabloc or Kif that prevent damage to the delicate pivots of the balance wheel, maintaining accuracy even when subjected to shocks.

Optimizing amplitude – Ensuring the balance wheel swings between 270° and 315° to avoid over-rotation or under-rotation. Regular servicing helps maintain the ideal amplitude by reducing mechanical resistance [24].

Testing in various positions – Mechanical watches are typically adjusted in multiple positions (e.g., dial up, crown down) to minimize positional variance. Watchmakers adjust the watch to minimize deviations across different orientations.

Using High-Precision Components – The escapement controls the release of energy and the ticking rate. Enhancing its precision improves the watch's accuracy.

Regular Maintenance – Over time, oils dry out, and dirt accumulates. Regular service ensures all components function smoothly. Components like the mainspring or the escapement may need replacement to restore accuracy [10].

Environmental Control – Modern watches may include anti-magnetic materials to prevent the balance spring from becoming magnetized. Controlling temperature and humidity is necessary because extreme conditions can affect the metal components, altering the watch's accuracy.

Use of advanced technologies like implementing silicon hairsprings which these are less affected by temperature, magnetism, and wear. Use of advanced technologies like implementing silicon hairsprings which these are less affected by temperature, magnetism, and wear. Other advanced technology is the use of high-beat movements which are increasing the frequency of the balance wheel oscillations e.g., 36000 BPH enhances timekeeping stability.

D. Accuracy Measurement System for Mechanical Watch via LabVIEW

A LabVIEW measurement system was developed to analyze the acoustic signals from the watch operation – fig. 3. This LabVIEW measurement system is designed for the real-time acquisition, filtering, spectral analysis, and visualization of sound signals [4]. The system utilizes a continuous data acquisition method, processes the data through configurable filters, performs spectral analysis, and displays the data in both time and frequency domains [15]. Below is a detailed step-by-step description of how each component functions and interacts within the system.
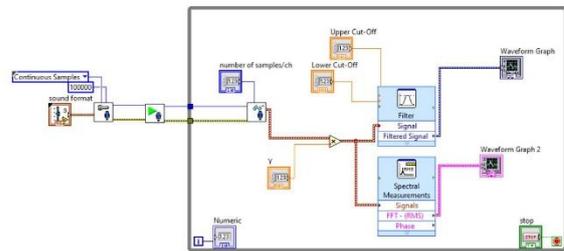

Fig. 3. Block diagram of the measuring system in LabVIEW

The built-in microphone on the laptop was used for the measurement. The system begins by configuring a virtual channel DAQmx for sound input with continuous sampling mode. The sample rate is set to 100,000 samples per channel, ensuring high-resolution data acquisition. Shell sound format is appropriately configured to match the input device specifications [12].

DAQmx Start Task – This VI initializes the acquisition process, enabling the continuous collection of sound data from the input source [17].

DAQmx Read – The DAQmx Read VI captures the waveform data based on the defined sample rate and the number of samples per channel. The captured waveform is output for further processing.

Signal Filtering – Filter VI – Filters are used to remove noise from the signal. The raw signal is processed through a configurable filter (e.g., a bandpass or bandstop filter). The Upper Cut-Off and Lower Cut-Off frequency controls allow the user to define the passband of the filter, removing unwanted frequencies from the signal. The output of the

filter is a Filtered Signal, which is then ready for visualization and analysis.

Time-Domain Visualization – The filtered signal is displayed in real-time on a Waveform Graph, allowing the user to visualize the signal in the time domain. This view is useful for observing how the filtering process affects the raw signal, showing wave shapes and amplitude changes over time.

Spectral Analysis – The filtered signal is also fed into the Spectral Measurements VI for frequency domain analysis. The spectral [18] measurements VI computes the FFT (RMS) (Fast Fourier Transform - Root Mean Square) and Phase of the signal. The FFT provides insight into the frequency components present in the signal, revealing peaks at dominant frequencies and overall spectral distribution. The frequency domain data (FFT) is displayed on a second waveform graph. This graph presents the power spectrum of the signal, showing frequency versus amplitude, which is valuable for identifying specific frequencies present in the sound input. The spectral analysis of the signal in this case has nothing to do with the measurement. It can be used for diagnostics on the work of the mechanical watch.

The addition of the Spectral Measurements VI enhances the system's capability by providing insights into the frequency spectrum of the signal, making it particularly useful for applications in audio analysis, noise reduction, and frequency-specific monitoring. This is necessary to understand the condition of the watch and if you need to service the movement.

This LabVIEW system is a real-time measurement system for sound pulses coming from a mechanical watch, which receives sound data, filters it according to user-defined frequency ranges, and visualizes the processed signal – fig. 4 [23].
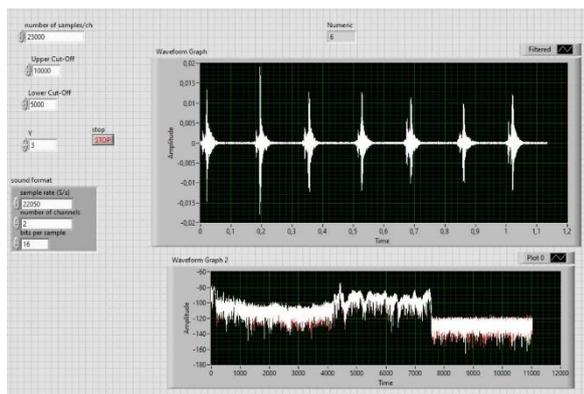

Fig. 4. LabVIEW measurement signal visualization

The data from the measuring system can be transferred to Excel and from there the time between individual pulses can be determined and the clock error calculated for 24 hours [1]. The period on the clock T_i is determined by the impulse in Excel. The absolute error for a time equal to a period is determined by the expression:

$$\Delta T = T_i - T_0 \qquad (10)$$

T_i – measured value for the period,

T_0 – nominal value for the period.

The time for which the clock is ahead or behind in one day is determined by the expression in seconds per 24 hours (s/24h):
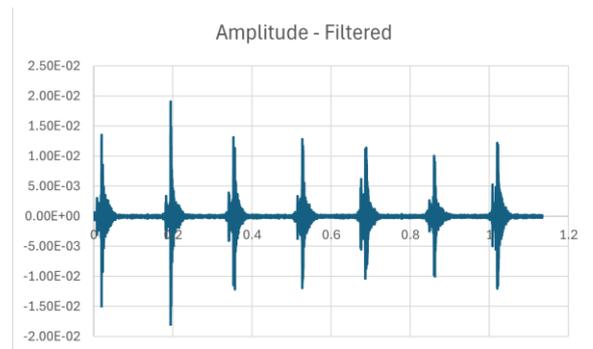
$$\omega = 86400 \frac{\Delta T}{T} \qquad (11)$$

Fig. 5. Measurement signal in Excel

E. Experimental Data and Results

TABLE 1 MEASUREMENT RESULTS

№	Measured error – s/24h		
	Brand watch	Timegr.	LabVIEW
1	Zaria	+23	+24
2	Poljot	+9	+6
3	Molnija	-10	-8
4	Pobeda	+27	+24
5	Seiko 5	+11	+11
6	Orient	+9	+9
7	Citizen	-3	+1
8	Certina	-5	-7
9	Slava	+11	+9
10	Doxa	+3	+3

The measurements were taken with professional Timegrapher No.1000 and the developed LabVIEW system at temperature 20 °C and at the same watch position.

CONCLUSIONS

The developed system for testing and determining the accuracy of mechanical watches provides a reliable and practical solution for watchmakers and researchers. By leveraging acoustic analysis and the LabVIEW platform, the system offers a cost-effective and efficient alternative to traditional measurement devices such as professional timegraphers. The experimental results demonstrate that the system delivers comparable accuracy, with minimal

deviation between measurements. Moreover, the system's adaptability for real-time analysis and its ease of use makes it a valuable tool for ongoing studies of the dynamic characteristics of mechanical watches.

REFERENCES

[1] J. Song, L. Cao, Y. Wang, F. Zhang, Y. Shi, G. Wang, X. Li, and Y. Chen, "A LabVIEW-Based Generalized Experimental Test Platform for Precision Machining Control Algorithms," Processes, vol. 12, p. 2542, 2024, doi: 10.3390/pr12112542.

[2] T. Aihara, C. Kamio, Y. Hara, K. Ito, and K. Jujo, "Dynamic accuracy measurement system for mechanical wristwatch," Precision Engineering, vol. 70, pp. 117–123, 2021, doi: 10.1016/j.precisioneng.2021.01.018.

[3] D. Dichev, F. Kogia, H. Koev, and D. Diakov, "Method of analysis and correction of the error from nonlinearity of the measurement instruments," Journal of Engineering Science and Technology Review, vol. 9, no. 6, pp. 116-121, 2016, doi: 10.25103/jestr.096.17.

[4] S. Su and R. Du, "Signature analysis of mechanical watch movements," Mechanical Systems and Signal Processing, vol. 21, pp. 3189–3200, 2007, doi: 10.1016/j.ymssp.2007.04.006.

[5] B. Zhang, S. Sun, and S. Zhang, "Research on Acoustic Characteristics Measurement by Using LabVIEW," Applied Mechanics and Materials, vols. 644-650, pp. 920-924, 2014, doi: 10.4028/www.scientific.net/AMM.644-650.920.

[6] D. Dichev, H. Koev, T. Bakalova, and P. Louda, "A Gyro-Free System for Measuring the Parameters of Moving Objects," Measurement Science Review, vol. 14, no. 5, pp. 263-269, 2014, doi: 10.2478/msr-2014-0036.

[7] G. Xu, P. Ko, and R. Du, "A study on the precision of mechanical watch movement with Tourbillon," Journal of Sound and Vibration, vol. 330, no. 16, pp. 4019-4028, 2011, doi: 10.1016/j.jsv.2011.03.020.

[8] L. Lazov, E. Teirumnieks, N. Angelov, and E. Teirumnieka, "Proceedings of the 12th International Scientific and Practical Conference," Rezekne, Latvia, vol. III, pp. 134-136, 2019, doi: 10.17770/etr2019vol3.4143.

[9] Measuring Shock and Vibration with Accelerometer Sensors, Dewesoft Test & Measurement. [Online]. Available: https://dewesoft.medium.com/measuring-shock-and-vibration-with-accelerometer-sensors-246b47d8feed [Acceesse: May 24, 2020].

[10] Y.H. Anis, W.L. Cleghorn, and J.K. Mills, "Modal analysis of microgrippers used in assembly of MEMS devices," 2005 International Conference on MEMS, NANO and Smart Systems, Banff, Canada, July, 2005.

[11] D. Dichev, H. Koev, D. Diakov, N. Panchev, R. Miteva, and H. Nikolova, "Automated System for Calibrating Instruments Measuring Parameters of Moving Objects," in Proc. 59th Int. Symp. ELMAR, Zadar, Croatia, 2017, pp. 219-224, doi: 10.23919/ELMAR.2017.8124472.

[12] N. Sato et al., "Novel MEMS Power Generator With Integrated Thermoelectric and Vibrational Devices," in Proc. 13th Int. Conf. Solid-State Sensors, Actuators and Microsystems, Korea, 2005, pp. 295–298.

[13] E. Teirumnieks, L. Lazov, A. Snikeris, and I. Balchev, "Laser marking and engraving of household and industrial plastic products," Journal of Physics: Conference Series, vol. 1859, 2020, doi: 10.1088/1742-6596/1859/1/012016.

[14] N. Robuschi, F. Braghin, A. Corigliano, A. Ghisi, and A. Tasora, "On the dynamics of a high frequency oscillator for mechanical watches," Mechanism and Machine Theory, vol. 117, pp. 276-293, 2017, doi: 10.1016/j.mechmachtheory.2017.07.013.

[15] Y. Fu and R. Du, "A Study on the Dynamics of Swiss Lever Escapement Mechanism," International Symposium on Collaborative Research in Applied Science, Vancouver, Canada, 2005, pp. 8–15.

[16] D. Dichev et al., "A method for correction of dynamic errors when measuring flat surfaces," Sensors, vol. 24, no. 16, 2024, doi: 10.3390/s24165154.

[17] G. Johnson and R. Jennings, LabVIEW Graphical Programming, McGraw-Hill Professional, 2001, ISBN: 0071370013.

[18] R. Bitter, T. Mohiuddin, and M. Nawrocki, LabView, Advanced Programming Techniques, 2nd ed., 2007, eBook ISBN 9781315222097, doi: 10.1201/9780849333255.

[19] L. Lazov, N. Angelov, and E. Teirumnieks, "Influence of pulse duration on the process of laser marking of CT80 carbon tool steel products," Laser Physics, vol. 31, 2021, doi: 10.1088/1555-6611/abe5af.

[20] L. Sigcha et al., "Occupational risk prevention through smartwatches: precision and uncertainty effects of the built-in accelerometer," Sensors, vol. 18, no. 11, p. 3805, 2018.

[21] D. Dichev et al., "Analysis of instrumental errors influence on the accuracy of instruments for measuring parameters of moving objects," in Proc. 31st Int. Sci. Symp. Metrology and Metrology Assurance, Sozopol, Bulgaria, 2021, doi: 10.1109/MMA52675.2021.9610855.

[22] S. Liu, J. Zhang, and Y. Zhang, "A wearable motion capture device able to detect dynamic motion of human limbs," Nat. Commun., vol. 11, p. 5615, 2020, doi: 10.1038/s41467-020-19424-2.

[23] D. Pulov and P. Tsvyatkov, "Optical Systems for Reducing the Divergence of Laser Beams," in Proc. 14th Int. Sci. and Practical Conf. Environment. Technology. Resources., Rezekne, Latvia, 2023, vol. 3, pp. 339–343, doi: 10.17770/etr2023vol3.7217.

[24] G. Aiello, G. La Scalia, M. Vallone, P. Catania, and M. Venticinque, "Real time assessment of hand-arm vibration system based on capacitive MEMS accelerometers," Comput. Electron. Agric., vol. 85, pp. 45–52, 2012.