MACHINE BUILDING

Original article

UDC 004.413.4:[625.1/.5+004.9]

https://doi.org/10.23947/2541-9129-2023-1-56-69

Integral Risk Assessment in Steel Ropes Diagnostics Using Computer Vision

Aleksey V. Panfilov, Nikolay N. Nikolaev ✉, Aleksandr R. Yusupov, Anatoliy A. Korotkiy

Don State Technical University (Rostov-on-Don, Russian Federation)

✉ nnneks@yandex.ru

Abstract

Introduction. Currently, the technical condition of ropes of cable-working machines is evaluated periodically according to regulatory documentation. At the same time, methods of visual and instrumental control are used, which depend on the skills and physical capabilities (vision) of the personnel performing the work. There is no unified system of continuous assessment of the technical condition based on a set of factors that does not depend on the human factor. As a result, emergencies occur even when all routine maintenance is carried out on time. To correct this situation, it is proposed to use a computer vision system and neural networks, which allows determining its suitability for further operation by risk levels based on the totality of detected and identified defects, with the interpretation of their results in the color scheme: green — acceptable, yellow — increased, red — high. The work objective is to propose an integral method for risk assessment of operating machines with rope traction when defects and their combinations are detected in a steel rope using computer vision while excluding the influence of the human factor.

Materials and Methods. Training of the neural network was carried out on the basis of statistical data of defects obtained from the results of technical inspections of machines with rope traction, on sections of the rope, multiples of its six and thirty nominal diameters according to GOST 33 718. Indexing of risks in the color scheme was carried out according to GOST 55 234.3 to develop a strategy for steel ropes maintenance. A certificate of registration of a computer program was obtained for the neural network program code. The neural network processes visual and measurement control data based on computer vision.

Results. An integrated risk assessment system has been created for the diagnosis of steel ropes using computer vision, which allows you to detect defects in steel ropes timely, assess the existing risk of further operation and give recommendations to specialists of operating organizations in real time. This will dramatically reduce the risk of accidents, injury and death of people at facilities using steel ropes.

Discussion and Conclusion. The proposed integrated risk assessment system can be applied in any facility that uses rope traction. These are elevators for various purposes, funiculars, cable cars, cranes and many other machines. It should be noted that the estimated commercial cost of the system is low; therefore, the system is available to a wide range of consumers.

Keywords: integrated system, risk assessment, steel rope, computer vision, neural network, recommendation system.

Acknowledgements. The authors would like to thank their colleagues from DSTU for their help in developing the system and to express gratitude to the Innovation Promotion Fund for financial support of the research.

For citation. A. V. Panfilov, N. N. Nikolaev, A. R. Yusupov, A. A. Korotkiy. Integral Risk Assessment in Steel Ropes Diagnostics Using Computer Vision. Safety of Technogenic and Natural Systems, 2023, no.1, pp. 56–69. https://doi.org/10.23947/2541-9129-2023-1-56-69

Introduction. Timely assessment of technical condition of facilities directly responsible for safety of various technological operations is the most important task. This will reduce or eliminate emergencies with injury, loss of life and damage to material objects [1, 2]. Such critically important technical facilities from the point of view of risk assessment include: elevators (passenger, hospital and cargo); cable cars (passenger and cargo); mine hoisting installations; oil and gas drilling rigs; lifting cranes; hoists; ship lifting devices; skip hoists; rope mechanisms of offshore platforms; mechanisms on offshore pipelayers and others.

To carry out continuous monitoring of the parameters of steel ropes technical condition, a recommendation system of integrated risk assessment of the continuation of steel ropes work in mechanisms with the use and interpretation of computer vision system data has been developed.

The urgency of the problem is confirmed by the available statistics of accidents at facilities using cable traction, which occur despite the existing system of periodic inspections and flaw detection of steel ropes [3–5].

The work objective is to propose an integral method of risk assessment of operating machines with cable traction when defects are detected in a steel rope and combined with the use of computer vision during routine maintenance.

Tasks to be solved to achieve this goal in the course of this study:

1. Describe the existing regulations on visual and measuring control of steel ropes on machines with cable traction.
2. Propose a method of visual and measuring control using computer vision in a steel rope.
3. Show that computer vision is an artificial intelligence technology.
4. Define the intelligent decision support system (IDSS) in relation to the proposed method of risk assessment of operating machines with rope traction when defects are detected and combined with the use of computer vision in a steel rope during routine maintenance.
5. Apply one of the known methods of risk analysis for an integral assessment of the technical condition of steel ropes.
6. Propose an algorithm and a computational procedure for an integral risk assessment of operating steel rope with defects at a fixed length equal to six and thirty nominal rope diameters.

The starting point for the creation of the product was the emerging problems with elevators (and other cable cars) and the possibility of using video information analytics, which is based on deep learning algorithms for pattern recognition. This will significantly increase the objectivity of the information received about the parameters of technical condition of the steel rope, balancing devices, fastenings of the ends of the seals and ensure the level of safety of the operation of machines on cable traction, while eliminating the human factor [6, 7].

Materials and Methods. Steel ropes are subjected to daily, periodic and special inspections in all types of lifting structures. Operating instructions is the document used by the personnel during repair and maintenance work. In its absence, it is necessary to use Safety Rules or GOST standards.

Elevator electricians, crane operators, machinists, mechanicians, electricians and other categories of service personnel carry out visual inspections of steel ropes periodically or immediately before starting work. Inspections are carried out in the following order:

1. Familiarization with the entries in the journal (journal of the elevator daily inspection; watch — for the lifting crane; changeable journal — for suspended cable cars, etc.).
2. Inspection of the sections of rope wound on the drum, as well as those passed through the rope-carrying pulley, block, resting on shoes, fixed in couplings, couches and clamps.

The operator (driver) of the lifting structure has a log in which the results of inspections are recorded.

The frequency of flaw detection of steel ropes for specific lifting structures and their frequency are shown in Table 1.

Table 1

Frequency of inspections and flaw detection of steel ropes[1]

No.	Name of the lifting device	Purpose of the steel rope	Frequency of flaw detection (month)	Note
1	Hoisting crane	cargo	12	*
		boom	12	**
		traction	12	*
		guy	36	**
2	Cable crane	track	subsequent every 24	the first one at commissioning
		traction	12	
		cargo	12	
		guy	36	
		support	not subject	
		cable suspensions	not subject	
		holding the crane (support)	not subject	
3	Lifts and winches for lifting people	cargo	6	
		traction	12	
4	Removable lifting bodies		not subject	
5	Removable lifting devices		not subject	
6	Electric hoists	cargo	12	*
7	Elevators	traction	6	
		tail	not subject	
8	Lifts (towers)		not subject	

No.	Name of the lifting device	Purpose of the steel rope	Frequency of flaw detection (month)	Note
9	Overhead passenger (cargo) cable cars	track, traction, carrier and traction tension	the second one is after 36, the next one every 12 not subject	the first one at commissioning
10	Inclined rail-rope lifts (funiculars)	traction tension (tail) safety	the second one is after 36, the next one every 12 not subject not subject	the first one at commissioning
Note: low rotation ropes, regardless of their purpose, are subject to flaw detection every 12 months; * during intensive operation in an aggressive environment and elevated temperature; ** for ropes operated without replacement on cranes with expired service life.				

Rules[1] require periodic (in some cases, daily) visual and dimensional examination (VDE) of steel ropes with the detection of external defects, information about which is entered in the inspection log.

Defects in steel ropes arise as a result of:

– external influences with mechanical equipment or the external environment in the elevator shaft, including the formation of an electric arc discharge;

– inadequate quality of the supplied steel rope as a component product;

– improper quality of steel ropes installation;

– malfunctions of mechanical parts of the elevator, the indicator of which is the rope.

It can be stated that their defects in steel ropes are an "indicator" of technical condition of all mechanical equipment of the lifting structure, namely: wear of the pulley groove; rope slipping on the pulley, including as a result of excessive lubrication; misalignment of the winch attachment; backlash in the elements of the transmission mechanisms of the drive, etc. [8-12]. Possible malfunctions of the mechanical parts of the elevator, depending on the defective indicators, are presented in Table 2.

The VDE method is proposed[2], which makes it possible to carry out an integral assessment of the technical condition of a steel rope, implemented in the form of a software and hardware complex, which is a computational recommendation system for decision-making for service personnel when they perform maintenance work on machines with cable traction. This allows you to get the necessary safety level, while eliminating the subjectivity of the human factor, namely, physiological limitations associated with vision.

The proposed method provides for the creation, development and implementation of artificial intelligence, namely, a set of technological solutions that allow simulating human cognitive functions (vision and self-learning), including the search for solutions to identify the discovered defects in steel ropes with the results of human intellectual activity.

[1] Ob organizatsii bezopasnogo ispol'zovaniya i soderzhaniya liftov, pod"emnykh platform dlya invalidov, passazhirskikh konveierov (dvizhushchikhsya peshekhodnykh dorozhek), eskalatorov, za isklyucheniem eskalatorov v metropolitenakh. Government of the Russian Federation. Electronic fund of legal and regulatory documents. Available from: https://docs.cntd.ru/document/436745439?section=text (accessed 23.01.2023). (In Russ.).
[2] Korotkiy A. A. et al. Sposob vizual'no-izmeritel'nogo kontrolya stal'nogo kanata. Patent 2775348, Russian Federation, D07B 1/00; B66B 7/1215; G05B 99/00. No. 2021107842, 2022. 16 p. (In Russ.).

Table 2

Possible malfunctions of the elevator mechanical equipment depending on defects types

No.	Rejection rate	"Indicator" of a possible malfunction
1	Breaks of external wires	– Wear of the pulley groove – Misalignment of the rope-carrying pulley during installation or maintenance – Contact with external elements when moving in the mine – Inadequate quality of the supplied steel rope
2	Surface wear of the rope	– Wear of the pulley groove – Misalignment of the rope-carrying pulley during installation or maintenance
3	Surface corrosion	Impact of corrosion factors (oxygen, electrochemical, chemical)
4	Local reduction of rope diameter	– Inadequate quality of the supplied steel rope – Core damage – Damage to internal strands
5	Local increase of rope diameter	– Inadequate quality of the supplied steel rope – Swelling of the fiber core from excess moisture
6	Waviness	– Inadequate quality of the supplied steel rope – Defects in the installation or improper maintenance of balancing devices, places of sealing their ends
7	Temperature impact (electric arc discharge or lightning strike)	Exposure to electric current during installation, improper maintenance and during operation
8	Twist	– Overload – Incorrect reeving – Incorrect laying of the new rope on the drum
9	Elongation (residual)	– Inadequate quality of the supplied steel rope – Overload – Core damage – Damage to internal strands
10	Defects of balancing devices, places of sealing of their ends	Defects in installation and improper maintenance

Artificial intelligence technologies, in accordance with "National Strategy ..."[3] (subparagraph "a" of paragraph 5), include technologies based on the use of computer vision and intellectual decision support.

Artificial intelligence should be understood as a set of technological solutions that allows you to simulate human cognitive functions (including self-learning and finding solutions without a predetermined algorithm) and perform specific tasks with results comparable to or superior to the results of human intellectual activity.

The claimed method includes a set of technological solutions consisting of computer vision, information and communication infrastructure, software (including the implementation of machine learning methods), processes and services for data processing and solution search.

For an integral assessment of the steel rope technical condition, an intelligent decision support system (IDSS) using artificial intelligence (AI) methods was used (Fig. 1, 2).

[3] O razvitii iskusstvennogo intellekta v Rossiiskoi Federatsii (vmeste s «Natsional'noi strategiei razvitiya iskusstvennogo intellekta na period do 2030 goda»). President of the Russian Federation. Electronic fund of legal and regulatory documents. Available from: https://docs.cntd.ru/document/563441794/titles/64U0IK (accessed 23.01.2023). (In Russ.).

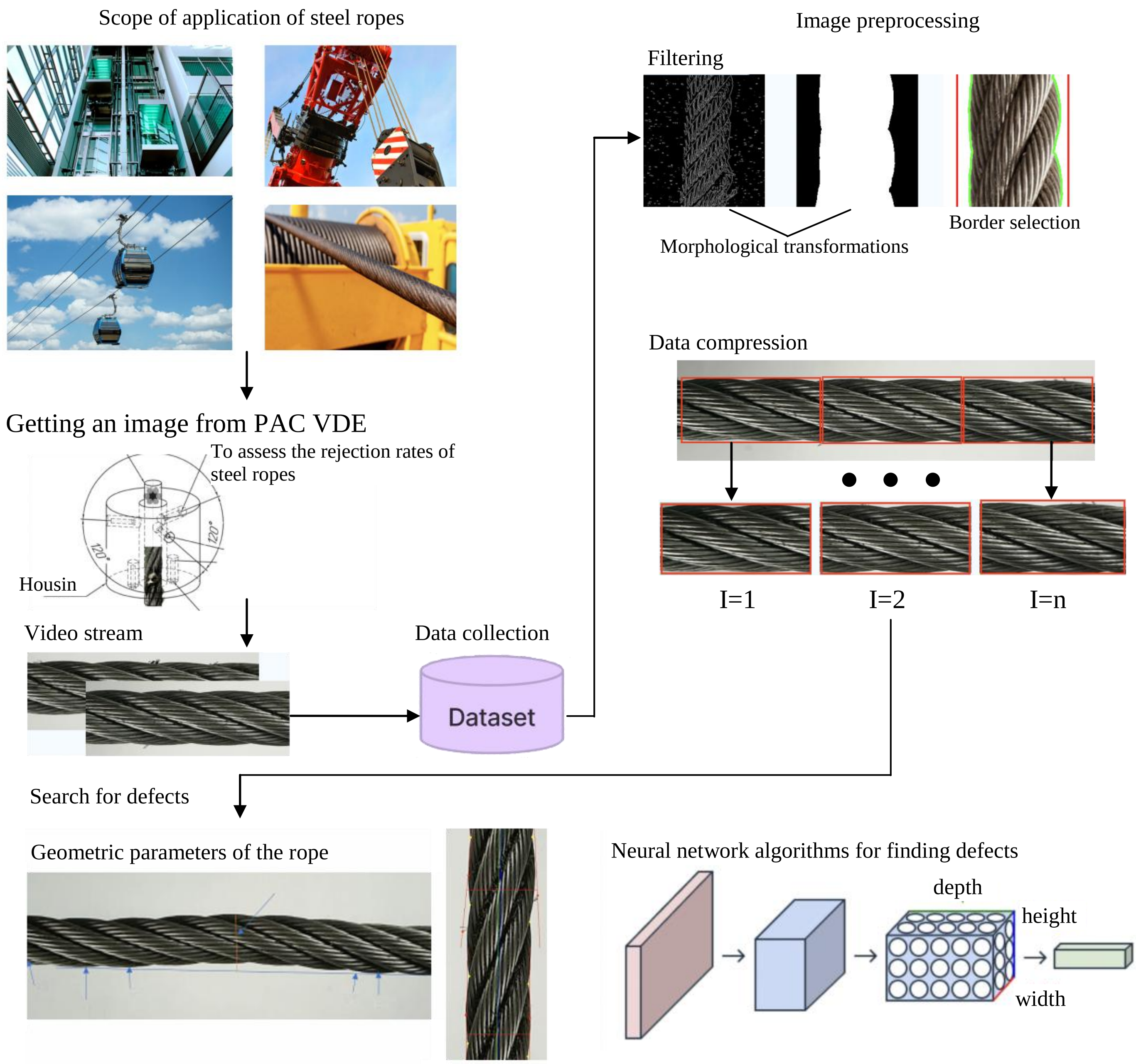


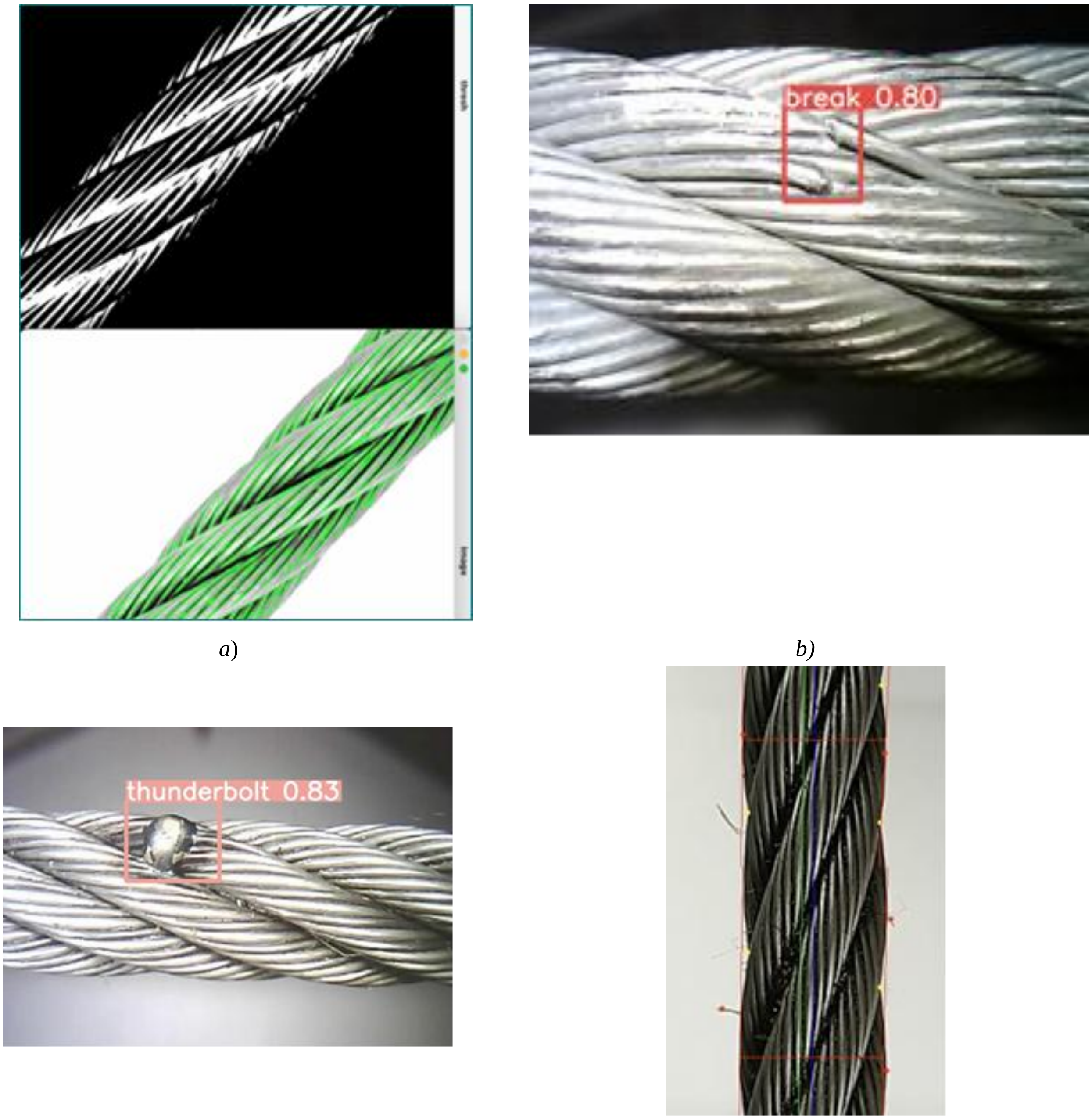
Fig. 1. Functional diagram of the method of visual and dimensional examination of a steel rope (Authors' figure)

An intelligent decision support system replaces a human consultant. It provides support to decision makers by collecting and analyzing factual data on detected defects, provides suggestions of possible options for action and their assessment. The purpose of artificial intelligence methods embedded in an intelligent decision support system is to allow a computer to perform these tasks, mimicking human capabilities as much as possible.

The proposed IDSS implementation is based on expert systems that encode knowledge and simulate cognitive behavior of human experts using predicate logic rules.

An expert system is a computer system that simulates the ability of a human expert to make decisions. Expert systems are designed to solve complex problems by reasoning with the help of a body of knowledge, presented mainly in the form of "if-then" rules, and not with the help of ordinary procedural code. The expert system is divided into two subsystems — the output mechanism and the inference mechanisms. The knowledge base represents facts and rules.

The inference mechanisms apply rules to known facts to infer new facts. Inference mechanisms may also include explanation and debugging capabilities.



a) *b)* *c*) *d*)

Fig. 2. Detection of defects by means of computer vision:
a — determination of external wires wear; *b* — wire breakage;
c — temperature effect; *d* — local decrease/increase in diameter
(Authors' figure)

The created method makes it possible to automate processes when assessing the safety of using steel rope on cable traction machines. This makes it possible to provide users (staff) with a visual recommendation system for decision-making in the form of a web application that is not influenced by the human factor. This ensures increased security and reduced costs. This method automates and combines two control methods: visual and instrumental [14-16].

An expert system for risk assessment can be implemented based on well-known methods, such as[4]: Delphi method; failure mode and effects analysis (FMEA); failure mode effects and criticality analysis (FMECA); reliability-centered maintenance (RCM); risk indices; scenario analysis; structured method "What if?" (SWIFT); fuzzy logic methods, etc.

Regardless of the methodology used, risk assessment is carried out using a risk assessment matrix or a similar tool (for example, see GOST R 58 771[4] or GOST R 55 234.3[5], or GOST 12.0.230.5[6]).

The axes of the matrix can be both the probability and consequences of risk, as well as any other technical parameters of mechanical equipment that characterize their importance or criticality.

According to the results of such an assessment, risk is usually assigned one of three levels — high (red), medium (yellow) or low (green).

It is possible to increase the number of levels. The names of the colors are given as part of the most common scheme.

Standardization recommendations[7] also provide for the use of a color scheme in risk assessment.

To assess risk levels and develop maintenance and culling strategies based on a recommendation decision-making system, we apply the RIMAP approach — procedures for monitoring technical condition and maintenance based on a risk-oriented approach (recommended by GOST 55 234.3[5]). The approach allows us to successfully combine all known methods of risk assessment and decision-making.

The application of the RIMAP approach solves the following tasks:

- identification of hazards;
- determination of the mechanisms of defects and failures;
- determination of the probability of failure;
- determination of the consequences of failure;
- risk level assessments.

The main danger for rope systems is the risk of rope breakage, as well as the destruction of the sealing points of the rope ends.

Table 3 shows the rejection rates of steel ropes and the mechanisms of damage development.

Next, you need to determine the probability of failure. This requires initial data on various defects listed in Tables 2 and 3.

[4] GOST R 58771-2019. Risk management. Risk assessment technologies. NPO RusRisk, Technical Committee for Standardization "Risk Management", Federal Agency for Technical Regulation and Metrology. Available from: https://docs.cntd.ru/document/1200170253 (accessed 23.01.2023). (In Russ.).

[5] GOST R 55234.3-2013. Practical aspects of management of risk. Risk-Based Inspection and Maintenance Procedures. ANCO "NITS KD", Technical Committee for Standardization TC 010 "Risk Management", Federal Agency for Technical Regulation and Metrology. Electronic fund of legal and regulatory documents. Available from: https://docs.cntd.ru/document/1200108150 (accessed 23.01.2023). (In Russ.).

[6] GOST 12.0.230.5-2018. Occupational safety standards system. Health management systems. Risk assessment methods to ensure the safety of work. Federal Agency for Technical Regulation and Metrology, Interstate Council for Standardization, Metrology and Certification. Electronic fund of legal and regulatory documents. Available from: https://docs.cntd.ru/document/120016046 (accessed 23.01.2023). (In Russ.).

[7] R 50.1.090-2014. Risk management. Key risk indicators. NP RusRisk, Technical Committee for Standardization TC 010 "Risk Management", Federal Agency for Technical Regulation and Metrology. Electronic fund of legal and regulatory documents. Available from: https://docs.cntd.ru/document/1200120834 (accessed 23.01.2023). (In Russ.).

Table 3

Rejection indicators of steel ropes and mechanisms of damage development

Designation	**Name of the defect type**	**Rejection standards according to regulatory and technical documents**	**Mechanisms of damage development**
A (at length 6d) B (at length 30d)	Breaks of outer wires	According to the operating manual of the rope (depending on the type and brand)	Fatigue wear, mechanical wear, corrosion (oxygen, electrochemical, chemical)
C	Surface wear of the rope	Reduction of the diameter of the outer wires by 40% or more	Mechanical wear
D	Surface corrosion	Rope diameter reduction by 7% or more	Corrosion (oxygen, electrochemical, chemical)
E	Local reduction of rope diameter	Reduction by 3-6% of the rope diameter from the nominal one	Core damage, damage to internal strands
F	Local increase in rope diameter	Increase by 3-6% of the rope diameter from the nominal one	Swelling of fiber core from excess moisture
G	Waviness	When the directions of spiral waviness coincide with the direction of the rope lay and the waviness step and the rope lay step are equal at db = 1.08 dk (where db and dk, respectively, are the diameter of the waviness and the diameter of the rope). In other cases, at db≥1.33dk	Bending of sheave grooves of small radii
H	Temperature effect	If soot, scorching, or a characteristic color change is detected on the surface of the rope	Static electric discharge, lightning strike, heating
I	Twist	1) When reeving 1:1 — 0.5 turns per 10 meters 2) When reeving 2:1 — 0.5 turns per 20 meters 3) For ropes with an organic core — 1 turn per 10 meters	Overload, incorrect reeving, incorrect laying of a new rope on the drum
J	Elongation (residual)	With a residual elongation of more than 0.5% of the working length after wear-in	Overload, core damage, damage to internal strands
K	Defects of balancing devices, rope sealing sites	Deviation of position and shape from the original arrangement of elements	Overload, wear of parts and elements

To obtain a reliable sample of data based on the available rope defect results, the Monte Carlo method was used, with the help of which a sample of 1000 rope sections was generated, multiples of its 6 nominal diameters, allowing considering all combinations and variations of defects. The estimation of the total probability of failure for the sample was carried out in accordance with the algorithm shown in Figure 3. The resulting sample was used to train a neural network in order to implement the risk indexing method of the RIMAP approach.

Since the output data is discrete, the neural network must solve the classification problem. A multilayer perceptron is selected as the type of neural network.

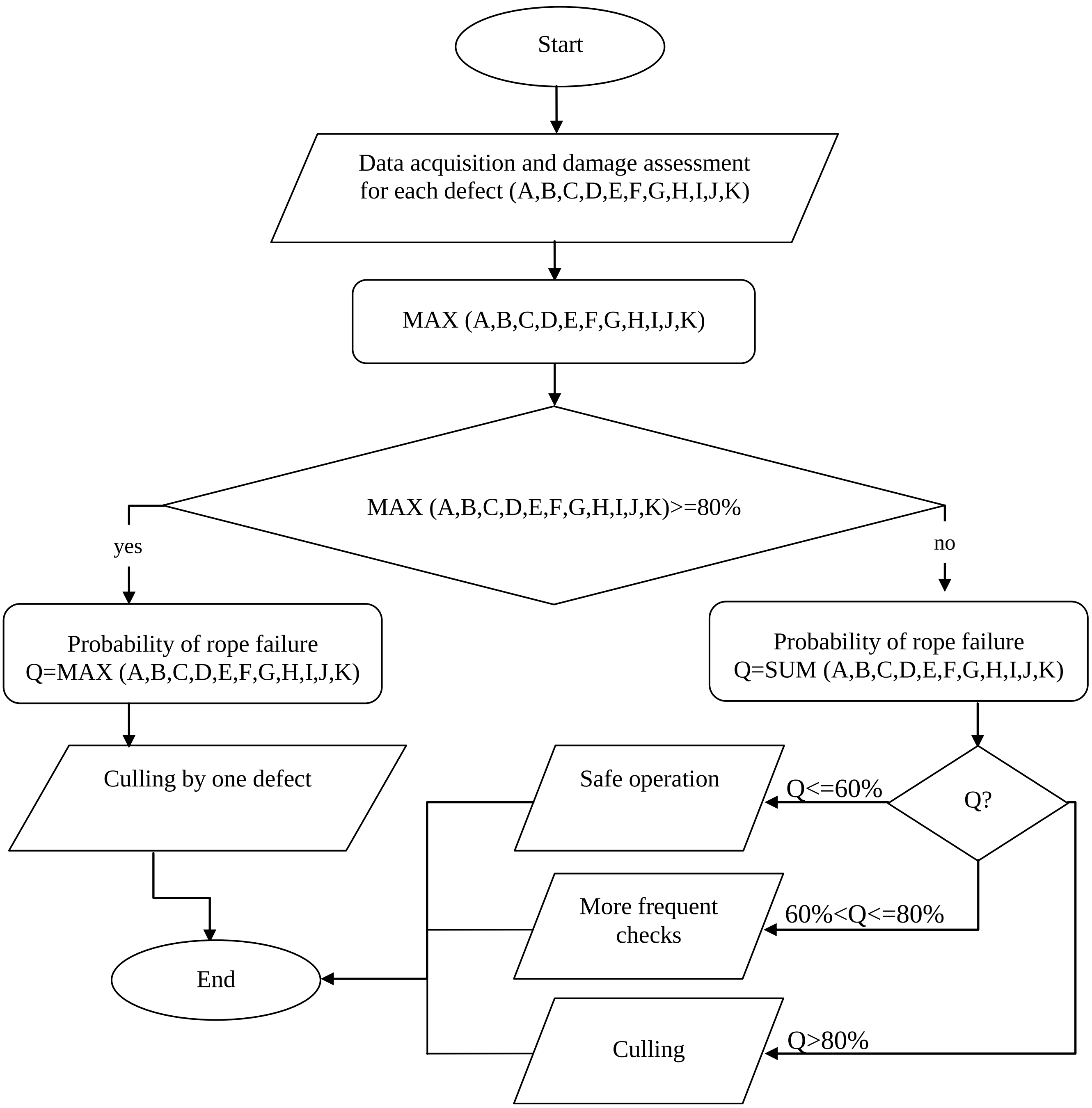


Fig. 3. Algorithm for estimating the total damage to the rope section (Authors' figure)

During the training, 20 neural networks were obtained, from which the top five were automatically selected (Fig. 4).

Among the neural networks obtained, the MLP 11-9-3 network can be distinguished, which has the best performance on the test sample of 96 %, and on the training and control samples — 98 %.

Summary of active networks (Spreadsheet in Risk_Estimation)								
Index	Net. name	Training perf.	Test perf.	Validation perf.	Training algorithm	Error function	Hidden activation	Output activation
1	MLP 11-4-3	95,85714	95,33333	98,00000	BFGS 36	SOS	Tanh	Identity
2	MLP 11-14-3	96,28571	94,66667	96,00000	BFGS 50	SOS	Logistic	Tanh
3	MLP 11-7-3	96,42857	95,33333	98,00000	BFGS 16	SOS	Exponential	Logistic
4	MLP 11-14-3	97,57143	94,66667	97,33333	BFGS 92	SOS	Logistic	Identity
5	MLP 11-9-3	98,14286	96,00000	98,00000	BFGS 155	SOS	Logistic	Tanh

Fig. 4. The best neural networks out of 20 trained ones (Authors' figure)

These are the best indicators, therefore, for further work in the intelligent decision support system, we will use the specified neural network. This neural network has 11 neurons in the input layer (according to the number of defects at the input), 9 neurons in the hidden layer, as well as 3 neurons in the output layer (according to the number of possible risk assessments of further operation of the steel rope). A logistic function is used as the activation function of the neurons of the hidden layer, and a tangential function is used for the output layer.

Analysis of the sensitivity of the MLP 11-9-3 neural network to changes in influencing wear indicators showed that changes in the indicators J (elongation), I (torsion), E (local decrease in rope diameter) and G (waviness) have the greatest impact (Fig. 5).

	Sensitivity analysis (Spreadsheet in Risk_Estimation) Samples: Train										
Networks	J	I	E	G	A	F	K	H	C	D	B
1.MLP 11-4-3	4,09029	3,78539	3,538596	2,999158	2,547528	2,325594	1,647709	1,675373	1,173743	1,138040	1,004637
2.MLP 11-14-3	3,10473	2,80809	2,788032	2,397576	1,973580	1,837489	1,595495	1,540505	1,102962	1,130396	1,012868
3.MLP 11-7-3	3,28691	2,97724	2,869449	2,475196	2,139719	2,020911	1,700607	1,700192	1,151866	1,085886	1,003372
4.MLP 11-14-3	7,30974	6,61641	6,316661	5,374687	4,347702	3,728140	2,721447	2,575235	1,506436	1,705318	1,137510
5.MLP 11-9-3	11,24972	10,23045	9,817238	8,400586	7,023844	5,798566	5,965579	5,509112	2,803276	2,617175	1,092058
Average	5,80828	5,28351	5,065995	4,329440	3,606475	3,142140	2,726167	2,600083	1,547656	1,535363	1,050089

Fig. 5. Sensitivity analysis of the MLP 11-9-3 neural network (Authors' figure)

A certificate of registration of a computer program was obtained for the neural network program code[8].

Results. An integrated risk assessment system has been created for the diagnosis of steel ropes using computer vision, which allows detecting defects in steel ropes in a timely manner, assessing the existing risk of further operation and giving recommendations to specialists of operating organizations in real time. This will dramatically reduce the risk of accidents, injury and death of people at facilities using steel ropes.

This system is the core of the product — a software and hardware complex (PAC) (Fig. 6) automating the processes of assessing the safety of using steel ropes, defects in balancing devices and places of sealing their ends on machines using cable traction, which is a visual recommendation system for decision-making for specialists. At the same time, the human factor is eliminated, which ensures increased safety and reduced costs.

The main functional purpose of PAC is the automatic detection of defects in steel ropes, balancing devices and fasteners of the ends of rope seals by special optical means (photo and video fixation), followed by processing of the received digital information by photo and video analytics based on machine learning, including an integral assessment of suitability for further operation by risk analysis methods, which is translated into the risk assessment color scheme on users' mobile devices.

[8] Korotkiy A. A. et al. Integral'naya otsenka tekhnicheskogo sostoyaniya stal'nogo kanata : progr. dlya EVM. Cert. No. 2022683712. Inzhenerno-konsul'tatsionnyi tsentr «Mysl'». No. 2022683761, 2022. (In Russ.).

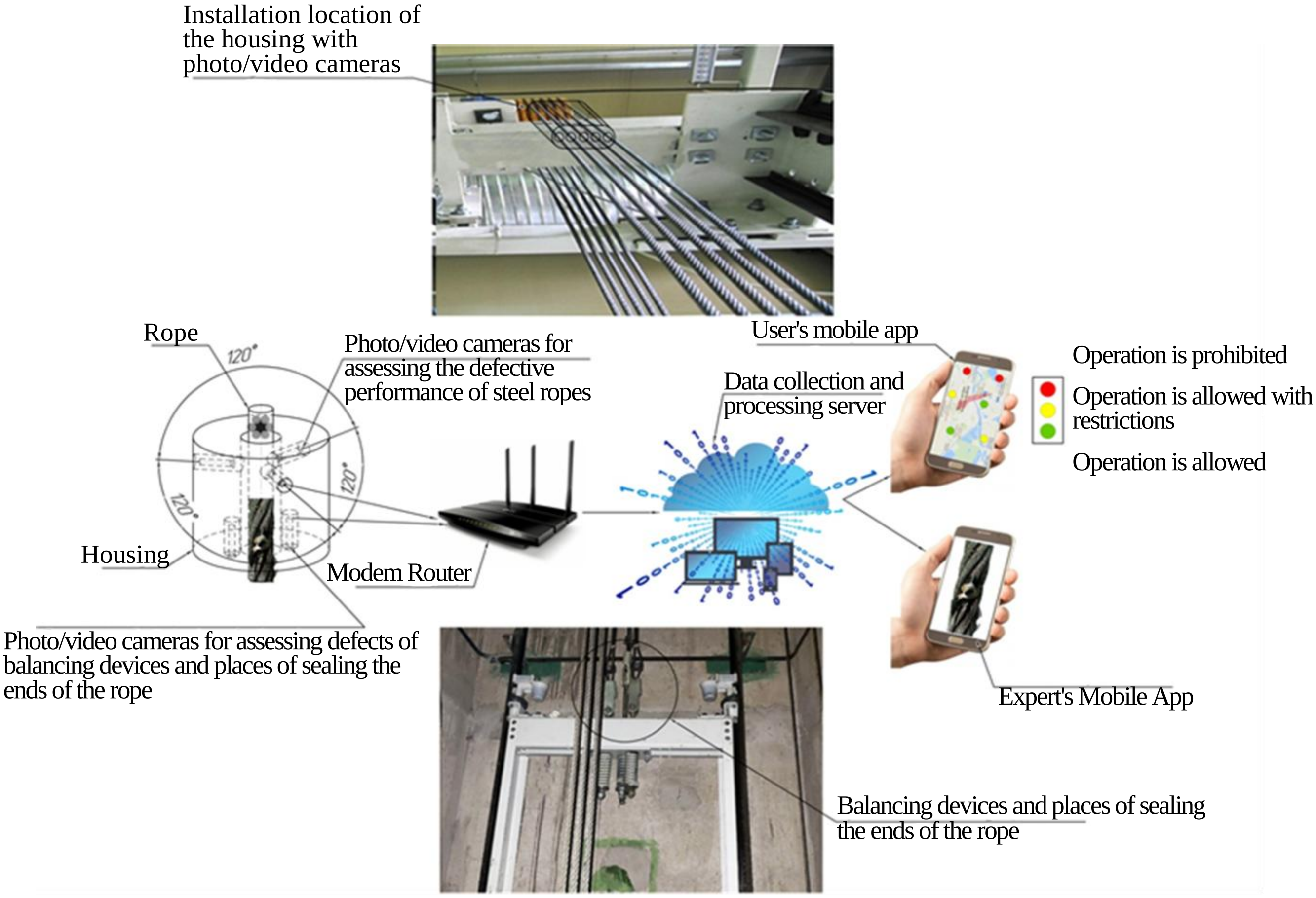


Fig. 6. PAC functional scheme (Authors' figure)

Discussion and Conclusion. Integral risk assessment in the diagnosis of steel ropes using computer vision, taking into account its advantages over the traditional visual and instrumental control system will be in demand by the industry of cable traction machines. This market is the target for the use of the product created by the authors. For example, the number of passenger elevators in operation on the territory of the Russian Federation is 450 thousand units. More than 50 thousand organizations are engaged in elevator maintenance. Each elevator requires a hardware part of the complex, i.e. the volume of the consumer market is 450 thousand pcs. The software part is necessary for each service organization, i.e. 50 thousand licenses. The mobile application is necessary for the specialists of each service organization, which must have at least three specialists, i.e. 150 thousand licenses. Taking into account the technological and economic advantages (the price is about 55 thousand rubles), the developed system will take a strong position in the industry of cable cars.

References

1. Martinod R., Estepa D., Paris C., Trujillo A. Journey Safety Assessment to Urban Aerial Ropeways Transport Systems Based on Continuous Inspection During Operation. Journal of Transportation Saropefety & Security. 2015;7:279-290. 10.1080/19439962.2014.942018

2. Ferrarese M., Loner E., Pulina M. Demand, business profitability and competitiveness in the cableway system: A multidimensional framework. Research in Transportation Economics. 2021;90:101041. https://doi.org/10.1016/j.retrec.2021.101041

3. Piskoty G., Affolter Ch., Sauder M., Nambiar M., Weisse B. Failure analysis of a ropeway accident focussing on the wire rope's fracture load under lateral pressure. Engineering Failure Analysis. 2017;82:648-656. https://doi.org/10.1016/j.engfailanal.2017.05.003

4. Peterka P., Krešák J., Vojtko M., Mantič M. Failure analysis of the journal bearing pulley of the cargo cable way. Engineering Failure Analysis. 2020;111:104329. https://doi.org/10.1016/j.engfailanal.2019.104329

5. Mapelli C., Barella S. Failure analysis of a cableway rope. Engineering Failure Analysis. 2009;16(5):1666-1673. 10.1016/j.engfailanal.2008.12.011

6. Panfilov A. V., Deryushev V. V., Korotkiy A. A. Recommended Safety Systems for Risk-Oriented Approach. Occupational Safety in Industry. 2020;5:48–55. (In Russ.).

7. Panfilov A. V., Bakhteev O. A., Deryushev V. V., Korotkiy A. A. Adaptive remote monitoring and control system for the operation of hazardous facilities based on a risk-based approach. Safety of Technogenic and Natural Systems. 2020;2:19–29. https://doi.org/10.23947/2541-9129-2020-2-19-29 (In Russ.).

8. Panfilov A. V., Korotkiy A. A., Ivanov B. F., Panfilova E. A. About criteria and standards for discharge of ropes of passenger ropeways. Scientific and Technical Journal of Bryansk State University. 2021;1:53–65. (In Russ.).

9. Shakti P. J., Mohd I., Subbaratnam B., Naresh K. Dynamic behavior of ropeway string. IOP Conf. Series: Materials Science and Engineering 998. 2020:012068. 10.1088/1757-899X/998/1/012068

10. Kattimani M. A., Ibrahim M., Ahmed M. A., Salam M. A. Modelling and analysis of helical ropeway string. Journal of Emerging Technologies and Innovative Research. 2022;9(6):357-365. Available from: https://www.researchgate.net/publication/361612084_MODELLING_AND_ANALYSIS_OF_HELICAL_ROPEWAY_STRING

11. Fontanari V., Menapace C., Pedrotti E. Study of the lightning damage produced in a full-locked wire rope of an aerial cableway. Engineering Failure Analysis. 2019;103:530-539. 10.1016/j.engfailanal.2019.05.002

12. Wahid A., Mouhib N., Ouardi A., Sabah F., Chakir H., Lghorba M. E. Experimental prediction of wire rope damage by energy method. Engineering Structures. 2019;201:109794. https://doi.org/10.1016/j.engstruct.2019.109794

13. Peterka P., Kačmáry P., Krešák J., Šimoňák J., Bindzár P., Mitrík D. Prediction of fatigue fractures diffusion on the cableway haul rope. Engineering Failure Analysis. 2016;59:185-196, https://doi.org/10.1016/j.engfailanal.2015.10.006

14. Collini L., Degasperi F. MRT detection of fretting fatigue cracks in a cableway locked coil rope. Case Studies in Nondestructive Testing and Evaluation. 2014;2:64-70. https://doi.org/10.1016/j.csndt.2014.09.001

15. Yanfei Kou, Jiujiang Guo, Jingjing Li, Shaoni Jiao, Jiquan Liu, Zhiwei Yan, Kun Zhu A New Detection Method of the Surface Broken Wires of the Steel Wire Rope Using an Eddy Current Differential Probe. IEEE Access. 2022;10:63619–63625. https://doi.org/10.1109/ACCESS.2022.3183097

16. Kumar K., Goyal D., Banwait S. S. Effect of Key Parameters on Fretting Behaviour of Wire Rope. Archives of Computational Methods in Engineering. 2020;27:549–561. https://doi.org/10.1007/s11831-019-09326-y

Received 11.01.2023

Revised 16.01.2023

Accepted 16.01.2023

About the Authors:

Panfilov, Aleksey V., associate professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), Cand. Sci. (Eng.), associate professor, ScopusID, ORCID, panfilov@ikcmvsl.ru

Nikolaev, Nikolay N., associate professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), Cand. Sci. (Eng.), associate professor, ResearcherID, ScopusID, ORCID, nnneks@yandex.ru

Yusupov, Aleksandr R., senior lecturer of the Robotics and Mechatronics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ORCID , temple_black@mail.ru

Korotkiy, Anatoliy A., head of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), Dr. Sci. (Eng.), professor, ScopusID, ORCID, korot@novoch.ru

Claimed contributorship

A. V. Panfilov: formulation of the basic concept, goals and objectives of the study; N. N. Nikolaev: data preparation, text preparation, conclusions formulation; A. R. Yusupov: data preparation, text preparation, illustrations preparation; A. A. Korotkiy: academic advising, analysis of the research results, revision of the text, correction of the conclusions.

Conflict of interest statement

The authors do not have any conflict of interest.

All authors have read and approved the final manuscript.