Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk
Acta Montanistica Slovaca

Innovative solution for the LHD loader intended for operation in low workings of underground mines

Łukasz BOŁOZ[1]*

Authors' affiliations and addresses:
[1] AGH University of Krakow, Department of Machinery Engineering and Transport,
A. Mickiewicza Av. 30, 30-059 Krakow, Poland
e-mail: boloz@agh.edu.pl

***Correspondence:**
Łukasz Bołoz, AGH University of Krakow, Department of Machinery Engineering and Transport, A. Mickiewicza Av. 30, 30-059 Krakow, Poland
phone: +48 617 30 71
e-mail: boloz@agh.edu.pl

How to cite this article:
Bołoz, Ł. (2024). Innovative solution for the LHD loader intended for operation in low workings of underground mines. *Acta Monstanistica Slovaca*, Volume 29 (3), 548-560

DOI:
https://doi.org/10.46544/AMS.v29i3.03

Abstract
The article presents the results of comparative numerical tests of typical operating systems of LHD loaders with a proprietary solution based on a patent. LHD loaders belong to the group of basic machines working in various operating systems, including room-and-pillar systems. Due to the thickness of the deposits, mining is frequently carried out in low workings. In the case of typical T-kinematic or Z-kinematic systems, the operation of LHD loaders is more difficult. Due to the low height of the excavation, the excavated material is loaded in several cycles. A smaller machine generates less thrust force, which also negatively affects loading efficiency. Additionally, there are typical operational problems associated with the use of hydraulic actuators, the piston rods of which are exposed to mechanical damage and loss of tightness. In the presented proprietary solution of the working system, the bucket is attached to a telescopic boom system moved by hydraulic rotary actuators (Saga et al., 2019). Moreover, the loader is equipped with spreaders to stabilize the machine. The use of rotary actuators and a lowered pivot point of the bucket, together with a telescopic arm and spreaders, allows the bucket to be loaded in one cycle. In the article, the results of simulation tests of three kinematic systems have been presented. The analysis included, among others, the movement of the bucket, the duration of the cycle, and the related demand for hydraulic oil, as well as the load on the most important structural elements and nodes. The research has shown that the proposed solution can successfully compete with classic systems in terms of load and oil demand while offering an advantage in terms of functionality.

Keywords
LHD loaders, low workings, Z-kinematic system, T-kinematic system, model tests, dynamic tests.

Introduction

In the exploitation of deposits in underground mines, activities related to the loading and transporting of mined material are hard and labor-intensive. In modern mines, these processes are almost entirely mechanized. Only minor auxiliary or ad hoc works are performed manually. Many mining systems worldwide use articulated self-propelled mining machines, including articulated bucket loaders, abbreviated as LHD, after the processes performed (loading, hauling, dumping). The widespread use of self-propelled machines was determined by their high speed and easy maneuverability. LHD loaders are adapted to the changing work front, the height of workings, large slopes of the floor, and cooperation with other means of transport. At the same time, they move quickly to any area of the mine. These machines can work independently or cooperate with transfer points, haul trucks, or conveyors.

LHD loaders are widely used in underground mines of metal ores, including copper ones. The principle of operation and construction of mining loaders is similar to that of universal bucket loaders used in the construction industry. The difference lies in the fact that underground mining machines are low and elongated, and the operator's cabin, to facilitate forward and reverse driving, is placed on the side while the operator sits perpendicular to the direction of travel. In addition, the rear and front parts are connected by a joint, which increases the maneuverability of the machine (Korski et al., 2023). The LHD loader consists of a so-called engine unit and a payload unit *II*, to which the kinematic system with the bucket is attached (Fig. 1). The engine unit and the payload unit are connected by the so-called center articulation (orange axle).

Typical LHD loaders use a Z-kinematic or T-kinematic system (Fig. 1). When working in low excavations, LHD loaders display a number of drawbacks, which reduce their work efficiency. The solution to these problems is the proposed proprietary design of the LHD loader, especially its working system.

Front-discharge bucket loaders can be equipped with various operating systems. In the case of loaders for underground mining, it is usually the Z- and T-kinematic system. The most frequently applied is the Z-kinematic system, which is a simple solution with a small number of components but performs its functions well.

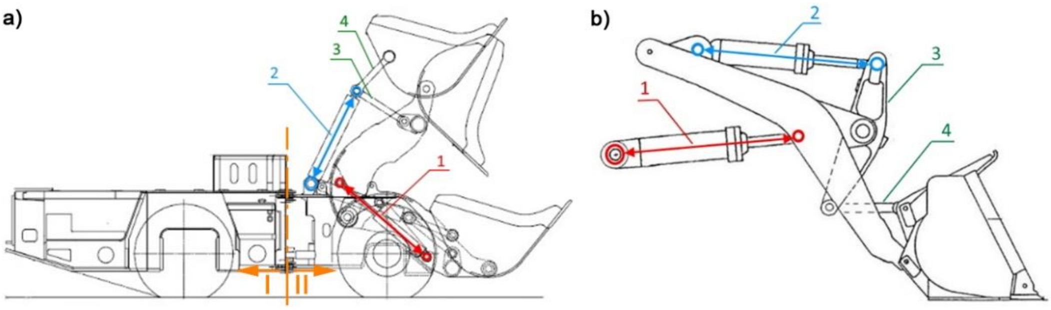

Fig. 1. Typical working systems of LHD loaders: a. T-kinematic, b. Z-kinematic - description in the text

In the Z-kinematic system, the boom with the bucket is lifted using the hydraulic actuator 1, while the bucket itself is rotated by the hydraulic actuator 2 and the system of levers 3 and 4. This design allows for more efficient bucket maneuvering in extreme positions and requires less force to turn the bucket.

The T-kinematic system is similar to a parallel system of units and is used much less frequently than the Z-kinematic system. This structure is characterized by reduced load on the system elements (bearings, pins, connectors). Another feature of this design is the reduced torque for bucket rotation, which is compensated by the use of a larger bucket rotation actuator. In the T-kinematic system, the main movements, i.e., lifting the boom arm with the bucket, are carried out by the hydraulic actuator *1*. The bucket is rotated by the movement of the hydraulic actuator *2*, which is connected to it by connector *4* and auxiliary connector *3*.

An example of the LKP-0301 loader from KGHM ZANAM S.A. with the Z-kinematic system is shown in Fig. 2, whereas Fig. 3 shows the LF-3 loader with the T-kinematic system from GHH Fahrzeuge GmbH.

Fig. 2. LKP-0301 loader with the Z-kinematic system, produced by KGHM ZANAM S.A. (KGHM Zanam, 2024)

Fig. 3. LF-3 loader with the T-kinematic system, produced by GHH Fahrzeuge GmbH (GHH Fahrzeuge, 2024)

Current state of the art

LHD loaders are used in various underground mines around the world. Depending on local conditions, they are developed in different directions, for instance, greater load capacity or smaller width. The problem of the height of machines used to exploit thin mineral deposits arose as early as forty years ago (Trueman, 1984). This problem still exists, and frequently, the only solution is to make excavations higher than the thickness of the deposit, which results in unnecessary exploitation of waste rock. The problem with LHD loaders working in low excavations is related to loading the bucket in a limited space, which requires several cycles of opening and closing the bucket so that the excavated material can slide to its bottom. In addition, a small loader is lighter, so the thrust force resulting from wheel adhesion is also limited.

In the field of numerical research, the first articles on the working system of LHD loaders date back to fifteen years ago (Li et al., 2007). Next, numerical tests were also used to simulate the operation of the remotely controlled loader (Jiang et al., 2022). Numerical studies, especially the Engineering Discrete Element Method (EDEM), were also used to optimize loading resistance by modifying the bucket trajectory (Meng et al., 2019). One can also find studies presenting the results of research based on an analytical model and a numerical model of a typical design of the LHD loader kinematic system (Kuric et al., 2022; Liang et al., 2023).

The development of LHD loaders is also moving towards battery power, as presented in two articles describing the effects of a project implemented in Poland (Bołoz, Kozłowski, and Horak, 2022; Korski et al., 2023). There are also studies regarding remote control and autonomous operation (Tampier, Mascaró and Ruiz-del-Solar, 2021; Kovanič et al., 2023), including modern sensor solutions (Inostroza, Parra-Tsunekawa, and Ruiz-del-Solar, 2023; Kovanič et al., 2024a; Kovanič et al., 2024b).

In order to develop a new working system solution, a detailed analysis of patent solutions for LHD loaders, especially their working systems, was carried out. None of the analyzed solutions was close to the one in question. However, it is worth paying attention to several completely different solutions, although they are also concerned with the working system of loaders. These solutions can be found in the Espacenet database by entering the numbers provided below (*Espacenet – patent search*, no date).

One of the inventions is a new loading solution that excludes the boom arm, which enables a direct self-load of the haul truck. This solution does not have a boom, and the movement is based on hydraulic actuators (EP3359746). Many subsequent patents offer new solutions for working systems other than the typical Z- and T-kinematic, which, however, are also based on hydraulic arms and actuators (JP2018199993, US20119003147, EP0036455, WO2018112211, SE531215, KR101299860, US2012128456).

Research methodology

The results described in the article are the effect of numerous activities carried out. The developed proprietary solution is the effect of conceptual work aimed at solving a number of common problems encountered in the currently used LHD loaders. Conceptual work was carried out in a 3D environment. An analysis of known solutions and patents was conducted to exclude the existence of a similar solution. These works, involving the examination of the state of the art and patent purity, were carried out using electronically available databases. As a result of these activities, patent protection was obtained after submitting a relevant application (Bołoz and Uchwat, no date). Further work required developing a design of the working system and alternative Z- and T-kinematic systems intended for a bucket with the same capacity. Next, model tests in the field of dynamics, loads, and FEM numerical tests were carried out. Calculations were carried out in accordance with the methodology found in the subject literature to load the bucket with forces and torques of appropriate value (Pieczonka, 2009). Calculations of the demand for hydraulic oil as a function of time were also performed. The results of the tests, especially those concerning the load, allowed the selection of specific hydraulic receivers and the preparation of a preliminary design of the working system.

Proprietary solution of the LHD loader working system

In the original design of the front loader for low underground mine workings, the classic kinematic system was replaced with a system based only on rotational movement, which can be affected by the use of hydraulic rotary actuators. Hydraulic rotators are compact hydraulic rotary actuators. The location of the bucket and arms pivot points has also been changed. In addition, telescopic arms of the bucket boom have been applied, and a set of hydraulic spreaders of the loader itself are located on the machine's payload unit.

The use of hydraulic rotary actuators eliminated the exposure of hydraulic cylinders, particularly their piston rods, which are frequently scratched, resulting in damage to the cylinder. Moving the axis of rotation of the boom arms downwards and the axis of rotation of the bucket inwards has improved the trajectory of the bucket's movement in low excavations and in the process of unloading the mined rock onto a haul truck or conveyor. The use of telescopic arms for the boom allows changing its length and, in consequence, loading the bucket only with the use of the arms. The additional use of hydraulic spreaders allows for increasing the force of the bucket's penetration into the pile of material by using these telescopic arms instead of the machine's pressure force. Hydraulic spreaders make it possible to stabilize the machine and increase the force of the bucket's penetration into the excavated material, which in the previous solutions was limited by wheel slip, especially in light loaders for low workings.

The main element of the lifting and rotation mechanism are telescopic arms, consisting of a fixed part (2) and an extendable part (3), connected by an in-built hydraulic actuator (4). The arm may have a prismatic or circular shape in cross-section. The circular cross-section of the arms allows the bucket to tilt to the side. On one side, the arms are connected to the payload unit (1) by means of hydraulic rotary actuators (5) and, on the other side, by means of hydraulic rotary actuators (6) to the bucket (7). The payload unit (1) is equipped with lower (8) and upper (9) hydraulic spreaders on both sides, allowing the machine to be stabilized in an excavation, especially in a low one. The rotary actuators (6) are located inside the bucket. For further simplicity, this arrangement was called 'O-kinematic'.

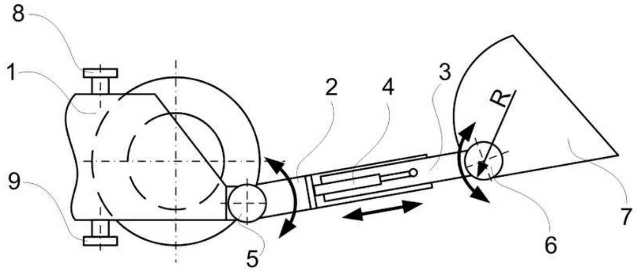

Fig. 4. Diagram of the payload unit and front loader, especially for low underground mining excavations

Comparative studies of kinematic systems

CAD (Computer Aided Design) programs, such as Autodesk Inventor Professional, enable carrying out complex dynamic tests, thanks to which it is possible to determine velocities, accelerations, as well as forces and torques at individual points and nodes of structural mechanisms already at the 3D design stage. At the same time, such tests allow for collision analysis and functionality assessment in cooperation with other machines. The obtained test results can be exported directly to the FEM module to perform numerical strength calculations.

Preparing a simulation

In order to perform a dynamic simulation, it was necessary to prepare a 3D design of all system elements, including the assignment of materials. Three kinematic systems with the same bucket lifting height and two buckets with a capacity of 1.6 m^3 were developed.

The Z-kinematic system was modeled on the LKP-0301 loader from KGHM ZANAM S.A. (Fig. 2). The T-kinematic system – on the LF-3 loader, produced by GHH Fahrzeuge GmbH (Fig. 3). The same buckets, differing only in their mounting points, were used for the Z- and T-kinematic systems. In contrast, in the case of the O-kinematic system, due to the necessity of installing the rotatory actuators inside, the bucket had to be enlarged in order to obtain the same capacity. Steel was assigned to all the elements, while the mass of the rotary actuators and cylinders was assigned in accordance with catalog data. The mass of hydraulic hoses and oil was omitted in all the systems.

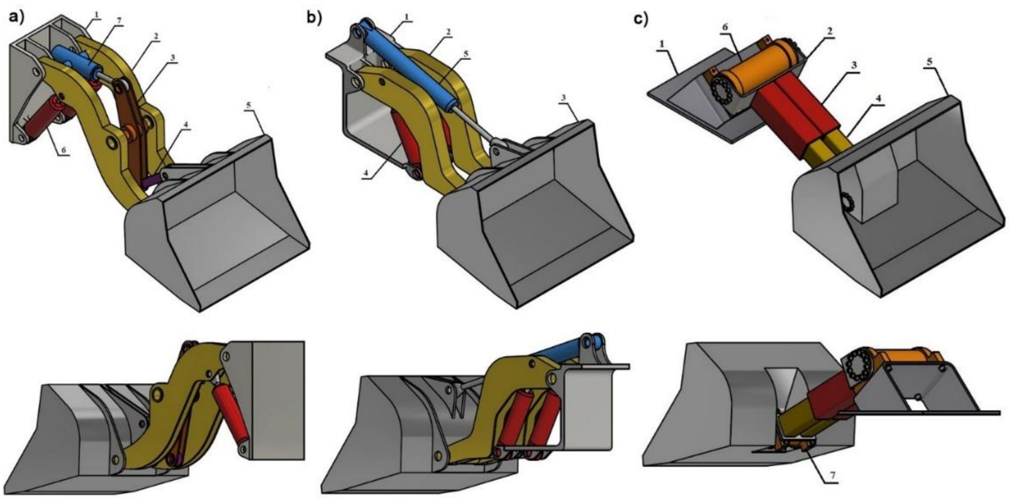

Fig. 5. Kinematic models of the LHD loader: a. Z-kinematic system, b. T-kinematic system, c. O-kinematic system (description in the text)

The Z-kinematic system consists of the following elements: 1 – base, 2 – arm, 3 – connector, 4 – tie rod, 5 – bucket, 6 – arm lifting cylinder, 7 – bucket rotary actuator. The T system consists of: 1 – base, 2 – arm, 3 – bucket, 4 – arm lifting cylinder, 5 – bucket rotary actuator, whereas the O-kinematic system is made up of: 1 – base, 2 – arm mounting, 3 – fixed arm, 4 – movable arm, 5 – bucket, 6 –arm lifting rotary actuator, 7 – bucket rotary actuator.

The next step was to create an assembly of mechanism elements using kinematic connections (Tlach et al., 2019). Kinematic connections consider the appropriate number of degrees of freedom and parameters such as friction and damping. In the analyzed case, rotary joints with one degree of freedom were mostly used. Additionally, prismatic connections were applied with one degree of freedom to ensure the cooperation of pistons with cylinders and the telescopic arms of the O-kinematic system. The finished mechanism was loaded (gravity, forces, and torques from the mining process) and set in motion.

During the simulation, all mass elements are affected by apparent forces (inertial, centrifugal). Depending on the assumptions and the purpose of the simulation, a distance, speed, force, or torque in the case of a rotary connection can be set (forced) in each kinematic connection. In the studies in question, the distance (feed, rotation) was set as a function of time to obtain the same duration of each cycle stage (closing, lifting, opening of the bucket). An example of the course of forcing the movement of the bucket rotation actuator of the Z-kinematic system has been presented in Fig. 6, whereas Fig. 7 shows the final stage of bucket lifting for the Z-, T-, and O-kinematic systems, respectively.

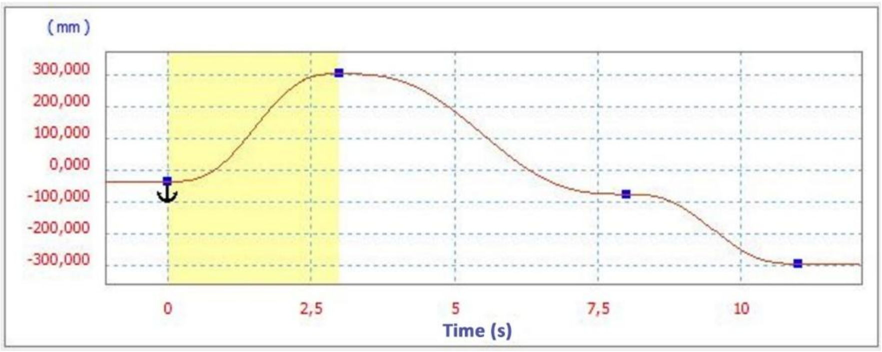

Fig. 6. Forcing the movement of the bucket rotation actuator of the Z-kinematic system

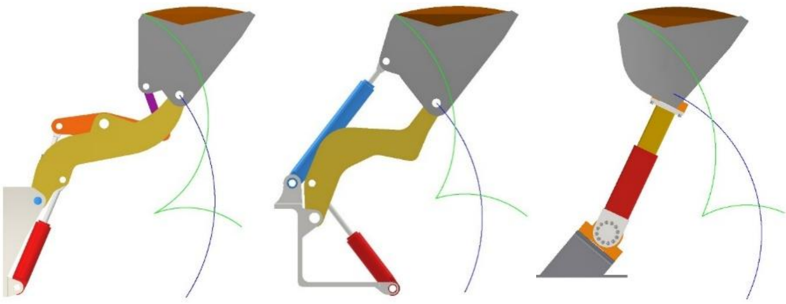

Fig. 7. Final stage of bucket lifting for the Z-, T- and O-kinematic systems

It was assumed that the loaded material was copper ore with a density of 2800 kg/m^3 and a loosening factor of 1.6, which resulted in a mass of 2.8 Mg for a full bucket. In addition, loads resulting from loading resistance were calculated as a function of the distance covered by the bucket in the mined rock pile in accordance with the methodology described in the literature (Pieczonka, 2009).

Required forces and torques

As a result of comprehensive simulation tests, a number of results, including the courses of force and torque values, were obtained. The forces and torques imposed on the cylinders and rotary actuators were analyzed in the first step. The charts below present the values of forces and torques imposed on the actuators at different time intervals, i.e., different cycle stages. The imposed forces and torques are values required to ensure the set movement. They depend not only on the mass of the excavated material and external loads (friction, resistance to penetration into the pile of excavated material) but also on the mass of the mechanism elements, their trajectories, and their set accelerations.

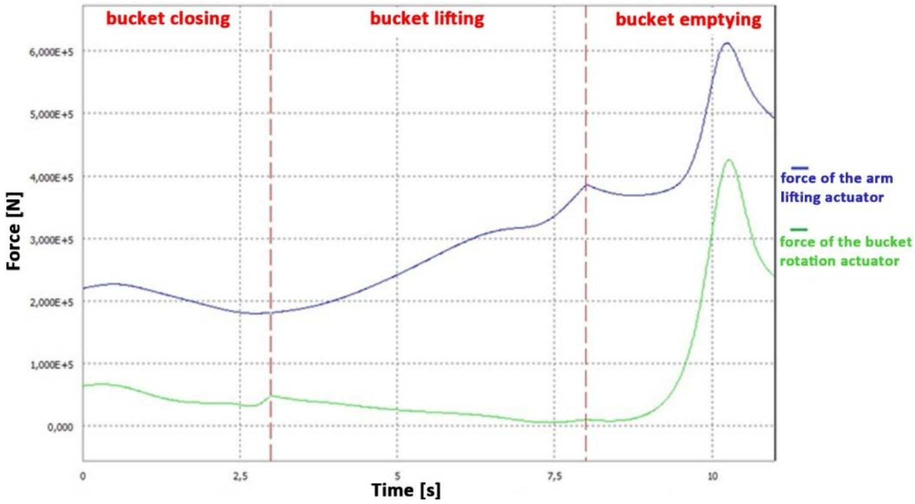

Fig. 8. Z-kinematic system - a graph of the forces imposed on the actuators versus time

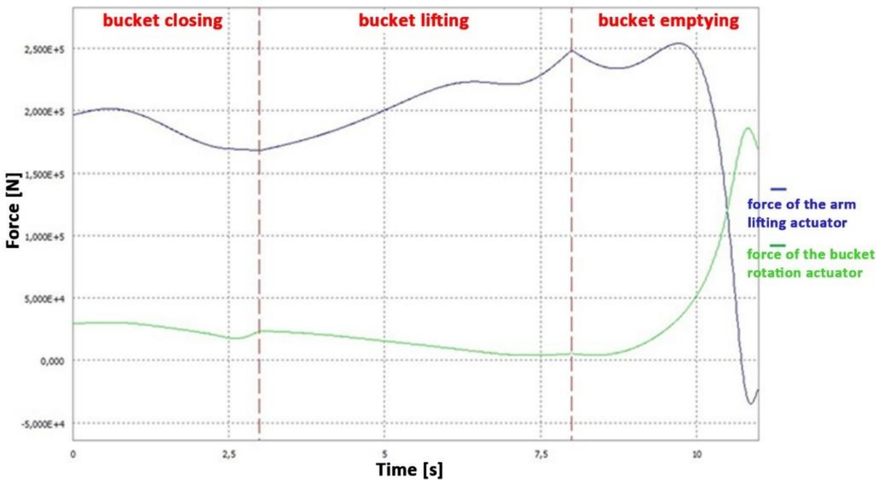

Fig. 9. T-kinematic system - a graph of the forces imposed on the actuators versus time

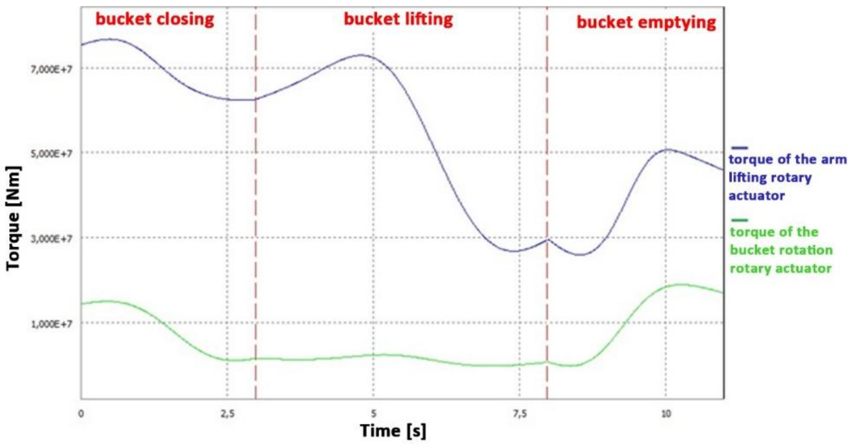

Fig. 10. O-kinematic system - a graph of the torques imposed on the actuators versus time

The diagrams of the forces needed to operate the mechanism in a given cycle clearly indicate that the greatest force is required when emptying the bucket (damping). This is related to the change in the position of the bucket's center of gravity and the arrangement of the actuators' mountings. An increase in the force needed to rotate the bucket in its final emptying stage is particularly noticeable. In the case of the Z-kinematic system (Fig. 8) and T-kinematic system (Fig. 9), the difference is significant, as the earlier stage requires a minimum value of the force in rotation actuators. It can also be noticed that the Z-kinematic system requires higher values of forces generated by the actuators than the T-kinematic system. The values of forces needed to rotate and lift the bucket for the T-kinematic system are more than twice higher than in the case of the Z-kinematic system.

In the O-kinematic system (Fig. 10), the increase in torque needed to empty the bucket is not so significant, exceeding slightly the value required for closing the bucket. Tab. 1 presents the maximum values of forces and torques for each receiver and system.

Tab. 1. Maximum values of forces and torques in three cycles

		Bucket closing	Bucket lifting	Bucket emptying
Z-kinematic system	Lifting cylinder	227 kN	386.4 kN	612.7 kN
	Rotation actuator	66.7 kN	48.5 kN	426 kN
T-kinematic system	Lifting cylinder	201.6 kN	248.6 kN	254 kN
	Rotation actuator	30.4 kN	23.5 kN	186 kN
O-kinematic system	Lifting rotary actuator	77.7 kNm	72.9 kNm	50.6 kNm
	Rotation rotary actuator	15.8 kNm	2.4 kNm	18.8 kNm

Speed of movement of hydraulic receivers

The next stage of tests was to determine the linear and angular speed of the hydraulic actuating elements in each system. The charts below present their courses at subsequent time intervals.

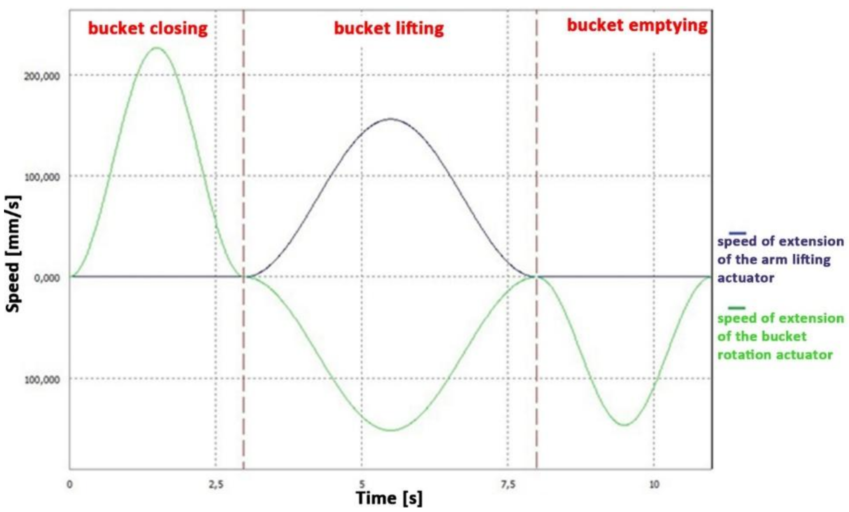

Fig. 11. Z-kinematic system - a graph of the speed of actuator extension versus time

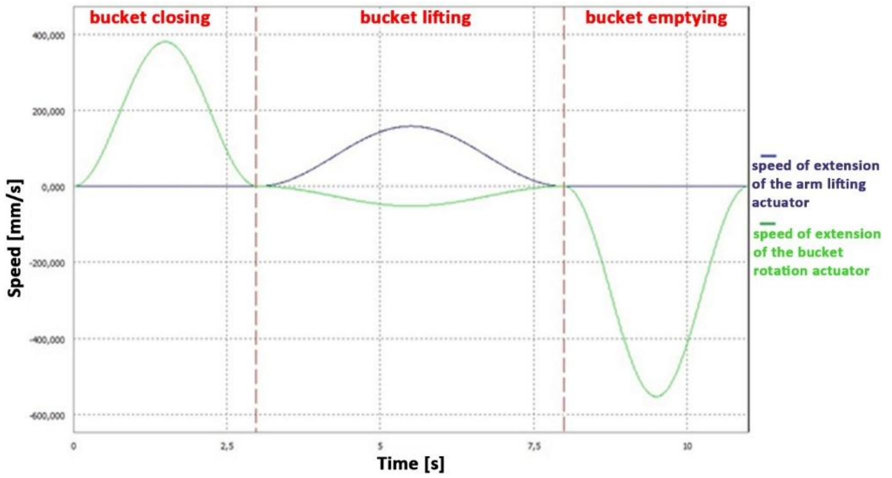

Fig. 12. T-kinematic system - a graph of the speed of actuator extension versus time

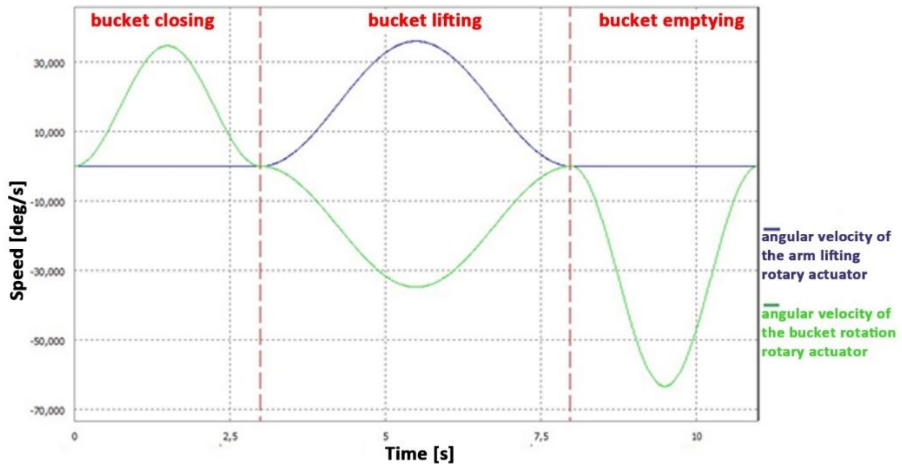

Fig. 13. O-kinematic system - a graph of the angular velocity of the rotary actuators versus time

The above graphs can be used to read the values of the speed of movement of cylinders and hydraulic rotary actuators that the mechanism needs to perform each movement in a specific time. One can compare the speed of Z-kinematic actuators (Fig. 11) with that of the actuators in the T-kinematic system (Fig. 12). The values differ significantly, which is related to different translations of the actuators' movement into the movement of the bucket (mounting points of the actuators and connectors). The T-kinematic system requires a greater extension of the actuators at the same time. Hence, its actuators must have a higher speed for both closing and opening the bucket. Due to the rotational movement of the rotary actuators, the O-kinematic system cannot be directly compared to other systems. However, the curves obtained for all three systems allow for the calculation of the required demand for hydraulic oil, which can be directly compared with each other. Tab. 2 lists the maximum speed values for each receiver and system.

Tab. 2. Summary of maximum speed values in three cycles

		Bucket closing	Bucket lifting	Bucket emptying
Z-kinematic system	Lifting actuator	-	156 mm/s	-
	Rotation actuator	226.7 mm/s	152 mm/s	146.7 mm/s
T-kinematic system	Lifting actuator	-	158 mm/s	-
	Rotation actuator	380 mm/s	152 mm/s	553.336 mm/s
O-kinematic system	Lifting actuator	-	36 deg/s	-
	Rotation rotary actuator	38 deg/s	34.8 deg/s	63.33 deg/s

Required flow rate of hydraulic oil

Based on the previously obtained simulation results, the maximum required values of forces and torques, as well as the required range of motion (linear or angular), were determined. Based on these values, cylinders and rotary actuators were selected, which allowed the required demand for hydraulic oil to be calculated. The obtained results, in the form of a graph showing the values of flow rate l/min (dm^3/min) during a full cycle, are presented in Fig. 14, whereas Tab. 3 shows maximum values for each cycle, system, and receiver, as well as the total required flow rate.

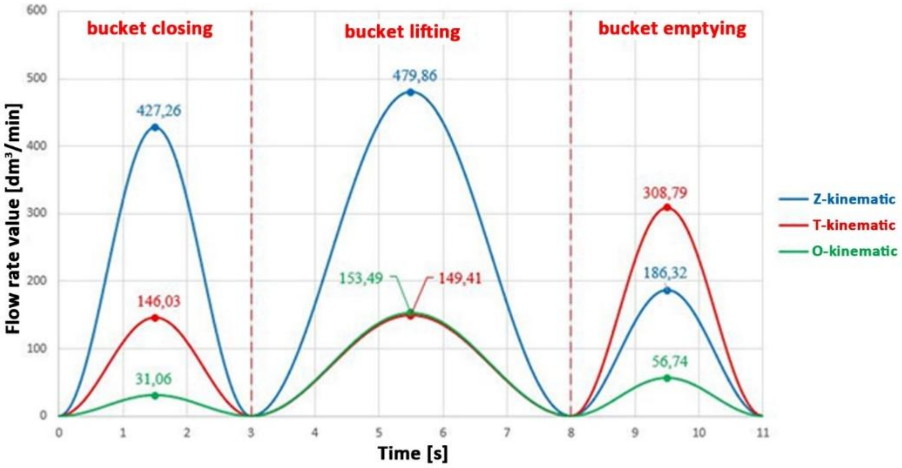

Fig. 14. Total values of hydraulic oil flow for both actuators

Tab. 3. Summary of flow rate values [l/min] in three cycles

		Bucket closing	Bucket lifting	Bucket emptying
Z-kinematic system	Lifting actuator	-	286.76	-
	Rotation actuator	427.26	193.10	186.32
	Total	427.26	479.86	186.32
T-kinematic system	Lifting actuator	-	120.39	-
	Rotation actuator	146.03	29.02	308.79
	Total	14603	149.41	308.79
O-kinematic system	Lifting rotary actuator	-	122.31	-
	Rotation rotary actuator	31.06	31.18	56.74
	Total	31.06	153.49	56.74

The curves of the oil flow rate values (Qazizada and Pivarciová, 2018) needed to operate the mechanisms clearly show that the mechanism in the Z-kinematic system, in most cases, has the highest demand for oil. Although the actuators must move at the highest speed in the T-kinematic system, such high flow rates are not required because lower forces are needed. A lower flow rate is achieved by using actuators with smaller diameters. Only when emptying the bucket does the T-kinematic system display higher flow values, i.e., when the bucket rotates outwards. The system, which is based on rotary actuators, has the great advantage of having the lowest flow rates. In nearly every cycle, these values are the lowest among the mechanisms studied.

Selected elements load

Each of the three systems was subjected to analysis under the load resulting from the bucket digging into the pile of spoil. This is the initial stage of filling the bucket, in which the bucket moves inwards without turning (Fig. 15). To perform such an analysis, it was necessary to calculate the total cutting resistance of the bucket per the previously mentioned calculation methodology. The force in pins 1 and 2 was analysed as marked in the diagram.

The cutting force increases almost linearly. Therefore, the load on the systems also changes in a similar way, which is visible in Fig. 16.

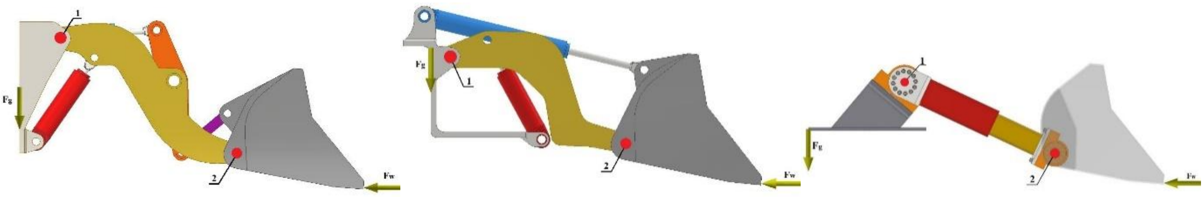

Fig. 15. Loading method and marking of measurement points for the Z-, T- and O-kinematic systems

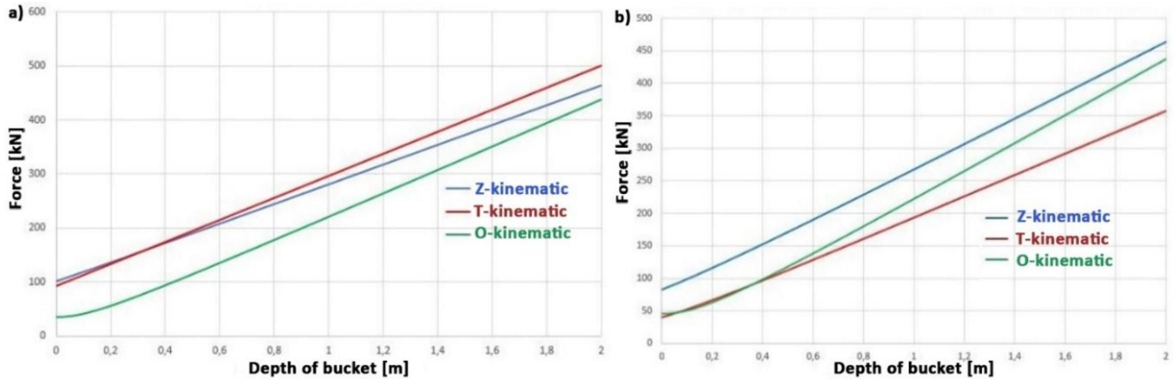

Fig. 16. Course of the values of forces in pin 1 (a) and 2 (b)

An analysis of the diagrams of forces in the pins allows for the noting that the greatest loads are generated in the axis of rotation of the arm (measuring point 1). Their highest values were recorded for the T-kinematic system, whereas in the bucket rotation axis (measuring point 2), the highest values can be observed in the case of the T-kinematic system.

The next step of the research was to determine the loads acting on the main elements of the mechanism (moment [kNm] in function of time [s]). Several dozen analyses and diagnostics (Stepanov and Nikitin, 2014) (Jóźwik et al., 2015) of the elements of the Z-, T-, and O-kinematic systems were carried out. The results of selected analyses have been summarized in the figures below (Fig. 17 - Fig. 20). They present the course of the values of torques and their location on the arm of subsequent systems. In the case of the O-kinematic system, two analyses were performed because the telescopic arm was divided into a fixed and extendable one. No legend for the values of stresses was provided, as the only purpose of these analyses was to estimate the load values. The map of stresses is shown only to illustrate their distribution. Analyses allowing for a quantitative assessment of strength require optimization of the arm design.

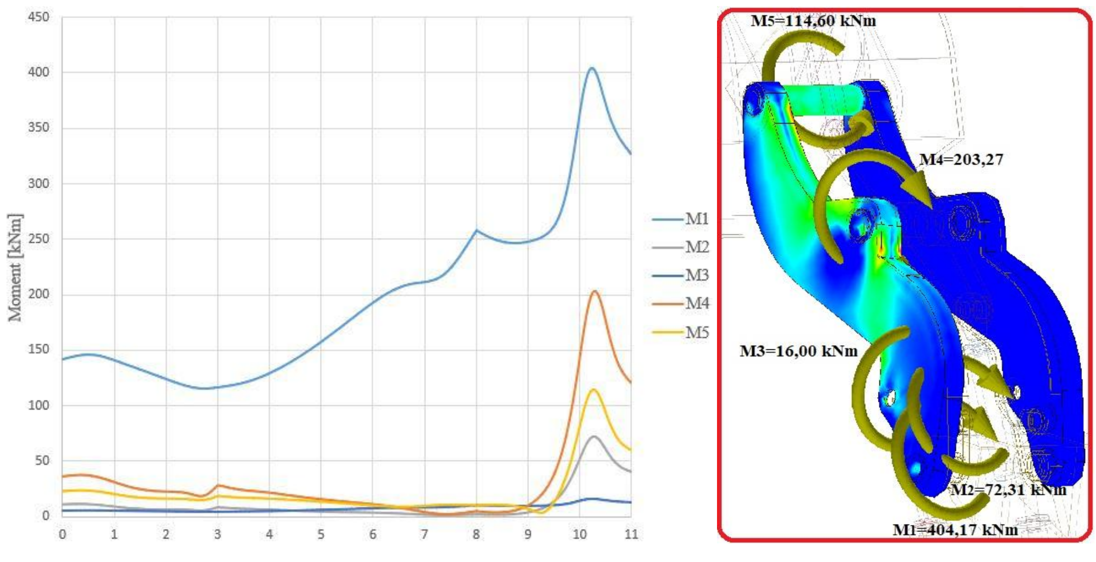

Fig. 17. Z-kinematic system – a course of the values of torques and their location on the arm

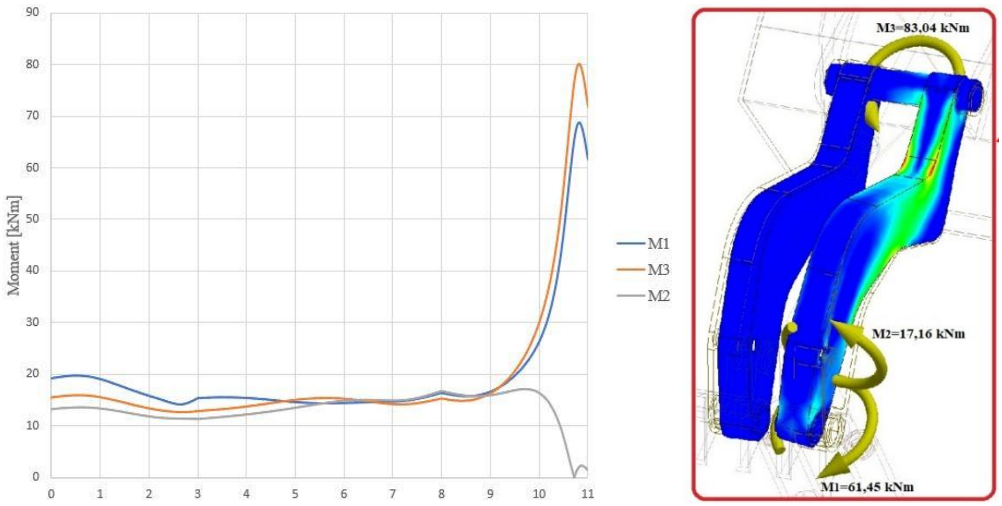

Fig. 18. T-kinematic system – a course of the values of torques and their location on the arm

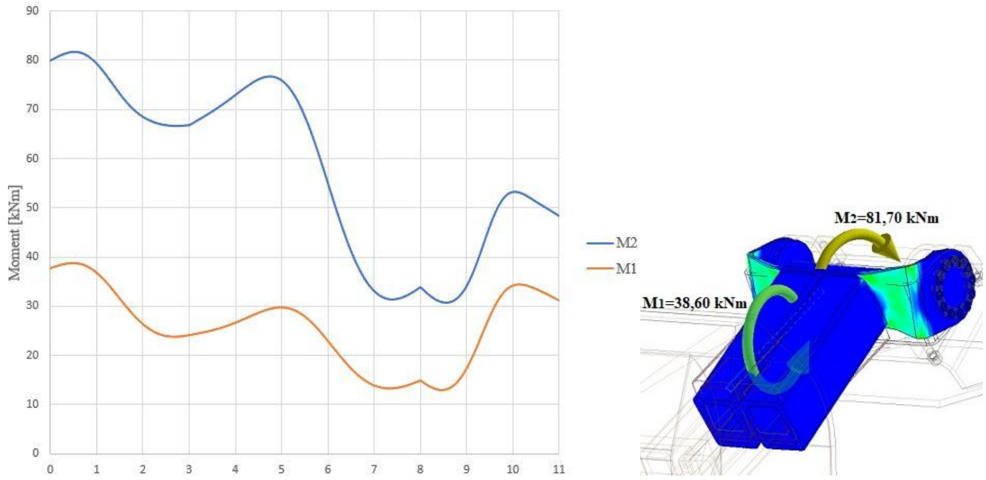

Fig. 19. O-kinematic system – a course of the values of torques and their location on the fixed arm

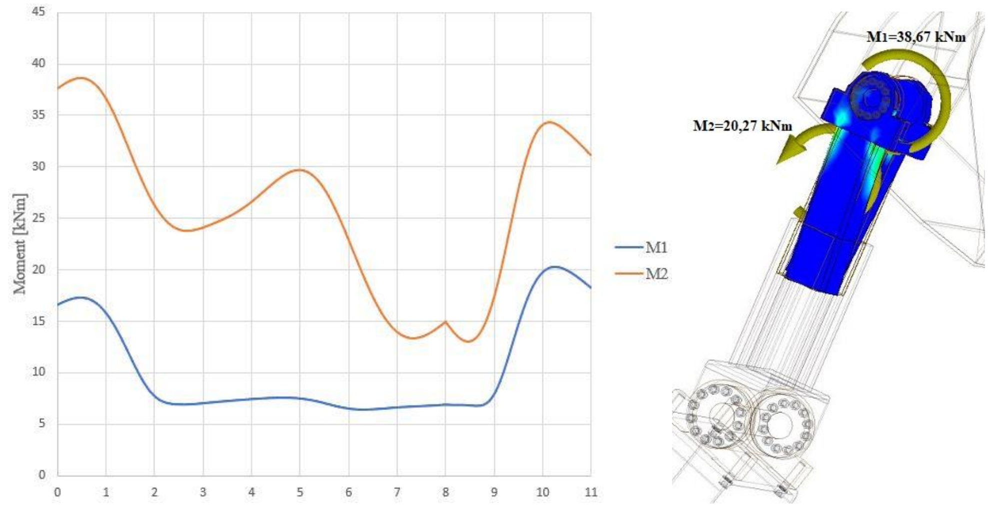

Fig. 20. O-kinematic system – a course of the values of torques and their location on the extendable arm

The above graphs show that the greatest loads on the elements occur in the Z-kinematic system. This is consistent with previous observations of forces generated by the actuators of both the lifting and rotation of the bucket. In the T-kinematic system, the loads on the elements are much lower. In practice, this influences the diameter of the pins and bearings needed or the possibility of achieving higher safety factors. The loads in the O-kinematic system are comparable to those in the T-kinematic system.

Summary

LHD loaders, which belong to the group of basic machines used in many underground mining systems, are constantly improved and developed. However, the typical Z- and T-kinematic systems developed many years ago have remained almost unchanged. When working in low excavations, classic loaders encounter a number of problems that reduce their effectiveness. The solution to these problems may be a special LHD loader designed to work in low excavations. Apart from a unique kinematic system based on hydraulic rotary actuators and equipped with additional telescopic arms, the proposed loader has optional spreaders.

The comprehensive simulation and analytical tests have demonstrated that the system based on hydraulic rotary actuators can compete with currently used solutions in various respects. There are fewer moving parts in this system. Uncovered actuators, which are vulnerable to damage, have also been eliminated. Particular attention should be paid to the demand for hydraulic oil flow, the value of which is much lower than in the other two systems. In addition, the Z-kinematic system requires the highest forces generated by the actuators, and its connections are the most loaded, which results in a greater bucket rotation torque. In the T-kinematic system, the undoubted advantage is the relatively lower load on the nodes, i.e., pins and bearings. Moreover, in the Z-kinematic system, the forces required in the actuators are lower, but this is at the expense of a larger stroke and, consequently, a larger oil flow to obtain the same cycle time. The O-kinematic system is characterized by forces in structural nodes comparable to those in the T-kinematic system, with a lower demand for hydraulic oil.

References

Bołoz, Ł., Kozłowski, A. and Horak, W. (2022) 'Assessment of the Stability of BEV LHD Loader', Management Systems in Production Engineering, 30(4), pp. 377–387. Available at: https://doi.org/10.2478/mspe-2022-0048.

Bołoz, Ł. and Uchwat, K. (no date) 'Ładowarka czołowa zwłaszcza do niskich, podziemnych wyrobisk górniczych'. Kraków.

Espacenet – patent search (no date). Available at: https://worldwide.espacenet.com/patent/ (Accessed: 3 July 2024).

GHH Fahrzeuge (2024) LHD - LF-3 Water cooled. Available at: https://ghhmm.co.za/lf3-lhd/ (Accessed: 10 July 2024).

Inostroza, F., Parra-Tsunekawa, I. and Ruiz-del-Solar, J. (2023) 'Robust Localization for Underground Mining Vehicles: An Application in a Room and Pillar Mine', SENSORS, 23(19), p. 8059. Available at: https://doi.org/10.3390/s23198059.

Jiang, Y. et al. (2022) 'Modeling and Simulation of Unmanned Driving System for Load Haul Dump Vehicles in Underground Mines', Sustainability, 14(22), p. 15186. Available at: https://doi.org/10.3390/su142215186.

Józwik, J., Semotiuk, L., Kuric, I. (2015) Diagnostic of cnc lathe with qc 20 ballbar system. ADVANCES IN SCIENCE AND TECHNOLOGY-RESEARCH JOURNAL. Volume 9, Issue 28, Page 96-102. DOI 10.12913/22998624/60793

KGHM Zanam (2024) Ładowarka kołowa – przegubowa LKP-0301. Available at: https://www.kghmzanam.com/produkty/maszyny-gornicze/ladowarki/lkp-0301-2/ (Accessed: 10 July 2024).

Korski, W. et al. (2023) 'Lightweight LHD BEV Loader with an Individual Drive for Each Wheel', Management Systems in Production Engineering, 31(3), pp. 281–290. Available at: https://doi.org/10.2478/mspe-2023-0031.

Kovanič, Ľ.; Štroner, M.; Urban, R.; Blišťan, P. Methodology and Results of Staged UAS Photogrammetric Rockslide Monitoring in the Alpine Terrain in High Tatras, Slovakia, after the Hydrological Event in 2022. *Land* 2023, *12*, 977. https://doi.org/10.3390/land12050977

Kovanič, Ľ.; Peťovský, P.; Topitzer, B.; Blišťan, P. Complex Methodology for Spatial Documentation of Geomorphological Changes and Geohazards in the Alpine Environment. *Land* 2024, *13*, 112. https://doi.org/10.3390/land13010112

Kovanič, Ľ.; Peťovský, P.; Topitzer, B.; Blišťan, P. Spatial Analysis of Point Clouds Obtained by SfM Photogrammetry and the TLS Method—Study in Quarry Environment. *Land* 2024, *13*, 614. https://doi.org/10.3390/land13050614

Kuric, I., Klacková, I., Domnina, K., Stenchlák, V., Saga, M. Implementation of predictive models in industrial machines with proposed automatic adaptation algorithm. APPLIED SCIENCES-BASEL, 2022, Volume 12, Issue4, DOI 10.3390/app12041853

Li, Y. et al. (2007) 'Three dimensional modeling of the working linkage of load-haul-dump loader', The International Journal of Advanced Manufacturing Technology, 32(9), pp. 856–862. Available at: https://doi.org/10.1007/s00170-006-0407-8.

Liang, G. et al. (2023) 'Dynamic Modeling and Analysis of Loader Working Mechanism Considering Cooperative Motion with the Vehicle Body', Machines, 11(1), p. 9. Available at: https://doi.org/10.3390/machines11010009.

Meng, Y. et al. (2019) 'Bucket Trajectory Optimization under the Automatic Scooping of LHD', Energies, 12(20), p. 3919. Available at: https://doi.org/10.3390/en12203919.

Pieczonka, K. (2009) . Inżynieria maszyn roboczych. Część 1. Podstawy urabiania, jazdy, podnoszenia i obrotu. II. Wrocław: Oficyna Wydaw. Politechniki Wrocławskiej.

Qazizada, M.E. and Pivarciová, E. (2018) 'Reliability of parallel and serial centrifugal pumps for dewatering in mining process', Acta Montanistica Slovaca 23 (2), pp. 141–152. Available at: https://actamont.tuke.sk/pdf/2018/n2/3qazizada.pdf

Saga M., Vasko M., Handrik M., Kopas P. (2019) Contribution to random vibration numerical simulation and optimisation of nonlinear mechanical systems. Scientific Journal of Silesian University of Technology-series Transport, Vol. 103, pp. 143-154. DOI: 10.20858/sjsutst. 2019.103.11, 2019

Stepanov, P. and Nikitin, Y. (2014) 'Diagnostics of Mechatronic Systems on the Basis of Neural Networks with High-Performance Data Collection', 10th International Conference on Mechatronics Mechatronics 2013: Recent Technological And Scientific Advances, pp. 433–440. Available at: https://link.springer.com/chapter/10.1007/978-3-319-02294-9_55

Tampier, C., Mascaró, M. and Ruiz-del-Solar, J. (2021) 'Autonomous Loading System for Load-Haul-Dump (LHD) Machines Used in Underground Mining', Applied Sciences, 11(18), p. 8718. Available at: https://doi.org/10.3390/app11188718.

Tlach, V., Kuric, I., Ságová, Z ., Zajacko, I. Collaborative assembly task realization using selected type of a human-robot interaction. 13TH INTERNATIONAL SCIENTIFIC CONFERENCE ON SUSTAINABLE, MODERN AND SAFE TRANSPORT (TRANSCOM 2019), Volume 40, Page 541-547. DOI 10.1016/j.trpro.2019.07.078

Trueman, R. (1984) 'An evaluation of the equipment used in South Africa for the bord-and-pillar mining of thin coal seams', JOURNAL OF THE SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY [Preprint].