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Cyber-physical predictive diagnostics system for servos of mobile construction robots

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Abstract. The article is devoted to solving the urgent scientific and technical problem of increasing the operational reliability of mobile construction robots. The cyber-physical system for predictive diagnostics of their servo drives is proposed. A five-level structure of a cyber-physical predictive diagnostics system is proposed. A description of each level is provided. An effective set of diagnostic parameters for predictive diagnostics of servo drives has been selected. A method is proposed to distinguish a faulty state from a load change based on wavelet transform and neural networks. A method for predicting the technical state of construction robots and electric motors based on neural networks has been developed. A fuzzy decision-making model based on the results of predictive diagnostics to optimize the trajectory of a mobile construction robot is described in detail. This allows to significantly extend the operational life of the mobile construction robot to eliminate sudden malfunctions and downtime of the construction site.

Keywords: Cyber-physical system, construction robots, servos, predictive diagnosis, neural networks classification, fuzzy decision-making model.

1. Introduction

The increasing requirements for reliability and efficiency of construction robots entails the need for constant monitoring of the technical condition of all final controlling drives with further optimization it's operating mode and equipment as a whole. This problem can be solved using a technical condition monitoring system incorporate into the robot's end-effectors.

Servos are the main executive elements of mobile construction robots. Many methods have been developed for the servos technical condition predictive diagnosis [1-5]; however, they require complex measuring equipment installed on the motor housings. It can have a significant impact on the mobile robot operation. Also, the existing diagnostic methods do not allow performing a joint analysis of the servos technical condition and optimizing robots operating mode taking into account its states. To solve this problem, it is necessary to develop a system for continuously measure parameters with the special sensors, analyze obtained information and determinate current and prediction technical condition and defects, optimizing the parameters of the construction robot operation mode

The goal of the research is improving the construction robots reliability assumes o the computer resources into physical process integration, i.e. application of cyber-physical systems [6]. In such systems, sensors, final controlling drives and information systems are interacting with each other using standard Internet protocols in order to predict and adapt to changes in operating conditions and the equipment technical condition. The cyber-physical prediction diagnosis system structure include five levels (Figure 1) [2].



At the first level, sensors are selected and installed to the construction robots servos.

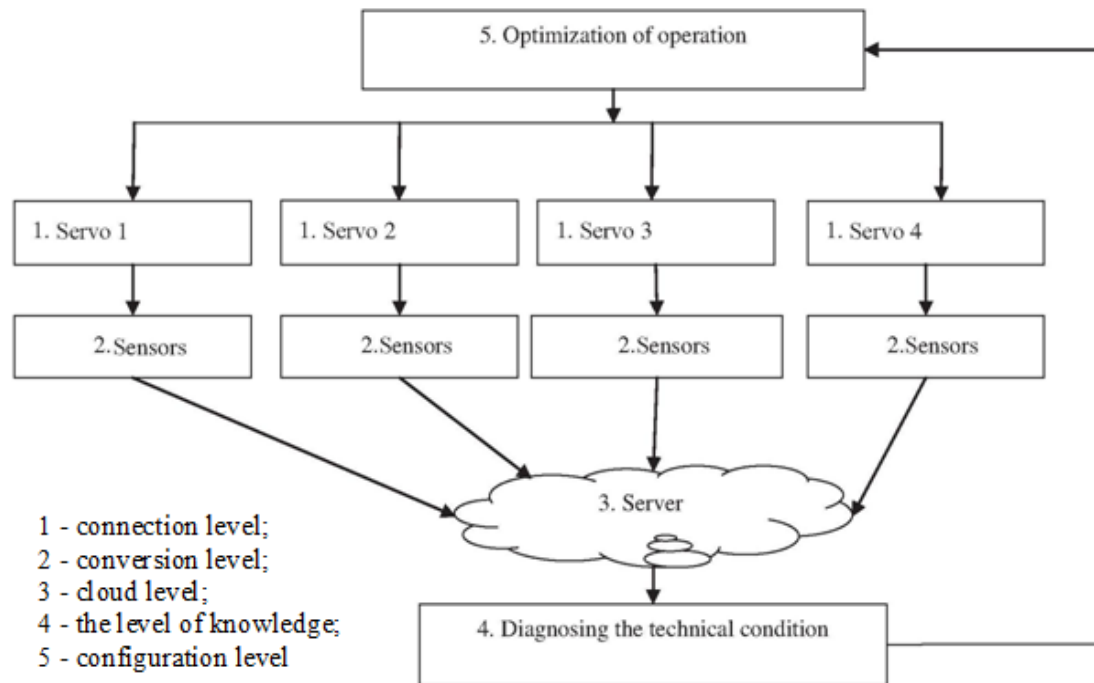


Figure 1. The structure of the cyber-physical predictive diagnostic control system of a construction mobile robot.

The second level allow to choice methods for measurement and analyze of the diagnosis parameters that will be used to servos malfunctions.

All models and current diagnosis information will be storage in cloud servers (level three). It will be necessary for communication between construction mobile robot servos for the technological process starts taking into account the state of a separate actuating element optimization.

At the fourth level, predictive technical condition diagnostic of each service servos is performed.

The fifth level provides for the construction mobile robot operating mode optimization, taking into account the technical condition of all its servos.

During a cyber-physical diagnostic system development, the methods used for the technical condition predictive diagnosis, as well as the method for the optima decision - making on the choice for the construction mobile robot operating mode are of particular importance.

The application of the cyber-physical approach is to develop a diagnostic platform. The forecasting systems will significantly improve the reliability of the constructions robots. Information links between the robots at the constructions site through the Internet protocol will allow optimizing the entire constructions process, depending on the technical condition of the executive equipment each drive. This will maximize performance and minimize the likelihood of failure.

2. Method of research

The main component powering up the end-effectors of the robots is the servos which operate in a short-time mode and must have a high overload capacity and dust and waterproof design criteria known as IP standard. The available statistics [3, 4] shows that all engine failures of the aforementioned types are of mechanical or electrical origin.

The most promising approach for servos technical condition determination methods is multivariable diagnostics combine thermal, electrical and mechanical defects monitoring of operating voltage [5].

This methods allow to determine the technical state, but at the present time, the analysis of diagnostic information is currently done manually by troubleshooting experts, which is absolutely not cost effective.

Hence, it is necessary to choose a list of diagnostic parameters that allow determining all possible classes of defects, having accepted sensitivity features over the changes in the values of structural parameters, minimum composition, accessibility for monitoring, measurement and software analysis without operator's involvement, cost and time effectiveness and sufficient degree of segregation when recognizing individual defects.

Constructions robots operate in complex non-deterministic conditions with high alternating loads in conditions of high humidity and dust; their drives are often installed on a mobile base. To identify their technical condition it is necessary to develop methods and tools which minimum numbers of measured parameters without complex, bulky measuring tools on the servo housing with the ability to automatically analyze the measurement results [5].

The most common diagnostic parameters for servos are a partial discharge, supply and capacitive current, vibration and temperature [6]. A comparative adequacy analysis of methods based on the control of these parameters [7, 8], taking into account the limiting requirements, allows to make the following conclusions:

- the diagnostic of mechanical defects in medium power engines, instead of vibration analysis, harmonic analysis of motor feed currents (MCSA technology), harmonic analysis of capacitive currents to ground (CTG technology) can be used;
- as for the diagnostic of electrical defects, it is advisable to combine harmonic analysis of supply and capacitive currents in the ground circuit.

Analysis of the majority of servos electrical and mechanical faults can be detected by monitoring the supply and capacitive current.

The analysis of current supply harmonics (MCSA - Technology) consists in the decomposition of the signal using Fourier transform and amplitude analysis at characteristic frequencies. Each fault has its own characteristic frequencies, including sub-harmonics, harmonics and inter-harmonics between the spectral lines of the reverse frequency. The analysis of the capacitive currents harmonics (CTG-Technology) studies the capacitive currents to ground. In the case of vibration, the capacities change with frequencies proportional to the vibration of the active part in the engine [9, 10], i.e. it is possible to determine the regularities of vibration phenomena in the engine itself, and therefore it exceeds the harmonic analysis of the currents feeding the motor in terms of information.

This diagnostic method measures the servo current using one of the following measurement schemes:

- low-frequency range representing the "mechanical defects": the informative characteristics of which are supply current spikes in the "power supply wires or motor leads", these defects can be detected by the harmonic analysis of the supply current (MCSA) during the galvanic analysis from the supply wire or input into the motor (e.g. see Figure 2, a).
- circuit in the high-frequency range or "defects of the electric type": the informative characteristic of which is the voltage surges on the "motor power wires". These defects are fixed by the measurements of pulsations (voltage surges) on the motor power cables during galvanic analysis of capacitive currents from the motor to ground (CTG) (e.g. see Figure 2, b).

At the "Cognition" level, methods of diagnosing and forecasting the technical condition of constructions robots drives are chosen [11].

The existing methods for measuring and analyzing selected parameters have been described and a method for analyzing diagnostic parameters is proposed, which made it possible to determine the technical condition of the robot servos under various drive load conditions[12]. To implement this method, wavelet transformation and neural networks for the classification of signals were proposed. It was further established that any maternal wavelet may be used. Finally, the validity of the theoretical calculations and the adequacy of the model were confirmed by the large volume of experimental studies.

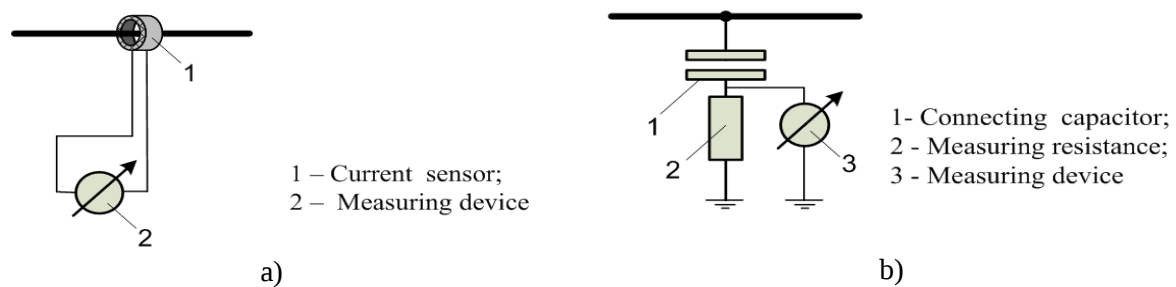


Figure 2. General scheme of galvanic connection for measurements and harmonic analysis of the current feeding the motor a) for the control of "mechanical defects" (MCSA-Technology), b) for the control of "electric nature" defects (CTG-Technology).

The method of contractions robot drives intelligent diagnostics is obtained. It allows to determinate the technical condition and operation mode of the equipment using wavelet analysis and neural networks in combination.

The servos technical condition diagnosis results are recorded to the cloud server and used to predict the development of constructions robot defects. The input data for prediction are the wavelet coefficients trend of current, voltage or vibration velocity diagnostic signals on characteristic scales for previous periods of operation distributed over equal time intervals.

The three-level neural network was used for electric motors technical condition prediction, combining a direct signal transmission network and a radial basic neural network [13]. The result of forecasting is the number of maintaining workability time intervals. The proposed method will allow implementing short-term and long-term forecasting of defects of each motor of the construction's robots. It provides the necessary information to optimize the mode of operation of the constructions robots. The results of diagnostics and forecasting are presented to users and transmitted to the mathematical model of the object for further optimization of the robot operation mode.

Knowing the current and predicted state of the servo drive of each motor, it is possible to adjust the operating mode of the entire construction mobile robot (Figure 3).

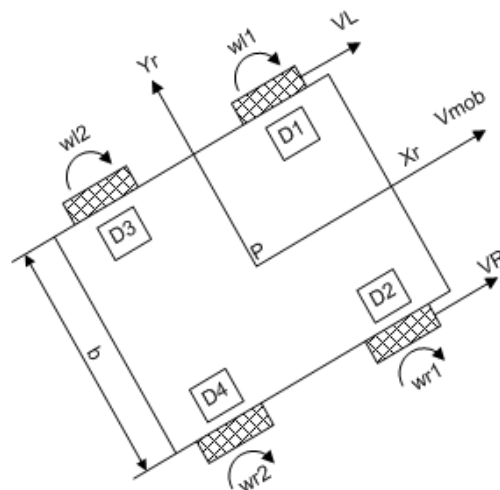


Figure 3. Four-wheeled mobile robot kinematic model.

A four-wheeled construction mobile robot with a differential drive can move in space in one of three ways:

- using wheels $D1$ and $D2$ (front wheel drive);
- using wheels $D3$ and $D4$ (rear wheel drive);

- using all four wheels (four-wheel drive) [13].

The current state of each servo can be attributed to one of the following classes of diagnoses is:

- "11" – healthy without load;
- "12" – healthy with load;
- "21" – fault without load;
- "22" – fault with load.

The preferred mobile robot operation mode is four-wheel drive, therefore, if all servos are serviceable and unloaded ($D1 = D2 = D3 = D4 = "11"$) it is advisable to choose this mode.

If all servos are healthy with load ("12") it is also advisable to use all-wheel drive.

If the front drives ($D1, D2$) work under a loaded, when the robot is travelling on a downward slope, it is necessary to increase the load on the rear servos ($D3, D4$).

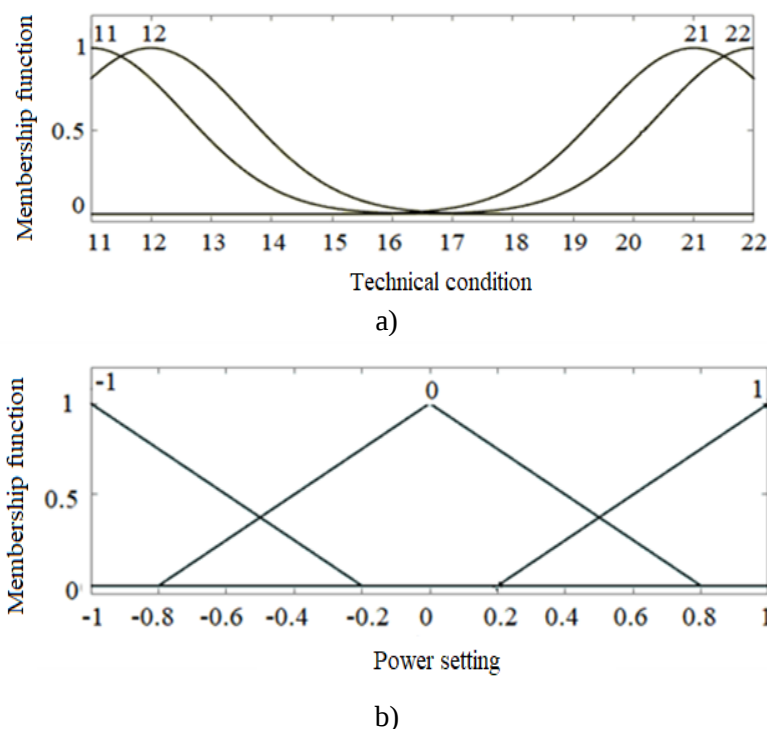


Figure 4. Membership functions of fuzzy decision-making model: a) input functions; b) output functions.

If the rear servos ($D3, D4$) are loaded, which corresponds to the upward slope movement, it is necessary to increase the rotation speed of the front servos ($D1, D2$).

When one of the front drives ($D1$ or $D2$) is overloaded, which is typically when the wheel stuck, it is necessary for the rear wheel ($D3, D4$) rotation speed increase of the same nomination.

If the rear wheel ($D3, D4$) is stuck, it is necessary to increase front wheels ($D1, D2$) load. Changing the mobile motor operation mode occurs when the "21" or "22" condition of one of the drives is faulty. If one or two rear-wheel drive failure, it is necessary to switch off the front-wheel drive and use rear-wheel drive. If one front and one rear drive are faulty, it is necessary to stop the robot operation.

This logic scheme can be implemented using fuzzy logic model Mamdani which includes four inputs and four outputs. The four states possible for each servo (Figure 4, a) as input parameters and current operation mode for each mobile robot servo (Figure 4, b) as system outputs.

The output variables are set in the range [11]. The value "-1" corresponds to the servo shutdown; "0" - use the current mode; "1" - increase the servo speed.

The output control solution for each of the four wheels can be obtained using the algorithm [9], which has the following form:

1. It is assumed that the input variables have acquired some specific (clear) values $x_1^0, x_2^0, x_3^0, x_4^0$ and there are levels of "clipping" for the prerequisites of each of the rules:

$$\alpha_1 = \min[A_1(x_1^0), A_1(x_2^0), A_1(x_3^0), A_1(x_4^0)] ; \quad (1)$$

$$\alpha_2 = \min[A_2(x_1^0), A_2(x_2^0), A_2(x_3^0), A_2(x_4^0)] ; \quad (2)$$

$$\alpha_3 = \min[A_3(x_1^0), A_3(x_2^0), A_3(x_3^0), A_3(x_4^0)] ; \quad (3)$$

$$\alpha_4 = \min[A_4(x_1^0), A_4(x_2^0), A_4(x_3^0), A_4(x_4^0)] . \quad (4)$$

2. Individual outputs are calculated for each rule

$$y_1^* = f_1; \dots y_n^* = f_n. \quad (5)$$

3. The aggregate output of fuzzy logic system is calculated

$$y_i^* = \sum_{i=1}^n \alpha_i \cdot \frac{y_i^*}{\sum_{i=1}^n \alpha_i} . \quad (6)$$

An example of graphic interpretation of this fuzzy inference is the response surface (Figure 5).

After substitution of the coefficients which was determinate using fault diagnosis model [14] showing the current state of each electric drive, for each of the four drives the coefficient defining the required operating mode will be defined. The negative value indicates that the motor must be switched off. If this value close to zero - the operating mode should be left unchanged. The number close to 1 indicates the need to increase the servo speed. The results of the decision-making model can be used to optimize the trajectory of the construction mobile robot.

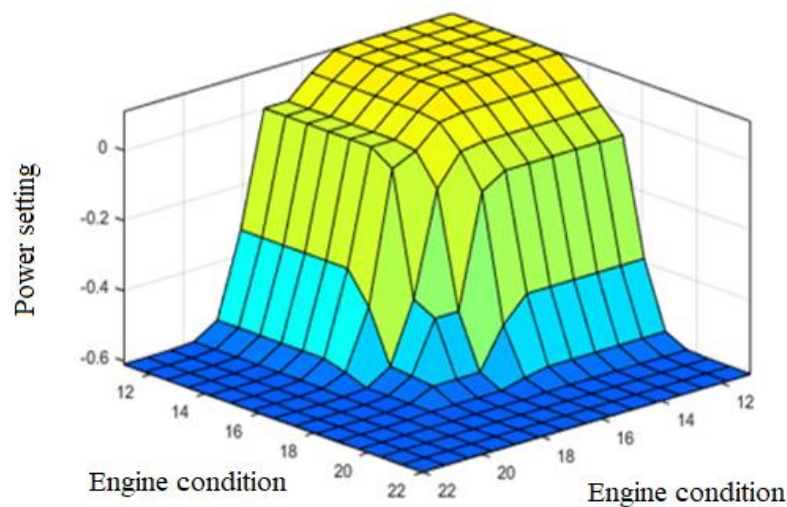


Figure 5. The response surface of the intelligent decision model.

3. Results and discussion

For experimental researches, a four-wheel all-wheel drive mobile robot was used to transport goods at a construction site. Servo drives MAXON EC 60 with a power of 400 W are used as executive elements. The cyber-physical system has been developed for this robot according to the structure shown in Figure 1. All drives are equipped with current sensors according to Figure 2 b.

The purpose of the experiment was to check the adequacy of the proposed diagnostic and decision-making models. The experimental results are shown in Table 1.

Table 1. Diagnosis and decision making model experimental researches

Diagnosis results				Decision – making model results			
Front drive		Rear servos		Front drive		Rear servos	
D1	D2	D3	D4	P1	P2	P3	P4
11	11	11	11	0	0	0	0
12	12	12	12	0	0	0	0
12	12	11	11	0	0	1	1
11	11	12	12	1	1	0	0
11	11	21	11	1	1	-1	-1
22	12	11	11	-1	-1	1	1
11	21	21	11	-1	-1	-1	-1
21	21	21	21	-1	-1	-1	-1

In the first experiment (the first row of Table 1), a mobile robot drives across a flat area without a load. As a result of diagnostics, it was found that all servos are in good working order, not loaded (state 11). The decision-making model shows that the mode of operation of the robot should remain unchanged.

In the second experiment (second row in Table 1), the robot is traveling on a flat surface with a load. As a result of diagnostics, it was found that all servos are properly loaded (state 12). The decision-making model shows that the mode of operation of the robot should remain unchanged.

In the third experiment (third row of Table 1), the robot drives up the slope without load. In this case, the diagnosis model shows that the front-wheel drive servos are loaded and the rear-wheel drive servos are not loaded. In this case, all drives are serviceable. In this case, the decision model suggests increasing the load on the rear wheel drive and leave the operating mode of the front drive unchanged.

In the fourth experiment (the fourth row of Table 1), the robot drives without load down the slope. In this case, all drives are serviceable. The rear-wheel drive servos are loaded and the front-wheel drive is unloaded. In this case, the decision model suggests increasing the front-wheel drive load and leaving the rear-wheel drive load unchanged.

In the fifth experiment (the fifth row in table 1), a resistance of 2 ohms was introduced into the stator winding of the D3 drive, which simulates a stator malfunction. The robot rides on a flat surface without load. In this case, the diagnostic system indicates that the D3 drive is faulty without load (state 21). All other drives are OK without load (state 11). In this case, the decision-making system proposes to disable rear-wheel drive and increase the load on the front, that is, switch from all-wheel drive to front-wheel drive.

In the sixth experiment (the sixth row in Table 1), a resistance of 2 Ohm was introduced into the stator winding of the D1 drive, which simulates a stator malfunction. The robot travels up an incline without load. In this case, the diagnostic system indicates that the D1 drive is faulty loaded (state 22). The D2 drive is healthy and loaded. Motors D3 and D4 are healthy without load (state 11). In this case, the decision-making system proposes to turn off the front-wheel drive and increase the load on the rear-wheel drive, that is, switch from all-wheel drive to rear-wheel drive. A similar solution is to turn 180 degrees and keep driving in front wheel drive. This decision can be made depending on the technological process in which the robot works.

In the seventh experiment (seventh row in table 1), a resistance of 2 ohms was introduced into the stator winding of drives D2 and D3, which simulates stators malfunction. The robot rides on a flat surface without load. In this case, the diagnostic system indicates that the D2 and D3 drives are faulty off load (state 21). Actuators D1 and D4 are OK without load (state 11). In this case, the decision-making system recognizes the robot as faulty and offers to turn off all its drives.

In the eighth experiment (the eighth row in table 1), a fault was introduced into the stator winding of the drives of all four drives. The robot rides on a flat surface with a load. In this case, the diagnostic system indicates that all drives are faulty with load (state 22). In this case, the decision-making system recognizes the robot as faulty and offers to turn off all its drives.

It can be seen from the experiment that the cyber-physical system controls of the servos construction mobile robot is performed in groups (front and rear drives). In case of correct operation of the drives of both groups, the operating mode of the robot remains unchanged. In case of faulty drives of both groups, the operation of the robot is terminated. In the event of a failure of one of the drives in the group, the drives of this group are switched off and the load on the other group increases. In the event of a malfunction of one of the two drives of the group, the operation of the robot stops.

4. Conclusion

In this paper, the design of five levels the cyber-physical predictive diagnostic system is determined and the operation of each level of the system is described. This system use fault prediction diagnosis method allows to determinate electric motors technical condition distinguishing it from the load changes and the number of maintaining workability time intervals. The results of the decision-making multidimensional method for the constriction robot movement trajectory optimization taking into account its drives wear and technical condition.

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