ISSN 2223-3911

РОССИЙСКИЙ ИНДЕКС НАУЧНОГО ЦИТИРОВАНИЯ
Science Index

IPR SMART
Электронно-библиотечная система

INDUSTRIAL TECHNOLOGY AND ENGINEERING

№4 (53)
2024

ISSN 2223-3911

Industrial Technology and Engineering

№ 1 (50) 2024

The journal is being published since 2011, Periodicity: 4 issues per year

Editor in chief: *A. Bayeshov*

The Owner: Ministry of Education and Science of the Republic of Kazakhstan
Non-Profit Joint Stock Company «M. Auezov South Kazakhstan University»

Certificate of registration of the periodic printed publication and (or) news agency № 11566-Ж issued on 04.04.2011 by Ministry of Communication and Information of the Republic of Kazakhstan.
The journal is registered at the International Centre for Registration of serial editions (UNESCO, Paris, France) in June 2011 under registration number ISSN 2223-3911.

Address:
Tauke khan avenue, 5
160012 Shymkent, Kazakhstan
Phone/Fax: +7 (7252) 21-19-82/21-19-89.
E-mail: ite_sksu@mail.ru

2024, M. Auezov South Kazakhstan University *Printed in Kazakhstan*

Kazim Nadirov – Dr.Chem.Sc., Professor, M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. (22/7)
Saule Akhmetova – Cand.Tech.Sci., Associate Professor, Almaty Technological University, Almaty, Kazakhstan. (29/6)

Svetlana Yefremova – Dr.Tech.Sci., Professor, National Center on Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan, Almaty, Kazakhstan (17/6)

Irina Pochitalkina – Dr.Tech.Sc., Professor, D.I. Mendeleyev Russian Chemical and Technological University, Moscow, Russia. (31/5)

Malik Satayev – Dr.Tech.Sc., Professor, M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. (24/5)

Sergey Kalugin – Dr.Chem.Sci., Professor, Al Farabi Kazakh National University, Almaty, Kazakhstan (18/5)

Sarsenbek Turtabayev – Dr.Tech.Sci., Professor, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkistan, Kazakhstan (14/5)

Ulzhalgas Nazarbek – PhD Associate Professor, M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. (25/4)

Umirzak Dzhusipbekov - Dr.Chem.Sci., Professor, Institute of Chemical Sciences named after A.B. Bekturov, Corresponding member of National Academy of Science of the Republic of Kazakhstan, Almaty, Kazakhstan. (9/3)

Gulnora Ikhtiyarova - Dr.Chem.Sci., Professor, Tashkent State Technical University, Tashkent, Uzbekistan

IRSTI 06.75.02

INDICATORS FOR ASSESSING THE LEVEL OF ECONOMIC SECURITY OF SMALL BUSINESSES

Aidarova A.B.*, Bitemirov B.T.
M. Auezov South Kazakhstan University, Shymkent, Kazakhstan
[*]***Corresponding author's e-mail:*** ab_moon@mail.ru

ABSTRACT

In today's environment, the issue of economic security is increasingly important as businesses face a range of external and internal risks, while the competitive economic landscape conceals numerous potential threats. This situation necessitates that business managers develop a comprehensive system focused on enhancing economic security. To evaluate the effectiveness of an enterprise's economic security system, various indicators are used to identify weaknesses in its operations, outline key areas for improvement, and determine the most efficient strategies to enhance business performance. Currently, there is no unified approach for establishing threshold values for these economic security indicators. During times of economic crisis in Kazakhstan, the actual and forecasted quantitative measures for most of these indicators often fall significantly below the required economic security thresholds. This issue could be addressed by developing a methodological framework for defining indicators that take into account the unique aspects of a company's operations, such as its industry sector, capital structure, ownership type, and current organizational and technical capabilities.

The article suggests a system for developing enterprise economic security indicators, which are categorized into seven functional components: financial, production and technological, personnel, legislative and legal, information and analytical, environmental, and power security.

Keywords: economic security, enterprise, indicators, competition, risks, efficiency

INTRODUCTION

At the close of the 20th century, amid the processes of globalization and significant changes in the global political landscape, the importance of economic security became increasingly prominent. These changes, which involved the transformation of old centers of power and the emergence of new ones, along with other notable global shifts, heightened the need to address economic security. The widespread advancement of globalization across all aspects of life in modern nations has had a profound effect on the economic security of all entities involved in economic relations.

Economic security refers to a state in which the economy ensures a sufficient level of social, political, and defense stability, fostering the progressive development of the country while safeguarding its economic interests from potential external and internal threats[1].

As a result of the analysis of literary sources [2,3], the following levels of economic security were identified:

- international economic security;
- national economic security;
- economic security of a region (within the country);
- economic security of an organization (enterprise);
- economic security of an individual.

The development of the global economy and intensifying competition introduce new rules for enterprises, nations, regions, and other economic actors.

The current economic environment is shaped in such a way that no participant in economic activities can effectively address their economic and social challenges without considering security concerns, due to the significantly increased interdependence at all levels. As global interdependence grows, every country must address the question: how can it strike the right balance between an "open" economy and the protection of national interests? This question is particularly relevant for Kazakhstan in its current context.

The reality of Kazakhstan necessitates the creation of an economic security system for enterprises that ensures the protection of the essential interests of individuals and legal entities within the country.

MATERIALS AND METHODS

The methodological foundation is based on the theoretical concepts and practical contributions of both domestic and international scholars on the subject, as well as materials from scientific conferences.

RESULTS AND DISCUSSION

The economic security system of an enterprise is a state of legal, production relations and organizational ties, material and intellectual resources, which ensures the stability of functioning, financial and commercial success, progressive scientific, technical and social development.

The selection of its indicators is the fundamental element in the study of the economic security of the enterprise.

Indicators of economic security of an enterprise are indicators of the level of economic security of an enterprise, which allow to identify pain points in its activity, determine the main directions and the most effective ways to increase the efficiency of its work. It is possible to include those that quantitatively reflect the level of threat, endowed with a significant level of sensitivity and, accordingly, the ability to warn about the possibility of danger. In addition, it is advisable to use either a separate indicator or a system of indicators, with the help of which it becomes possible to determine the level of provision of individual internal components and/or functional components of the economic security of the enterprise, and in the future - to calculate its integral (general) indicator.

Scientists [4,5] believe that there cannot be a single unchanging list of indicators of economic safety of business, since each company has its own peculiarities in business activity. But the list of indicators can include only those whose value is one-dimensional, their limit values correspond to the principle of uniformity, are dimensionless (relative), satisfactory minimum values and permissible ranges of changes must be justified for the indicators, there must be an opportunity to compile a rating of enterprises, including in dynamics.

A general assessment of the level of economic security of the enterprise can be carried out on the basis of a comparison of the limit (critical and normal) and actual values of indicators, while it can be carried out on the basis of graphic analysis, which allows to distinguish the zone of normal, critical level of security and the pre-crisis zone.

The graphical representation of the obtained estimates enhances the understanding of the results and provides insight not only into the current state of the enterprise's economic security but also into the desired state it should strive for. This approach allows for the analysis of the factors influencing the current condition and development trends of the enterprise's economic security.

It is essential to emphasize that the highest level of economic security can be achieved only when the entire system of indicators remains within the permissible limits of their threshold values, and the limit values of one indicator are not compromised at the expense of others. Threshold values represent the critical limits, beyond which the normal development of various elements of reproduction is hindered, leading to the emergence of negative and destructive trends in economic security.

Based on the actual values of the indicators and their deviations from the threshold limits, the state of the enterprise's economic security can be characterized as follows:

- normal: when the indicators remain within the threshold values.
- pre-crisis: when the limit values of at least one indicator are exceeded.
- crisis: when the barrier value of most of the key indicators is exceeded.
- critical: when all barrier values are violated, both primary and secondary.

However, while this methodology has several advantages, it does not provide specific recommendations regarding the selection of estimation coefficients or the establishment of normative limits for the level of economic security.

It is logical that the goal of selecting a set of indicators to assess the level of economic security, establishing an information base, and calculating these indicators is to determine an integral indicator that collectively reflects the overall level of economic security. The analysis of the methodological approach to evaluating the level of economic security of an enterprise allows for the identification of specific indicators (as shown in Table 1) that are used in this process.

Table 1 – Indicators of the level of economic security of the enterprise

Components of economic security	Indicators
Financial component	1. Excess or deficiency: - own working capital; - own working capital and long-term loan sources for the formation of stocks; - the total value of the main sources of formation of reserves
	2. Profitability
	3. Business activity
	4. Financial sustainability
	5. Solvency

Table 1 continuation

Personnelcomponent	1. Indicatorofpersonnelturnover
	2. Coefficient of qualification of employees of the enterprise
	3. Indicatorofinventiveactivity
	4. Share of the company's income from the use of intellectual property
	5. Level of discipline
Production andtechnologicalcomponent	1. The level of technological progress
	2. Level ofproductprogressivity
	3. Level oftechnologicalpotential
	4. Capital-laborratio
	5. Fixedassetsdisposalrate
	6. Fixedcapitalrenewalrate
	7. Product defectrate
	8. Return onfixedassets
	9. Materialconsumption
	10. Depreciation rate of fixed assets
	11. Capacityutilisationlevel
	13. Investment ratio
Legislativeandlegalcomponent	1. Share of enterprise contracts for which legal cases have been opened in the total number of enterprise business contracts
	2. Share of received fines in the total amount of obligations under business contracts of the enterprise
	3. The proportion of paid fines in the total amount
Informationalandanalyticalcomponent	1. Information completenesscoefficient
	2. Information accuracycoefficient
	3. Information inconsistencycoefficient
	4. Information productivity
	5. Information supportcoefficient
	6. Information securitycoefficient
Ecological component	1. Product safetycoefficient
	2. Coefficient of "ecological ballast"
	3. Coefficient of rational waste utilization
	4. Profitability of products made from waste
	5. Environmentalpollutioncoefficient
	6. Degreeofenvironmentalpollution
	7. Environmentalprotectionindicator
Power component	1. Transport safetycoefficient
	2. Property and personnel security coefficient

At present, there is no unified approach to determining the threshold values for economic security indicators of an enterprise. Researchers and academic groups have different viewpoints: some suggest implementing a single threshold value for the indicator, which would result in two possible states: one indicating heightened security threats, and the other representing normal conditions. Others advocate for multi-threshold systems, where each indicator is assigned three or more threshold levels, leading to a greater number of potential security states.

Calculating an integrated indicator allows for forecasting economic security threats and effectively managing the volume and structure of expenses related to economic security. This approach can positively influence the overall financial health of the enterprise and, ultimately, contribute to the recovery of the national economy.

CONCLUSION

At the time of crisis in the economy of the Republic of Kazakhstan, the forecast and actual quantitative values for most indicators are considerably worse than the required threshold values for economic security. However, it is not feasible to simply adjust the threshold values to match the forecast and actual parameters. The deviations between these parameters and the threshold values are precisely what indicate the level of threats to economic security and guide the process of addressing them. It is crucial to continuously monitor these deviations and take measures to minimize potential negative impacts.

One possible solution is to develop a methodological framework for establishing indicators that take into account the specific characteristics of a company's operations, such as its industry, structural capital, ownership form, and existing organizational and technical capabilities.

REFERENCES

1. Dvorjadkina E.B., Novikova N.V. Jekonomicheskaja bezopasnost': ucheb. posobie / Ural. gos. jekon. un-t, Centr distancionnogo obrazovanija. – Ekaterinburg: Izd-vo Ural. gos. jekon. un-ta, 2010. – 177 s.

2. Gaponenko V.F., Bespal'ko A.L., Vlaskov A.S. Jekonomicheskaja bezopasnost' predprijatij. Podhody i principy. – M.: Izdatel'stvo «Os'–89», 2007. – 208 s.

3. Kolpakov V.A. Sistema jekonomicheskoj bezopasnosti firmy // Jelektronnyj nauchno-prakticheskij zhurnal «Jekonomika i menedzhment innovacionnyh tehnologij»: http://ekonomika.snauka.ru.

4. Ginis L.A. Ierarhicheskaja struktura sistemy jekonomicheskoj bezopasnosti: http://scjournal.ru/.

5. Chumarin I.G. Chto takoe kadrovaja bezopasnost' kompanii? // Kadry predprijatija. – № 2. – M.: Izd-vo «Delo i Servis», 2003.

IRSTI 06.71.03

ANALYSIS OF THE EXPORT POTENTIAL OF THE MANUFACTURING INDUSTRY OF THE REPUBLIC OF KAZAKHSTAN

Aidarova A.B.*, Alimbay B.Zh.
M. Auezov South Kazakhstan University, Shymkent, Kazakhstan
***Corresponding author's e-mail:** ab_moon@mail.ru*

ABSTRACT

The role of industrial enterprises in the global economy is of significant importance. Both developed and developing nations strive to enhance their economic strength by fostering a diverse range of industrial enterprises capable of producing goods that meet the needs of all market segments. Undoubtedly, the process of increasing the export potential of industrial enterprises is not without its challenges. However, it is evident that carefully planned, gradual development can serve as a catalyst for achieving this goal. In all developed nations, industrial enterprises also initially encountered various obstacles.

The study conducted revealed that, in the Republic of Kazakhstan, amid persistent economic challenges, the strategic approach to state support for the manufacturing industry has evolved. Furthermore, based on an analysis of the factors and trends affecting the industry's development, it was found that government measures aimed at improving the situation have contributed to a reduction in regional disparities regarding the number of operational enterprises, production scale within the manufacturing sector, and investment volumes.

Keywords: industry, manufacturing industry, sector, market, export potential, competitiveness

INTRODUCTION

Industrial enterprises serve as a key driver of national development. The expansion of production not only meets domestic demand for goods but also contributes to job creation across various sectors, thereby fostering growth in the service industry. For a nation capable of exporting competitive products abroad, the development of robust industrial enterprises is of paramount importance. To ensure that industrial enterprises can continuously produce goods that align with current market demands, it is essential for their economic potential to experience consistent growth.

In Kazakhstan, significant efforts are being made to enhance the export potential of industrial enterprises. These include beneficial reforms aimed at improving the efficiency of natural resource utilization, as well as the rational allocation of financial and labor resources, creating the necessary conditions for boosting the export potential of industrial enterprises.

The conceptualization of industrial policy, its key directions, and distinctive features in developing economies has been the focus of numerous studies by both foreign scholars (such as S. Kuznets, P. Krugman, D. Rodrik) and Russian researchers (including E. B. Lenchuk, A.

I. Tatarkina, etc.). The analysis of forms and instruments for implementing industrialization programs is addressed in the works of A. Andreoni, J. Lin, H.-J. Chang, and others [1]. In recent decades, governments have increasingly recognized the necessity of a "new industrialization" – the creation of conditions for innovative and industrial development –in many countries with emerging market economies, including Kazakhstan.

Since 2003, Kazakhstan has been developing strategies and state programs aimed at the innovative and industrial development of its industry, particularly the manufacturing sector. However, many of the target indicators set for the effectiveness of these programs were not only unmet but also proved to be lower than those of previous periods. In this context, it is crucial to identify the reasons behind the failure to achieve the established goals, as well as to outline the directions for improving the strategy for innovative and industrial development and the mechanisms for its implementation[2].

MATERIALS AND METHODS

The methods of scientific inquiry, including comparison and generalization, induction and deduction, as well as statistical analysis, are employed in this study. The research utilizes scientific publications by foreign and Russian economists, regulatory legal acts, and official statistical data.

RESULTS AND DISCUSSION

Before delving into the topic, it is essential to understand the nature of the term "potential." The concept of "potential" was first introduced in the late 1970s and early 1980s, and in contemporary conditions, it has become a crucial economic category. The concept of "enterprise potential" is based on one of the following approaches:

1. Potential as a set of means, factors of production, and opportunities.
2. Potential as a collection of resources.
3. Potential as an opportunity for development.

In our view, the potential of an enterprise should be understood as a collection of essential material and non-material resources, along with development opportunities, that enable the enterprise to produce competitive products and maximize consumer satisfaction under specific conditions.

Now, let us examine the concept of "economic potential." Among the contemporary approaches to defining this term, three primary directions can be identified:

- accounting approach;
- resource approach;
- performance approach.

Based on the above, we define economic potential as the entirety of available and unused assets and resources of an enterprise, along with the mechanisms that enable the enterprise to formulate and achieve the objectives of its strategic planning system in both domestic and international markets through the effective utilization of resources and opportunities. As we have outlined, a critical factor in ensuring the competitiveness of an enterprise is its foreign economic activities, particularly its export activities.

Export serves as an outcome of the enterprise's effective operation and is only achievable when its products can withstand competition in global markets. However, it is important to recognize that all forms of market entry are associated with certain risks. These risks can be mitigated through a comprehensive analysis of market characteristics, conditions, and the evaluation of the enterprise's export potential.

According to P.V. Manin [3], export potential should be categorized into general and local (private) types. Private export potential refers to the maximum capacity of an enterprise to produce and sell a specific product in a particular foreign market. In the concept of "general export potential," P.V. Manin includes the enterprise's overall capacity for export production, as well as its export and sales activities. The aggregate of the private export potentials of an industrial enterprise constitutes its general export potential. By detailing the concept of private export potential in relation to the types of goods and the markets in which they are sold, P.V. Manin identifies four distinct types of export potential:

1. Export potential of an existing product in a developed market.
2. Export potential of an existing product in a promising market.
3. Export potential of a new product in a developed market.
4. Export potential of a new product in a promising market.

This classification is based on the I. Ansoff matrix, a classic marketing tool whose limitations include a narrow focus on growth and reliance on just two characteristics.

Each country must continuously strive to enhance the competitiveness of its products in the global market.

The competitiveness of a product is a crucial element of economic potential, particularly in terms of its market competitiveness within its specific segment. As components of economic potential, we can consider a range of industries involved in the production of scientific and technical, industrial, agricultural, social, and construction products. The full realization of economic potential can only be achieved through the development of these components.

A market economy thrives on constant competition. Therefore, by increasing economic and export potential, a country can enhance its share in the global market.

In this context, we deemed it necessary to analyze the level of industrial development in Kazakhstan from 2019 to 2023.

In 2023, the country's enterprises produced industrial products worth 46,991,787 million tenge, with the physical volume index of industrial production being 104.4% compared to the previous year.

In 2023, the largest share of industrial production was accounted for by the manufacturing industry, which contributed 46.9% to the total volume of industrial output. The mining and quarrying industries followed as the second-largest contributors.

Let's analyze the economic indicators of the manufacturing industry(Table 1).

Table 1 - Dynamics of economic indicators of the manufacturing industry

	2019	2020	2021	2022	2023
Amount of industrial production, million tenge	11573350	13232696	17121392	21161830	22047486
Industrial production index compared to the previous year, in percent	105,8	104,1	104,7	103,6	104,0
Share of industry output in the total amount of industrial production, in percent	39,4	49,0	45,5	43,4	46,9
Number of enterprises and production facilities – total	9196	9245	9839	10492	10531
Of which: With the main type of activity	6798	6818	6921	7457	7790
Number of personnel in core business, thousand people	299,8	290,5	290,2	296,1	309,6

Table 1 continuation

Share of personnel employed in the industry's core activities in the total number of personnel employed in the industry's core activities, in percent	46,7	46,6	46,8	47,0	47,9
Average monthly salary of personnel of the main activity, tenge	210753	236040	278182	352086	416708
Ratio of the average monthly wages of the personnel of the main activity of the industry as a percentage to the average monthly wages of the personnel of the main activity of the industry	80,1	82,7	84,4	83,4	83,7
Profit (loss) before tax, million tenge	1640090	1932040	3542925	3055619	2890766
Profiability, in percent	14,0	13,7	21,8	12,1	14,1

Table 1 continuation

Investments in fixed assets, million tenge	1017089	1077819	1541742	1586872	1633025
As a percentage of the previous year	79,2	104,4	137,4	97,6	98,9

The amount of industrial production in 2023 increased by 10,474,136 million tengecompared to 2019, and the number of enterprises and industries increased by 1,335 units, the number of personnel in the main activity by 9.8 thousand people, the average monthly salary of personnel in the main activity by 205,955 tenge, profit (loss) before tax by 1,250,676 million tenge, profitability by 0.1%, investments in fixed assets by 615,936 million tenge[4].

Table 2 shows the volumes of exports of goods of medium and high technological complexity in the manufacturing industry.

Table 2 - Amount of exports of goods of medium and high technological complexity of the manufacturing industry

	2019	2020	2021	2022	2023
Amount of exports of goods of medium technological complexity of the manufacturing industry, million USD					
Republic of Kazakhstan	2865,8	2944,8	4088,9	4829,8	4467,5
Amount of exports of high-tech goods of the manufacturing industry, million USD					
Republic of Kazakhstan	3449,8	3746,6	4552,0	7924,1	9698,4
Share of large and medium-sized enterprises in the manufacturing industry using digital technologies, in percent					
Republic of Kazakhstan	4,8	6,1	7,8	12,9	16,4
Share of innovatively active enterprises in the manufacturing industry, in percent					
Republic of Kazakhstan	14,4	15,4	12,9	14,8	14,7

Let's analyze the volume of exports of goods of medium technological complexity of the manufacturing industry increased by 1601.7 million USD, the volume of exports of goods of high technological complexity of the manufacturing industry increased by 6248.6 million USD, and the share of large and medium-sized enterprises in the manufacturing industry using digital technologies increased by 11.6% in percentage, the share of innovatively active enterprises in the manufacturing industry increased by 0.3%[5].

Special new measures are envisaged to stimulate the export of medium- and high-tech products, including:

- reimbursement of exporters' expenses - expenses on advertising goods abroad, participation in foreign exhibitions (fairs, festivals, forums, congresses), production, translation and publication of catalogues distributed abroad, maintenance of branches, representative offices, warehouses, retail shelves abroad, registration of trademarks, delivery of goods to the final destination, etc.;

- reduction of the list of documents submitted to receive reimbursement of expenses (submission of waybills, certificates, etc. has been cancelled);
- extension of benefits for reimbursement of expenses to traders, distributors, etc.;
- establishment of a differentiated amount of reimbursement depending on the complexity of the exported goods (from 30% for low-end goods to 80% for high-end goods).

The decisions made by the Government of the Republic of Kazakhstan to stimulate consumer demand and improve the business environment are aimed at fostering economic growth and enhancing industrial development. These measures include the cancellation of more than 6,500 regulatory requirements across various sectors that were deemed inconsistent with the country's regulatory policy. Additionally, the government has significantly increased support for the real sector, raising the funding volume to 3.4 trillion tenge (approximately 7.2 billion dollars). These actions are designed to facilitate the creation of new production capacities and sustain the positive dynamics of innovative and industrial development in the country, particularly within the manufacturing sector[6].

CONCLUSION

Increasing the investment attractiveness of industrial enterprises plays a critical role in enhancing the economic and export potential of the country. Key initiatives include developing factors that attract foreign investors, further expanding legislation that supports the export activities of industrial enterprises, and facilitating their ability to achieve higher export potential. Additionally, the government aims to support activities focused on fostering innovation within manufacturing sectors, promoting the accelerated implementation of digital economy technologies across industries, and maintaining an optimal balance between socio-economic goals and industrial development. This includes addressing the social provisions of industrial policy to ensure sustainable growth and broad-based benefits from industrial advancements.

REFERENCES

1 Kuznets S. Modern Economic Growth. New Haven, CT: Yale University Press, 1966. 529 p
2 O promyshlennoj politike. Zakon Respubliki Kazahstan ot 27 dekabrja 2021 goda № 86-VII ZRK.
3 Manin P.V. Upravlenie jeksportnym potencialom promyshlennyh predprijatij (na primere Respubliki Mordovija): dis. … kand. jekon. nauk. Tol'jatti, 2005. 245 s
4 Promyshlennost' Respubliki Kazahstan / ctatisticheskij sbornik / na russkom jazyke / 194 s. Astana, 2024
5 Kazahstan v 2023 godu / statisticheskij ezhegodnik / na russkom jazyke / 273 s. Astana, 2024
6 Vlaskin G.A., Lenchuk E.B. Promyshlennaja politika v uslovijah perehoda k innovacionnoj jekonomike. M.: Nauka, 2006. 245 s.

IRSTI 61.13.15

INVESTIGATION OF A LITHIUM CHLORIDE EXTRACTION PROCESS FROM HYDROMINERAL RAW MATERIAL

Anarbayev A.A.[*], Kabylbekova B.N., Ulbekova M.M., Tleuova S.T., Anarbayev N.A.

M. Auezov South Kazakhstan State University, Shymkent, Kazakhstan
[*]Corresponding Author's Email: abib_28@mail.ru

ABSTRACT

The purpose of the research is to create technology for processing hydromineral raw material to produce lithium salts and rare earth elements, to develop a highly efficient technology for products of lithium, lithium compounds and rare earth elements of the Aral region of Kazakhstan.

The chemical and mineralogical compositions of hydromineral raw material of the Aral region lakes have been studied by method of precipitation. The conditions for obtainment of lithium concentrates have been studied. Conditions for lithium minerals concentration and production of concentrates for lithium chloride extraction have been studied. Purification of lithium concentrates off calcium and magnesium ions and chemical composition of hydromineral raw material, effective methods of lithium precipitation in the form of lithium carbonate, its purification off Ca^{2+}, Mg^{2+} impurities by method of precipitation have been studied. The extraction methods for processing lithium-containing sediments and sorption methods of lithium extraction from brines have been studied. Water-salt systems have been studied for the directed search of effective methods for obtainment of lithium salts from brine and sediments of salt lakes.

Key words: hydromineral raw material, salt solution, sludge, lithium chloride, brine, extraction.

INTRODUCTION

Lithium is the lightest alkali metal and is considered to be the "future and strategic metal" widely used in the fields of porcelain and glass production, refrigeration engineering, metallurgy, medicine, aerospace industry, defense industry, nuclear energy, electronics, alloys and batteries, etc. Lithium resources exist in nature either in solid ores or liquid brine. However, the limited reserves of solid lithium ores and high expenses incidental to its extraction, indicate that lithium isolation /extraction from salts will be the future trend.

From among rare metals, lithium and its compounds are widely used in the world. The annual demand for lithium is 65-70 thousand of tons. Large parts of lithium up to 80% are concentrated in natural waters. Therefore, foreign countries: the USA, Chile, Italy, Japan and others constantly conduct research on lithium isolation/extraction from specific natural waters, since the source of raw materials is groundwater which is cheap full-value raw material [1].

The largest deposits of lithium are known in granitic pegmatites of sodium-lithium type as lithium in nature is closely associated with sodium (due to the similarity of the energy characteristics of lithium ions and sodium ions), especially in deposits of residual crystallization. However, in recent years, deposits of sedimentary type and underground mineralized waters and waters of salt lakes become increasingly important [2, 3].

FMC Lithium Division from the United States, as well as SQM from Chile, are now the world market leaders ,each of them controls 30% of the world market of lithium. In South America, this metal is mined at the bottom of dried salt lakes. Numerous studies [4, 6] are devoted to extracting REE (rare earth elements) from brine and from solid deposits.

MATERIALS AND METHODS

Currently sorption methods are widely used in applied radiochemistry: in processing the irradiated nuclear fuel (INF), isolation and separation of rare-earth (REE) and transuranic elements (TUE), as well as in the processing liquid radioactive waste (LRW). Synthesized ion-exchange materials of the AXION series (Am, Pu) are gel phosphorus-nitrogen-containing ion-exchange polymers, which have a high selectivity related to REE and TUE ions in strongly acidic media. High perspective of the AXION ion-exchange materials for extraction of uranium, REE and TUE from nitrates, and also for indium extraction from waste of zinc producing units is presented.

Well-known scientists isolate/extract tantalum and niobium from concentrates by extraction method. Depending on the chosen scheme at the concentrating processing it is possible to obtain concentrates with a content of 20-45% of Nb_2O_5 and 2-4.5% of Ta_2O_5. Method of extraction from fluoride-sulphate solutions was used for isolation/ extraction and separation of niobium and tantalum. The effect of HF, H_2SO_4 consumption and other concentrate decomposition conditions on the transition of Ta, Nb and related elements into the solution, the effect of the volume ratio of the organic and aqueous phases of Vo:Vb, concentrations of HF and H_2SO_4 on the distribution of Ta, Nb and admixtures on the extraction operations, washing and re-extraction were studied. According to the research results a principal scheme was proposed [5]. Octanol-1 was used as an extractant. According to this scheme, the planned extraction of Ta and Nb in the solution during the concentrate decomposition is not less than 95% and 98%, respectively, into the finished product - 92% and 94%, respectively.

Isolation/extraction of lithium from hydromineral raw material is a necessary and topical task because of the limited ore reserves (the main reserves of lithium have been identified as associated with deposits of tantalum, niobium, wolfram and tin). Extraction, reagent or adsorption methods are used for lithium isolation/ extraction from solutions. Electro coagulation method with soluble iron-aluminum anodes was tested [6] to obtain lithium from the thermal waters of oil fields; the degree of lithium isolation/ extraction was 70.5%. The results obtained showed high performance and low energy intensity of the process. However, it requires further development. In particular, the issues of thickening, filteration and utilization of the isolated lithium-containing sediment have not been solved. Work continues on the isolation/extraction of lithium out of multicomponent solutions using chemisorption on aluminum hydroxide [7]. Lithium is precipitated using various aluminum-containing reagents: sodium hydroalumocarbonate (SHAC), active forms of aluminum hydroxide (AHO), soluble salts of aluminum, and various composite mixtures [6].

Methods for lithium extraction/ isolation from solutions of magnesium chloride by extraction, using an extractant with iron-containing tributyl phosphate, with addition of water-insoluble carboxylic acid and re-extraction of lithium with solution of hydrochloric acid with obtainment of the target product with low concentration on lithium are known [9].

A large deposit with proven reserves of lithium is located in the east of Kazakhstan - in the Kalbinsky Range. However, theoretically, a larger lithium deposit is located in the Aral Sea region - at the bottom of the dried-up sea**.** Information that lithium reserves are in the salt marshes of the Aral Sea region is mentioned in old Soviet reference books.

A significant part of lithium is found in lakes and lake slimes, ground waters, in sea water (1.5-10.5 wt. %). In the process of obtaining lithium salts from hydromineral raw material, inorganic and organic sorbents were used formerly, depending on lithium content in various forms of compounds. Isolation/extraction of lithium from complex mineral compounds was not always resolved successfully because of the low degree of lithium isolation into the commercial product.

The brine volume of the Southern and Northern Basin of Zhaksykylysh lake contains 40-60mg/l of Litium(not more than 0.2% of Mg^{2+}, not more than 0.4% of Ca^{2+}, not more than 1.2% of SO_4^{2-}), in slimes the content significantly exceeds and amounts 60-120mg/kg. In addition, the enrichment of brine to the required quality of lithium concentrate is necessary. The available reserves of hydromineral raw material (lakes and lake muds, brine and saline deposits) in the Aral region provide annual need in lithium.

Technological principles for the use of mineral raw material available in the Aral region will be developed taking into account the particular qualities of this hydromineral raw material. Modernization of chemical equipment is planned to ensure the integrated use of raw material according to non-waste technology.

RESULTS AND DISCUSSION

Brine of salt lakes of the Aral Sea region is used for the experiment, the composition of brine is presented in Table 1.

Table 1- Composition of the Zhaksykylysh field brine *

Number of sample	Sample 1	Sample 2	Sample 3	Sample 4
Li, mg/kg	262.50	259.25	312.94	280.28
B, mg/kg	101.93	87.40	749.75	700.58
Na, mg/kg	70639.89	68056.06	89061.57	82418.29
Mg, mg/kg	23513.36	22467.09	43707.03	39545.03
Ca, mg/kg	2110.24	1898.49	3536.85	2361.25
S, mg/kg	4314.42	4080.36	10058.80	5429.23
Fe, mg/kg	620.17	682.79	1424.15	581.04

*brine selected from different trajectories of the field

From the data in table 1, it follows that lithium content in the sample fluctuates within the limits of 128.38-263.50 mg/kg and rare-earth elements are almost insignificant.

For the experiment, a sample of the brine is averaged out, an aliquot is selected (table 2) and placed in a 100 ml flask, mounted on a magnetic stirrer with an rpm governor (set to 600 rpm), then butyl alcohol (30 ml) is added. The sample, consisting of a layer of alcohol and water, is stirred for the predetermined time. White precipitate, consisting of sodium chloride, falls out at the alcohol-water interface in the process of mixing with the use of anhydrous butanol.

After the predetermined time (table 2), the sample is put into a separating funnel, where after the separation of butanol and water, the lower aqueous layer is discharged. The alcohol layer is stripped to dryness in vacuum (water-jet air pump). The residual matter is “dried” off butanol traces in a drying oven at the temperature of 130°C.

The obtained precipitate was studied in an ICP device to determine lithium content, and according to the results obtained, the degree of lithium extraction was calculated. The precipitate was studied using SEM. The results of the experiment are presented in Table 2 and 3 and shown in Figure 1, 2 and 3.

Table 2 – Change in precipitation yield depending on the brine volume

V, ml	m, g	Time of extraction, min	Degree of LiCI extraction, %
10	0,3498	15	86.9
20	0,3032	15	84.4
30	0,3097	15	84.2
50	0,3031	15	83.9

From the data of Table 2 it can be seen that with an increase in the brine volume at fixed rate of flow of butyl alcohol extractant and time, the degree of lithium extraction gradually decreases. The degree of lithium extraction is 96.9% at the brine flow rate equal to 10 ml, the degree of lithium extraction decreases till 83.9% with the increase of the brine flow rate up to 50 ml.

Later, brine extraction was carried out in the time interval of 10-30 minutes. The results of the experiment are presented in table 3.

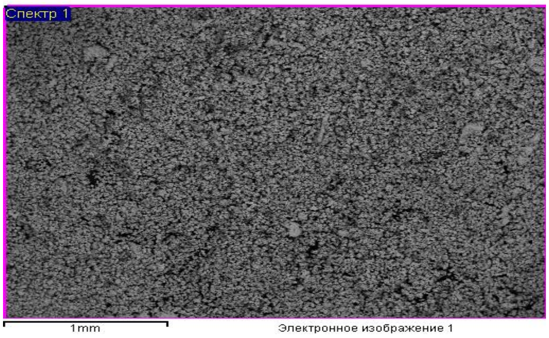
Table 3 – Dependence of the degree of lithium chloride extraction on the process time

No.	V_{sample}, ml	$V_{extragent}$, ml	Time of extraction, min	m, g	Degree of LiCI extraction, %
1	10	30	10	0.33	86.9
2	10	30	15	0.48	96.7
3	10	30	20	0.47	95.9
4	10	30	25	0.42	92.6
5	10	30	30	0.36	88.7

From data of table 3 it follows that at fixed rate flow of 10 ml of brine and volume of extractant equal to 30 ml and with an increase in the extraction duration, the degree of lithium

extraction gradually increases. At duration of 10 minutes, the degree of lithium extraction is 86.95, at 15 minutes it is 96.7%, and at further time equal to 30 minutes the degree of lithium extraction decreases and is 88.7%. It means that the highest degree of lithium extraction is reached during 15 minutes. At the same time at first the mass yield of the brine precipitate increases, then with increase of extraction time, the mass yield of the precipitate decreases.
The precipitate probably consists of salts of lithium chloride and sodium. To determine the composition of the precipitate after the separation of lithium chloride, the divided mass was studied on SEM. Fig. 1 presents the elemental analysis of precipitate.

Element	Weight %	Atomic %
O	4.64	8.25
Na	34.45	42.62
Mg	0.62	0.73
S	0.39	0.34
Cl	59.90	48.05



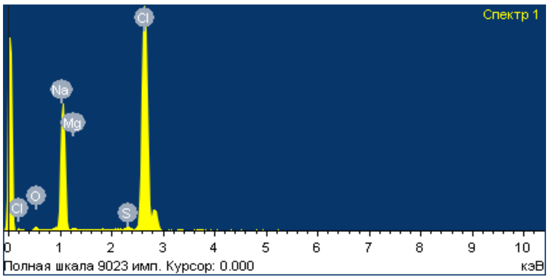


Fig. 1 - Elemental analysis of the precipitate obtained from brine of salt lakes of the Aral Sea region.

From Fig. 1 it is seen that the precipitate mainly consists of sodium and chlorine and a small amount of magnesium and sulfur.

CONCLUSION

Thus, the data received allow producing valuable products of lithium chloride and cooking salt from the brine of the Aral Sea saline lakes. At the same time, as the volume of brine increases at fixed rate of flow of butyl alcohol extractant and time, the degree of lithium extraction gradually decreases from 96.9% to 83.9%. With the fixed rate of flow of brine (10 ml) and volume of extractant (30 ml) and with an increase of extraction duration, the degree of lithium extraction gradually increases. With duration of 10 min up to 15 min it is 96.7 %, and with an increase in time up to 30 minutes the degree of lithium extraction from then on decreases to 88.7%.

REFERENCES

1 Ostroushko Yu.I., Degtyarova A.V. *Gidromineral'noye syr'yo neischerpayemyy istochnik litiya* [Hydromineral raw materials are an inexhaustible source of lithium]. – Moscow: TsNIIAtomInform, 1999. – 64 p.

2 Kogan V.I. *Redkiye metally. Sostoyaniye i perspektivy* [Rare metals. State and prospects]. Moscow, Nauka, 1979. 356 p.

3 Patent RU 2 515455. Gadzhiyev G.R., Bobrov A. F.*Sposob polucheniya adaptivno-selektivnogo k redkozemel'nym metallam ionoobmennogo materiala* [Method of obtaining an ion-exchange material adaptively- selective to rare-earth metals].Published: 10.05.2014. Bulletin No.13

4 Kondrutskiy D.A., Gadzhiyev G.R., Bobrov A.F., Tret'yakov V.A. *Novyye templatnyye ionoobmennyye materialy dlya izvlecheniya redkozemel'nykh i transuranovykh elementov iz kislykh sred* [New template ion-exchange materials for extraction of rare-earth and transuranium elements from acidic media]. V-Mezhdunarodnyy internet-simpozium po sorbtsii i ekstraktsii(v protsessakh pererabotki mineral'nogo syr'ya) Available: http://www.ich.dvo.ru/~isse/2012.

5 Nikolayev A.I., Koznov A.V., Glushchenko Yu.G., Mayorov V.G., Baltsat V.I., Nechayev A.V. *Ekstraktsiya tantala i niobiya v tekhnologii kolumbitovogo kontsentratazashikhinskogo mestorozhdeniya* [Extraction of Tantalum and Niobium in Columbite Concentrate Technology of Zashiinsky Deposit]. V Mezhdunarodnyy internet-simpoziumpo sorbtsii i ekstraktsii (v protsessakh pererabotki mineral'nogo syr'ya). Available: http://www.ich.dvo.ru/~isse/2012.

6 Litvinenko V.I., Varfolomeyev B.G. *Problemy osvoyeniya gidromineral'nogo syr'ya Timano-Pechorskoy neftegazonosnoy provintsii* [Problems of mastering hydromineral resources of the Timan-Pechora oil and gas province]. Mezhdunarodnaya konferentsiya-seminar “Voprosy teorii i praktiki geologicheskoy interpretatsii gravitatsionnykh, magnitnykh i elektricheskikh poley”: Materialy konferentsii. Ukhta: UII, 1998. P. 88-90.

7 Kan S.M., Murtazin Ye.ZH., Issabekov R.B. and others. *Analiz tekhnologiy izvlecheniya litiya iz prirodnykh rassolov*[Analysis of technologies for extracting lithium from natural brines]. News of the National Academy of Sciences of the Republic of Kazakhstan, Section 1, No. 416 (2016), pp.112-118.

8 Patent RU №2091306. Samoilov Yu.M., Isupov V.P. *Sposob izvlecheniya litiya iz rastvorov khlorida magniya* [Method of lithium extraction from magnesium chloride solutions]. C01D15/04; B01D11/04.27.09.1997.

IRSTI 61.13.21

OPTIMIZATION OF COMPLEX REACTOR SYSTEMS USING THE METHOD OF SITUATIONAL DECOMPOSITION

Khu Ven-Tsen, Кozhabekova P.A., Iztaev Zh.D., Baynazarova I.K.[*], Berkimbayeva G.C.

M. Auezov South Kazakhstan State University, Shymkent, Kazakhstan
[*]Corresponding Author's Email: b.k.indira@mail.ru

ABSTRACT

The problem of optimization of multi-element reactor systems with a continuous type of technological process within the framework of automated control systems is considered. The high complexity and multidimensionality of the emerging optimization problems make it difficult to apply traditional approaches based on a holistic view of the optimization object. Implemented in this case, the centralized approach to solving the optimization problem is highly costly because of the need for significant computing resources.

The proposed approach is characterized by using a structured representation of the reactor system with the subsequent structuring of the optimization problem. At the same time, the solution of the problem is assumed in the decentralized control system, consisting of a set of local control systems that operate autonomously, and coordinating their coordinating body. The desired optimum for the reactor system as a whole is achieved as a result of information exchange between local management systems and the coordinating authority. In the process of this interchange, local control systems solve optimization tasks for individual elements of the reactor system, taking into account the actions of the coordinating body, whereas the coordinating body solves the global task of optimizing the reactor system as a whole by properly coordinating solutions of local problems.

The positive effect of decentralization of management is achieved due to the fact that the emerging local optimization problems and the global coordination problem are much simpler than the initial task of controlling the reactor system. Therefore, their solutions are much less expensive in terms of consumed computing resources.

Keywords: complex technological system, mathematically method, optimization, system, account, coordination task, management system.

INTRODUCTION

To implement the decentralized approach, it is proposed to use the method of situational decomposition. This method provides ample opportunities for varying control, which does not impose special requirements on the structure of the original optimization problem, in contrast to the classical decomposition methods.

Reactor systems with a continuous type of technological process are characteristic for the majority of chemical, petrochemical, biological and allied industries. In this regard, their optimization in the automated control of the technological process is an important and urgent task.

In cases where the reactor system contains a small number of elements, its optimization is not particularly difficult on the basis of a well-established traditional approach, which uses a holistic view of the reactor system and a centralized approach to its optimization.

However, when the reactor system contains a large number of elements with numerous and diverse mutual relations, which is typical for technological processes in the scale of completed production and production associations, its optimization often turns into an intractable problem. Meanwhile, at the present time, it is the automated control systems that cover the completed production cycle that are ensuring its optimization.

The difficulties are caused by the fact that the emerging optimization problems usually have high dimensionality, a large number of complex constraints requiring consideration, so that their solution, involving traditional approaches in the conditions of centralized control systems, requires increased amounts of computing resources that significantly increase the cost of creating and maintaining such systems.

Elimination of these difficulties can be achieved through the use of a decentralized approach to the creation of a management system [1] based on the decomposition of the emerging optimization problem. The essence of decomposition methods lies in the fact that a complex multidimensional optimization problem reduces to an equivalent set of simpler problems that can be solved together. The resulting tasks include local optimization tasks for individual structural elements - the subsystems of the object under consideration and the global task of coordinating local tasks. Local and coordination tasks are solved jointly within the hierarchical iterative procedure of information interchange, in the process of which local tasks are solved autonomously taking into account the impacts generated in the process of solving the coordination problem. Whereas the solution of the coordination problem is to find such effects for local problems in which the coordinated solution of the latter causes the solution of the initial optimization problem.

The application of mathematical methods of decomposition is facilitated by the structural decomposition of the optimized object, i.e. its representation in the form of a complex technological system (CTS) (Fig. 1).

As an integral control object (Fig. 1), the STS is characterized by the following set of vector state parameters: w - external disturbances; u - controls; z - outputs. As a result of the structural decomposition, CTS is transferred to another state space, characterized by the states of its interconnected subsystems (Fig. 1b). Each i- subsystem (Fig. 1c) defines its state with the following vector coordinates: w - external disturbances, x - inputs that are outputs of other subsystems, u - controls, y - inputs that are inputs of other subsystems, z - outputs, which are also outputs of the CTS.

Structural decomposition allows us to represent the mathematical model of the CTS by a set of models of subsystems of the form:

$$y_i = g_i(w_i, x_i, u_i), \quad i = 1,2,\dots, N$$
$$w_i = \hat{g}_i(w_i, x_i, u_i), \quad i = 1,2,\dots, N. \tag{1}$$

In these models, the output outputs of the subsystems include their own output variables y_i, arriving at the inputs of other subsystems, and the variables w_i, identified with the outputs of the CTS, which also allow determination via the coordinates of the subsystem data. In the sequel, both of them will be considered jointly as generalized outputs of y_i. Separation of these into related and unrelated is possible in describing the mutual relationships between subsystems. Such descriptions, supplementing the models (1) to the full description of the CTS, can be represented in the form:

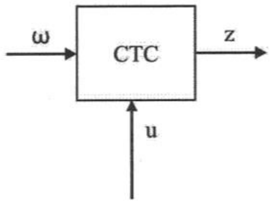
$$x_i = c_{ij} \cdot y_j, \quad i = 1,2,\ldots,N, \quad j = 1,2,\ldots,N, \quad i \neq j, \tag{2}$$

where c_{ij} is the operator that converts the outputs of the j-x subsystems to the inputs of the i-x subsystems.

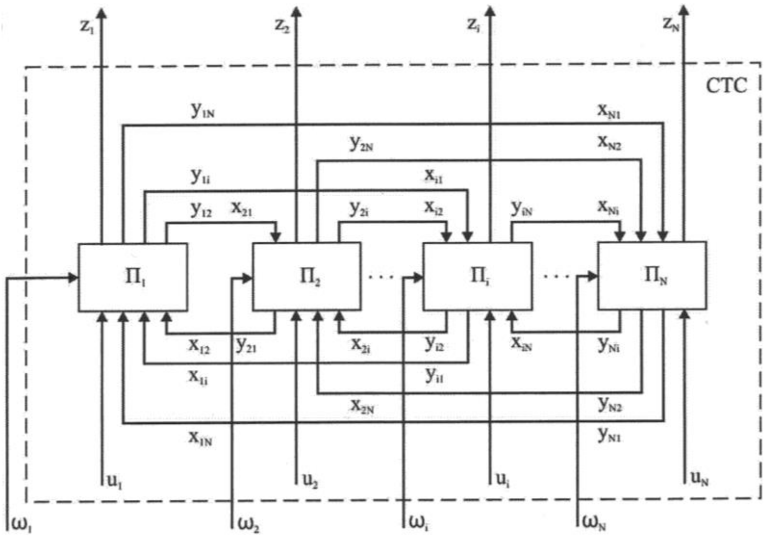
This makes it possible to formulate the optimization problem for the CTS also in a structured formulation, in which for each subsystem a particular optimization criterion can be formulated:

$$f_i = f_i(w_i, x_i, u_i), \quad i = 1,2,\ldots,N. \tag{3}$$

a)



b)



c)

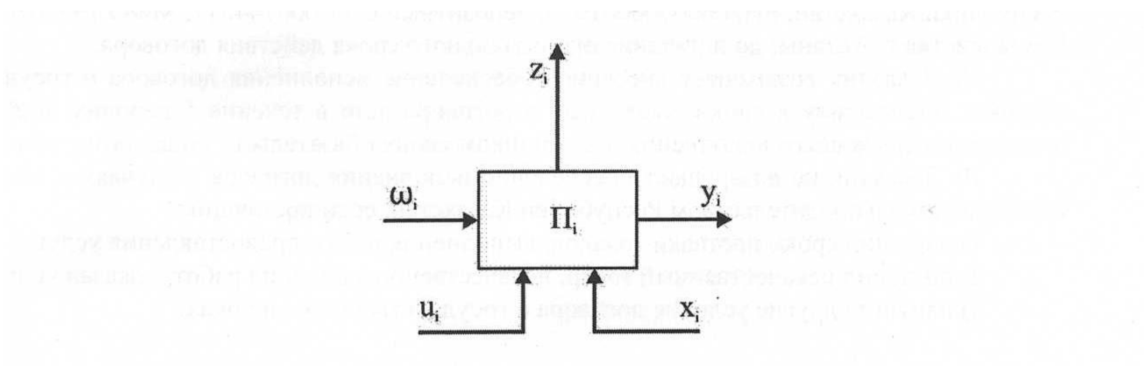


Fig. 1. Holistic (a) and structured (b), representation of the CTS, isolated i-th subsystem (c).

Accordingly, the existing limitations on the modes of operation of the CTS can be represented in the form

$$h_i\left(w_i, x_i, u_i\right) \geq 0, \quad i = 1,2,\dots, N , \tag{4}$$

where h_i is a definite vector-valued function.

RESULTS AND DISCUSSION

Having a mathematical description of the CTS, objective functions and constraints for the subsystems, one can put a formalized optimization problem for the CTS as a whole, structured along separate subsystems, of the form:

$$\begin{gathered} F[\, f_i(x_i, u_i), i = 1,2,\ldots, N\,] \rightarrow \max_{u_i,\, i = 1,2,\ldots, N} \\ y_i = g_i(x_i, u_i), i = 1,2,\ldots, N \\ h_i(x_i, u_i) \geq 0, i = 1,2,\ldots, N \\ x_i = \sum_{j=1}^{N} c_{ij} \cdot y_j, \;\; i = 1,2,\ldots, N \end{gathered} \tag{5}$$

Here F is a scalar objective function, identified with the criterion of optimality of the CTS state; c_{ij} is the adjacency matrix describing the relationship of the elements of the vector xi to the elements of the vector y_j. The number of rows of the matrix n is determined by the dimension of the vector xi, and the number of columns of m by the dimension of y_j. If the k-th component of the vector x_i corresponds to the e-th component of the vector y_j, then the matrix element located in the k-th row and the e-th column is equal to one. Otherwise, this element is zero.

To solve problems of the type (5), it is proposed to use the situational decomposition method [2]. The advantage of this method is that it does not impose any requirements on the structure of the elements of the problem, whereas all known classical decomposition methods require an obligatory separable problem. This requirement, implying the freedom to divide all the structural elements of the problem, significantly narrows their scope of applicability.

The method of situational decomposition assumes reduction of the original problem of optimization of type (5) to a set of simpler private subtasks, each of which corresponds to a certain situation that has developed in the STS. In this case, an additional problem arises of recognizing situations, taking into account which the corresponding particular problems are addressed. This problem of recognition of situations can be interpreted as a coordination problem, whereas a particular problem is treated as an analog of a local control problem.

The task of recognition of situations can be formulated in a general way as follows

$$(\overset{o}{x},\overset{o}{u},\overset{o}{y}):\overset{R}{\rightarrow} i,\overline{D}_i\,, \tag{6}$$

In this case, it is possible to take into account the situations that develop in the CTS at the time of making management decisions, and modify the management task by eliminating insignificant variables. The result of such a modification can be a maximum simplification of the problem, which allows us to speak about a unique decomposition of the original problem, since it reduces to a set of simplified tasks that can be solved separately.

When problem (1.2) is reduced to a set of modified (partial) subtasks, an additional problem arises for recognizing situations that are taken into account in particular problems. This problem can be treated as a coordination problem, whereas a partial subtask is regarded as an analog of a local control problem.

The problem of recognition of situations can be formulated as follows

$$(\overset{o}{x},\overset{o}{u},\overset{o}{y}):\overset{R}{\rightarrow} i,\overline{D}_i\,, \tag{7}$$

Where $\overset{o}{x},\overset{o}{u},\overset{o}{y}$ - the concrete values of the input variables x, controls u and outputs of the STS, respectively, i is the number of the situation, $\overline{D_i}$ - the set of variables of the problem (5), taken into account in the i-th situation , $\overline{D}_i \subset D = X \cup U \cup Y$, *X*, *U*, *Y* – sets of variables x, u, y, respectively, R is the vector mapping operator $\left(\overset{o}{x},\overset{o}{u},\overset{o}{y}\right)$ in pair i, $\overline{D_i}$

A particular control problem that takes into account the situation can be formulated in the form

$$\begin{gathered}
F_i(x_i,u_i,y_i) \rightarrow \max_{u_i \in U_i \subset U} \\
U_i = \left\{ u_i : \begin{matrix} g_i(x_i,u_i,y_i) = 0 \\ h_i(x_i,u_i y_i) \geq 0 \end{matrix} \right\} \\
\bigcup U_i = U \\
i = 1,2,\ldots,N.
\end{gathered} \tag{8}$$

where i is the number of the situation; N - number of possible situations; x_i, u_i, y_i - modified vectors of inputs, controls and outputs of the CTS; F_i - modified objective function; U_i is the modified set of admissible solutions of the problem, due to the modified functions g_i, h_i ,; U is the set of admissible solutions of the original problem (5).

The particular problem (8) for different situations in the general case will be different, so the implementation of the method leads to a decentralized control system with variable structure.

The task of identifying the situation R in an analytical form, in particular, as a function of R (x, u, y), as a rule, is not possible. For this reason, the main way to set it is to build numerical procedures for selective selection of signs of situations. Allocation of a set of significant variables $\overline{D_i}$, which are to be taken into account in problem (8), involves evaluating the sensitivity of the output variables y_i to the permissible changes in the i-th situation for the values of u_i for a given x_i, or the solution of the additional problem of identifying the CTC model with the definition of its optimal structure. All this in practice is problematic enough.

To solve these problems, it is suggested to consider only typical situations, to correlate with them the emerging current situations and, if certain conditions are met, to equate current situations with specific standard situations. The quality of management can be improved by simultaneously taking into account two or more typical situations when the current situation can not be unambiguously assigned to one of the standard ones. In this case, a mechanism should be provided for identifying common variables for overlapping typical situations.

Situations can often be estimated from the values of the variable inputs x. In this case, the problem (1.1) can be reduced to a sequence of particular static problems of the form

$$
\begin{gathered}
f(x_i, u_i, y_i) \to \max_{u_i} \\
x_i \in X, \quad u_i \in U, \quad y_i \in Y \\
i = 1, 2, \ldots, N.
\end{gathered}
\tag{9}
$$

where N is the number of considered situations.

The formalization of the coordination task of recognition of situations can be made as follows. Denote by D the set of situations considered in the control problem of the CTS (5), each of which has its own composition of effective variables. Suppose that D admits a partition into L of subsets D_k, k = 1,2, ..., L corresponding to standard situations. All current situations are subject to an assessment of belonging to D_k, k = 1,2, ..., L, and task (5) is an equivalent task for the identified model situation D_k.

In the simplest case, typical situations do not intersect, i.e.

$$D_k \cap D_j = \varnothing,\ k=1,2,\ldots,L;\ j=1,2,\ldots,L;\ k \neq j \tag{10}$$

In the general case, in the case of particular problems, all the typical situations in which intersection takes place must be taken into account. With this in mind, the task of coordination can be formulated as follows:

$$
\begin{gathered}
d = 0; a_j = 0,\ j = 1,2,\ldots L; \\
\exists k = 1,2,\ldots,L;\ p_s \in P_k, s = 1,2,\ldots,S \Rightarrow \\
\Rightarrow d = 1; b_{ks} = 1; a_k = 1 \\
\overline{D} = \bigcup \overline{D}_j,\ j = 1,2,\ldots,\ L
\end{gathered}
\tag{11}
$$

where d, bks and aj are auxiliary variables used as indicators; ps is the s-th sign of the situation; Pk is the set of distinctive features of the k-th model situation: $\overline{D}$ - a set of effective variables that are taken into account in the modified control problem; $\overline{D}_i$ - intersecting sets of typical situations for which $a_j \neq 0$. In the absence of intersecting features, problem (11) is reduced to a sequential search of systems of signs of typical situations Pk in order to find a system completely coinciding with the signs of the current situation. This problem can be formulated as:

$$
d = 1 \Rightarrow \sum_{s=1}^{S} b_{ks} \to \max_{k}, k = 1,2,\ldots,L;\ \overline{D} = D_{k^*} \tag{12}
$$

The solution of the problem is k = k*, for which the sum of the significant characteristics of a typical situation $\sum_{s=1}^{S} b_{ks}$ -is maximal. Accordingly, the set of accounted variables of the modified control problem is D_{k^*}.

Taking into account the problem of the lower level (8) identified by the typical situation, k is solved with respect to the variable u_k on the set U_k.

The method of situational decomposition is well applicable to optimization problems of complex reactor systems, since the latter are characterized by operating modes in which the need for generating control solutions usually arises when changing the quality characteristics of the processed raw materials, or when changing the type of the final product. In both cases, it is possible to clearly identify the emerging typical situations in terms of raw material quality at the inputs of the reactor system. At the same time, for each situation, a transition to a different composition and structure of the reactors involved is possible. Such a transition requires only specifying an appropriate topology of the modified reactor system by reformatting the contiguity matrix describing the connections between the reactors. The arising particular problems (8) are simply modified simply by taking into account the models and limitations for the reactors involved.

This approach was tested on the model problem of cascade optimization of reactors of the type [3,4]:

$$
F = C_{0Co} - \sum_{i=1}^{3} \Delta C_{iCo} \to \max_{q_{ci}},
$$

$$
q_i \cdot C_{ij}^{\ 0} - q_i \cdot C_{ij} \pm V \cdot r_{ij} = 0
$$

$$C_{3Fe} < 0.03 \text{ g/l} \tag{13}$$

$$C_{3Cu} < 0.01 \text{ g/l}$$

$$C_{ij} = \bar{C}_{(i+1)j}, \text{ i=1,2,3; j=1,…5.}$$

This task is typical for the technological processes of hydrometallurgical processes, in particular for the process of hydro treating cobalt.

Here: F - the criterion of the efficiency of the technological process; ΔC_{iCo} - losses of cobalt at the i-th stage; qi is the flow of liquid through the i-th reactor; q_{ci} is the consumption of soda ash in the i-th reactor; C_{ij}, is the concentration of j components at the outlet and the entrance to the i-th reactor (j = 1, .., 5 are indices for iron, copper, nickel, cobalt, hydrogen ions, respectively), i = 0,1,2, 3; V - volume of reactors; r_{ij} - the reaction rates at the i-th stage for the j-th components; $C_{ij} = \bar{C}_{(i+1)j}$ - the equation of communication between the stages of the process.

When treating poor solutions, the minimum concentration of impurities is already reached in the first stages, i.e. the degree of recovery of cobalt is weakly dependent on the operation of other reactors. As the flow rate and the concentration of the solution at the input of the process change, the influence of subsequent stages increases. With this in mind, it becomes possible to identify typical situations that link the concentration of the product at the entrance to the cascade with the number of reactors to be controlled.

In the simplest case, when only model situations are taken into account without their combinations, the coordination problem can be formulated as follows

$$q_n, C_{0Co} \in D_1 \Rightarrow k = 1; i = 1;$$
$$q_n, C_{0Co} \in D_2 \Rightarrow k = 2; i = 1,2;$$
$$q_n, C_{0Co} \in D_N \Rightarrow k = N; i = 1,2,..., N; \tag{14}$$

where D_1, D_2, ..., D_N are the specified ranges of load values for the input flow of the solution q_n and the cobalt concentration C_{0Co} at the inlet of the reactor system.

CONCLUSION

In this case, the modified or particular control problem for the k-th model situation will have the form

$$F_k(C_{iCo}, i = 0,1,2,3) \rightarrow \max_{q_{ck}}$$

$$
\begin{gathered}
C_{0Co} = C_{зад},\, q_n = q_{n\,зад} \\
C_{ij} \le C_{ij}^{*}, \quad i = 1,2,3;\; j = 1,2,...,5 \\
\frac{dC_{ij}}{dt} = f_{ij}\left(C_{ij}, g_{ji}, q_{ci}\right), \quad i = 1,2,3;\; j = 1,2,...,5 \\
C_{ij} = \overline{C}_{(i+1)j},\; i = 1,2,3; \quad j = 1,\ldots 5.
\end{gathered} \tag{15}
$$

Here $F_k\,(C_{iCo}, i = 0,1,2,3)$ - criterion of optimality of the initial control problem (6.6), modified taking into account the k-th model situation, C_{ij} - concentration of impurities in the reactors, determined by the model of the process adapted to the k-th model situation.

For the joint solution of problems (14) - (15), the developed algorithm of situational control was used on the basis of the Complex Box method. The solution of the particular problems (15) was carried out using the algorithm for finding the optimum using the sliding tolerance method [5].

The computational experiments carried out showed the high efficiency of the proposed approach for optimization of complex reactor systems.

REFERENCES

1 Khu Ven-Tsen, Osobennosti optimal'nogo upravleniya slozhny’mi texnologicheskimi sistemami [Features of optimal control of complex technological systems]. Vestnik Kazaxskoj akademii transporta i kommunikatcij im. M.Ty’ny’shpaeva [Newsletter Kazakh Academy of Transport and Communications. M.Tynyshpaeva], Almaty- 2008, P. 78-83.

2 Khu Ven-Tsen, Optimal'noe upravlenie na osnove situatcionnoj dekompozitcii [Optimal control based on situational decomposition]. Voprosy’ sovremennoj nauki i praktiki [Issues of modern science and practice]. Universitet im. V.I.Vernadskogo [University named after V.I.Vernadsky], Kiev-2008,P. 50-54.

3 Volodin V.M., Khu Ven-Tsen, Mokrova N.V., Decentralizovannoe upravlenie slozhny’mi texnologicheskimi sistemami: Monografiya [Decentralized management of complex technological systems: Monograph], Shymkent -2008, P. 260-264.

4 Bol’shakov K.A., Ximiya i texnologiya kobal'ta [Chemistry and technology of cobalt]. Moscow -1981, P. 82-84

5 Ximmel'blau D., Prikladnoe nelineynoe programmirovanie [Applied nonlinear programming], Moscow-1975, P. 534-536.

6 Belyaev PS, Ven-Tsen K, Varepo LG, Makhanova ZA, Belousov OA, Ussenova A. Decentralized optimal control of multicomponent reactor systems in petrochemical and oil-and-gas production based on situational decomposition method. NANOSCIENCE AND NANOTECHNOLOGY: NANO-SciTech [Internet]. 2019;2151:050001. Available from: http://dx.doi.org/10.1063/1.5122144

7 Ven-Tsen K. Situational decomposition in controlling complex objects. Wissenschaftliche Beiträge / Technische Hochschule Wildau [Internet]. 2010; Available from: http://dx.doi.org/10.15771/0949-8214_2010_1_17
8 Flexible Runway Scheduling for Complex Runway Systems: Using a Multi-Objective Optimization. 2022 Jun 27; Available from: http://dx.doi.org/10.2514/6.2022-3222.vid
9 Ryoo J, Hajela P. Decomposition-based design optimization method using genetic co-evolution. Engineering Optimization [Internet]. 2004 Jun;36(3):361–78. Available from: http://dx.doi.org/10.1080/03052150410001657587
10 MODELING AND SITUATIONAL QUALITY MANAGEMENT OF COMPLEX SYSTEMS. 2020; Available from: http://dx.doi.org/10.31799/978-5-8088-1449-3-2020-1

IRSTI 50.47.29

AUTOMATION OF CONTROL OF SELECTIVE SEDIMENTATION PROCESSES IN DISPERSED SYSTEMS AND METHODS OF THEIR CALCULATION

Kocherova A.N.*, Musabekov A.A., Mirzabaev B.I.
M. Auezov SKU, Shymkent, Kazakhstan
***Corresponding Author's Email:** aynur.kocherova@mail.ru*

ABSTRACT

This paper considers the calculation and automated control methods for selective sedimentation processes in dispersed systems. The main theoretical aspects, including the Stokes equation and particle sedimentation models, are described, and approaches to their practical implementation are presented. Particular attention is paid to the development of automated control systems using modern programmable logic controllers (PLC), sensors and SCADA systems for monitoring and optimizing processes.

The proposed solutions are aimed at increasing control accuracy, reducing resource costs and improving the efficiency of process operations in areas such as wastewater treatment, mineral separation, pharmaceuticals and chemical industries. Automation allows minimizing the influence of the human factor, ensuring stability and high quality of system operation. This work emphasizes the importance of integrating scientific knowledge and modern technologies to improve selective sedimentation processes.

Keywords: automation and control**,** disperse systems, Stokes equation, process control, ANSYS Fluent, multiphase flows, SCADA platforms, process automation

INTRODUCTION

The automation of control processes in dispersed systems is an essential task in various industrial and scientific applications. Selective sedimentation, which involves the separation of particles of different sizes and densities, plays a crucial role in fields such as chemical engineering, environmental protection, and materials science. Effective control of these processes requires advanced computational methods and automation technologies to ensure high precision and efficiency [1-5].

The development of automated control systems for selective sedimentation involves integrating real-time monitoring, data processing, and feedback mechanisms. These systems enhance process efficiency, reduce human intervention, and improve the accuracy of sedimentation calculations. Key methodologies [1-3] include mathematical modeling, algorithm optimization, and the application of modern computational tools.

This paper explores the automation of selective sedimentation control processes in dispersed systems, emphasizing computational approaches and optimization methods. It presents an overview of control strategies, discusses key challenges, and evaluates the effectiveness of automation techniques in improving process stability and accuracy. The findings contribute to the advancement of sedimentation process automation, facilitating better decision-making and operational efficiency in industrial and research applications.

MATERIALS AND METHODS

The study utilized the following components: Experimental Setup: A laboratory-scale sedimentation tank equipped with real-time monitoring sensors. Sensors: Optical and acoustic sensors for particle size distribution analysis. Computational Tools: MATLAB and Python for data analysis and process modeling. Automation System: A programmable logic controller (PLC) with integrated feedback control mechanisms.

Data Collection: Sedimentation experiments were conducted under varying conditions to record particle behavior and settling rates.

Mathematical Modeling: The sedimentation process was described using Stokes' law and other relevant hydrodynamic equations.

Algorithm Development: Custom control algorithms were designed to optimize sedimentation efficiency using real-time sensor data.

System Implementation: The developed algorithms were integrated into the PLC for automated process control.

Performance Evaluation: The system's efficiency was assessed based on parameters such as sedimentation rate, particle separation accuracy, and energy consumption.

This structured methodology ensures a comprehensive approach to automating the selective sedimentation process, facilitating improved accuracy and operational efficiency.

RESULTS AND DISCUSSION

Selective sedimentation in dispersed systems is a complex process in which solid particles of different sizes, densities or shapes are deposited in a liquid medium for the purpose of their separation. This process has wide application in industry, including chemical, mining, pharmaceutical and environmental industries. However, the high complexity of particle-liquid interactions, as well as the need for precise control of process parameters, require the implementation of modern automation methods.

Automation of selective sedimentation processes allows to significantly increase their efficiency by using sensors, actuators and programmable logic controllers (PLC). This ensures not only constant monitoring of key parameters, such as particle concentration, medium viscosity or liquid level, but also the possibility of dynamic process control. Thus, automation reduces the influence of the human factor, minimizes energy and material costs, and improves the quality of separation.

The automated approach is based on mathematical models describing the physical processes of sedimentation. The use of the Stokes equation and other calculation formulas allows for accurate prediction of the particle sedimentation rate, optimization of system parameters, and provision of the most efficient separation. Modern software solutions, such as SCADA platforms, and equipment, including sensors, pumps, and flow meters, are used to implement such systems.

This work is aimed at studying the methodology of calculation and control of selective sedimentation processes in automated systems. It considers theoretical foundations, calculation algorithms, approaches to the selection of equipment and control schemes. This knowledge can be applied in the design and operation of modern particle separation systems, ensuring a high level of productivity and stability of operation.

To automate the processes of selective sedimentation in dispersed systems, it is necessary to combine theoretical knowledge of sedimentation with the practical application of automatic control systems (ACS). Key materials and calculations for automation are presented below.

Automation tasks

Monitoring parameters: control of particle concentration, sedimentation rate, viscosity and density of the medium.

Process control: adjusting the liquid feed rate, adding coagulants, setting up equipment.

Optimizing efficiency: reducing energy costs, minimizing material losses, improving separation quality.

General automation scheme

Main components:

Sensors and detectors:

Ultrasonic sensors for measuring particle concentration.

Viscosity sensors for monitoring liquid properties.

Level sensors for measuring the height of the sediment layer.

pH meters and redox sensors for monitoring chemical parameters of the environment.

Actuators:

Liquid supply pumps.

Dispensers for introducing coagulants or flocculants .

Drives for controlling the rotation speed of centrifuges.

Controllers:

Programmable logic controllers (PLC) for real-time process control.

SCADA systems for visualization and control at the operator level.

Software:

SCADA platforms: Siemens WinCC, Wonderware, GE iFIX.

Programming PLC: Tia Portal (Siemens), Codesys, Allen Bradley Studio 5000.

Calculation formulas for automation

Sedimentation velocity: The Stokes equation is used:

$$v=(2/9)*((r^2)(\rho_s-\rho_l)*g/\eta)$$

Where:

v — sedimentation velocity (m /s),

r — particle radius (m),

ρ_s — particle density (kg /m³),

ρ_l — liquid density (kg /m³),

g— acceleration of gravity (9.81 m/ s²),

η — viscosity of the liquid (Pa s).

Automation : connection of viscosity (η\ etaη) and density (ρs,ρl \ rho_s ,\ rho_lρs , ρl) sensors for dynamic speed calculation.

Supply of coagulants :

$$Q_c = C_c \cdot V_l$$

Where:

Q_c — the required amount of coagulant (m^3 /h),
C_c — concentration of coagulant in solution (%),
V_l — volume of liquid (m^3).
Automation : dosing pump with flow control via PID controller.
Optimization of particle concentration :

$$C = m_p / V_C$$

Where:

C— particle concentration (kg /m^3),
m_p — mass of particles (kg),
V is the volume of liquid (m^3).
Automation : use of ultrasonic concentration sensors.
Liquid flow control :

$$Q = v \cdot A$$

Where:

Q — volumetric flow rate (m^3 /h),
v — flow velocity (m /s),
A— cross-sectional area of the pipe (m^2).
Automation : control valve and flow meter connected to PLC.
Process control algorithm
Data collection :

The sensors record the concentration, viscosity, level and chemical parameters of the liquid.

Transferring data to the controller.

Analysis of the state :

The PLC performs calculations: sedimentation rate, particle concentration, feed volume of coagulants.

Comparison of current parameters with specified ones.

Decision making :

Increase/decrease the supply of liquid or coagulant.

Adjusting the speed of rotation of the centrifuge or the liquid feed into the hydrocyclone.

Action of actuators :

Control of pumps, dispensers and valves.

Visualization :

The system status is displayed in SCADA: graphs, tables, alarms.

Equipment for automation

Siemens S7-1200/1500 - controllers for small and large systems.

Viscosity sensors : Brookfield or Anton Paar .

Flow meters : Krohne , Endress+Hauser .
Ultrasonic level sensors : Siemens , ABB.
Dosing pumps : Grundfos , Prominent .
Calculation example
Initial data:
Particle density: $\rho_s = 2500$ kg/m ^{3}
Liquid density: $\rho_l = 1000$ kg/ ^{m3} ,
Liquid viscosity: η=0.001 Pa/ s ,
Particle radius: r=0.0005 m $_r$ = 0.0005m.
Calculation of sedimentation rate:
$v=2/9 \cdot ((0.0005)^2 \cdot (2500-1000) \cdot 9.81))/0.001=0.109$ m/s
Calculation of liquid consumption:
Sedimentation velocity: v=0.109 m/ s ,
Pipe diameter: d=0.1 m,
Pipe area: A=πd24=0.00785 ^{m2} .
$Q= v \cdot A =0.109 \cdot 0.00785=0.000856$ m ^{3} /s=3.08 m ^{3} /h
PLC programming
Example of PID controller logic:
Input: data from concentration and level sensors.
Output: signal to pump or dispenser.
Regulation: maintaining a given concentration C and flow rate Q.
The program code can be written in Ladder Logical or Structured Text (depending on equipment).

CONCLUSION

Selective sedimentation processes play an important role in separating dispersed systems, ensuring effective separation of solid particles of different sizes and densities. Automation of these processes allows not only to increase control accuracy, but also to significantly improve productivity, minimize resource costs and ensure the stability of technological operations.

Modern automation methods based on the use of sensors, programmable logic controllers and SCADA systems enable continuous monitoring of key parameters such as particle concentration, liquid viscosity and sedimentation rate. This allows for prompt response to changing conditions, process optimization and high separation accuracy.

The use of mathematical models, including the Stokes equation and flow control formulas, provides a basis for designing and tuning systems. The implementation of automated solutions helps solve many industrial problems, including wastewater treatment, mineral separation, pharmaceutical production, and improving environmental safety.

Thus, automation of selective sedimentation in dispersed systems is a promising direction that opens up new opportunities for increasing the efficiency and reliability of technological processes. These approaches can be adapted and applied in a wide variety of industries, which emphasizes their importance and practical value.

REFERENCES

1 E.A. Shashkin. Fundamentals of disperse systems . Selective Sedimentation in Industrial Applications" //Chemical Engineering Journal, 2020. - Volume 49, No. 2. - P. 249-258.

2 R. Bailey , Sedimentation And separation particles Optimization of Settling Processes (Journal of Multiphase Flow, 2021 - S. 195.

3 Baloch MH, Chauhadary ST, Ishaq D., Kaloy GS, Nadeem MH, Wattoo VA, Yunas T, Hamid HT. The state of hybrid energy sources in Pakistan: the optimal technical proposal for solving the problem of energy crisis // Energy Strategy Rev. - 2019 . - Tom. 24 . - P. 132-153.

4 Merlet JP // Springer Publishers, Dordrecht. - 2006. - S. 332.

5 Gasch R., Twele J. Windcraft Langer Grundlagen . Entwurf . Planung und Betrieb // Springer. XXIII. – 2016. – S. 599.

IRSTI 59.71.35

USING OPENCV WITH LEGO MINDSTORMS ROBOTS

Izturganov N.D., Musabekov A.A., Baygabulova D.K., Akhmetova K.T., Markabaeva D.B.*

M. Auezov South Kazakhstan University, Shymkent, Kazakhstan

***Corresponding Author's Email:** berik.mirza@mail.ru

ABSTRACT

The use of OpenCV with LEGO Mindstorms robots opens up wide possibilities for creating projects that include image recognition and processing, adding the ability for robots to perceive and interpret visual data. LEGO Mindstorms is a popular platform for creating robotic systems, well-known among students and developers for its flexibility and accessibility. The integration of OpenCV, a powerful computer vision library, with LEGO Mindstorms enables the implementation of new features such as object detection, motion tracking, and recognition of colors and shapes, making the robot more interactive and adaptive.

In a typical configuration for connecting OpenCV and LEGO Mindstorms, Raspberry Pi is used to manage the camera and process images, while LEGO Mindstorms executes commands based on the obtained data. This combination of software and hardware allows building systems that can track moving objects, avoid obstacles, and react to specific colors and shapes. This approach expands the possibilities of robotics projects, making them more functional and engaging for practical training in programming and robotics.

Keywords: OpenCV, LEGO Mindstorms, Machine Vision, Robot, Smart Systems, Robotics, Raspberry Pi.

INTRODUCTION

Computer vision plays a crucial role in modern robotics, enabling machines to perceive and interpret their surroundings. OpenCV, an open-source computer vision library, provides a versatile toolkit for image processing, object detection, and feature recognition. When integrated with LEGO Mindstorms robots, OpenCV enhances their ability to navigate, interact with objects, and perform complex tasks autonomously.

LEGO Mindstorms is a popular robotics platform designed for education and research. It combines modular hardware components with programmable software, allowing users to develop and test various robotic applications. By incorporating OpenCV, these robots can leverage advanced image processing techniques to improve performance in tasks such as line following, object tracking, and facial recognition.

This paper explores the integration of OpenCV with LEGO Mindstorms robots, detailing the hardware and software setup, implementation strategies, and performance evaluations. The study aims to demonstrate the feasibility and benefits of using OpenCV for enhancing the vision capabilities of LEGO Mindstorms robots in educational and experimental contexts.

MATERIALS AND METHODS

Hardware Components. The integration of OpenCV with LEGO Mindstorms robots requires specific hardware components: LEGO Mindstorms EV3/NXT: The core robotics kit, including motors and sensors. Camera Module: A USB or Raspberry Pi-compatible camera for image capture. Processing Unit: A Raspberry Pi or a laptop running Python and OpenCV for image processing. Communication Module: Bluetooth or Wi-Fi for transmitting data between the processing unit and the LEGO robot.

Software Framework. The software environment used in this study consists of: Operating System: Raspberry Pi OS or Windows/Linux with Python support. OpenCV Library: For image processing and computer vision tasks. LEGO EV3/NXT Python API: To control the robot’s motors and sensors. ROS (optional): For integrating additional functionalities and scalability.

Implementation Procedure. System Setup: Install OpenCV and necessary dependencies on the processing unit. Camera Integration: Configure the camera module for real-time image capture. Preprocessing: Convert images to grayscale, apply noise reduction, and enhance features. Object Recognition and Tracking: Utilize OpenCV algorithms like Haar cascades, HOG, or CNN-based models to detect objects. Robot Navigation: Process vision data to control the LEGO robot’s movement based on detected objects or lines. Communication and Execution: Transmit processed commands from the processing unit to the LEGO robot for real-time execution.

Performance Evaluation. The system was tested under various conditions to evaluate: Accuracy of Object Detection: Measured using precision and recall. Processing Speed: Evaluated in frames per second (FPS). Response Time: Latency between image capture, processing, and robot actuation. Adaptability: Performance under different lighting conditions and object variations.

This methodology provides a structured approach to integrating OpenCV with LEGO Mindstorms robots, ensuring efficient vision-based control and interaction

RESULTS AND DISCUSSION

The use of OpenCV with LEGO Mindstorms robots opens up wide possibilities for creating projects that include image recognition and processing, adding the ability for robots to perceive and interpret visual data. LEGO Mindstorms is a popular platform for creating robotic systems, well-known among students and developers for its flexibility and accessibility. The integration of OpenCV, a powerful computer vision library, with LEGO Mindstorms enables the implementation of new features such as object detection, motion tracking, and recognition of colors and shapes, making the robot more interactive and adaptive. In a typical configuration for connecting OpenCV and LEGO Mindstorms, Raspberry Pi is used to manage the camera and process images, while LEGO Mindstorms executes commands based on the obtained data. This combination of software and hardware allows building systems that can track moving objects, avoid obstacles, and react to specific colors and shapes. This approach expands the possibilities of robotics projects, making them more functional and engaging for practical training in programming and robotics.

To use OpenCV with LEGO Mindstorms robots, it is essential to understand how to connect the capabilities of computer vision with the robot's hardware. This is typically achieved using a Raspberry Pi or another mini-computer that connects to the LEGO Mindstorms robot and processes the images. OpenCV on the Raspberry Pi is used for capturing and analyzing images, and the information is then sent to the LEGO robot for task execution.

Example**:** Identifying and tracking a colored object with LEGO Mindstorms and OpenCV. In this example, we will program the LEGO Mindstorms to track a colored object (e.g., a red ball) using a camera connected to the Raspberry Pi, leveraging the OpenCV library. The robot will turn towards the object and move to follow it.

Requirements

- LEGO Mindstorms EV3 or LEGO Mindstorms Robot Inventor with the EV3Dev or Pybricks programming environment installed.
- Raspberry Pi (or another mini-computer) with OpenCV library installed.
- Camera for Raspberry Pi.
- EV3dev or Pybricks for programming the EV3 in Python.

Steps to Create the Program

1. Set Up the Camera: Connect the camera to the Raspberry Pi and ensure OpenCV is installed.
2. Image Processing in OpenCV: Write a Python program using OpenCV to capture and process images from the camera.
3. Connection Between Raspberry Pi and LEGO Mindstorms: The Raspberry Pi will send commands to the LEGO robot via Bluetooth or a wired connection.

Example Python Code

This code will search for a red object and send commands to the LEGO Mindstorms via Bluetooth based on the object's position.

python Копировать код

```python
# Импортируем библиотеки
import cv2
import numpy as np
import time
from ev3dev2.motor import LargeMotor, OUTPUT_A, OUTPUT_B, SpeedPercent
from ev3dev2.sensor.lego import ColorSensor
from ev3dev2.sensor import INPUT_1
from ev3dev2.led import Leds
from ev3dev2.sound import Sound

# Подключение моторов
motor_left = LargeMotor(OUTPUT_A)
motor_right = LargeMotor(OUTPUT_B)

# Функция для поворота робота
def turn_robot(direction, speed=30):
    if direction == 'left':
        motor_left.on(SpeedPercent(-speed))
        motor_right.on(SpeedPercent(speed))
    elif direction == 'right':
        motor_left.on(SpeedPercent(speed))
        motor_right.on(SpeedPercent(-speed))
```

```python
        # Прерывание цикла по нажатию клавиши 'q'
        if cv2.waitKey(1) & 0xFF == ord('q'):
            break

    # Освобождаем камеру и закрываем окна
    cap.release()
    cv2.destroyAllWindows()

# Запуск функции отслеживания
track_red_object()
```

Explanation of the Code

1. Capturing Image from Camera (cap = cv2.VideoCapture(0)) — The Raspberry Pi captures real-time images using the camera.
2. Converting Image to HSV (cv2.cvtColor(frame, cv2.COLOR_BGR2HSV)) — The image is converted to the HSV color space, making it easier to highlight the red color.
3. Creating a Mask for Red Color — We use the lower_red and upper_red ranges to create a mask that highlights only the red areas of the image.
4. Determining the Object's Position — We find the contours on the mask and select the largest contour, which is likely the target object.
5. Robot Commands — If the object is on the left, the robot turns left. If it's on the right, the robot turns right. When the object is in the center, the robot moves forward.
6. Stopping — If no object is found, the robot stops.

This code can be modified for other colors, shapes of objects, and lighting conditions.

Of course, several improvements and additional features can be added to make the robotic system more robust and flexible. Here are some ideas and corresponding changes to the code:

1. Noise Filtering and Mask Improvement

To get a more accurate mask, especially when the colored object is not clearly defined, smoothing and morphological operations can be used. These methods help reduce noise and improve object segmentation.

Adding morphological operations to the code:

```python
# Применяем размытие к изображению, чтобы снизить шум
blurred = cv2.GaussianBlur(mask, (5, 5), 0)

# Применяем морфологические операции для улучшения маски
mask = cv2.morphologyEx(blurred, cv2.MORPH_CLOSE, np.ones((5, 5), np.uint8))
mask = cv2.morphologyEx(mask, cv2.MORPH_OPEN, np.ones((5, 5), np.uint8))
```

These operations will help make the mask clearer, avoiding the appearance of random small contours that could mislead the robot.

2. Motion Control Optimization

Instead of simple turning, you can implement smoother tracking of the object, where the rotation speed will depend on the distance to the center of the image. This will make the robot's movements more precise and smooth.

Adding proportional control (P-controller).

```python
# Определение отклонения центра объекта от центра кадра
error = object_center - frame_center
kp = 0.1  # Коэффициент пропорциональности

# Рассчитываем скорость поворота в зависимости от отклонения
turn_speed = kp * error

if abs(error) > 50:
    if error > 0:
        print("Turning right with speed:", turn_speed)
        motor_left.on(SpeedPercent(20 + turn_speed))
        motor_right.on(SpeedPercent(20 - turn_speed))
    else:
        print("Turning left with speed:", -turn_speed)
        motor_left.on(SpeedPercent(20 - turn_speed))
        motor_right.on(SpeedPercent(20 + turn_speed))
else:
    print("Object is centered. Moving forward.")
    motor_left.on(SpeedPercent(20))
    motor_right.on(SpeedPercent(20))
```

A proportional coefficient `kp` has been added here, which adjusts the rotation speed depending on how far the object is from the center.

3. Additional Stop Conditions and Safe Distances

To prevent collisions with the object, you can add a stop condition based on the distance to the object. Since LEGO Mindstorms doesn't have a built-in distance sensor in this example, we can use a condition based on the size of the object — the closer the object is, the larger its contour in the image.

Adding a stop condition based on the size of the object.

python Копировать код

```python
# Устанавливаем порог для остановки робота, если объект слишком близко
if w * h > 10000:  # Подстройте это значение в зависимости от камеры и объекта
    print("Object is too close. Stopping.")
    motor_left.off()
    motor_right.off()
else:
    # Выполняем поворот или движение вперед, как описано выше
```

4. Improving Communication and Command Processing

If the Raspberry Pi and LEGO Mindstorms are connected via Bluetooth or Wi-Fi, you can enhance command processing by adding feedback about the robot's status, such as receiving data on the status of motors or sensors. This allows the robot to consider its current position or orientation, responding more accurately.

Example of using the EV3Dev API to send commands.

python Копировать код

```python
from ev3dev2.motor import MoveSteering, OUTPUT_A, OUTPUT_B
from ev3dev2.sensor.lego import UltrasonicSensor
from ev3dev2.sensor import INPUT_1

# Подключение ультразвукового датчика для определения расстояния
us = UltrasonicSensor(INPUT_1)

steering_drive = MoveSteering(OUTPUT_A, OUTPUT_B)

# Ожидание команды, пока объект не находится в пределах 30 см
if us.distance_centimeters < 30:
    print("Object is too close. Stopping.")
    steering_drive.off()
```

5. utomatic Calibration for Lighting Conditions

Lighting conditions can significantly affect the color mask. Adding an automatic calibration procedure will help the system adapt to changes in lighting.

Example of automatic calibration.

```python
# Определяем средний цвет на кадре при запуске и подстраиваем диапазон
_, frame = cap.read()
avg_color_per_row = np.average(frame, axis=0)
avg_color = np.average(avg_color_per_row, axis=0)

# Настройка диапазона цвета с учетом калибровки
lower_red = np.array([max(0, avg_color[0] - 10), 120, 70])
upper_red = np.array([min(180, avg_color[0] + 10), 255, 255])
```

6. Recording Video for Debugging

To improve the algorithm and understand how the robot perceives its environment, you can add video recording during tests.

```python
# Настраиваем запись видео
fourcc = cv2.VideoWriter_fourcc(*'XVID')
out = cv2.VideoWriter('output.avi', fourcc, 20.0, (640, 480))

# Внутри основного цикла записи кадра
out.write(frame)

# Освобождаем видеозапись при завершении
out.release()
```

7. Error Handling and Safety Timer

Sometimes the camera or sensors may operate unpredictably. Adding a timer and error handling will help prevent issues if the robot fails to detect an object or encounters a malfunction.

```python
import time

# Включаем таймер
start_time = time.time()

# В основном цикле
if contours:
    start_time = time.time()  # Сбрасываем таймер, когда объект виден
else:
    if time.time() - start_time > 5:  # Если объект отсутствует более 5 секунд
        print("Object lost. Stopping.")
        motor_left.off()
        motor_right.off()
        break  # Прерываем выполнение программы
```

CONCLUSION

The conclusion about the use of OpenCV with LEGO Mindstorms highlights the immense potential for creating smarter and more autonomous robots. Integrating OpenCV, a computer vision library, with LEGO Mindstorms goes beyond basic programming and mechanics, giving the robot the ability to perceive and analyze the world around it. With features such as object recognition, color tracking, and motion analysis, the robot becomes more "aware," and its reactions to external stimuli are more accurate and diverse.

Using OpenCV with LEGO Mindstorms provides students and developers with an excellent tool for learning and experimenting in the fields of computer vision and robotics. It not only develops programming and design skills but also helps gain a better understanding of artificial intelligence and machine learning fundamentals. As technologies progress and computational power increases, integrating computer vision into educational and research robotics platforms will become increasingly popular and in-demand, fostering the emergence of new ideas and innovative projects.

These improvements make the robot system more reliable and effective. You've added filtering, smooth motion control, adaptation to lighting conditions, safety checks, and error handling—all of which make your project suitable for real-world conditions and enhance the robot's interaction with its environment.

REFERENCES

1 Kerr D.R. analysis, Propertie sand Designofa Stewart Platform Transducer // Trans. ASME. Journal Mechanisms, Transmissions and Automationin Design. 2018.No1.P.25-28.

2 K. Makino, H. Terada, VISUALISATION APPROACH FOR PREDICTION AND ANALYSIS OF EFFICIENCY OF AN OIL PUMP BASED ON GEOMETRICAL ARRANGEMENT, International Journal of Mechanics and Control, (Vol. 24, No. 1) pp. 97-106, 2023.

3 K. Berns and D. Görges, Preface for the Special Issue of the International Journal of Mechanics and Control (JoMaC) dedicated to 28th International Conference on Robotics in Alpe-Adria-Danube Region (RAAD 2019), International Journal of Mechanics and Control, Vol. 21, No. 01, p. 1, 2020.
4 4 M. Oehler, S. Kohlbrecher and O. von Stryk, Optimization-Based Planning for Autonomous Traversal of Obstacles with Mobile Ground Robots, International Journal of Mechanics and Control, Vol. 21, No. 01, pp. 33-40, 2020.
5 L. Scalera, A. Giusti, V. Di Cosmo, M. Riedl, R. Vidoni and D.T. Matt, Application of Dynamically Scaled Safety Zones Based on the ISO/TS 15066:2016 for Collaborative Robotics, International Journal of Mechanics and Control, Vol. 21, No. 01, pp. 41-50, 2020.
6 Ben-Hasan A., Daliri M. Arabian/Persian Gulf artisanal fisheries: magnitude, threats, and opportunities, Rev. Fish Biol. Fish. (2022), pp. 1-19.
7 Andrew J., Baker M., The general data protection regulation in the age of surveillance capitalism, Journal of Business Ethics, 168 (3) (2021), pp. 565-578.
8 Löhle S., Zander F., Eberhart M., Hermann T., Meindl A., Massuti-Ballester B., Leiser D., Hufgard F., Pagan A.S., Herdrich G., Fasoulas S.,Assessment of high enthalpy flow conditions for re-entry aerothermodynamics in the plasma wind tunnel facilities at IRS, CEAS Space J., 14 (2022), pp. 395-406.

IRSTI 61.13.17

METHODOLOGICAL FOUNDATIONS FOR SOLVING GEOMETRIC INVERSE HEAT TRANSFER PROBLEMS

Altynbekov R.F.[*1], Matsevity Yu.M.[2], Kostikov A.O.[2], Saipov A.A.[1], Janaliyev B.M.[1]
[1]*M. Auezov South Kazakhstan University, Shymkent, Kazakhstan*
[2]*Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine*
[*]***Corresponding Author's Email:*** *rustik2030@inbox.ru*

ABSTRACT

This article examines methodological approaches to solving geometric inverse problems arising in heat transfer, focusing on identifying unknown geometric parameters of heat transfer objects. Geometric inverse problems are crucial for engineering applications that require precise determination of shape, dimensions, location, and thermal source characteristics for analyzing and controlling thermal processes. The study describes key optimization and regularization methods used to solve these problems and discusses their application in conditions of incomplete and noisy information. The authors analyze the stability and robustness of numerical methods, such as the finite element method, finite difference method, and various iterative schemes, which enhance solution accuracy and reliability. The paper presents practical examples of the proposed methods in designing and optimizing heat exchange systems, particularly in industry and energy sectors, where efficient thermal process management directly impacts equipment reliability and cost-effectiveness. The conclusions emphasize the significance of the developed methodological foundations for specialists working on the creation and improvement of heat exchange systems and highlight future research prospects in this field.

Keywords: geometric inverse problems, heat exchange, heat transfer, methodology, optimization, regularization, numerical methods, computational algorithms, thermal processes, engineering problems.

INTRODUCTION

It is evident that the completeness, accuracy, adequacy, and other properties of a mathematical model largely depend on how the geometry of the considered physical object is represented. One of the key aspects in solving geometric inverse heat transfer problems (IHTPs) is the formulation of the uniqueness condition, which is the subject of the problem. In problems concerning the determination of body dimensions, source placement, or coordinate identification, the sought-after geometric information can be uniquely represented as a finite set of scalar values (for geometric parameters that remain constant over time) or as functions dependent on time (for geometric parameters that change over time). From an algorithmic perspective, these cases are not fundamentally different from internal or boundary inverse problems. If the sought information is expressed as functional dependencies, it is typically represented as a linear combination of known basis functions with unknown coefficients, reducing the problem to a search for a vector of scalar values. This ensures the automation of the computational process without major difficulties.

A different approach is required for geometric IHTPs that involve determining the boundary of a region or the interface between subdomains. Here, a critical challenge is formalizing the description of the unknown boundary. To solve such a geometric IHTP using an extremal method, the formalization must allow automatic and sufficiently flexible boundary modifications during the minimization of the objective function while ensuring that the computational model can handle any current boundary position automatically.

Several studies [1-5] have employed grid-based methods to solve inverse heat transfer problems (IHTPs), ensuring that the identified boundary strictly conforms to the grid cells. Deformable grids are often used in such cases. However, this approach is not universal and is only applicable when prior geometric information about the unknown boundary is available, imposing significant constraints on possible variations. For instance, in studies on welding process identification, the molten zone is often assumed to be circular [3-12].

In contemporary computational graphics and shape modeling, boundaries are widely represented using splines passing through control points with specified coordinates [2, 5]. However, the use of splines for solving geometric IHTPs related to defining body boundaries or subdomain interfaces remains limited, with few studies addressing this approach [2-17]. Neglecting spline approximation could lead to challenges in industrial implementation of geometric IHTP solutions. For instance, if the boundary derived from a geometric IHTP solution differs from a spline representation, its integration into production-level computational graphics software may introduce errors affecting the temperature field of the designed object.

Several methods for minimizing the objective function impose additional requirements on boundary formalization. For example, when using gradient-based methods or methods relying on sensitivity coefficients, it is necessary to differentiate the equations of the original problem with respect to the parameters of the unknown boundary. This allows for a numerical representation of how boundary changes affect the temperature field inside the body. In the literature on geometric inverse heat transfer problems (IHTPs), such derivatives are referred to as domain derivatives or shape derivatives, while their combination is known as the shape gradient.

When using the conjugate gradient method, shape derivatives for objects of a given configuration have been determined for external fixed boundaries of a region [12], external moving boundaries [8, 10], and internal interfaces between subdomains [15]. In [13], a quasi-Newton method was applied, which also required computing shape derivatives. In studies [12-16], the determination of sensitivity coefficients involved differentiating the heat conduction equation with respect to the coordinates of the spline control points used to approximate the unknown boundary.

In [15], an approach is described in which an additional parameter (analogous to time) is introduced to compute shape derivatives, characterizing the evolution of the spatial domain during the iterative process. Differentiating integrals of the scalar field (in the case of inverse heat transfer problems – temperature) over the spatial domain or its boundary leads to expressions similar to the substantial derivative. The subsequent application of the Lagrange multiplier method and the adjoint variable method allows for obtaining the shape gradient.

The level-set method [8, 13] is also based on the evolution of the domain during the iterative process and the computation of substantial and spatial derivatives. Study [12] demonstrated that this method results from the combined application of the Tikhonov regularization method and projection methods.

By generalizing the concept of shape derivatives, the authors of [13, 14] examined second-order shape derivatives and introduced the concept of the shape Hessian. This allowed them to apply second-order optimization methods in solving geometric inverse heat transfer problems (IHTPs) for boundary identification.

Among other methods for boundary identification, the fictitious domain method [13] can be highlighted. However, similar to the level-set method, it has not found widespread application in solving geometric inverse heat transfer problems (IHTPs).

To transition to the mathematical formulation of the problem, the desired geometric characteristics must be expressed in a parametric form. This means selecting one or more scalar values from the available geometric information that can vary according to the problem conditions. These scalar values may include: Coordinates of specific points, such as the locations of heat sources when determining their placement. Parameters of a functional dependency describing the geometry, such as the parameters of the boundary equation when defining a region’s shape. In the latter case, the dependency on unknown parameters can be either linear or nonlinear.

MATERIALS AND METHODS

Traditional stochastic (heuristic) optimization methods, such as the Monte Carlo method [8], simulated annealing [9, 12], and tabu search [11], allow finding local minima that may be superior to those obtained using deterministic methods. However, they are inefficient when dealing with objective functions containing multiple local minima, as they evaluate only one point in the search space per iteration, potentially trapping the algorithm in a local minimum.

In recent years, optimization methods based on evolutionary algorithms [9] have gained widespread popularity. Unlike traditional optimization methods, which consider only a single approximate solution (a point in the space of optimized parameters), evolutionary algorithms simultaneously evaluate multiple approximate solutions, known as a population of individuals. This allows for analyzing a larger region in the parameter space, escaping local minima upon their detection, while still retaining information about them. Among these methods, genetic algorithms (GA) [10, 13] have become the most widely used. When initialized with a sufficiently large random starting population, they enable the discovery of a global minimum. A key advantage of evolutionary algorithms is that they do not require differentiation of the objective function, making them more versatile for solving inverse heat transfer problems (IHTPs). Genetic algorithms are inspired by the principles of natural selection and reproduction in biological systems. Any genetic algorithm is based on the sequential iterative application of three genetic operators: selection, crossover, and mutation, which guide the transition from the current population of approximate solutions to the next generation. The selection operator chooses individuals from the current population that are the most adapted according to the optimization criterion (i.e., “the fittest survive”). The crossover operator generates new individuals for the next population based on the selected ones (the parent generation produces offspring). The mutation operator introduces a random factor into the generation process (a random gene modification due to external influence). It is precisely the mutation operator – along with other factors, such as the fact that genetic algorithms process encoded representations of optimization parameters rather than their actual values – that enables genetic algorithms to escape the vicinity of a previously found local minimum and move toward another local minimum, which may be better than the one initially identified. The real-coded genetic algorithm (RCGA) [14] is more effective for solving optimization problems involving functions defined over a continuous set of parameters, including inverse heat transfer problems (IHTPs) solved using extremal methods, compared to traditional genetic algorithms. Due to a more accurate encoding of values from the continuous space, this method improves the speed of minimization and allows for the consideration of small variations in optimized parameters.

It should be noted that gradient-based methods, particularly the conjugate gradient method, allow for faster and more accurate identification of a local minimum compared to genetic algorithms, provided that the initial approximation is located in its vicinity. However, the use of genetic algorithms as a tool for minimizing the objective function in solving geometric inverse heat transfer problems (IHTPs) is more effective – not only compared to the conjugate gradient method but also to other traditional optimization methods – precisely because they enable the transition from the vicinity of a found local minimum to the vicinity of another local minimum, potentially leading to a better solution.

The study utilized ready-made software packages for solving problems in computational fluid dynamics (CFD) and heat and mass transfer, including ANSYS, COSMOSWORKS, FLUENT, PHOENICS, STAR-CD, COSMOS-Works/FlowWorks, and others [9]. These packages are universal, meaning they are designed to solve a wide range of problems. They incorporate well-developed and verified numerical algorithms for solving the considered systems of differential equations.

RESULTS AND DISCUSSION

As previously noted, in nonlinear and multidimensional cases, the only way to solve a geometric inverse heat transfer problem (IHTP) is by minimizing a functional of the form (1) or a similar one. This is achieved through the iterative construction of a minimizing sequence $\{g^k\}$ in the space G, such that:

$$J(g^k) > J(g^{k+1}) \quad \text{and} \quad J(g^k) \to J_{\min} \quad \text{as} \quad k \to \infty. \qquad (1)$$

This iterative approach ensures a gradual convergence to the optimal solution.

The limit of the sequence $\{g^k\}$, if it exists, represents the exact solution to the original problem. However, it is important to note that in most practical geometric inverse heat transfer problems (IHTPs), proving the convergence of the minimizing sequence and explicitly finding its limit is unnecessary. This is due, on the one hand, to the fact that inverse heat transfer problems (IHTPs) are generally ill-posed, meaning they lack stability (i.e., the inverse operator A is unbounded). As a result, regularization methods must be applied to obtain an approximate solution. On the other hand, in practical applications, an approximate solution is sufficient, rather than an exact one. As a quantitative measure of solution accuracy, the value of the functional $J(g)$ computed at each iteration can be used – whether in the classical case of residual minimization or for other types of objective functionals, as described in [15].

When constructing the minimizing sequence, as in other types of inverse heat transfer problems (IHTPs), it is advisable to use existing numerical methods for constrained (if constraints are present) or unconstrained (if constraints are absent) minimization [16, 17]. The direct application of the necessary and sufficient conditions for a minimum is not feasible in this case because the form of the function to be minimized is determined by the operator B. In most real-world problems, B can only be computed numerically, making it impossible to obtain an analytical expression for the derivatives of the objective function with respect to the unknown parameters. As a result, solving the system of equations that appear in the necessary condition for a minimum becomes impractical.

It should be noted that the numerical optimization method used must be universal with respect to the form of the objective function. Additionally, the computational complexity of evaluating the operator B (and consequently, the functional J) largely determines which specific minimization method is most appropriate. As is well known, the more efficient a minimization method is, the more evaluations of the objective function and its derivatives are required at each iteration [12].

Among universal zeroth-order methods, the deformable polyhedron method (also known as the simplex method or Nelder-Mead method) [17] is considered one of the most efficient. It has been applied in the automated selection method [15], developed for solving internal inverse heat transfer problems (IHTPs). Among gradient-based methods, the steepest descent method and the conjugate gradient method [11] have proven to be highly effective. These methods have also been successfully applied to various types of IHTPs. To determine the search direction and the optimal value of the functional in a chosen direction [1-5], they use both differentiation formulas derived from the operator A and approximate expressions based on finite difference approximations of derivatives. A more efficient first-order method in terms of convergence speed – the Newton-Gauss method [6] – has been used for solving internal and boundary IHTPs in [12]. However, the use of second-order optimization methods, such as the classical Newton method, is relatively rare in studies on IHTPs. This may be due to the complexity and high computational errors associated with calculating second-order derivatives of the objective function.

It is also important to note that when the components of the vector g differ significantly in magnitude, standard optimization methods lose efficiency. This occurs because the objective function exhibits a ravine-like structure near the minimum, making convergence more challenging. In such cases, modified minimization procedures should be used, where the search is performed sequentially for certain variables or in groups of variables to improve efficiency and stability.

From the perspective of the computational cost of evaluating the functional B, the type of inverse heat transfer problem (IHTP) being considered is not significant. Therefore, it would be logical to apply the Nelder-Mead method or gradient-based methods to solve geometric IHTPs, as these methods have proven effective for other types of IHTPs. However, due to the multi-extremal nature of geometric IHTPs, these methods often fail to produce satisfactory results, as they tend to find only a local minimum near the chosen initial approximation, rather than the global optimum.

Most stochastic minimization algorithms are specifically designed to search for the global minimum [9]. One of the simplest methods for finding a global minimum is the sequential search of local minima. This involves repeatedly performing the local minimization procedure, each time starting from different randomly selected points in the parameter space. The smallest value among the obtained local minima is then chosen as the optimal solution [3].

In recent years, genetic algorithms (GAs) – optimization methods based on stochastic approaches – have gained widespread popularity. Unlike traditional minimization methods, genetic algorithms simultaneously evaluate multiple approximate solutions instead of a single point in the space of optimized parameters. As previously mentioned, genetic algorithms offer several advantages over traditional minimization methods, including: the ability to efficiently escape local minima, and greater universality, as they do not require differentiation of the objective function. However, they also have disadvantages, such as low convergence speed near the global minimum, and lower accuracy compared to deterministic optimization methods.

In our view, combining the advantages of traditional deterministic optimization methods (rapid descent to a local minimum from a nearby starting point) with those of genetic algorithms (the ability to efficiently escape local minima) can lead to new qualitative results in the theory of solving inverse heat transfer problems (IHTPs). In particular, this study proposes using a hybrid method, where: In the first stage, a genetic algorithm is used to search for multiple points in the parameter space G. In the second stage, these points serve as initial approximations for further minimization using a deterministic method. A modification of this method involves cyclic repetition of these two stages. In this study, a hybrid approach was applied to solve both methodological and practical problems, combining a genetic algorithm with decimal encoding and the Fletcher-Reeves method.

To determine the functional values for each element of the minimizing sequence, it is necessary to solve an inverse heat transfer problem (IHTP) with known uniqueness conditions, which are defined by the vector g^k. In most optimization methods, finding the next element in the minimizing sequence requires computing multiple values of the objective function for different values of the vector g – meaning that several IHTPs must be solved. For example, in the steepest descent method with finite difference approximation of the objective function's derivatives, if the objective function value is known for the current element of the minimizing sequence, then: The IHTP must be solved n times (where n is the dimension of space G) to compute the objective function and determine the descent direction. When searching for a new element of the minimizing sequence in the chosen direction, the objective function must be evaluated multiple times (requiring additional IHTP solutions) to find the best approximation in that direction.

Thus, when solving a geometric inverse heat transfer problem (IHTP) using an extremal method, it is necessary to solve a series of IHTPs for different trial values of the unknown parameters. In many cases, an approximate mathematical model is used, which is obtained by discretizing the original mathematical model – for example, using finite difference, finite volume, or finite element methods. Moreover, the development of a computational module for solving IHTPs can itself be a computationally intensive and time-consuming process.

CONCLUSION

Theoretical Significance: This study presents methodological foundations for solving geometric inverse heat transfer problems (IHTPs), enabling the determination of unknown geometric parameters of objects based on temperature field data. This expands the theoretical framework for analyzing and modeling thermal processes in complex systems.

Practical Applicability: The developed methods can be successfully applied across various industries, including energy, mechanical engineering, aerospace, and materials science, where precise determination of geometric parameters is crucial for optimizing thermal regimes.

Use of Numerical Methods: The study highlights the importance of numerical methods, including the finite element method (FEM) and finite difference schemes, for solving inverse problems. These approaches enable the consideration of nonlinear effects and complex boundary conditions, ensuring accurate and reliable solutions.

Role of Regularization: Special attention is given to regularization methods, which are essential for the stable solution of ill-posed inverse problems. Regularization ensures the derivation of physically meaningful results, even in the presence of errors in the input data.

Future Prospects: The authors emphasize the need for further development of algorithms, including the integration of machine learning and artificial intelligence methods, to enhance the accuracy and speed of solving inverse heat transfer problems.

Experimental Verification: The study emphasizes the importance of experimental validation of the developed methods to confirm their efficacy and reliability under real-world conditions.

Interdisciplinary Approach: Solving geometric inverse heat transfer problems (IHTPs) requires the integration of knowledge from various fields, including mathematical modeling, thermophysics, and computational mechanics, creating new opportunities for interdisciplinary research.

Overall Contribution: This study makes a significant contribution to the development of inverse heat transfer problem-solving methods, providing both theoretical foundations and practical tools for their implementation.

REFERENCES

1 Alifanov OM. The Extremal Formulations and Methods of Solving Inverse Heat Conduction Problems. Inverse Heat Transfer Problems [Internet]. 1994;150–91. Available from: http://dx.doi.org/10.1007/978-3-642-76436-3_7

2 Özisik MN, Orlande HRB. Techniques for Solving Inverse Heat Transfer Problems. Inverse Heat Transfer [Internet]. 2018 May 2;35–112. Available from: http://dx.doi.org/10.1201/9780203749784-2

3 Heat Transfer Fundamentals. Solving Direct and Inverse Heat Conduction Problems [Internet]. 2006;53–139. Available from: http://dx.doi.org/10.1007/978-3-540-33471-2_6

4 Matsevityi YuM. METHODS FOE SOLVING INVERSE NON-LINEAR HEAT-CONDUCTION PROBLEMS. Proceeding of International Heat Transfer Conference 6 [Internet]. 1978;239–44. Available from: http://dx.doi.org/10.1615/ihtc6.330

5 Allard D, Najafi H. A Novel Approach for Solving Inverse Heat Conduction Problems Using Genetic Algorithm. ASME 2023 Heat Transfer Summer Conference [Internet]. 2023 Jul 10; Available from: http://dx.doi.org/10.1115/ht2023-108259

6 Approximate Analytical Methods for Solving Transient Heat Conduction Problems. Solving Direct and Inverse Heat Conduction Problems [Internet]. 2006;587–604. Available from: http://dx.doi.org/10.1007/978-3-540-33471-2_20

7 Taler J, Duda P. Experimental verification of space marching methods for solving inverse heat conduction problems. Heat and Mass Transfer [Internet]. 2000 Jul 27;36(4):325–31. Available from: http://dx.doi.org/10.1007/s002310000082

8 Safari F. Solving multi-dimensional inverse heat problems via an accurate RBF-based meshless technique. International Journal of Heat and Mass Transfer [Internet]. 2023 Aug;209:124100. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2023.124100

9 Al-Khalidy N. APPLICATION OF STOCHASTIC METHOD FOR SOLVING INVERSE HEAT CONDUCTION PROBLEMS. Numerical Heat Transfer, Part A: Applications [Internet]. 1998 Aug;34(3):331–42. Available from: http://dx.doi.org/10.1080/10407789808913990

10 Guzik A, Styrylska T. AN APPLICATION OF THE GENERALIZED OPTIMAL DYNAMIC FILTRATION METHOD FOR SOLVING INVERSE HEAT TRANSFER PROBLEMS. Numerical Heat Transfer, Part A: Applications [Internet]. 2002 Oct;42(5):531–48. Available from: http://dx.doi.org/10.1080/10407780290059684

11 Berger J, Orlande HRB, Mendes N. Proper Generalized Decomposition model reduction in the Bayesian framework for solving inverse heat transfer problems. Inverse Problems in Science and Engineering [Internet]. 2016 Mar 28;25(2):260–78. Available from: http://dx.doi.org/10.1080/17415977.2016.1160395

12 Chen HL, Yu B, Zhou HL, Meng Z. Improved Cuckoo Search Algorithm for Solving Inverse Geometry Heat Conduction Problems. Heat Transfer Engineering [Internet]. 2018 Feb 8;40(3–4):362–74. Available from: http://dx.doi.org/10.1080/01457632.2018.1429060

13 Numerical Methods for Solving Conjugate Convective Heat Transfer Problems. Conjugate Problems in Convective Heat Transfer [Internet]. 2009 Aug 26;263–318. Available from: http://dx.doi.org/10.1201/9781420082388-17

14 Grysa K, Maciag A, Pawinska A. Solving nonlinear direct and inverse problems of stationary heat transfer by using Trefftz functions. International Journal of Heat and Mass Transfer [Internet]. 2012 Nov;55(23–24):7336–40. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.07.072

15 Wan S, Wang K, Xu P, Huang Y. Numerical and experimental verification of the single neural adaptive PID real-time inverse method for solving inverse heat conduction problems. International Journal of Heat and Mass Transfer [Internet]. 2022 Jun;189:122657. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2022.122657

16 Cui M, Duan W wei, Gao X wei. A new inverse analysis method based on a relaxation factor optimization technique for solving transient nonlinear inverse heat conduction problems. International Journal of Heat and Mass Transfer [Internet]. 2015 Nov;90:491–8. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.009

17 Higuera M, Perales JM, Rapún ML, Vega JM. Solving inverse geometry heat conduction problems by postprocessing steady thermograms. International Journal of Heat and Mass

Transfer [Internet]. 2019 Nov;143:118490. Available from: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2019.118490

INDUSTRIAL TECHNOLOGY AND ENGINEERING

Technical editor: *Nazarbek U.*

Signed for print on 18.12.2024

Format 70x100 1/16. Offset paper

Accounting-publishing list

Circulation 300 copies

CONTENTS

ISSN 2223-3911
04
9 772223 391166