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DIAGNOSIS OF MECHANICAL FAULTS IN ROBOTICS

Analysis of possible faults and diagnostic methods of the Cartesian industrial robot

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Abstract. The paper discusses problems that occur in robotic arm control. The specific problems arise due to the wear of various types of gears (in the presented case, belt gear and worm gear). It is important to note that such errors need to be diagnosed in time, and the way of their elimination has to be determined, which should be resource-intensive and cost-effective. This article describes the basic types of robotic manipulators (robotic arm, telpher and Cartesian), presenting a review and study of the possibilities of errors in the movement of a robot, adjustment of a mechanical system, and determination of a strategy for solving the emerging problems. A comparison between various types of gear faults is also provided. Different ways of diagnosing faults are discussed, based on the advantages and disadvantages of the methods. The main objective of this study is to provide a complete overview of the mechanical areas where disturbances occur, their diagnosing, and methods of their elimination.

Keywords: electrical drives, mechatronics system control, robotic control, diagnosis.

1. INTRODUCTION

Industrial development and energy crisis are two aspects linked to the development of modern manufacturing. Increasing industrial power leads to the design and construction of more complicated mechanisms and increased consumption of energy resources.

Nowadays, no manufacturing is complete without the implementation of machines and special mechanisms. The use of robots, manipulators, and other autonomous devices ensures greater productivity for enterprises and reduces the risk of defective products. Smooth and accurate movements of robotic manipulators lead to the desired result with minimal loss of material and energy resources [1,2].

However, like any other system, robotic manipulators are subject to wear, namely the parts in which the force is transmitted from the motor that controls the movement of the robot to various mechanical parts using different gears [2,3]. Several types of transmissions are utilized for this purpose, each of which is used under certain conditions, to perform specific tasks. The wear of mechanical assemblies leads to the appearance of nonlinearities in the operation of robotic manipulators, reducing their technical capabilities [4]. As a consequence, there is a violation of the technological process, defective products, and numerous increased resource costs [5].

Diagnostics of the overall performance of industrial robots is the main task for the standard operation of mechanisms. Diagnostics should be carried out for different systems [1,6,7]:

- control system;
- power electronics;
- motors;
- mechanical system.

Diagnosis of the control system and power electronics involves diagnostic sensors used to obtain feedback from a robot and for more effective control mechanisms. This

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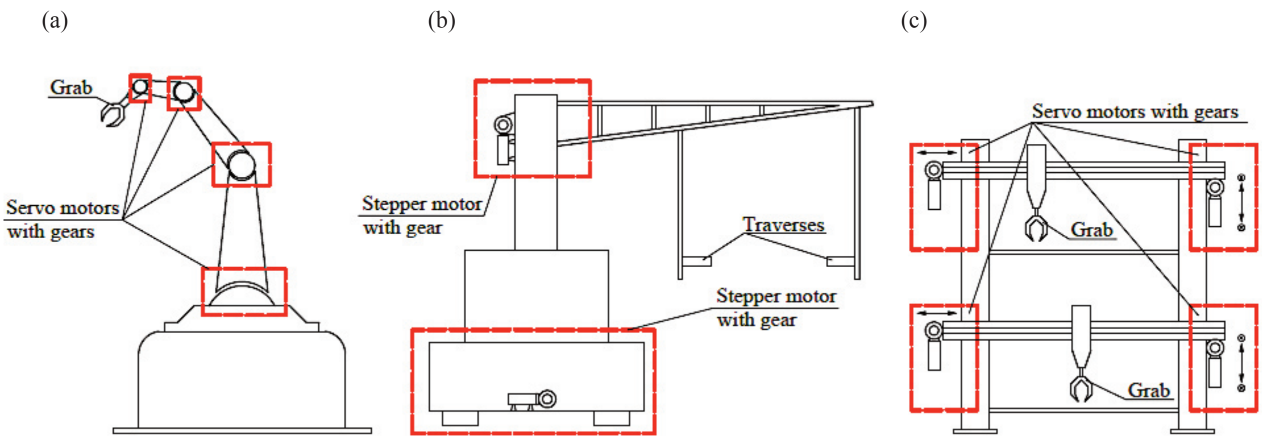

Fig. 1. Sketches of industrial robotic manipulators: (a) robotic arm manipulator, (b) telpher manipulator, (c) Cartesian robotic manipulator. Mechanical gear joints are areas marked by red lines.

type of diagnosis of the control system also includes checking of control algorithms and programs during the operation of an industrial robot [1,6,7].

The main research questions of this article are:
- definition of the character of gear faults;
- overview of diagnostic methods;
- showing the influence of the faults of different mechanical parts on each other.

This review is organized as follows. Section 2 describes industrial robots, motor types used to move parts of a robot, and how to transmit force to other parts of the robot. Section 3 specifies the types of gears that transmit force from the motor to other parts of the mechanisms. For every type of gear, the advantages and disadvantages are given, and problem areas are indicated. A comparison of gears based on common properties is also provided. Section 4 summarizes the types of diagnostic and monitoring methods related to transmission problems. The Hirata Cartesian robot is used as an example for comparing each type of diagnostic method.

Diagnosis of the motor and mechanical components as well as mapping of the most probable damage minimize the risks associated with malfunctioning of mechanisms and prevent serious damage. Moreover, diagnostics of different types of gears allows to understand how to eliminate emerging problems with minimal cost, which is an essential criterion in the context of globally developing production and caring for the environment [1,6,7]. This article is a general overview of gears used for industrial robots and the related faults. The basic types of industrial robots presented in this article, which have the same transmission as the Hirata Cartesian robot, will be the main subject of future research.

2. ROBOTS AND MOTORS

Industrial robots cover an essential segment of industry [1], they are used to perform work that poses a threat to human life and health [8,9]. Any industrial robot consists of mechanical parts to perform specific functions, such as moving weights or the structure of the robot, or grabbing details or parts of another mechanism. Each part is represented by a specific gear, specifically suited for the particular type of operation [1,10].

For a more detailed consideration of transmission types, an example of some of the main robotic manipulators is presented in Fig. 1 [8]. The robotic arm manipulator (Fig. 1a) is designed to move small details during the technological process and assemble other mechanisms. The telpher manipulator (Fig. 1b) is an industrial manipulator designed for operation with special attachments and devices as well as for moving heavy cargo along the technological line. The Cartesian robot (Fig. 1c) is designed for operation in technological processes of assembling and installing, usually applied in electronics manufacturing and conveyor systems [11,12].

As can be seen from the literature, servo drives and stepper motor drives are the most commonly used propulsion devices that satisfy high-performance requirements and allow the robot to move smoothly with precise accuracy. Both motor types have their advantages and disadvantages, and a comparative analysis from the point of view of the dedicated application (robotic manipulator) is presented in Table 1 [13–16].

As seen from the comparison, the servo motor is the best drive element in terms of backlash presence, the range of power used, and wear. However, its control

Table 1. Comparison of servo and stepper motors for a robotic manipulator

Criteria	Servo motor	Stepper motor
Requirements for the motor in terms of power and the type of gearbox	not needed	needed
Accuracy	high accuracy	high accuracy
Backlash/slippage	absent	present
Wear	low degree of wear	medium degree of wear
Immediate detection of failure	present	present
Need for additional sensors	needed for normal operation	needed to simply improve normal operation
Complexity of the control system	complex	not complex
Fixing of the motor shaft	needed	not needed
Cost	high price	low price

system is more complex than that of the stepper motor, and there is no holding torque. Therefore, several transmission types are used for servos, mainly the worm gear and the screw gear [16–19].

The areas marked by red lines in Fig. 1 indicate mechanical gears. The main task is to transmit force from the motor drive shaft to other parts of the robotic manipulator, allowing independent control for its different parts.

As shown in Table 1, each motor type should use additional sensors for higher operation accuracy. The number of faults occurring during the motor's operation is increasing, which means that diagnosis of the robot's operation should be performed on the mechanical and electrical systems. Therefore, diagnosis is further performed on control systems, power electronics, and the mechanical parts.

Faults occurring in the control system and power electronics lead to increased product failure, breaking the correct regime of operation, but do not allow the parts of the robot to be destroyed through protecting the systems.

Damage to the mechanical system causes more negative consequences because minor changes in smaller mechanical parts lead to the nonlinear character of the robot's operation. The situation leads to an increased consumption of energy resources and possible destruction of critical mechanical parts of the robot, which will require renovation and increase the consumption of material resources.

3. FAULTS IN THE TYPES OF GEARS

3.1. Gear train

A gear train is a mechanism that has gears to transmit force directly. It usually consists of two toothed wheels, one of which is called a cogwheel with fewer teeth, the other with more teeth is called a wheel [2,3,20]. A sketch of a gear train is presented in Fig. 2. The problem areas of the gear train (the possibility of jamming and overheating) are highlighted in red.

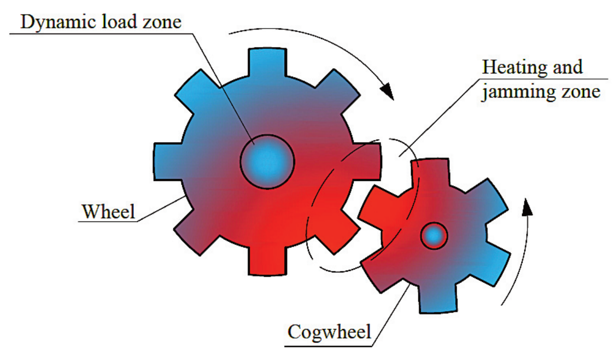

Fig. 2. Faults of the gear train.

The main advantages of the gear train are high efficiency, compactness, and high rotational speed, which allows it to be used at high power [21–23]. On the other hand, the disadvantages of the gear train which reduce the scope of its application are noise, increased dynamic load, frequent need for lubrication to avoid tooth jamming and abrasion, transmission rigidity [21–23]. Gear drives are mainly used for two purposes [24]: force transmission between parallel shafts and conversion of translational motion into rotary motion and vice versa. Therefore, those types of gears are used in cases where translational and rectilinear movement of a load or a high-power motor is used, e.g. moving the structure of a robotic manipulator along a technological line [25].

3.2. Belt gear

The belt gear is a mechanism that consists of at least two pulleys, with a belt stretched between them. The belt gears can be with or without teeth, depending on the load being transferred [2,3,20]. A sketch of the belt gear is presented in Fig. 3. The main failures that potentially affect belt gear performance are slippage and overheating.

The advantages of belt gears are closely linked to their disadvantages, e.g. belt slippage causes transmission

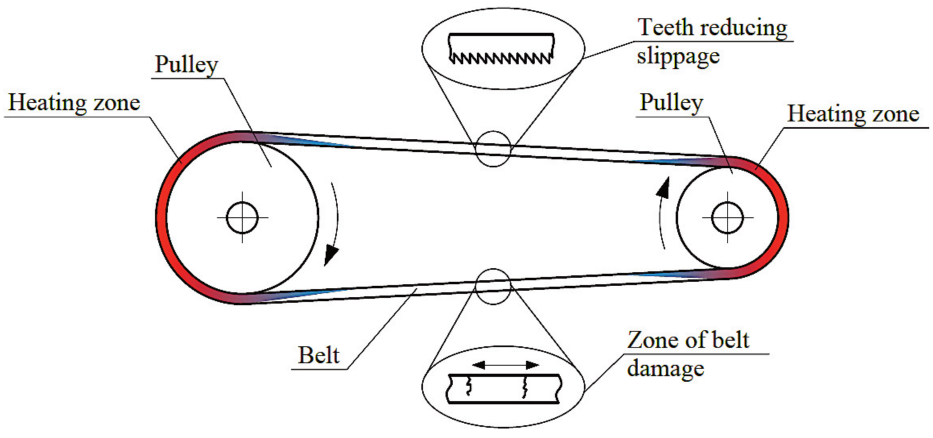

Fig. 3. Faults of the belt gear.

disruption and relieves shaft overload. Belt tension makes the transmission operation quiet and smooth, but it leads to additional heating. Some additional advantages include low cost and minimal damage to the structure in the event of some belt failures [21,26,27]. Usually, the belt gear is used to transmit force from the motor shaft to those parts of the mechanism that are in continuous motion and employed for variable small and medium loads. However, the belt gear is also used to transmit tractive effort over long distances, e.g. conveyor-type machines [28,29].

3.3. Worm gear

A sketch of the worm gear is presented in Fig. 4. Possible failures of the worm gear are jamming, overheating, and increased friction.

The worm gear is a mechanism that has a helical pair with teeth usually located orthogonally to each other. In the worm gear, the teeth of the worm slide over the teeth of the wheel, which leads to certain restrictions on its operation [2,3,20].

The advantages of the worm gear are smooth and quiet operation, compactness, and high kinematic accuracy, as well as the possibility of self-braking due to friction [21,30,31]. The disadvantages of the worm gear are associated with the friction of the teeth against each other, namely heating and low efficiency, the need to use antifriction materials, and jamming of the gear [21,30,31]. The significant performance characteristic of the worm gear is its assembly accuracy, which helps to reduce the chances of some imperfections and increases the service life [20]. Worm gears are used for direct force transmission, similar to the gear train, e.g. in industrial manipulators [32,33].

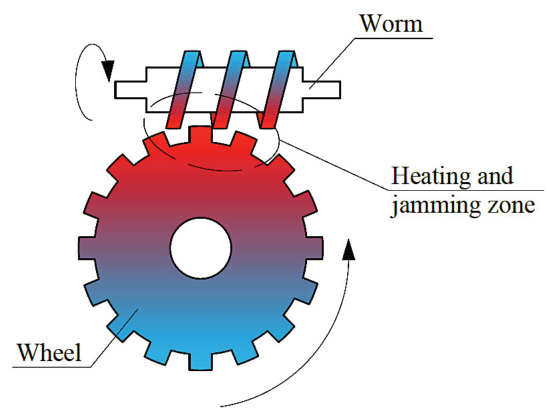

Fig. 4. Faults of the worm gear.

3.4. Chain gear

The chain gear is a mechanism that combines the gear train and the belt gear. Instead of cogwheels and wheels, sprockets are used, and instead of a belt, a chain is used that meshes with the sprockets [2,3,34]. A sketch of the chain gear is presented in Fig 5. The problem areas are related to abrasion and wear.

Since the chain gear is a combination of the gear train and the belt gear, its advantages are similar to those of such types of transmissions, such as high efficiency, the possibility of short-term overloads, the ability to transmit force over long distances, and no tension due to the chain engagement [21,35–37]. The disadvantages are similar to these of the gear train – the need for lubrication, noise, and additional dynamic load. The disadvantage of the chain transmission is the wear and tear of the chain joints [21,35,37]. Consequently, due to its design, the chain gear can be used where using a gear train is not possible

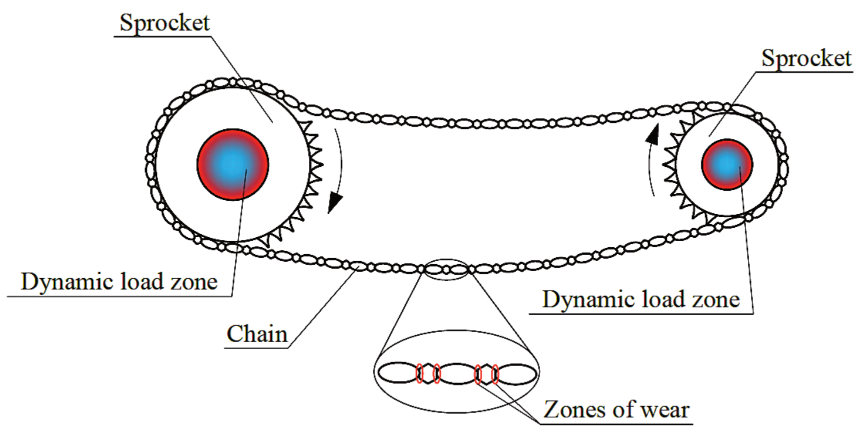

Fig. 5. Faults of the chain gear.

and the belt gear is not suitable for such operation [2,38,39].

3.5. Analysis of a gear type based on the application of the industrial robotic manipulator

Based on the above, each type of force transmission from the motor to other parts of the robot is used for performing specific tasks. It is necessary to consider separately each of the types for each system, and the expediency of using that particular transmission for the assigned task. When developing mechanisms, several criteria can be distinguished by which transmissions can be compared and according to which a suitable transmission can be chosen: compactness, power/area of application, degree of wear, and the possibility of transmitting force over long distances. A comparative analysis based on the authors' evaluation is presented in Fig. 6, where "5" is the highest and "1" the lowest proximity to the criterion.

As illustrated by the comparative diagram (Fig. 6), each of the presented gears has several advantages over the others in specific criteria, which allows one to select the gear best suited for particular operating conditions. However, the degree of wear of each gear is relatively high. This is due to the constant friction of the gear parts against each other, tension, and heating. Therefore, during the operation of the mechanism, errors caused by the degree of gear wear may occur. To prevent more damage to the mechanism, it is necessary to diagnose the parts that are subject to wear over time.

4. BEARING FAULTS

A bearing is a fundamental part of any gear or motor. A bigger part of the dynamic load is directly transferred to the bearing during the operating time of the motor. This means that many faults occur for different reasons, such as overload, friction, current on the shaft of the motor, damage due to improper lubrication, etc. [40]. As seen in Fig. 7, the following types of bearing damage occur most frequently [41]:

- material wear,
- cracks due to the wrong emplacement,
- friction due to insufficient lubrication,
- damage due to shaft current.

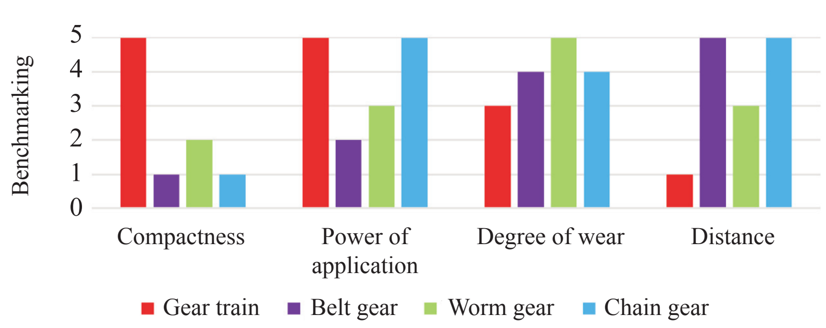

Fig. 6. Comparative analysis of gear types for industrial robotic manipulators.

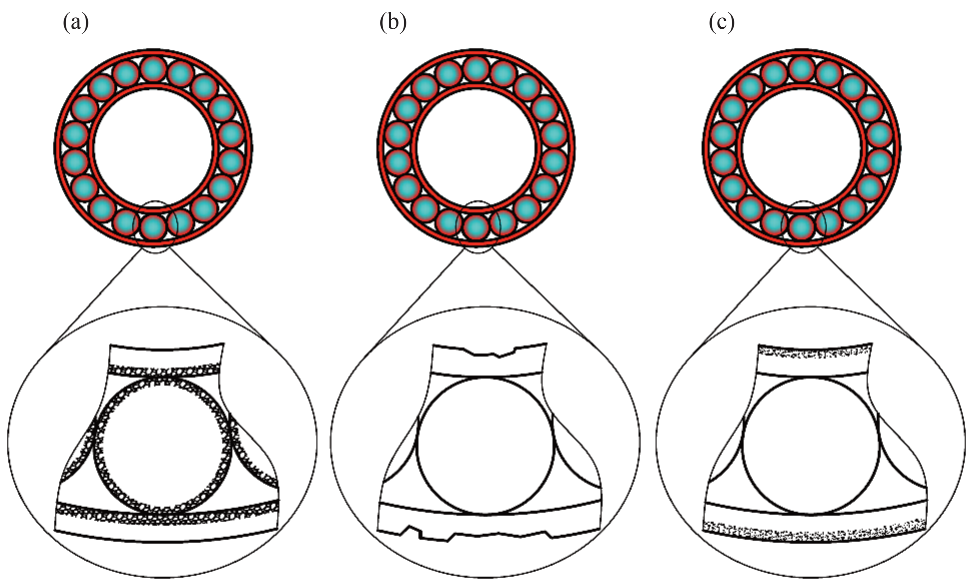

Fig. 7. Damage types of bearings: (a) material wear and friction due to insufficient lubrication, (b) crack due to the wrong emplacement, (c) pitting due to shaft current. The highlighted zones indicate the zones of increased friction.

Wear in the bearing usually occurs due to cyclic operation of the mechanism and when the motor is operating at different high speeds [42]. Overload occurs during the motor's operation in a stressed situation for the bearing, for example, as a result of additional tension or friction damage on the bearing surfaces. This damage causes unwanted vibration and increases the dynamic load on the motor shaft [43].

Wrong emplacement leads to an unequal load on the bearing and, as a result, an additional dynamic load on different areas. In this case, the bearing should be properly installed [44]. Before the installation it is required to check the shaft of the motor and the mounting surface of the bearing. If it is not done, it should be ensured that the bearing is mounted properly as its damage can lead to the destruction of the motor shaft or the different mechanisms connected with the shaft [43].

The latter type of fault can be caused by current in the motor. In this case, frosting or pitting take place on the surface of the bearing. As a result, the motor operation has nonlinear character [43]. No type of damage can be found without special devices, but this minor damage leads to bad faults in the operation of the mechanism. In this case, every damage should be diagnosed and steps should be taken to repair it [45].

5. METHODS OF DIAGNOSIS

It is essential to predict damage before starting work on an industrial robot. The performance, accuracy, and energy efficiency depend on the overall condition of the device. Even a minor deviation from the standard operation of one part of the mechanisms over time can have serious consequences [6,46]. Damage to transmissions is of difficult nature. There are spalls of a cogwheel, over-friction of gear parts, overheating and failure of the wheels, and breakage of the belt or chain, caused by tension or over-wear of the elements [7,40].

Various types of fault prediction and diagnostic methods are used to obtain information about the damage. Several types of diagnostics are used in practice, mainly [40,47]:

- Fast Fourier Transform (FFT),
- Short-Time Fourier Transform (STFT),
- Continuous Wavelet Transform (CWT),
- Advanced Diagnostic Techniques (ADT).

5.1. Fast Fourier Transform

The FFT is used to transform the input signal into different types of spectral analysis. This transformation provides information about the "degree of presence" of this or that frequency in the spectrum of the signal [48]. The FFT is used for stationary signals that do not change their spectral parts during that time. The pros and cons of the FFT analysis are schematically shown in Fig. 8.

The FFT analysis has several advantages. Firstly, it allows to reduce the number of calculations needed for the analysis of the input signal. Secondly, the FFT provides a prediction of the result, obtaining the result of the spectral analysis of the entire time axis. Thirdly, it also has a

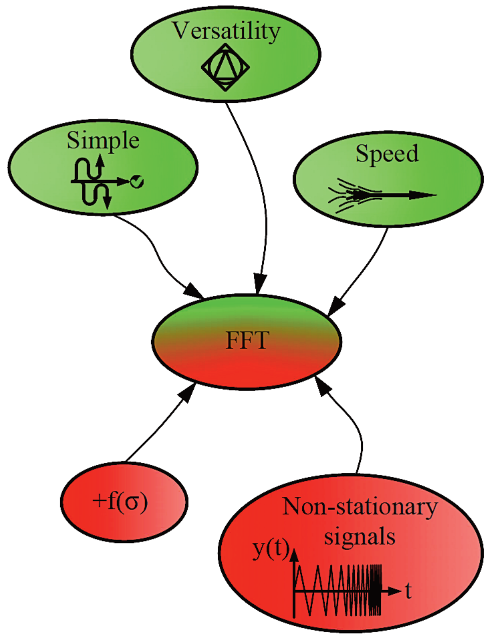

Fig. 8. Advantages and disadvantages of FFT.

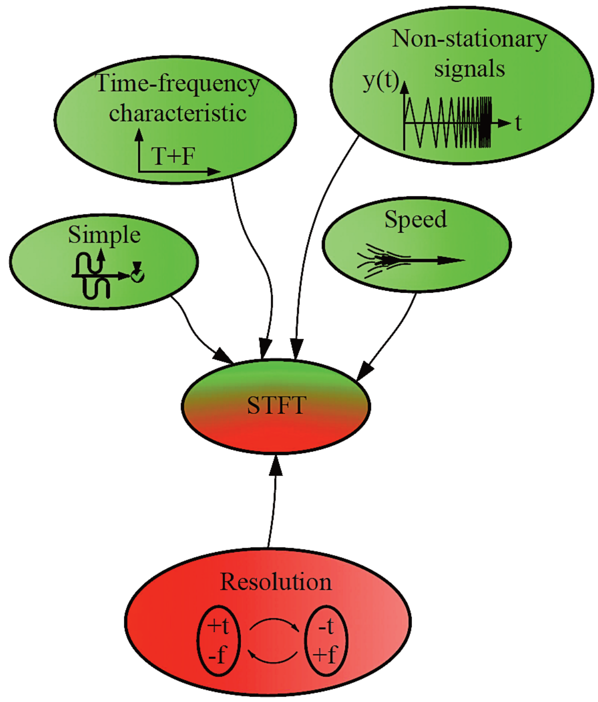

Fig. 9. Advantages and disadvantages of STFT.

simple structure without additional equations for the stationary signal [49,50].

At the same time, the following disadvantages need to be discussed. In the case of the FFT, it is impossible to analyze non-stationary signals as these signals have a complex structure with a different set of frequencies, which allows additional spectra to occur in the spectral analysis of the FFT. Furthermore, it is necessary to use a window weighting function f(σ) for the waveform to compensate for spectral dissipation, reducing the loss of information [51–54].

5.2. Short-Time Fourier Transform

The STFT can be used for non-stationary signals, and in this case the STFT is a function of two variables – time and frequency [55]. Non-stationary signals have a few frequencies for problem analysis, but the STFT takes a small amount of time, providing thus a good basis for the signal analysis. The pros and cons of the STFT analysis are schematically shown in Fig 9.

Unlike the FFT, the frequency-time characteristic is obtained. Unfortunately, the STFT has a significant disadvantage, which is related to the Heisenberg's principle [56,57]. This principle is based on two characteristics (momentum and position) of a point in an area that cannot be found with the same accuracy. If the STFT is used, a signal will disperse along one axis, narrowly localized along the other axis, and vice versa [58]. So, if a wide window is taken to localize a signal, poor resolution in time will be obtained, and in the other case, if a narrow window is taken, the uncertainty in frequency will increase [49,50]. Based on the above, to find a better solution to this problem, other diagnostic methods for damage should be used.

5.3. Continuous Wavelet Transform

The CWT is an alternative to the STFT because the CWT enables to solve problems with poor resolutions in time and frequency [59]. Usually, the CWT is used for signals that have a short-time high frequency and fewer long-term frequency components [60]. The principle of the CWT is similar to the STFT but it has two crucial differences [61–63]:

- CWT does not use the Fourier Transform for weighted signals;
- CWT width changes for each part of the signal, allowing a better spectral analysis.

The main benefits and drawbacks of the Wavelet Transform are shown in Fig. 10.

In practice, many signals have the same structure that allows the use of the CWT for a spectral analysis [64]. It means that by using the CWT, good resolution in time and poor resolution in frequency are obtained for a high-frequency area, and vice versa for an area with lower frequency [49,50]. In this case, the CWT has a few disadvantages such as an increased number of calculations

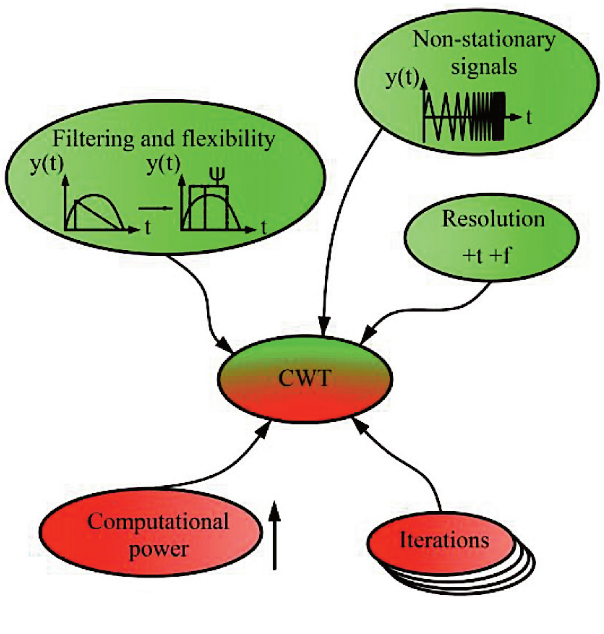

Fig. 10. Advantages and disadvantages of CWT.

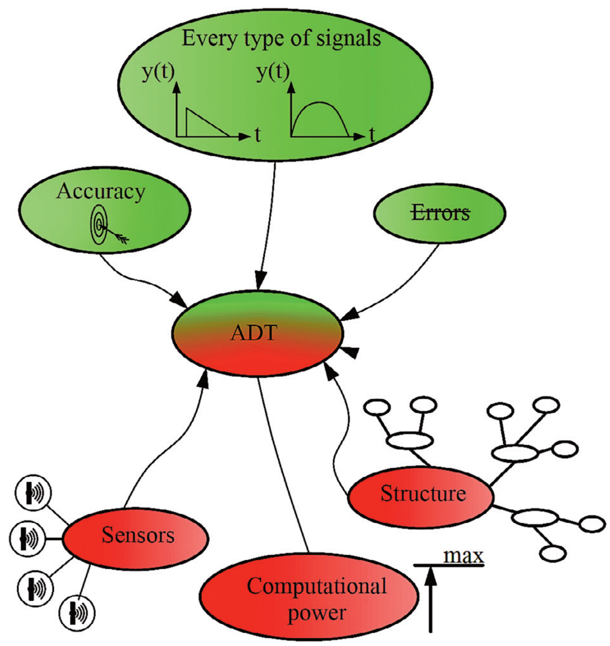

Fig. 11. Advantages and disadvantages of ADT.

for signal diagnosis, and as a consequence, necessary computational power is also increasing. Continuous Wavelet Transform is used in different fields: acoustics, medicine, industrial attachments, etc. Thanks to the CWT, various anomalies in the operation of different mechanisms can be detected [65].

5.4. Advanced Diagnostic Techniques

Advanced Diagnostic Techniques are modern methods that use artificial intelligence for faults diagnostics. These methods can include such algorithms as fuzzy logic (FL), machine learning (ML), and other methods to find slight deviations from the normal condition in mechanical and electrical parts of the robotic manipulator [66–69].

Fuzzy logic is used for the diagnosis of faults in gears or bearings. Fuzzy logic methods allow to adapt each control system to different failures [70–72] and to send a report about minor deviations from the normal operation of a mechanism [73–76]. At the same time, machine learning methods allow us to teach a control system that defines deviations and faults, the malfunctions of which lead to possible damage of the mechanism [77,78]. After a few tests the ML is able to find different types of faults without human control and perform operations for minimizing the consequences [79–81].

The main benefits and drawbacks of the above-mentioned techniques are shown in Fig. 11.

These methods have a complicated structure and many calculations but they have good accuracy and a low probability of errors. Moreover, the advanced techniques can be used for different signals, but additional sensors should be installed [82–86].

6. COMPARISON OF DIAGNOSTIC METHODS BY THE EXAMPLE OF THE HIRATA CARTESIAN ROBOT

Each of the above methods can be applied to different conditions. It depends on the type of output signals, the construction of the robot, the type of operation, etc. To compare the diagnostic methods, the Hirata Cartesian robot is taken as an example. This robot consists of three orthogonal axes that are connected with different gears (belt gear and worm gear highlighted in Fig. 12). The driving force is transmitted by the belt gear, the worm gear, and the gear train to move different parts of the robot. It means that any fault that can occur during the robot's operation leads to different types of disturbances, such as unwanted vibrations, increased friction, wear of the parts of the robot, and other disturbances. One can conclude that different types of signals are emitted in the case of damaged gears or disturbances of operating sensors [87]. The main aspects of the diagnostics of the Hirata Cartesian robot are presented in Table 2.

The comparison of the diagnostic methods is based on the advantages and disadvantages of the presented methods and is recommendatory in nature, based on the opinion of the authors.

(a) (b)

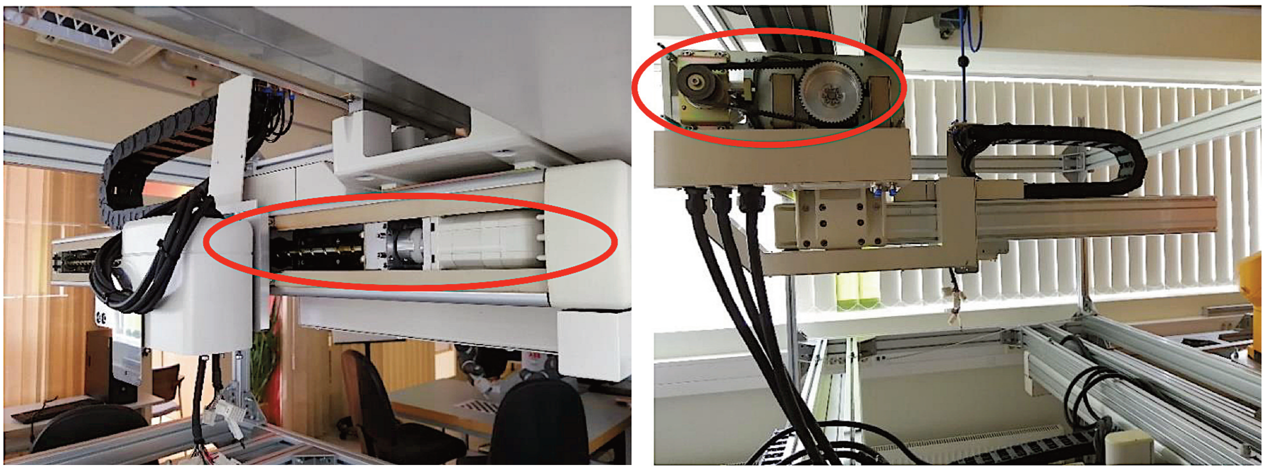

Fig. 12. Hirata Cartesian robot: (a) view with the worm gear, (b) view with the belt gear.

Table 2. Aspects of diagnostics

Aspect	Value
Model of the robot	CRWQ-H2010APHT-11.5-7-2LL-B
Diagnosis of the transmission	Toothed belt transmission
Parameters of the transmission:	
- diameter of the driving pulley;	75 mm
- diameter of the driven pulley;	150 mm
- length of the belt;	500 mm
- distance between centers.	200 mm
Working conditions	Soft, dust-free area, motors without load

Each of the above types of diagnostic methods can be used for finding and describing faults that can occur during the operation of the robot. Nevertheless, the CWT and ADT methods can work and perform the spectral analysis of signals without noise and do not depend on the type of signals. At present, the FFT and the STFT have a simple structure, and these methods do not need additional sensors and computational power.

Taking the above into account, it can be concluded that each type of diagnostic method can mark different types of damage and faults during the robot's operation, depending on the aims that are set. The FFT and STFT methods can be used for fast and straightforward marking when we have stationary signals or signals with a small amount of noise. The CWT and ADT methods can be used for more complicated faults, where we should mark different types of signals without any errors.

When examining Hirata Cartesian robots and which damage and faults can occur during operation, better methods for diagnosing faults in the control system of the robot and in the complex mechanical parts would be the CWT and the ADT. As the structure of the robot includes a few types of gears (belt gear and worm gear) and a few ways to move each part of the robot, which leads to stochastic disturbances, the simple and fast FFT or STFT will not solve the task of diagnosing damage and faults in this case, but could be used for diagnosing simple mechanical faults such as damage to the tooth of the belt or pulleys.

For modeling artificial damage to a mechanical part of the robot, the timing belt gear was chosen as an object. This transmission has second-order aperiodic transfer function:

$$W(s) = \frac{s}{G_2 s^2 + G_1 s + G}, \tag{1}$$

$$G_2 = \frac{r_{n2}^2}{u^2}(\rho A r_{02} \alpha_2 + q_m b), \tag{2}$$

$$G_1 = \frac{r_{n1}}{Pu(1.1 * 10^3 - 3.2 * 10^2 \pi r_{n1})}, \tag{3}$$

$$G = bF_y, \tag{4}$$

where r_{02} is the outer diameter of the driven pulley; r_{nl}, r_{n2} denote the inner radius of the driving and driven

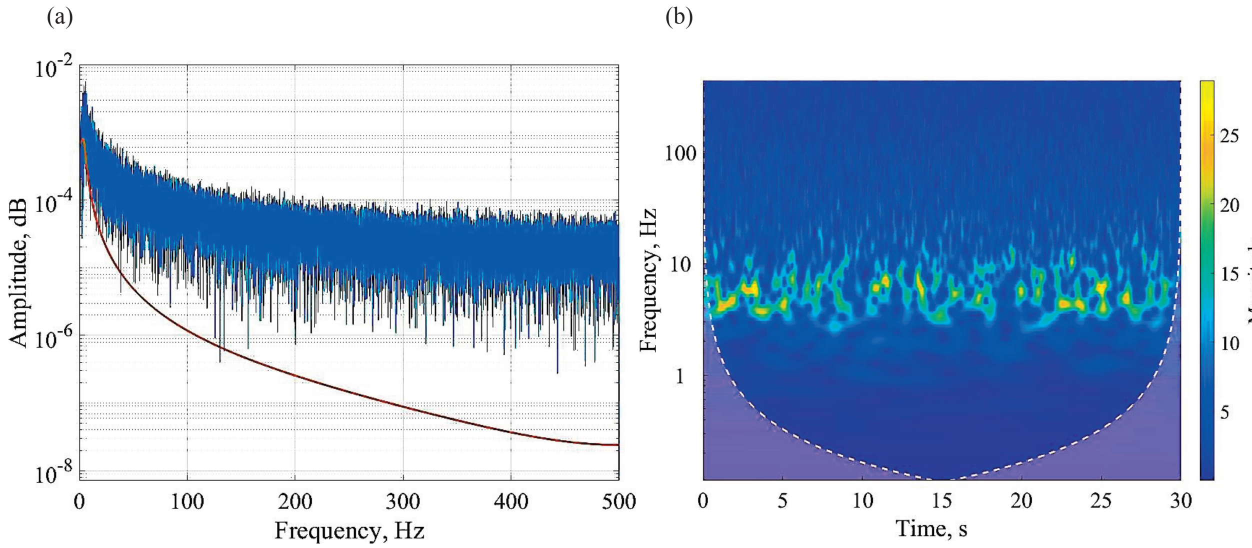

Fig. 13. Spectral analysis of the damaged toothed pulley of the belt gear in the Hirata Cartesian robot: (a) FFT method, (b) CWT method.

pulleys, respectively; ρ is the density of the belt, A represents the section of the belt; F_y denotes the beginning tension of the belt (table value); b is the width of the belt; q_m refers to the mass of 1 meter of the belt with a width of 1 mm (table value); α_2 is the angle of the belt girth at the driven pulley.

This transfer function was transformed into state-space, the response of the timing belt transmission to the pulley damage and the spectral analysis of this damage is shown in Fig. 13a,b.

The first graph is a spectral analysis of the output signal of the toothed belt gear by the FFT method presented in Fig. 13a. The graph shows the normal operation of belt transmission (red line) and the fully noisy output signal which occurred after disturbances (blue line). These disturbances occur during a transient process, for example, in the case of pulley or bearing damage or displacement of center pulleys. Figure 13b shows the diagnosis by the CWT method. The CWT method is a more presentable method than the FFT. In this case, additional information is provided about the faults. Based on these methods, it can be suggested which types of faults could occur in toothed belt transmission. This suggestion is based on the information about the character of faults. Each fault has a specific harmonic with definite frequency.

From a diagnostic point of view, the main problems of the robot and its own transmission are related to non-constant load, shift operation mode, and placement difficulty of additional sensors. In addition, working conditions must be considered. For example, if the robot is working in a dirty room, slippage of the belt may occur. In this case, it is difficult to isolate additional noise presented in the output signal.

CONCLUSIONS

Industrial robots have a complex mechanical structure, the joints of the robot parts, represented by transmissions that transmit force from the motor to other parts of the robot, are subject to various types of damage, such as friction, heating, wear, and others. The main aim of this research is to make an analysis of the transmission faults and diagnostic methods, to provide a comparison of transmission advantages of industrial robots and to suggest different diagnostic methods for improving the efficient operation of the mechanisms. The methods presented in this article for diagnosing the damage and identifying faults allow timely detection of a malfunction in the robot's operation, thereby preventing considerable damage. The article shows the possibility of using different diagnostic methods for the Hirata Cartesian robot, based on the opinion of the authors.

For future work, models of all the gears that are part of the robot will be developed and the necessary experiments will be carried out. The Hirata Cartesian robot has many mechanical parts represented by transmissions, which makes it possible to simulate various damage cases and understand which diagnostic method is the best for each transmission. The research is aimed at diagnostics, selecting the best control mode, and developing a control system that provides the required level of robotic control.

AUTHOR CONTRIBUTIONS

Conceptualization – S. Autsou, A. Rassõlkin; methodology – S. Autsou; validation – A. Rassõlkin, T. Vaimann, K. Kudelina; formal analysis – S. Autsou; investigation – S. Autsou; resources – S. Autsou; data curation – S. Autsou, A. Rassõlkin, K. Kudelina; writing: original draft preparation – S. Autsou; writing: review and editing – A. Rassõlkin, T. Vaimann, K. Kudelina; visualization – S. Autsou; supervision – A. Rassõlkin, T. Vaimann.

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REFERENCES

1. Karabegović, I. *Industrial Robots: Design, Applications and Technology*. Nova Science Publishers, New York, NY, 2020.
2. Vullo, V. *Gears. Volume 1: Geometric and Kinematic Design*. Springer, Cham, 2020.
3. Davis, J. R. (ed.) *Gear Materials, Properties, and Manufacture*. ASM International, Materials Park, OH, 2005.
4. Dudley, D. W. *Handbook of Practical Gear Design*. CRC Press, Lancaster, PA, 1994.
5. Radzevich, S. P. *Dudley's Handbook of Practical Gear Design and Manufacture.* 3rd ed. CRC Press, FL, 2016.
6. Rassõlkin, A., Orosz, T., Demidova, G. L., Rjabtšikov, V., Vaimann, T. and Kallaste, A. Implementation of Digital Twins for electrical energy conversion systems in selected case studies. *Proc. Estonian Acad. Sci.*, 2021, **70**(1), 19–39. https://doi.org/10.3176/proc.2021.1.03
7. Kudelina, K., Asad, B., Vaimann, T., Rassõlkin, A., Kallaste, A. and Lukichev, D. V. Main faults and diagnostic possibilities of BLDC motors. In *Proceedings of the 2020 27th International Workshop on Electric Drives: MPEI Department of Electric Drives 90th Anniversay (IWED), Moscow, Russia, 27–30 January 2020*. IEEE, 1–6. https://doi.org/10.1109/IWED48848.2020.9069553
8. Huat, L. K. (ed.) *Industrial Robotics: Programming, Simulation and Applications*. InTech, 2016.
9. Mortimer, J. and Rooks, B. Industrial robot specifications. In *The International Robot Industry Report*. Springer, Berlin, Heidelberg, 1987, 217–231.
10. Pires, J. N. *Industrial Robots Programming: Building Applications for the Factories of the Future*. Springer, New York, NY, 2007.
11. Colestock, H. *Industrial Robotics: Selection, Design, and Maintenance*. McGraw-Hill, New York, NY, 2005.
12. Miller, R. K. *Industrial Robot Handbook*. Springer, New York, NY, 1989.
13. Voss, W. *A Comprehensible Guide to J1939*. Copperhill Technologies Corporation, Greenfield, MA, 2008.
14. Stuart, S. *DC Motors, Speed Controls, Servo Systems: An Engineering Handbook*. Elsevier, 2013.
15. Acarnley, P. *Stepping Motors: A Guide to Theory and Practice*. IET, 2002.
16. Arduino Self Balancing Robot. www.askix.com (accessed 2021-06-05).
17. Firoozian, R. *Servo Motors and Industrial Control Theory.* Springer, New York, NY, 2009.
18. Tohid, Z. F. B. M. *Automatic control valve using servo motor*. Report. University Malaysia Pahang, Malaysia, June 2013.
19. Mangudi, A. *Design of a Stepper Motor Driver*. 3rd ed. Arizona State University, Tempe, AZ, 2013.
20. Dudás, I. *The Theory and Practice of Worm Gear Drives*. Penton Press, London, 2004.
21. Boner, C. J. Gear and transmission lubricants. *Ind. Lubr. Tribol.*, 1998, **50**(1), 121–131. https://doi.org/10.1108/ilt.1998.01850aad.001
22. Tang, Z., Wang, M., Hu, Y., Mei, Z., Sun, J. and Yan, L. Optimal design of traction gear modification of high-speed EMU based on radial basis function neural network. *IEEE Access*, 2020, **8**, 134619–134629. https://doi.org/10.1109/ACCESS.2020.3007449
23. Xu, X. and Luo, Y. Modeling and analysis of gear shifting process of non-synchronizer AMT based on collision model. *IEEE Access*, 2021, **9**, 13354–13367. https://doi.org/10.1109/ACCESS.2021.3052089
24. Shen, Y., Zhang, X., Jiang, H., Zhou, J., Qiao, S., Wang, C. and Ma, T. Comparative study on dynamic characteristics of two-stage gear system with gear and shaft cracks considering the shaft flexibility. *IEEE Access*, 2020, **8**, 133681–133699. https://doi.org/10.1109/ACCESS.2020.3009398
25. Ozawa, R., Mishima, Y. and Hirano, Y. Design of a transmission with gear trains for underactuated mechanisms. *IEEE Trans. Robot.*, 2016, **32**(6), 1399–1407. https://doi.org/10.1109/TRO.2016.2597319
26. Katsioula, A. G., Karnavas, Y. L. and Boutalis, Y. S. An enhanced simulation model for DC motor belt drive conveyor system control. In *Proceedings of the 2018 7th International Conference on Modern Circuits and Systems Technologies (MOCAST), Thessaloniki, Greece, 7–9 May 2018.* IEEE, 1–4. https://doi.org/10.1109/MOCAST.2018.8376636
27. Ma, K., Wang, X. and Shen, D. Design and experiment of robotic belt grinding system with constant grinding force. In *Proceedings of the 2018 25th International Conference on Mechatronics and Machine Vision Practice (M2VIP), Stuttgart, Germany, 20–22 November 2018*. IEEE, 2019. https://doi.org/10.1109/M2VIP.2018.8600899
28. Zhang, S. Model predictive control of operation efficiency of belt conveyor. In *Proceedings of the 29th Chinese Control Conference CCC'10, Bejing, China, 29–31 July 2010*. IEEE, 1854–1858.
29. Cao, X., Zhang, X., Zhou, Z., Fei, J., Zhang, G. and Jiang, W. Research on the monitoring system of belt conveyor

based on suspension inspection robot. In *Proceedings of the 2018 IEEE International Conference on Real-Time Computing and Robotics (RCAR), Kandima, Maldives, 1–5 August 2018*. IEEE, 2019, 657–661. https://doi.org/10.1109/RCAR.2018.8621649

30. Kozłowski, T., Wodecki, J., Zimroz, R., Błazej, R. and Hardygóra, M. A diagnostics of conveyor belt splices. *Appl. Sci.*, 2020, **10**(18), 6259. https://doi.org/10.3390/APP10186259
31. Shoaib, M., Kim, M. and Cheong, J. Friction modeling of a robot driven by worm gear transmission. In *Proceedings of the 2018 18th International Conference on Control, Automation and Systems (ICCAS)*, *October 2018*, 183–187.
32. Henson, P. and Marais, S. The utilization of duplex worm gears in robot manipulator arms: A design, build and test approach. In *Proceedings of the 2012 5th Robotics and Mechatronics Conference of South Africa (ROBMECH), Johannesburg, South Africa, 26–27 November 2012*. IEEE, 2013. https://doi.org/ 10.1109/ROBOMECH.2012.6558461
33. Tadakuma, R., Tadakuma, K., Takagi, M., Onishi, S., Matsui, G., Ioka, K. et al. The gear mechanism with passive rollers: The input mechanism to drive the omnidirectional gear and worm gearing. In *Proceedings of the 2013 IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, 6–10 May 2013*. IEEE, 1520–1527. https://doi.org/10.1109/ICRA.2013.6630772
34. Ma, B., Li, H., Zahrai, S. and Zhang, H. Virtual prototyping for drive chain optimization in an industrial robot. In *Proceedings of the 2013 IEEE International Conference on Robotics and Automation, Shanghai, China, 9–13 May 2011*. IEEE, 3–6. https://doi.org/10.1109/ICRA.2011.5980595
35. Yukawa, T., Takahashi, T., Satoh, Y. and Ohshima, S. Development of combined-type continuous variable transmission with quadric crank chains and one-way clutches. In *Proceedings of SICE Annual Conference, 2012*, 2151–2156.
36. Liu, W. and Gao, Y. Compensation of variable pitch roller chains for the polygon effect. In *Proceedings of the 2011 International Conference on Electronic & Mechanical Engineering and Information Technology (EMEIT), Harbin, China, 12–14 August 2011*. IEEE, 2900–2903. https://doi.org/10.1109/EMEIT.2011.6023654
37. Ingvast, J., Wikander, J. and Ridderström, C. The PVT, an elastic conservative transmission. *Int. J. Robot. Res.*, 2006, **25**(10), 1013–1032. https://doi.org/10.1177/0278364906069188
38. Prakash, S. and Hofman, T. Clamping strategies for belt-type continuously variable transmissions: an overview. In *Proceedings of the 2017 IEEE Vehicle Power and Propulsion Conference (VPPC), Belfort, France, 11–14 December 2017*. IEEE, 2018, 1–6. https://doi.org/10.1109/VPPC.2017.8330938
39. Litvin, F. L. *Development of Gear Technology and Theory of Gearing*. National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH, 1997.
40. Kudelina, K., Asad, B., Vaimann, T., Belahcen, A., Rassõlkin, A., Kallaste, A. and Lukichev, D. V. Bearing fault analysis of BLDC motor for electric scooter application. *Designs*, 2020, **4**(4), 42. https://doi.org/10.3390/designs4040042
41. Toma, R. N., Kim, C. and Kim, J.-M. Bearing fault classification using ensemble empirical mode decomposition and convolutional neural network. *Electronics*, 2021, **10**(11), 1248. https://doi.org/10.3390/electronics10111248
42. Cao, L., Shen, Y., Shan, T., Xia, Y., Wang, J. and Lin, Z. Bearing fault diagnosis method based on GMM and Coupled Hidden Markov model. In *Proceedings of the 2018 Prognostics and System Health Management Conference (PHM), Chongqing, China, 26–28 October 2018*. IEEE, 2019, 932–936. https://doi.org/10.1109/PHM-Chongqing.2018.00166
43. Dasgupta, A. and Pecht, M. Material failure mechanisms and damage models. *IEEE Trans. Reliab.*, 1991, **40**(5), 531–536. https://doi.org/ 10.1109/24.106769
44. Shijie, S., Kai, W., Xuliang, Q., Dan, Z., Xueqing, D. and Jiale, S. Investigation on bearing weak fault diagnosis under colored noise. In *Proceedings of the 32nd Chinese Control and Decision Conference (CCDC), Hefei, China, 22–24 August 2020*. IEEE, 5097–5101. https://doi.org/10.1109/CCDC49329.2020.9164548
45. Das, A. and Ray, S. A review on diagnostic techniques of bearing fault and its modeling in induction motor. In *Proceedings of the 2020 IEEE Calcutta Conference (CALCON), Kolkata, India, 28–29 February 2020*. IEEE, 502–505. https://doi.org/10.1109/CALCON49167.2020.9106511
46. Chatterton, S., Pennacchi, P. and Vania, A. Electrical pitting of tilting-pad thrust bearings: Modelling and experimental evidence. *Tribol. Int.*, 2016, **103**, 475–486. https://doi.org/10.1016/j.triboint.2016.08.003
47. Jnifene, A. and Andrews, W. Experimental study on active vibration control of a single-link flexible manipulator using tools of fuzzy logic and neural networks. *IEEE Trans. Instrum. Meas.*, 2005, **54**(3), 1200–1208. https://doi.org/10.1109/TIM.2005.847136
48. Murtadho, M., Prasetyono, E. and Anggriawan, D. O. Detection of parallel arc fault on photovoltaic system based on fast Fourier Transform. In *Proceedings of the 2020 International Electronics Symposium, Surabaya, Indonesia, 29–30 September 2020*, 21–25. https://doi.org/10.1109/IES50839.2020.9231780
49. Bishop, T. *Dealing with shaft and bearing currents.* Kentucky Service Co., Lexington, KY, 2017.
50. Tygert, M. Fast algorithms for spherical harmonic expansions, III. *J. Comput. Phys.*, 2010, **229**(18), 6181–6192. https://doi.org/10.1016/j.jcp.2010.05.004
51. Syafiri, M. H. R. A., Prasetyono, E., Khafidli, M. K., Anggriawan, D. O. and Tjahjono, A. Real time series DC arc fault detection based on Fast Fourier Transform. In *Proceedings of the 2018 International Electronics Symposium on Engineering Technology and Applications (IES-ETA), Bali, Indonesia, 29–30 October 2018*. IEEE, 2019, 25–30. https://doi.org/10.1109/ELECSYM.2018.8615525
52. Dehina, W., Boumehraz, M. and Kratz, F. Diagnosis of rotor and stator faults by Fast Fourier Transform and discrete wavelet in induction machine. In *Proceedings of the 2018 3rd International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, 28–31 October 2018*. IEEE, 2019, 6–11. https://doi.org/10.1109/CISTEM.2018.8613311
53. Fitrianto, M. I., Wahjono, E. D., Anggriawan, O., Prasetyono, E., Mubarok, R. H. and Tjahjono, A. Identification and protection of series DC arc fault for photovoltaic systems based on Fast Fourier transform. In *Proceedings of the 2019 International Electronics*

Symposium, Surabaya, Indonesia, 27–28 September 2019. IEEE, 159–163. https://doi.org/0.1109/ELECSYM.2019.8901605

54. Balamurugan, R., Al-Janahi, F., Bouhali, O., Shukri, S., Abdulmawjood, K. and Balog, R. S. Fourier Transform and Short-Time Fourier Transform decomposition for photovoltaic arc fault detection. In *Proceedings of the 2020 47th IEEE Photovoltaic Specialists Conference, Calgary, Canada, 15 June – 21 August 2020*. IEEE, 2021, 2737–2742. https://doi.org/10.1109/PVSC45281.2020.9300455
55. Burriel-Valencia, J., Puche-Panadero, R., Martinez-Roman, J., Sapena-Bano, A. and Pineda-Sanchez, M. Short-frequency Fourier Transform for fault diagnosis of induction machines working in transient regime. *IEEE Trans. Instrum. Meas.*, 2017, **66**(3), 432–440. https://doi.org/10.1109/TIM.2016.2647458
56. Bajpeyee, B. and Sharma, S. N. Detection of bearing faults in induction motors using short time approximate discrete Zolotarev transform. In *Proceedings of the International Conference on Signal Processing (ICSP 2016), Vidisha, India, 7–9 November 2016*. https://doi.org/10.1049/cp.2016.1467
57. Vippala, S. R., Bhat, S. and Reddy, A. A. Condition monitoring of BLDC motor using Short Time Fourier Transform. In *Proceedings of the 2021 IEEE 2nd International Conference on Control, Measurement and Instrumentation (CMI), Kolkata, India, 8–10 January 2021*. IEEE, 110–115. https://doi.org/10.1109/CMI50323.2021.9362938
58. Yu, L. Bearing fault diagnosis using time-frequency synchrosqueezing transform. In *Proceedings of the 2020 Chinese Automation Congress (CAC), Shanghai, China, 6–8 November 2020*. IEEE, 2021, 4260–4264.
59. Bentrah, W., Bessous, N., Sbaa, S., Pusca, R. and Romary, R. A comparative study between the adaptive wavelet transform and DWT methods applied to a outer raceway fault detection in induction motors based on the frequencies analysis. In *Proceedings of the 2020 International Conference on Electrical Engineering (ICEE), Istanbul, Turkey, 25–27 September 2020*. IEEE, 1–7. https://doi.org/10.1109/ICEE49691.2020.9249925
60. Merainani, B., Bouzid, A. A., Ratni, A. and Benazzouz, D. Detection of bearing fault using empirical wavelet transform and S transform methods. In *Proceedings of the 2020 1st International Conference on Communications, Control Systems and Signal Processing, El Oued, Algeria, 16–17 May 2020*. IEEE, 446–453. https://doi.org/10.1109/CCSSP49278.2020.9151834
61. Wang, X. and Zhang, R. A sensor fault diagnosis method research based on wavelet transform and Hilbert–Huang transform. In *Proceedings of the 2013 5th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), Hong Kong, China, 16–17 January 2013*. IEEE, 81–84. https://doi.org/10.1109/ICMTMA.2013.32
62. Patwary, R., Chatterjee, H. S., Roy, D. and Choudhury, A. B. Fault diagnosis of a passive magnetic fault current limiter using reverse biorthogonal wavelet transform. In *Proceedings of the 2017 IEEE Calcutta Conference (CALCON), Kolkata, India, 2–3 December 2017*. IEEE, 2018, 407–411. https://doi.org/10.1109/CALCON.2017.8280765
63. Zaman, S. M. K., Marma, H. U. M. and Liang, X. Broken rotor bar fault diagnosis for induction motors using power spectral density and complex continuous wavelet transform methods. In *Proceedings of the 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), Edmonton, Canada, 5–8 May 2019*. IEEE, 1–4. https://doi.org/10.1109/CCECE.2019.8861517
64. Chen, Q., Nicholson, G., Ye, J. and Roberts, C. Fault diagnosis using Discrete Wavelet Transform (DWT) and Artificial Neural Network (ANN) for a railway switch. In *Proceedings of the 2020 Prognostics and Health Management Conference (PHM-Besancon), Besancon, France, 4–7 May 2020*. IEEE, 67–71. https://doi.org/10.1109/PHM-Besancon49106.2020.00018
65. Park, B., Kim, D. and Kim, G. Using wavelet transform. *IEEE Trans. Plasma Sci.*, 2004, **32**(2), 355–361.
66. Wang, H., Kang, Y., Yao, L., Wang, H. and Gao, Z. Fault diagnosis and fault tolerant control for T-S fuzzy stochastic distribution systems subject to sensor and actuator faults. *IEEE Trans. Fuzzy Syst.*, 2021, **29**(11), 3561–3569. https://doi.org/10.1109/tfuzz.2020.3024659
67. Bhatnagar, M. and Yadav, A. Fault detection and classification in transmission line using fuzzy inference system. In *Proceedings of the 2020 5th IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE), Jaipur, India, 1–3 December 2020*. IEEE, 2021, 1–6. https://doi.org/10.1109/ICRAIE51050.2020.9358386
68. Yang, S., Sun, X. and Chen, D. Bearing fault diagnosis of two-dimensional improved Att-CNN2D neural network based on Attention mechanism. In *Proceedings of the 2020 IEEE International Conference on Artificial Intelligence and Information Systems (ICAIIS), Dalian, China, 20–22 March 2020*. IEEE, 81–85. https://doi.org/10.1109/ICAIIS49377.2020.9194871
69. Feng, J., Xian, R. and Xie, Y. Fault diagnosis of rotating machinery based on deep learning. In *Proceedings of the 2020 International Conference on Aviation Safety and Information Technology, Weihai City, China, 14–16 October 2020*. Association for Computing Machinery, 388–392. https://doi.org/10.1145/3434581.3434730
70. Djalab, A., Nekbil, N., Laouid, A. A., Kouzou, A. and Kadiri, K. An intelligent technique to diagnosis and detection the partial shading based on fuzyy logic for PV system. In *Proceedings of the 2020 17th International Multi-Conference on Systems, Signals & Devices (SSD), Monastir, Tunisia, 20–23 July 2020*. IEEE, 2021, 235–238. https://doi.org/10.1109/SSD49366.2020.9364109
71. Wang, X., Guo, F. and Xu, W. DGA fuzzy logic diagnostic method based on subordinating function. In *Proceedings of the 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC), Chongqing, China, 12–14 June 2020*. IEEE, 1381–1384. https://doi.org/10.1109/ITOEC49072.2020.9141578
72. Lukichev, D. V., Demidova, G. L. and Brock, S. Fuzzy adaptive PID control for two-mass servo-drive system with elasticity and friction. In *Proceedings of the 2015 IEEE 2nd International Conference on Cybernetics (CYBCONF), Gdynia, Poland, 24–26 June 2015*. IEEE, 443–448. https://doi.org/10.1109/CYBConf.2015.7175975
73. Zheng, Z., Shao, X. and Yu, D. Fault diagnosis of a wheel loader by artificial neural networks and fuzzy logic. In *Proceedings of the 2006 IEEE Conference on Robotics*

Automation and Mechatronics, *Bangkok, Thailand, 1–3 June 2006*. IEEE, 1–5. https://doi.org/10.1109/RAMECH.2006.252704

74. Yu, Y. and Yang, J. The development of fault diagnosis system for diesel engine based on fuzzy logic. In *Proceedings of the 2011 8th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), Shanghai, China, 26–28 July 2011*. IEEE, 472–475. https://doi.org/10.1109/FSKD.2011.6019556
75. Xie, L., Zhou, L., Tong, X.-J. and Chen, M.-Y. Fault diagnosis of power transformer insulation based on fuzzy normal partition and logic reasoning. In *Proceedings of the 2007 International Conference on Machine Learning and Cybernetics (ICMLC), Hong Kong, 19–22 August 2007*. IEEE, 1081–1085. https://doi.org/10.1109/ICMLC.2007.4370304
76. Lukichev, D. V., Demidova, G. L. and Brock, S. Comparison of adaptive fuzzy PID and ANFIS controllers for precision positioning of complex object with nonlinear disturbance – study and experiment. In *Proceedings of the 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, Latvia, 17–21 September* 2018. IEEE, P.1–P.9.
77. Tayebihaghighi, S. and Koo, I. Fault diagnosis of rotating machine using an indirect observer and machine learning. In *Proceedings of the 2020 International Conference on Information amd Communication Technology (ICTC), Jeju, South Korea, 21–23 October 2020*. IEEE, 277–282. https://doi.org/10.1109/ICTC49870.2020.9289590
78. Lim, H., Kim, T. H., Kim, S. and Kang, S. Diagnosis of scan chain faults based-on machine-learning. In *Proceedings of the 2020 International SoC Design Conference (ISOCC), Yeosu, South Korea, 21–24 October 2020*. IEEE, 2021, 57–58. https://doi.org/10.1109/ISOCC50952.2020.9333074
79. Gu, J., Luo, Z., Wang, J. and Shen, Y. Research on bearing cross-domain fault diagnosis based on invariant subspace learning with tensor alignment. In *Proceedings of the 2020 11th International Conference on Prognostics and System Health Management (PHM-2020 Jinan), Jinan, China, 23–25 October 2020*. IEEE, 461–465. https://doi.org/10.1109/PHM-Jinan48558.2020.00089
80. Zhang, C., Xu, L., Li, X. and Wang, H. A method of fault diagnosis for rotary equipment based on deep learning. In *Proceedings of the 2018 Prognostics and System Health Management Conference (PHM-Chongqing), Chongqing, China, 26–28 October 2018*. IEEE, 2019, 958–962. https://doi.org/10.1109/PHM-Chongqing.2018.00171
81. Shi, W.-W., Yan, H.-S. and Ma, K.-P. A new method of early fault diagnosis based on machine learning. In *Proceedings of the 2005 International Conference on Machine Learning and Cybernetics (ICMLC), Guangzhou, China, 18–21 August 2005*. IEEE, 3271–3276. https://doi.org/10.1109/icmlc.2005.1527507
82. Su, C. Q. A new fuzzy logic method for transformer incipient fault diagnosis. In *Proceedings of the 2016 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), Vancouver, Canada, 24–29 July 2016*. IEEE, 324–327. https://doi.org/10.1109/FUZZ-IEEE.2016.7737704
83. Leahy, K., Hu, R. L., Konstantakopoulos, I. C., Spanos, C. J. and Agogino, A. M. Diagnosing wind turbine faults using machine learning techniques applied to operational data. In *Proceedings of the 2016 IEEE International Conference on Prognostics and Health Management (ICPHM), Ottawa, Canada, 20–22 June 2016*. IEEE, 1–8. https://doi.org/10.1109/ICPHM.2016.7542860
84. Bangalore, P. and Tjernberg, L. B. An artificial neural network approach for early fault detection of gearbox bearings. *IEEE Trans. Smart Grid*, 2015, **6**(2), 980–987. https://doi.org/10.1109/TSG.2014.2386305
85. Kudelina, K., Vaimann, T., Asad, B., Rassõlkin, A., Kallaste, A. and Demidova, G. Trends and challenges in intelligent condition monitoring of electrical machines using machine learning. *Appl. Sci.*, 2021, **11**(6), 2761. https://doi.org/10.3390/app11062761
86. Wang, X., Li, L., He, K. and Liu, C. Dual-loop self-learning fuzzy control for AMT gear engagement: design and experiment. *IEEE Trans. Fuzzy Syst.*, 2018, **26**(4), 1813–1822. https://doi.org/10.1109/TFUZZ.2017.2779102
87. Timings, R. L. *Newnes Mechanical Engineer's Pocket Book*. Elsevier, 2005.

Tööstuslike kartesiaanrobotite võimalike rikete ja tuvastusmeetodite analüüs

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Käesolev artikkel kirjeldab probleeme, mis kerkivad esile seoses roboti manipulaatori juhtimisega. Nimetatud mured tekivad eri tüüpi ülekannete kulumisest (esitletud juhtudel rihm- ja tiguülekanne), nagu ka artiklis on kirjeldatud. Oluline on märkida, et sellised kõrvalekalded normaaltalitluselt on tähtis aegsasti tuvastada ning leida ka sobivad võimalused nende kõrvaldamiseks, arvestades ressursi- ja kulutõhusust. Artikkel kirjeldab eri tüüpi roboteid (manipulaator, telfer, kartesiaanrobot), millele tuginedes antakse ülevaade võimalikest esinevatest riketest, mehhaanilise süsteemi kohandamisest ning tulenevalt sellest ka probleemide lahendamise strateegiatest. Lisaks esitatakse eri tüüpi ülekannete rikete omavaheline võrdlus ning kirjeldatakse rikete tuvastamise meetodeid tuginedes nende eelistele ja puudustele. Uurimuse peamine eesmärk on esitada täielik ülevaade mehhaanika valdkondadest, kus nimetatud kõrvalekalded robotite puhul esinevad, ja näidata võimalikke rikketuvastuse meetodeid ning võimalusi rikete kõrvaldamiseks.