

European Journal of Technical and Natural Sciences

2026, No 5

European Journal of Technical and Natural Sciences

Scientific journal

2026, No 5

ISSN 2414-2352

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The journal has Index Copernicus Value (ICV) 92.08 for 2022.

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Section 1. Architecture

DOI:10.29013/EJTNS-26-5-3-7



PARAMETRIC MODELLING AS A METHOD FOR EXPLORING AND COMPARATIVELY EVALUATING ARCHITECTURAL DESIGN ALTERNATIVES

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Cite: Honcharyk R.P. (2026). *Parametric Modelling as a Method for Exploring and Comparatively Evaluating Architectural Design Alternatives*. *European Journal of Technical and Natural Sciences* 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-3-7>

Abstract

This article aims to establish a methodological basis for aligning the parametric generation of alternatives with architectural evaluation criteria at the early stages of design. The study uses conceptual analysis, a comparison of scholarly publications, and theoretical synthesis. It distinguishes between dimensional variation, transformations of spatial relationships allowed by the model, and revision of the model structure. A sequence of problem formulation, parameterisation, model verification, alternative generation, and comparative evaluation is proposed. The study identifies conditions for combining quantitative indicators with qualitative analysis of functional and spatial organisation, composition, and context. The author's contribution lies in relating types of design change to the conditions required for comparing alternatives and the procedures used to select them. The findings are theoretical and methodological; their practical effectiveness requires empirical validation.

Keywords: *parametric modelling, architectural design, design exploration, design space, comparative evaluation*

Introduction

Parametric modelling enables the exploration of interrelated changes in a building's functional and spatial organisation and its volumetric composition. Formalising dependencies allows elements to be updated consistently (Jabi, 2013; Woodbury, 2010). However, the number of generated alternatives alone does not indicate the diversity of

architectural exploration. Numerous geometric configurations may reproduce the same layout, while an improvement in one indicator may be accompanied by deterioration in other properties.

The research problem concerns the alignment of a parametric model's capabilities with the grounds for architectural decision-making. The aim is to establish

a methodological approach to generating and comparatively evaluating alternatives at the early stages of design. To this end, the study clarifies the conceptual boundaries of parametric exploration, distinguishes types of design change, and identifies the conditions under which alternatives are comparable. The subject of the study is the relationship between parametric dependencies and architectural evaluation procedures.

Research Method

The study is based on a targeted analysis of nine publications from 2010–2025, selected for their relevance to parametric representation, model flexibility, and the evaluation of alternatives. Available full texts were used alongside abstracts and publishers' descriptions for some sources; the corresponding claims are restricted to the information provided in those materials. This selection does not constitute a systematic review. Conceptual analysis is supplemented by a comparison of parameter sets, dependencies, available transformations, and selection criteria. Theoretical synthesis is used to formulate the methodological sequence; no computational experiment was conducted.

Theoretical Background

Woodbury (2010) and Jabi (2013) explain the parametric approach through relationships between elements of an architectural model. In this article, the design space denotes the set of configurations accessible within specified variables, ranges, and rules. It represents the capabilities of a particular model rather than every potential solution to the design problem. Drawing on the terminology distinguished by Caetano et al. (2020), parametric modelling is understood as the representation of dependencies, algorithmic design as the formalisation of operations, and generative design as the organisation of alternative generation. Optimisation additionally requires objective functions, constraints, and a search procedure.

Oxman (2017) relates parametric design to design thinking; Davis (2013) investigates model flexibility, while Harding and Shepherd (2017) examine meta-parametric design. Turrin et al. (2011) combine parametric geometry with genetic algorithms. The Design Space

Construction approach aligns problem formulation, alternative generation, and the assessment of their value (Haymaker et al., 2018). Bunt et al. (2025) address the interaction between design thinking and optimisation. These publications provide a basis for interpreting the limits of variation and the grounds for selection in architectural terms.

Results and Analysis Parameters and Types of Design Change

The architectural meaning of a parameter is determined by the property it represents: building depth describes an overall dimension, column spacing defines the structural and planning grid, and the position of a circulation core determines its relationship to functional zones. The model distinguishes between input data, independent variables, derived characteristics, constraints, and criteria. Constraints establish feasibility, whereas criteria identify the relative merits of alternatives. Mandatory requirements are separated from the architect's working assumptions, the revision of which defines a distinct exploration scenario.

Drawing on studies of the flexibility and structure of parametric models (Davis, 2013; Harding & Shepherd, 2017), three types of design change are distinguished. Dimensional variation alters dimensions and proportions while retaining the existing system of spatial relationships. Transformations of spatial relationships alter zone adjacency, access sequences, or circulation routes within the possibilities already allowed by the model's rules. Revision of the model structure introduces new variables or dependencies to enable previously unavailable transformations. The boundary between the second and third types depends on the initial model: changing the number of circulation cores requires restructuring only if this possibility has not already been parameterised.

The distinction between dimensional and organisational change is determined by its spatial consequences. Moving an entrance constitutes a dimensional change if the access sequence remains unchanged; it becomes an organisational change when it alters the relationship between the entrance, shared spaces, and private zones. Differences in co-

ordinates alone are therefore insufficient for assessing diversity. Changes in zoning principles, spatial hierarchy, and relationships between functional components are significant for architectural exploration.

This distinction is neither a universal classification nor a mandatory sequence of stages. It establishes the basis for comparison: dimensional alternatives are assessed in terms of the consequences of changing values, while organisational alternatives are assessed as different spatial relationships within a shared brief. After restructuring a model, the comparability of input conditions and indicator calculation methods must be checked. A common design task and shared criteria thus ensure comparability even when the algorithmic structures of the models differ.

Organising Design Exploration and Evaluation

The hierarchy of parameters should correspond to the scale of the question being investigated. The building as a whole, its functional components, and its individual elements require different levels of detail. Introducing secondary variables prematurely complicates concept revision and the interpretation of results. Analysis of individual parameters should be supplemented by testing their combinations: an acceptable change in one dimension may produce an undesirable outcome under a different circulation configuration or functional zoning arrangement.

To align problem formulation, modelling, and evaluation (Haymaker et al., 2018), exploration begins by defining the architectural question, the limits of variation, and the criteria. Parameterisation establishes variables, ranges, and dependencies; conflicting conditions are resolved before alternatives are generated. Computational correctness and the model's adequacy for the design task are checked at representative and boundary values. These checks address unintended intersections, the preservation of necessary relationships, and consistency with the spatial concept. The sampling method, variation increments, and termination conditions are specified for alternative generation.

Feasibility checks precede ranking. Alternatives that violate the mandatory conditions being checked are rejected or revised. Compli-

ance within the model confirms only that the requirements represented in it have been met; unchecked properties remain undetermined. Alternatives are compared using consistent indicators and graphic representations with comparable scales, viewpoints, and levels of detail. Insufficient diversity or conflicting criteria provide grounds for revising the model. Changes to the conditions require the entire comparison set to be re-evaluated.

The reproducibility of exploration depends on documenting its conditions. The initial brief, variable ranges, method of generating alternatives, and reasons for rejecting options are retained alongside the selected design. Recording this information makes it possible to distinguish the effects of architectural decisions from those of model settings. Terminating generation according to a specified rule does not imply that all possible solutions have been exhausted; conclusions apply to the investigated set and the adopted conditions.

Quantitative indicators require defined units, a comparison baseline, and calculation rules. An aggregate assessment requires justification of normalisation methods, preferred directions of change, and weights. A geometric quantity cannot substitute for the assessment of a performance characteristic: building depth, for example, does not fully describe daylighting conditions. Qualitative analysis considers zone adjacency and accessibility, spatial hierarchy, proportions, rhythm, and relationships with the surroundings. Expert assessments should rely on defined attributes and graphic materials; differences in judgement should be recorded.

To compare functional organisation, the proportion of circulation space is calculated against a consistently defined reference floor area, while route lengths are measured between fixed functional points. A shorter route does not necessarily provide better accessibility: changes in level, passage configurations, and the separation of movement flows must also be considered. Each indicator should therefore be accompanied by an explanation of the property it represents and the aspects it excludes from evaluation.

Where criteria conflict, the sensitivity of the selection to weights and initial assumptions is examined. With multiple numerical indicators, non-dominated alternatives may

be selected: no other alternative in the investigated set performs at least as well on every criterion and better on at least one. This selection describes trade-offs only within the evaluated set. The final decision requires an explanation of the design's functional and compositional advantages and of why losses against other criteria are acceptable.

Compositional analysis involves comparing proportions, rhythm, dominant and subordinate elements in relation to the spatial concept. Contextual assessment considers the scale of the surroundings, the character of the built frontage, and the organisation of open spaces. These properties may be described using expert rating scales, but the meaning of each scale level must be defined. An overall score without an explanation of the assessed attributes and design priorities is insufficient to justify an architectural decision.

The robustness of a comparative conclusion depends on whether a design retains its advantages when priorities are reasonably revised. If changes in weights substantially alter the ranking, the result should be presented as dependent on the evaluation scenario. An increase in usable floor area, for example, may reduce the space reserved for circulation or future adaptation. Choosing between such alternatives requires design priorities to be stated explicitly. Weights express those priorities rather than establishing the universal importance of particular architectural properties.

At the conceptual stage, exploration addresses the arrangement of building volumes, zoning, and access; at the schematic design stage, it addresses dimensions, room configurations, and circulation relationships. Further development involves coordination with structural, building services, and information models. Documenting variables, the model version, and the grounds for selection makes the origins of a design traceable; transferring geometry alone does not guarantee the preservation of parametric dependencies.

Discussion

The author's contribution lies in relating types of design change to conditions of com-

parability and evaluation procedures. The proposed distinction clarifies when changing parameter values is sufficient, when different spatial organisations should be compared, and when the model should be restructured. It supplements existing approaches with an architectural interpretation of transformations and does not constitute a new optimisation algorithm.

The methodological value of the approach lies in linking the assessment of an individual alternative to an analysis of how alternatives are generated. If a model permits only dimensional changes, its results cannot substantiate the superiority of the adopted layout over other layouts. Where spatial organisation changes, a common functional brief must be retained or its revision explicitly identified. This limits the unwarranted transfer of conclusions between different design scenarios.

Further validation should compare processes involving participants with comparable experience and defined time limits. Independent expert evaluation of the final designs should complement analysis of alternative diversity, the reasons for model restructuring, and the reproducibility of calculations. The effort required to establish and revise parametric dependencies must be included in the total workload. This approach would allow testing of whether the proposed organisation of exploration provides practical advantages and under which conditions they arise.

Conclusions

The study establishes a methodological basis for parametric exploration as an iterative process that combines alternative generation, constraint checking, and quantitative and qualitative evaluation. Its methodological conditions are the relevance of parameters to the design task, a common basis for comparison, and a reasoned selection. The findings are limited by the selective literature base and the absence of empirical validation. Further validation requires comparing design processes under a common brief and assessing the diversity of alternatives, their architectural quality, and the total modelling workload.

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submitted 15.09.2026;

accepted for publication 29.09.2026;

published 30.09.2026

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Section 2. Chemistry

DOI:10.29013/EJTNS-26-5-8-15



DEVELOPMENT OF A SEMICONDUCTOR-BASED SELECTIVE SENSOR FOR ACETONE VAPOR MONITORING AND DETERMINATION OF ITS METROLOGICAL CHARACTERISTICS

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Cite: Kholmurzaev F., Eshkobilova M. (2026). Development of a Semiconductor-Based Selective Sensor for Acetone Vapor Monitoring and Determination of its Metrological Characteristics. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-8-15>

Abstract

Based on the results of the conducted studies, a method for ensuring the selectivity of acetone detection has been proposed using semiconductor sensors integrated into a single unit containing catalysts with sufficient activity toward the analyzed mixture. The absolute and relative errors and variation of the analytical signal were determined in accordance with the parameters specified by the State Standard GOST 13320–81 and were found not to exceed the established limits. At a confidence level of 0.95, the total reduced error over the measured concentration range fully complies with the requirements of the State Standard GOST 52033–2003 for instruments of this type and does not exceed $\pm 1.5\%$.

Keywords: acetone, semiconductor sensor, catalyst, sensitivity, selectivity, dynamic parameter, absolute and relative errors, variation

Introduction

Acetone is a highly flammable substance, and its mixture with air is explosive (**GOST 2768–84**). In addition, acetone is a psychoactive substance that can adversely affect the human central nervous system (**GOST 12.1.007–76**). Therefore, highly sensitive and rapid methods for monitoring the concentration of acetone in the air are required to ensure occupational safety at various industrial and other facilities (**GOST 32419**). The problem of acetone monitoring can be

addressed through the development of reliable sensors and gas analyzers that meet all the required metrological characteristics. Semiconductor sensors and gas analyzers are among the most promising and reliable instruments and devices for monitoring combustible components in gas mixtures, particularly acetone.

Experimental Results and Discussion

Based on the experimental results obtained, a method was developed to ensure

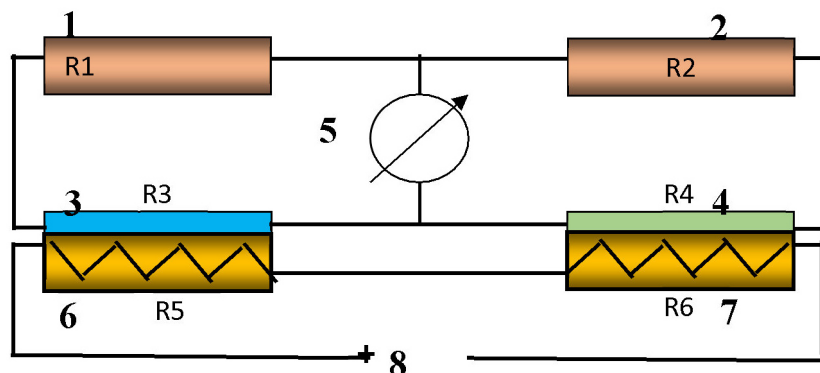
the selectivity of a semiconductor sensor for acetone in the presence of CO, H₂, and hydrocarbons. The proposed method is based on the use of sensing elements containing catalysts with different levels of activity toward the components of the gas mixture.

Using the developed catalysts, selective semiconductor acetone sensors were fabricated. Each sensor consisted of two sensing

elements – a measuring element and a compensation element – and two resistors connected in a bridge circuit (Fig. 1).

The gas-sensitive film of the measuring element had the composition **SiO₂/ (1.0TiO₂ + 0.75CuO)**, whereas the composition of the compensation element was **SiO₂/ (0.25Fe₂O₃ + 0Ni₂O₃)**.

Figure 1. Circuit diagram of the sensor for detecting acetone in a gas mixture



1 and 2 – fixed resistors; 3 and 4 – gas-sensitive elements; 6 and 7 – heating elements for the gas-sensitive layer (platinum wires coated with glass); 5 – signal measuring instrument; 8 – current source supplying power to the platinum-wire heaters.

The developed sensors enable the monitoring of micro- and macro-concentrations of acetone in gas mixtures. When the gas mixture enters the sensor chamber, the measuring element of the developed sensor generates a response to CO, H₂, and acetone, whereas the compensation element produces a corresponding response to CO. Under the selected operating conditions, hydrocarbons are practically not oxidized on either sensing element. Consequently, the difference between the signals of the measuring and compensation elements corresponds to the concentration of acetone in the gas mixture.

In accordance with the occupational safety requirements for handling acetone, the following main characteristics of the acetone sensor were determined:

a) dependence of the sensor response on the temperature of the sensing element (i.e., on the magnitude of the voltage/current supplied to the heating layer of the sensing element);

b) dynamic response of the sensor signal;

c) selectivity of the sensor toward the target component (discrimination capability);

d) variation of the output signal over a specified time interval, i.e., the change in the sensor response corresponding to a constant acetone concentration.

The optimal sensor supply voltage was experimentally determined. Its dynamic and calibration characteristics, selectivity, and signal stability were investigated. A batch of five selective semiconductor sensors operating as part of the acetone gas analyzer system was used in the tests.

Experiments to evaluate the semiconductor acetone sensor were conducted under normal, optimized, permissible extreme, and operating conditions. All experiments were performed using instruments and equipment that had undergone metrological certification.

The temperature of the gas-sensitive layer is maintained by the current supplied to the heating element. Therefore, during the development of various semiconductor sensors, the effect of the applied voltage on the sensor response is investigated, and the optimal supply voltage is determined.

The dependence of the response magnitude of the semiconductor acetone sensor

(SAS-Ac) on the voltage applied to the sensor was studied over the voltage range of 1.0–3.5 V. Experiments to determine the optimal supply voltage were conducted under normal operating conditions using

a gas–air mixture containing acetone at a concentration of 100 mg/m³. The results obtained for selecting the optimal supply voltage for the acetone sensor are presented in Table 1.

Table 1. *Dependence of the SAS-Ac response on the voltage applied to the sensor (acetone concentration: 100 mg/m³, n = 5, P = 95%)*

Sensor supply voltage, V	Sensor response, mV		
	$\bar{x} \pm \Delta X$	S	Sr*10 ²
1,0	0,4±0,01	0,01	2,0
1,2	0,5±0,01	0,01	1,4
1,4	0,6±0,01	0,01	1,5
1,6	3,8±0,02	0,02	0,4
1,8	7,6±0,11	0,09	1,2
2,0	8,3±0,16	0,13	1,9
2,2	8,5±0,18	0,15	1,7
2,4	8,4±0,18	0,14	1,6
2,6	8,3±0,16	0,13	1,8
2,8	8,2±0,11	0,08	0,9
3,0	8,9±0,12	0,10	1,2
3,5	7,9±0,14	0,12	1,4

The data presented in (Table 1) show that the optimal supply voltage for the semiconductor acetone sensor (SAS-Ac) is **2.2 V**. An increase or decrease in the supply voltage from the optimal value leads to a decrease in the useful analytical signal and a deterioration in the selectivity of acetone detection.

Considering the intended applications of the sensor and the high toxicity of acetone, an essential requirement for its operation is a rapid response, i.e., a short response time. Therefore, the acetone sensor should have good dynamic characteristics.

The transient response time of the SAS-Ac was investigated under conditions of a stepwise change in the acetone concentration at the sensor inlet. Gas mixtures containing acetone at concentrations of **75 mg/m³ and 150 mg/m³** were used in the experiments. The characteristics of the acetone sensor were evaluated by continuously recording the transient response on the chart tape of a **KSP-4 recording instrument**.

The change in acetone concentration at the inlet of the SAS-Ac was also recorded on

the chart tape and was taken as the starting point for time measurement.

The investigation of the dynamic characteristics of the developed acetone sensor included the study of its time-dependent characteristics, particularly the transient response processes.

Before starting the tests, the sensor baseline (background) signal had to be established. For this purpose, purified argon (or purified nitrogen) was supplied for 10 min to five semiconductor acetone sensors connected in series. The sensor signals, corresponding to the resistance values of the gas-sensitive layers, were recorded using a V7–35 voltmeter.

The transient response time of the SAS-Ac was investigated under conditions of a stepwise change in acetone concentration at the sensor inlet. Gas mixtures containing acetone at concentrations of **75 mg/m³ and 150 mg/m³** were used in the experiments. The characteristics of the acetone sensor were evaluated by continuously recording the transient response on the chart tape of a **KSP-4 recording instrument**.

The change in acetone concentration at the inlet of the SAS-Ac was simultaneously recorded on the chart tape and was taken as the zero point for measuring the response time.

The experiments were conducted under normal conditions: a temperature of **20 °C**, an ambient pressure of **730 mmHg**, and a relative humidity of **60%**.

In the experiments, each test point within the measurement range was characterized by six measurements: three measurements in the forward direction, corresponding to the time required to reach the maximum signal value, and three measurements in the reverse direction, corresponding to the time required to return to the initial signal value.

After the analytical signal of the sensors reached a constant value, the following parameters were determined as the dynamic characteristics of the semiconductor acetone sensor:

to.1 – initial response time, i.e., the time required for the signal to reach 10% of its final value, s;

to.65 – characteristic time, i.e., the time required for the signal to reach 65% of its final value, s;

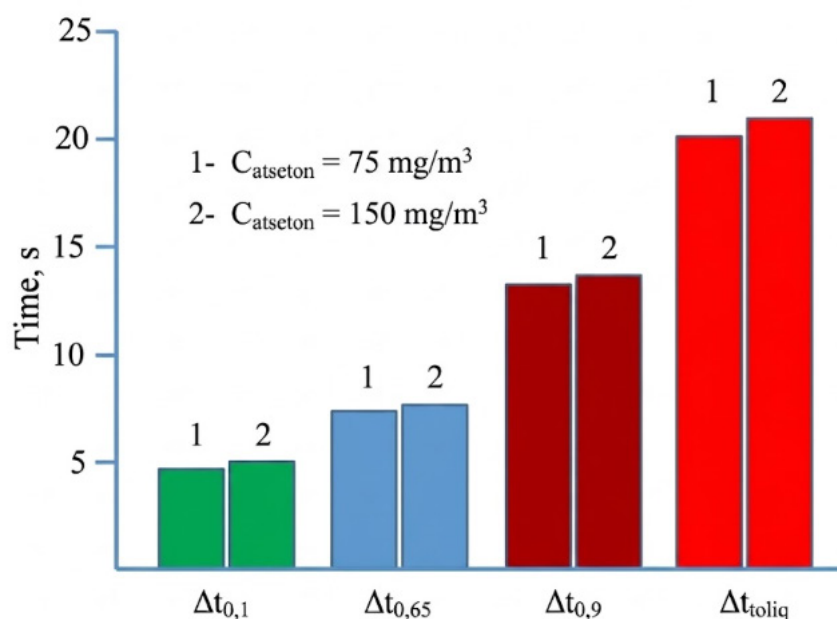
to.9 – signal stabilization time, i.e., the time required for the signal to reach 90% of its final value, s;

t(full) – total measurement time, i.e., the time required for the signal to reach its maximum value, s.

The results of determining the dynamic characteristics of the SAS-Ac are presented in (Fig. 1). As can be seen from the figure, for the gas-sensitive film with the composition **SiO₂/(TiO₂ + 0.75CuO)**, the dynamic parameters of the sensor were as follows:

- **to.1** – initial response time: **5 s**;
- **to.65** – characteristic time: **8 s**;
- **to.9** – signal stabilization time: **13–14 s**;
- **t(full)** – total measurement time: **20–21 s**.

Figure 2. Dynamic characteristics of the semiconductor sensor for acetone detection

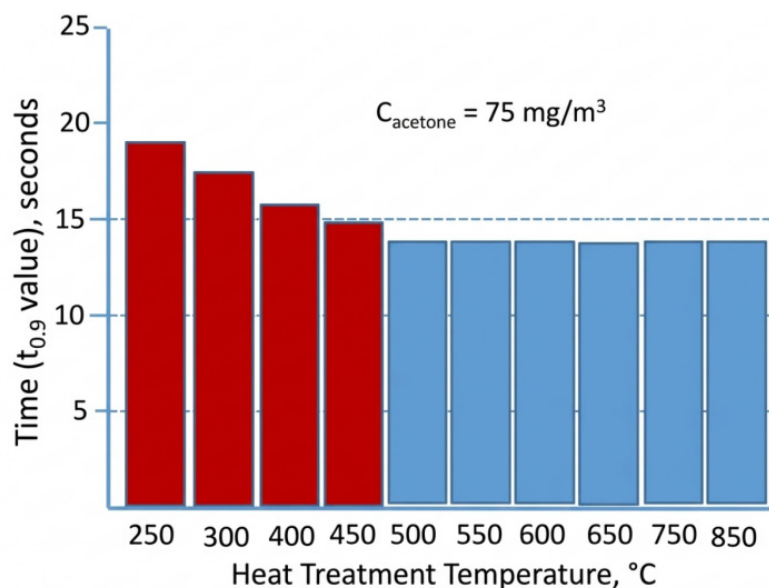


The figure shows that, for the gas-sensitive film with the composition **SiO₂/(TiO₂ + 0.75CuO)**, an increase in the acetone concentration in the gas mixture from **75 mg/m³ to 150 mg/m³** results in a slight increase in the dynamic characteristics of the sensor. In particular, the **total measurement time (t(full))** increases from **20 to 21 s**.

It has generally been established that, for semiconductor sensors, the time required to reach the maximum signal value depends on the heat-treatment conditions of the gas-sensitive film. For the acetone sensor, this parameter was investigated within the temperature range of **250–850 °C**. The dependence of the signal of the **SAS-Ac based on**

SiO₂/(TiO₂ + 0.75 CuO) on the firing temperature of the gas-sensitive material (GSM) is presented in (Fig. 3).

Figure 3. Dependence of the signal stabilization time ($t_{0.9}$) on the heat-treatment temperature of the gas-sensitive film during acetone detection ($C_{\text{acetone}} = 75 \text{ mg/m}^3$)



The figure shows that the time required for the sensor signal to reach its maximum value depends on the firing temperature of the gas-sensitive material (GSM). This time decreases with increasing temperature within the range of **250–500 °C** and remains practically unchanged at temperatures above **500 °C**.

The minimum time required for the sensor based on **SiO₂/(TiO₂ + 0.75CuO)** to reach its maximum signal value was **14 s**, corresponding to the signal stabilization time ($t_{0.9}$) of the gas-sensitive material thermally treated at **550 °C**. Considering the dependence of sensitivity on the porosity of the gas-sensitive material, it can be assumed that the gas-sensitive material reaches its maximum porosity at approximately **500 °C**.

The data presented in (Figure 2 and 3) confirm that the developed sensors are capable of rapid detection of acetone.

The reproducibility of the sensor response corresponding to the same constant concentration in repeated analyses was investigated using a gas mixture containing **100 mg/m³ of acetone**. Five replicate determinations were performed using five sensors simultaneously.

In these studies, the sensor response was recorded using a self-recording potentiometer. The results of the study demonstrated that the developed sensor, consisting of two

sensing elements, is characterized not only by high selectivity but also by good reproducibility of the analytical signal.

One of the most important characteristics of gas-analytical instruments is the selective determination of a target component in a mixture of analyzed gases. In the semiconductor sensors developed in this study, selectivity was ensured by selecting optimal operating temperatures and appropriate catalysts. The selectivity of acetone detection using the developed sensors was investigated with certified gas mixtures in accordance with the GOST requirements for gas-analytical instruments intended for closed environmental systems and chemical industry facilities.

The selectivity of the semiconductor acetone sensor (SAS-Ac) was determined at a temperature of **350 °C** using standard gas mixtures in the presence of hydrogen, carbon monoxide, and methane. Mixture No. 1 (**acetone + air**) was supplied to the SAS-Ac for **5 min**, and the sensor response was recorded using a digital voltmeter. Subsequently, mixture No. 2 (**acetone + hydrogen + air**) was supplied, and after 5 min, the digital voltmeter reading was recorded again. The same procedure was performed for mixture No. 3 (**acetone + carbon monoxide + air**) and mixture No. 4 (**acetone + meth-**

ane + air), and the corresponding sensor responses were recorded.

For each standard gas mixture, the number of parallel measurements was $n = 5$. The mean results obtained for determining the selectivity of the SAS-Ac are presented in (Table 2).

According to the obtained data, the presence of carbon monoxide (up to **830 mg/m³**), hydrogen (up to **604 mg/m³**), and methane (up to **540 mg/m³**) in the analyzed acetone–air mixture does not affect the output signal of the acetone sensor.

Table 2. Results of the selectivity testing of the semiconductor acetone sensor SAS-Ac-3M ($n = 5$, $P = 0.95$)

Composition of the gas mixture	Acetone found, mg/m ³					
	SAS-Ac.No 1		SAS-Ac.No 2		SAS-Ac.No 3	
	$\bar{x} \pm \Delta x$	Sr10 ²	$\bar{x} \pm \Delta x$	Sr10 ²	$\bar{x} \pm \Delta x$	Sr10 ²
Acetone-563±(air, balance)	560±3	1,7	566±5	1,5	565±3	1,4
Acetone-563±H ₂ -604± (air, balance)	562±2	1,4	562±4	1,4	562±3	1,6
Acetone-563±CO-830± (air, balance)	559±3	1,6	565±3	1,5	562±4	1,6
Acetone-563±CH ₄ -540± (air, balance)	560±4	1,2	564±4	1,1	564±5	1,4

The data presented in (Table 2) demonstrate that, within the investigated concentration range, the developed sensor enables the selective determination of acetone. The measurement error of the SAS-Ac due to the presence of non-measured components does not exceed **1.5%**.

Thus, a sensor has been developed that ensures selective determination of acetone in multicomponent gas–air mixtures containing hydrogen, carbon monoxide, and methane (natural gas) simultaneously with acetone. Such mixtures include various natural and technical gas mixtures, as well as gaseous emissions from industrial enterprises.

In all cases, the relative standard deviation (**Sr**) due to the presence of non-measured components does not exceed **0.05**. Within the investigated flow-rate range of **5–50 L/h**, changes in the flow rate of the gas mixture do not significantly affect the output signal of the sensor.

The output signal of the sensors is also independent of their spatial orientation and inclination angle, which makes it possible to classify the developed sensors as **independent-type sensors in accordance with GOST 13320–82**.

Conclusion

Semiconductor methods with improved metrological characteristics have been developed, and on their basis, a semiconductor sensor has been developed for the determination of acetone in the atmospheric air of closed ecological systems and in human exhaled breath, with a measurement error not exceeding **1.0%**.

The oxidation mechanisms of combustible substances (**H₂**, **CO**, **CH₄**, and **acetone**) by atmospheric oxygen in the presence of metal oxides were investigated. Based on these studies, the optimal nanocomposite material for the gas-sensitive element of the semiconductor acetone sensor was determined to have the composition **SiO₂/(TiO₂ + 0.75CuO)**. The experimental results demonstrated the feasibility of developing highly selective semiconductor sensors based on nanocomposite materials exhibiting different levels of activity toward the individual components of gas mixtures. The main metrological characteristics of the selective semiconductor acetone sensor were evaluated.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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Section 3. Computer science

DOI:10.29013/EJTNS-26-5-16-22



DESIGNING MODULAR AI INFRASTRUCTURE FOR STEEL AND METALWORKING OPERATIONS: SEPARATING ARCHITECTURAL INTEROPERABILITY FROM MODEL-LEVEL GENERALIZATION

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Cite: Elagin N. V. (2026). *Designing Modular AI Infrastructure for Steel and Metalworking Operations: Separating Architectural Interoperability from Model-Level Generalization*. *European Journal of Technical and Natural Sciences* 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-16-22>

Abstract

Modular architectures built from containerized microservices and standards-based communication layers deliver scalability and cross-plant portability to artificial intelligence systems in steel and metalworking operations. The interoperability these architectures deliver is a structural property of the deployment layer, separate from a statistical property: whether the AI models the architecture hosts generalize to a machine, material, or lighting configuration different from the one they were trained on. Container-orchestration benchmarks, cross-machine anomaly-detection studies, and steel-surface defect-detection results converge on one conclusion: a fully functioning modular deployment can host a model whose accuracy collapses outside its training distribution, and current reference architectures for industrial AI collapse the two properties into a single, undifferentiated claim of adaptability. Adoption decisions and vendor claims in this domain require two independent checklists, one architectural and one model-specific. Existing predictive-maintenance and computer-vision platforms already embed retraining pipelines that concede the model-level limit their surrounding language papers over.

Keywords: *modular architecture, industrial artificial intelligence, predictive maintenance, computer vision, model generalization, Industry 4.0 interoperability*

Introduction

Roughly 40–50% of the sensing and control assets already installed in U.S. metal-producing facilities would need upgrading before an Industry 4.0-class platform could run on them at all, and the equipment that

remains typically spans several generations of PLCs and ERP systems built for isolated operation, each generation running its own data format (Shargaev, 2025 b).

The seam between an architecture's interoperability and a model's generalization

across the machines, materials, and lighting conditions that same architecture serves is the field's central problem. Both properties share one vocabulary, adaptability and flexibility, which is exactly why a platform can be modular in every engineering sense and still fail the moment it meets a CNC cell, alloy grade, or camera angle outside its training data.

Literature Review

A microservice platform built around the MIMOSA interoperability schema decomposes predictive-maintenance functions, ingestion, feature extraction, model serving, into independently deployable services that communicate over REST interfaces, with containers that can be added or removed while the rest of the platform keeps running (Nikolakis et al., 2020). This same decomposability turns out to be compatible with a stricter requirement, formal AI governance: a 2026 reference architecture built to satisfy ISO/IEC 42001's AI-management standard defines four deployment tiers, device, edge, platform, and enterprise, and reports that this layering, validated against a production case, improved system traceability and maintenance-related downtime tracking while leaving the underlying microservice logic intact (Mateo-Casali et al., 2026).

A reference software architecture built to be framework- and technology-agnostic was instantiated separately for three industrial partners in the automotive, energy, and precision-machining domains, and the validation reported that the three instantiations produced diverging scalability and interoperability requirements despite sharing the same underlying blueprint (Haindl et al., 2022). A systematic review of container-based virtualization in real-time industrial systems narrows this to a measurable mechanism: processing latency inside an identical Docker container improved by a factor of 13.9, from 446 to 32 microseconds, simply by swapping the underlying kernel, and the standard deviation in scheduling precision under a demanding co-located workload ran two orders of magnitude larger than under a light one (Queiroz et al., 2023).

A predictive-maintenance platform for CNC-based metal-cutting systems is presented as modular because plants can begin with

a minimal sensor set and expand later, and its edge layer is described, in the same sentence, as accommodating different hardware configurations while its machine-learning pipelines retrain themselves as new datasets accumulate (Shargaev, 2025 a). The first half of that sentence, hardware accommodation and incremental sensor deployment, is an architectural claim of exactly the kind Nikolakis et al. (2020) and Mateo-Casali et al. (2026) document. The second half, pipelines that retrain themselves as data accumulates, is a different kind of claim: it concedes that the model must first see new data from the new deployment before its predictions earn trust there, which is precisely the generalization gap that Haindl et al.'s (2022) diverging site requirements and Queiroz et al.'s (2023) kernel-dependent latency locate outside the architecture layer.

Trained-model accuracy in this literature is a property of the specific dataset a model was evaluated on, once the deployment layer is held constant and only the input data varies. A one-dimensional convolutional network trained on sensor data from CNC and machining-center assets reaches 91.57% accuracy on held-out data from the same equipment, outperforming random forest, gradient boosting, and several other classifiers trained on the identical feature set (Athar et al., 2024); the result establishes a machine-matched accuracy ceiling specific to the equipment it was evaluated on. A CNN-LSTM hybrid architecture for predictive maintenance reaches 96.1% accuracy and a 95.2% F1-score specifically against the best of three named industrial sensor datasets, outperforming standalone CNN and LSTM baselines on those same datasets (Li & Li, 2025); the 96.1% figure is a property of the three datasets it was measured on, and applies to CNC or metal-cutting deployment only to the extent a new site's data resembles them. Steel-surface defect detection produces the identical pattern in a visual: a YOLOv5-based detector augmented with an attention mechanism and a bidirectional feature pyramid network reports accuracy gains on the steel surface defect categories present in its training set (Gao et al., 2024), specifically a mean Average Precision of 75.7%, a 4.2-percentage-point gain over the baseline model, at a throughput of 70 frames per

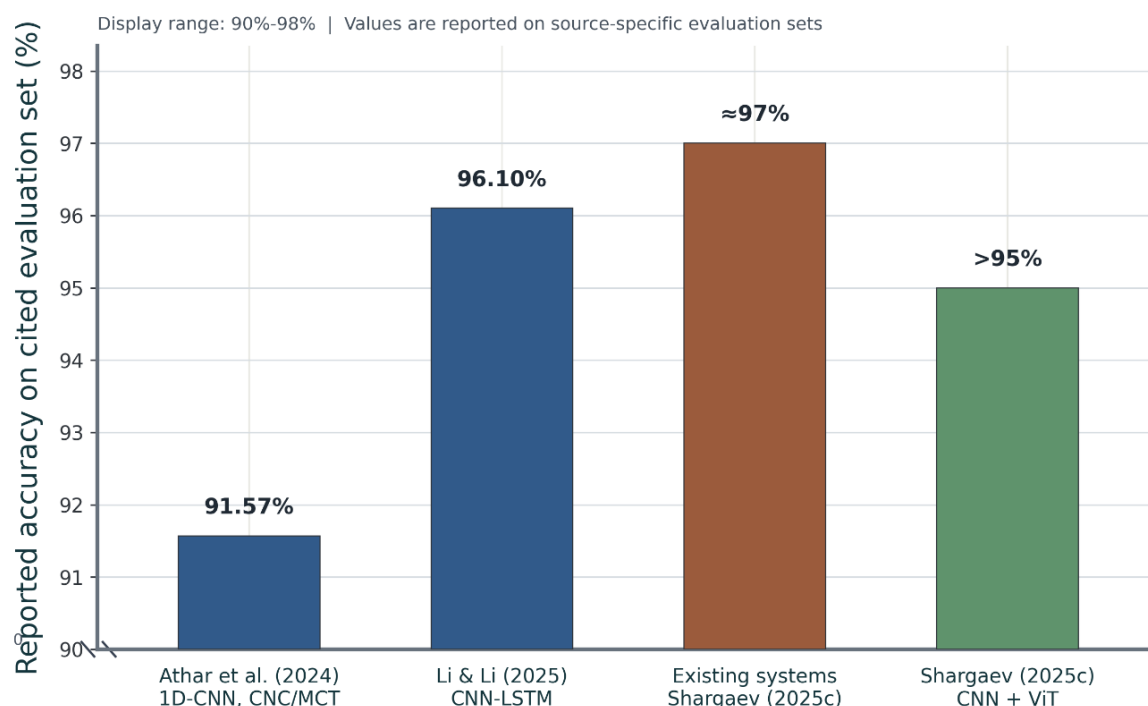
second (Gao et al., 2024); and an earlier detector built specifically to address small and structurally complex defect targets on steel surfaces reports its improvement against that same constraint, detection performance

measured relative to the defect population the model was shown during training (Zhao et al., 2021). Each of these four results is positive and reproducible, tied to a named dataset.

Table 1. Accuracy figures cited in this review, each anchored to a specific evaluation set

Source	Task / domain	Reported accuracy	Evaluation basis
Athar et al. (2024)	Anomaly detection, 1D-CNN, CNC / machine-center sensor data	91.57%	Held-out data from the same equipment
Li & Li (2025)	Predictive maintenance, CNN-LSTM hybrid	96.1% (F1=95.2%)	Best of three named industrial sensor datasets
Existing AI inspection systems (per Shargaev, 2025 c, prior-art comparison)	Metal defect detection, single-model CNN	~97%	Trained defect types only; new types require new training
Shargaev (2025 c), invention	Metal defect detection, CNN + ViT hybrid	>95%	Known defect types shown during training
Gao et al. (2024)	Steel surface defect classification, YOLOv5 + SE attention + BiFPN	75.7% mAP (+4.2 pts), 70 FPS	Defect categories present in training set
Zhao et al. (2021)	Steel surface defect detection, modified Faster R-CNN	75.2% mAP (+12.8 pts); per-class range 50.1%-90.5%	Defect population shown during training

Figure 1. Reported accuracy figures are anchored to the dataset or defect population each source evaluated



The patent for a computer-vision quality-analysis system embedded in metal-cutting lines documents this same ceiling from inside its own prior-art comparison. Existing AI-based inspection systems, the patent states, reach approximately 97% accuracy on trained defect types, but their adaptability is limited to their training data, and new defect types require new training before the system recognizes them (Shargaev, 2025 c). Read against Athar et al.'s and Li and Li's dataset-anchored accuracy figures, the patent's own architecture functions as an engineering acknowledgment of the model-generalization limit: the system retrain because every accuracy figure reported in this literature ties performance strictly to the data the model was shown, leaving new geometries, materials, and lighting rigs to be earned through the same retraining cycle.

Plants adopt modular, standards-based architecture for reasons that sit entirely on the standardization side of the ledger, independent of the generalization problem identified above; the standardization gap it closes is documented as severe enough on its own terms to justify the investment regardless of what happens to model accuracy afterward. A RESTful binding for OPC UA was proposed

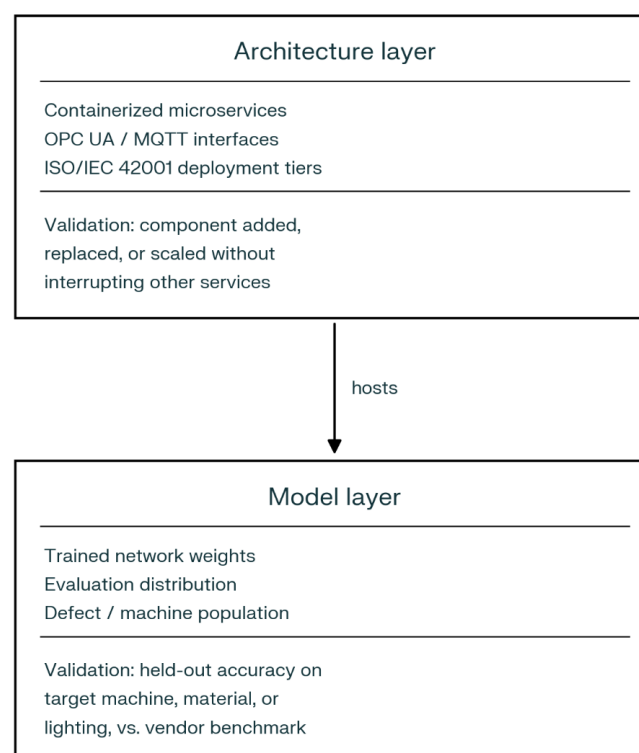
as a lighter-weight alternative to the standard's native service-oriented interface for accessing industrial data (Grüner, Pfrommer, & Palm, 2016), and the companion specifications built on top of OPC UA were designed so that devices from different manufacturers interpret the same variable without custom mapping (Schleipen, Lüder, Sauer, Flatt, & Jasperneite, 2016).

In U.S. metallurgy specifically, adoption of OPC UA and comparable standards is described as uneven, with different generations of PLCs and ERP systems installed in the same plant still failing to interoperate even where a nominal standard is present (Shargaev, 2025 b). This plant-level condition is what makes modular retrofit strategies attractive, independent of how mature any individual AI model is: plants adopt containerized, standards-based platforms because the alternative, a monolithic system assuming uniform legacy infrastructure, requires exactly the uniform starting point these plants lack.

Discussion

Modular architecture works, and the AI models tested in this literature perform at the levels their authors report.

Figure 2. *The architecture layer and the model layer*



Contrary to Haindl et al.'s (2022) framing of a framework- and technology-agnostic reference architecture as a blueprint that any manufacturing context can adopt through direct derivation, their own validation across automotive, energy, and precision-machining partners reports diverging scalability and interoperability requirements at the point of instantiation. This is a substantial finding: the framework-agnostic property holds at the

level of documentation and component naming, while the property that determines deployment cost and risk, how much site-specific data collection and model retraining each instantiation needs, is generated by the AI models the architecture hosts. A reference architecture agnostic to technology stays fully exposed to data, and the divergence Haindl et al. report across three unrelated manufacturing domains demonstrates exactly that exposure.

Table 2. *A two-checklist framework for evaluating modular AI platforms in steel and metalworking operations*

Checklist	Question it answers	Representative evidence
Architecture checklist	Can a component be added, replaced, or scaled while the rest of the system keeps running?	Nikolakis et al. (2020); Mateo-Casali et al. (2026); Queiroz et al. (2023)
Model checklist	Has the specific trained model deployed inside that architecture seen data resembling the target machine, material, or lighting condition?	Athar et al. (2024); Li & Li (2025); Shargaev (2025 c, prior-art comparison)

Under this separation, the computer-vision patent's own retraining subsystem reads as the correct engineering response to a limit the patent itself documents in its prior-art comparison: existing systems reach roughly 97% accuracy on trained defects but require new training for new ones (Shargaev, 2025c), and the invention's answer makes that retraining cycle a built-in, periodic feature of the architecture. That is a genuine, self-contained contribution to the architecture checklist. Set beside the four-source spread in Table 1, that ~97% figure sits at the same order of magnitude as Li and Li's (2025) 96.1% and above Athar et al.'s (2024) 91.57%, while the two visual-inspection results added above (75.7% and 75.2% mAP) sit roughly 20 points lower: the gap tracks task type, sensor-based anomaly detection versus image-based defect localization, at least as strongly as it tracks any architectural choice, which is further evidence that the accuracy number belongs to the model-and-task pairing.

This separation also reframes what standards-adoption barriers actually buy a plant. When OPC UA or an equivalent protocol closes the interoperability gap that Grüner et al. (2016) and Schleipen et al. (2016) address, and when Ladegourdie and

Kua's (2022) performance evaluation confirms the protocol remains feasible at the edge, a plant clears the architecture checklist: components from different vendors and different equipment generations exchange data in a common format. Solving the architecture checklist leaves the model checklist exactly where it was: the persistent obstacles that Hamdi Alaoui et al. (2026) identify under the heading of model robustness and cross-condition heterogeneity belong to the model checklist on their own terms, independent of how much standardization the plant has achieved. Conflating the two lets a genuinely modular, standards-compliant platform earn the label adaptive for its plumbing alone, as the CNC predictive-maintenance case above shows, while the label quietly expands to cover the model running inside it.

Conclusion

The distinction between an architecture's interoperability and a model's generalization, the seam separating two literatures that currently share one vocabulary, resolves a specific practical ambiguity in how modular AI infrastructure for steel and metalworking operations should be evaluated before purchase or deployment. A plant evaluating a predictive-maintenance or computer-vision platform

gains little by confirming only that the platform's services are containerized, standards-compliant, and independently scalable; the evidence reviewed here shows that property is now achievable and documented across two independent architectural traditions spanning 2020 to 2026. The same evidence stops short of supporting one further step: treating that achievement as a proxy for whether the specific model inside the platform performs on the plant's own machines, alloys, and lighting rig before first collecting site-specific data and running it through a retraining cycle of the kind the patented computer-vision system described above already builds in as a first-class feature. A vendor evaluation checklist built on this distinction requires accuracy figures reported separately for the target site's own defect population, material grade, and

lighting configuration, standing apart from the single aggregate figure inherited from the vendor's original training set. Testing whether such site-specific figures diverge from the vendor's published benchmark, and by how much, is the next empirical step the field owes its adopters.

Every accuracy figure in Table 1, 75.2% to 97%, comes from the same hardware, defect population, or sensor rig the model trained on, including Athar et al.'s (2024) 23.3-percentage-point spread across ten classifiers. Two adoption risks in this field already have numbers attached: roughly 40–50% of legacy sensing and control assets need upgrading before an Industry 4.0 platform runs at all (Shargaev, 2025b), and swapping a container's kernel alone can shift latency by 13.9x (Queiroz et al., 2023).

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-23-29



ECONOMIC EFFICIENCY OF IT INFRASTRUCTURE ENGINEERING OPTIMIZATION IN COMMERCIAL COMPANIES

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Cite: Otkidach I. (2026). *Economic efficiency of IT infrastructure engineering optimization in commercial companies. European Journal of Technical and Natural Sciences 2026, No 5.* <https://doi.org/10.29013/EJTNS-26-5-23-29>

Abstract

This article examines the economic efficiency of engineering optimization of IT infrastructure in commercial companies. It analyzes the impact of technical solutions on operating costs, service availability, computing resource utilization, and losses associated with infrastructure failures and downtime. Modern optimization methods are considered, including virtualization, rightsizing, autoscaling, Infrastructure as Code, observability, and Site Reliability Engineering. Particular attention is given to current approaches such as FinOps, AIOps, platform engineering, and intelligent energy management. The role of engineering solutions in improving business process resilience and achieving an economically justified balance between infrastructure costs, performance, and service reliability is also examined.

Keywords: *IT infrastructure, economic efficiency, engineering optimization, FinOps, AIOps, observability, autoscaling*

Introduction

Digital infrastructure has become an integral part of commercial organizations, since the operation of a significant share of internal and customer-facing processes directly depends on its stability and scalability. At the same time, more complex architectures, growing volumes of processed data, and the spread of cloud services increase the requirements for the quality of IT system operation. Under these conditions, infrastructure is no longer considered only as a technical environment and is increasingly becoming an object of management decisions related to cost control, risk management, and service quality.

The transition from mainly static infrastructures to dynamic environments, where resource usage, service configurations, and workload patterns can change continuously, increases the relevance of engineering optimization. This requires closer integration of technical decisions with economic criteria and supports approaches based on automation, forecasting, and better alignment of infrastructure resources with business needs. The goal of this research is to identify the main areas of engineering optimization of IT infrastructure in commercial companies and assess their impact on the economic indicators of an organization, taking into account modern approaches to resource management and operating costs.

Main part. Economic aspects of IT infrastructure operation in commercial companies

Generally, IT infrastructure in modern commercial companies is not only the technical basis of information systems but also a factor that directly affects operating costs, business process continuity, and financial performance. As digitalization increases dependence on computing resources, failures of servers, network infrastructure, or corporate applications can interrupt sales and customer service, reduce employee productivity, and create additional costs. Therefore, IT infrastructure efficiency should be assessed in terms of operating costs, resource utilization, and the required level of service availability.

The economic assessment of infrastructure traditionally includes capital and operating expenses. **Capital expenditures (CAPEX)** include the purchase of server and network equipment, data storage systems, construction or modernization of facilities, and other long-term investments. **Operating expenses (OPEX)** include electricity costs, maintenance, software licensing, cloud service payments, IT staff costs, and other ongoing expenses. However, the transition from CAPEX to OPEX does not itself mean higher economic efficiency. One of the empirical studies showed a positive relationship between cloud computing adoption and company profitability and market value, although the nature and size of the effect differed in the short and long term (Chen X. et al., 2022). At the same time, the results of a banking sector study show a more complex picture: the use of cloud technologies was associated with higher profit efficiency, but also with lower cost efficiency and higher operational risk (Cheng M. et al., 2022).

A more complete assessment of costs can be provided by **the Total Cost of Owner-**

ship (TCO) indicator. Unlike a comparison of equipment purchase costs or a cloud provider's monthly bill, TCO covers costs throughout the considered infrastructure lifecycle.

Actual **resource utilization** is an important factor in TCO. Overprovisioning helps systems handle peak loads but leads to payments for idle CPU, memory, and storage resources, while underprovisioning can reduce direct costs at the expense of performance and service quality. One study based on large-scale cluster data showed that when different types of workloads were executed separately, the average CPU utilization of the studied servers was only 29.29% for batch jobs and 7.4% for service jobs. Co-locating the workloads increased average utilization to 39.26%. The estimated TCO savings for the studied infrastructure segment, which included more than 4,000 machines, were about \$600,000, while scaling the same approach to a much larger server infrastructure could result in savings of tens of millions of dollars (Everman B. et al., 2021).

One of the important components of economic efficiency is **the availability of IT services.** For digital business processes, an infrastructure failure creates costs that may significantly exceed the cost of the failed equipment itself. Losses arise from lost revenue, employee downtime, recovery of data and systems, involvement of technical specialists, penalties for violations of service level agreements, as well as reputational consequences (Perelekhov I., 2026). The reliability of IT infrastructure can be assessed using several operational parameters that also have direct economic significance. The main indicators usually include Mean Time Between Failures (MTBF), Mean Time to Recovery (MTTR), Service Level Agreement (SLA) and Service Level Objective (SLO) (table 1).

Table 1. Reliability parameters of IT infrastructure and their economic significance

Parameter	Meaning	Economic significance
Availability	Share of time when the service is available.	Directly affects the probability and duration of business downtime.
MTBF	Mean time between failures.	Characterizes the frequency of infrastructure failures.

Parameter	Meaning	Economic significance
MTTR	Mean time to recovery.	Longer recovery increases losses caused by downtime.
SLA	Agreed service level.	Its violation may result in financial penalties and customer losses.
SLO	Internal target for service quality.	Helps define the required level of reliability.
Redundancy	Use of additional infrastructure resources for fault tolerance.	Reduces expected outage losses but increases infrastructure costs.

The economic importance of downtime is confirmed by industry statistics. According to 2024 data (Uptime Institute, 2024), 54% of respondents who had experienced a significant, serious, or severe outage during the previous three years estimated the cost of their most recent incident at more than \$100,000, while 20% estimated it at more than \$1 million. The assessment included direct costs, lost opportunities, and reputational losses. At the same time, the growing dependence of commercial processes on digital services increases the economic cost of even relatively short periods of unavailability.

From an economic point of view, not only the availability percentage itself is important, but also the cost of increasing it. For instance, moving from 99.9% to 99.99% availability requires additional redundancy of equipment, communication channels, computing resources, and organizational recovery mechanisms. Therefore, maximizing availability at any cost is not a rational goal. The engineering task is to achieve a level of reliability at which additional fault-tolerance costs are balanced against the expected reduction in losses from incidents.

Reducing infrastructure costs without considering performance and reliability can worsen overall business results, while excessive redundancy creates unjustified fixed costs. Engineering optimization should therefore focus on an economically justified balance between infrastructure cost, performance, and resilience.

Engineering methods for IT infrastructure optimization and their impact on economic indicators

Engineering optimization of IT infrastructure is aimed at providing the required performance and service availability while using computing and financial resources efficiently. Basic methods include server consolidation through virtualization, which makes it possible to increase equipment utilization and reduce costs for its purchase, power supply, cooling, and maintenance (fig. 1).

However, excessive consolidation can reduce performance because virtual machines compete for shared resources. In cloud and virtualized environments, rightsizing helps align allocated CPU, RAM, and other resources with actual demand while preserving the required performance margin.

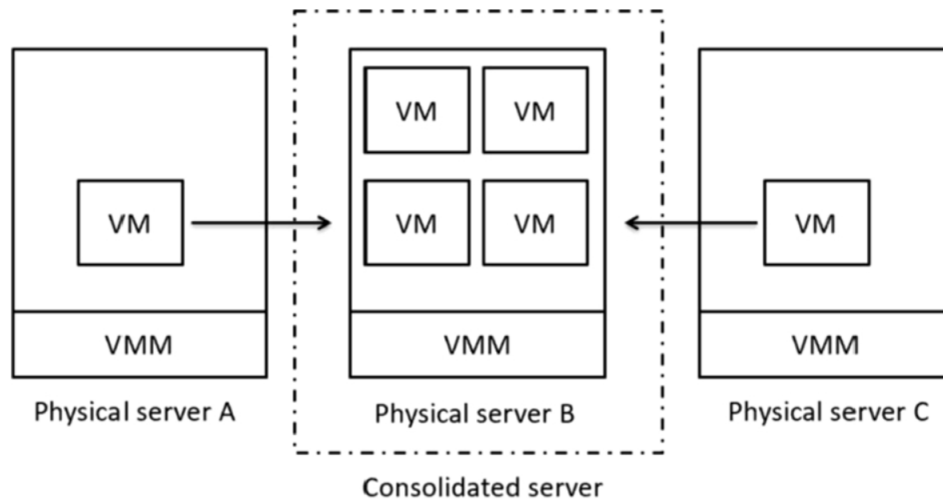
Containerization and orchestration systems provide more flexible resource management and allow individual application components to scale independently. The greatest economic effect is achieved when containerization is combined with autoscaling. One study proposed joint horizontal and vertical scaling of containers and virtual machines while considering placement costs (Entrialgo J. et al., 2024). In experiments on a real application, the resulting configurations were approximately 20% cheaper than those produced by the studied heuristic resource allocation algorithms.

Another study showed that the use of ML for cloud resource management reduced the number of QoS requirement violations by up to 80% compared with previously used algorithms, while virtual machine usage decreased by 3–50% depending on the experimental scenario (Pintye I. et al., 2024).

Thus, workload forecasting makes it possible to reduce both the amount of excessively reserved capacity and the probability of service degradation. Component redundancy, load

distribution, data replication, and automatic failover reduce expected losses from failures, although they require additional infrastructure resources.

Figure 1. *Traditional server consolidation (Bermejo B. & Juiz C., 2022)*



Infrastructure management automation also has a significant impact on operating costs. The **Infrastructure as Code (IaC)** concept involves describing infrastructure through machine-readable configurations, which makes its creation and modification automated and reproducible, while version control and testing can be applied to the configurations. The economic component is gradually being integrated directly into such processes. In a 2024 study, authors analyzed more than 152,000 repositories and then examined cost-related changes in projects using Terraform. The results showed that developers take the cost of cloud resources into account both before and after deployment and optimize it through service selection, resource allocation, and configuration changes (Feitosa D. et al., 2024).

For distributed and microservice systems, **observability** is especially important, combining the analysis of metrics, event logs, and distributed traces. Its economic value is mainly related to reducing the time required to detect and resolve failures and, therefore, reducing the duration of the resulting downtime.

Observability is closely related to the **Site Reliability Engineering (SRE)** approach, which involves reliability management based on measurable service quality objectives. Its economic meaning is to pro-

vide the required rather than the maximum possible level of availability, since additional reliability also requires additional infrastructure costs.

Thus, modern engineering optimization methods affect economic indicators in different ways. Consolidation and rightsizing reduce excess capacity, while containerization, autoscaling, and predictive algorithms help adapt resources to workload changes. Redundancy reduces potential losses from failures, while Infrastructure as Code, observability, and SRE lower manual effort, improve reproducibility, and support faster and more economically justified reliability management.

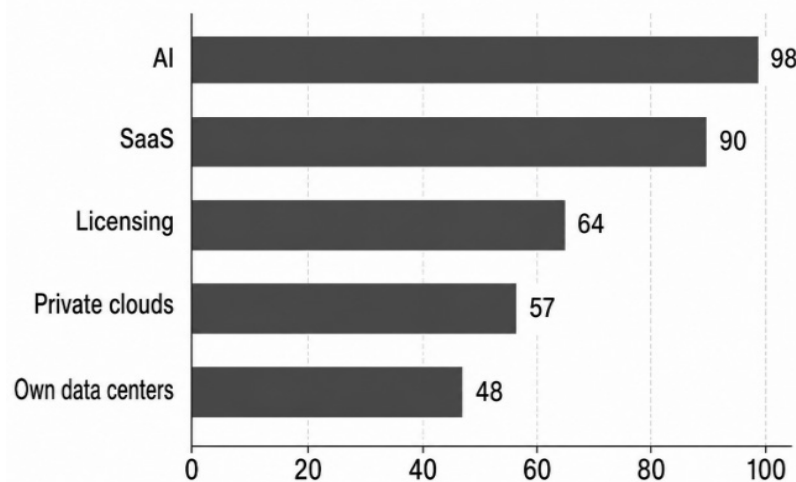
Modern approaches to intelligent and economic optimization of IT infrastructure

The development of cloud technologies, containerization, and distributed architectures has changed the approach to IT infrastructure optimization. Along with conventional methods of reducing operating costs, continuous infrastructure management based on data about its cost and technical condition is becoming increasingly relevant. Important areas include FinOps, the use of artificial intelligence (AI) in IT operations, the development of internal engineering platforms, and intelligent energy management.

One of the key modern approaches is **FinOps**, which involves joint management of technology costs by engineering and business departments. Its task is to reduce costs and relate infrastructure costs to the business val-

ue created. According to the State of FinOps 2026, its practice already goes beyond public clouds and covers cost management for AI, Software as a Service (SaaS), licensing, private clouds, and own data centers (fig. 2).

Figure 2. Areas of cost management in FinOps practice (FinOps, 2025)



An important development of FinOps is **the use of unit economics**, where the cost of not the entire infrastructure, but a separate unit of created result is evaluated. This approach becomes notably relevant for AI infrastructure, since its cost is determined by GPU usage, training and inference requests, the volume of processed data, and other parameters.

Another rapidly developing area is **AI for IT Operations (AIOps)**, which means the application of machine learning and other AI methods to IT infrastructure operations. The AIOps practice is used for anomaly detection, failure prediction, root cause identification, and support of recovery actions (Díaz-de-Arcaya J., 2024). Its economic effect is mainly associated with reducing specialist labor costs and incident duration. Automated analysis of metrics, logs, and traces makes it possible to detect deviations faster and move from responding to an already occurred failure to predicting potential problems.

The current stage of AIOps development is also associated with **the use of large language models and autonomous AI agents**. Intelligent agents can interact with cloud infrastructure, localize intentionally created failures, and take actions to eliminate them (Khlystun M., 2026). Fully autonomous management is still associated with

significant risks, so for critical infrastructure a more realistic model is one in which AI performs analysis and standard verifiable operations, at the same time potentially dangerous changes remain under the control of a specialist.

The reduction of operating labor costs is also connected with the development of **platform engineering**. This approach involves creating an internal platform that provides product teams with standardized access to computing resources, storage, databases, CI/CD, observability, and other infrastructure services.

Another direction is the combination of economic and energy optimization. Within **Green Ops**, reducing the number of idle resources, consolidating computing workloads or dynamically managing capacity make it possible to reduce both energy consumption and operating costs. Workload forecasting, dynamic consolidation and migration of virtual machines, as well as machine learning methods can be used to manage the energy consumption of cloud data centers.

Modern IT infrastructure is increasingly optimized continuously based on technical and economic data. Observability, AIOps, automated platforms, and FinOps make it possible to connect the state of the system, engineering actions, and their financial effect,

while their use is justified only when the final economic result is positive.

Conclusion

The economic efficiency of IT infrastructure is determined not only by the amount of direct costs for equipment, cloud resources, and maintenance, but also by how efficiently computing capacity is used, how quickly the system adapts to workload changes, and how stable critical services are. Engineering optimization makes it possible to influence these parameters through consolidation and rightsizing of resources, autoscaling, fault-tolerant architectures, IaC, observability, and SRE. Excessive reduction of resources can increase downtime risks, while excessive

redundancy leads to unjustified growth of operating costs.

Modern approaches develop this logic through a closer connection between technical and economic data. FinOps increases the transparency of technology costs and makes it possible to relate them to the business value created, AIOps expands the possibilities for workload forecasting and incident automation, while platform engineering helps standardize and reduce repetitive engineering operations. As a result, IT infrastructure optimization is gradually becoming a continuous process in which decisions are made taking into account cost, utilization, reliability, and business process requirements.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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Section 4. Materials science

DOI:10.29013/EJTNS-26-5-30-37



DETERMINATION OF THE DYNAMIC ADSORPTION CAPACITY OF ADSORBENTS FOR WATER VAPOR

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Cite: Ashurov Sh. M., Bozorov O. N., Kuyboqarov O. E. (2026). *Determination of the Dynamic Adsorption Capacity of Adsorbents for Water Vapor*. *European Journal of Technical and Natural Sciences* 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-30-37>

Abstract

The article presents a methodological and technological assessment of determining the dynamic adsorption capacity of composite adsorbents for water vapor under conditions relevant to natural gas drying. The study considers KA-series adsorbents prepared on the basis of activated Navbahor bentonite, zeolite 4A, activated alumina, silica gel and a binder. Dynamic capacity is treated not only as a mass balance value but also as an integral technological indicator connected with breakthrough time, saturation time, outlet moisture concentration, dew point depression, pressure drop, bed utilization and regeneration stability. The operating variables considered include gas flow rate, adsorbent mass, bed height, granule diameter, inlet moisture content, temperature, pressure and regeneration regime. Particular attention is paid to the KA-4 composite adsorbent, which combines a local mineral matrix, a selective microporous zeolite phase, a thermally stable alumina phase and a mesoporous silica-gel component. Representative dynamic drying data show that KA-4 provides a breakthrough time of 8.6 h, saturation time of 12.8 h, dynamic water adsorption capacity of 0.146 kg/kg, outlet dew point of about –43 °C and drying efficiency of 96.9%. The results demonstrate that the reliable determination of dynamic capacity requires simultaneous analysis of the breakthrough curve, mass-transfer zone and regeneration recovery, because static water uptake alone does not fully describe the industrial performance of an adsorbent bed. The proposed approach can be used for selecting optimal adsorbent composition and operating conditions for deep dehydration of natural gas.

Keywords: *natural gas drying; water vapor adsorption; dynamic adsorption capacity; composite adsorbent; KA-4; breakthrough curve; dew point; zeolite 4A; activated bentonite; regeneration*

Introduction

Natural gas normally contains water vapor, and its presence is undesirable during transportation, compression, cooling and further processing. Moisture can cause hydrate formation, corrosion of pipelines and process equipment, freezing in valves and heat exchangers, loss of throughput and instability in downstream separation units. Therefore, dehydration is one of the key stages in natural gas treatment before transmission through pipelines, cryogenic processing, NGL recovery or LNG production. In industrial practice, the target quality of dehydrated gas is often expressed through residual moisture content and dew point. A lower dew point indicates deeper drying and a lower risk of condensation under operating conditions (Gandhidasan P., Al-Farayedhi A. A., Al-Mubarak A. A., 2001; Mokhatab S., Poe W. A., Mak J. Y., 2015; Kohl A. L., Nielsen R. B., 1997; Kidnay A. J., Parrish W. R., McCartney D. G., 2011).

Several dehydration technologies are used in gas processing, including glycol absorption, condensation by cooling, membrane dehydration and adsorption drying. Adsorption drying is of particular importance when very low outlet moisture content is required. The method is based on the selective retention of water molecules on the surface and inside the pores of a solid adsorbent. Silica gel, activated alumina and molecular sieves are widely used adsorbents. Silica gel has a high affinity to water at moderate humidity but is usually less effective for very deep dehydration. Activated alumina has good mechanical and thermal stability, whereas molecular sieves such as zeolite 3A and 4A show high selectivity toward water molecules and can provide a low dew point (Gandhidasan P., Al-Farayedhi A. A., Al-Mubarak A. A., 2001; Tagliabue M., Farrusseng D., Valencia S., Aguado S., Ravon U., Rizzo C., Corma A., Mirodatos C., 2009; Santos K. M. C., Vilarrasa-Garcia E., Cecilia J. A., Rodriguez-Castellon E., Azevedo D. C. S., 2021; Bahadori A., 2014; Grande C. A., 2012).

Despite their advantages, conventional adsorbents have limitations related to cost, regeneration energy demand, mechanical degradation, sensitivity to liquid carry-over and loss of capacity during repeated cycles.

For this reason, composite adsorbents based on local mineral raw materials have scientific and technological relevance. Combining activated bentonite, zeolite 4A, activated alumina and silica gel makes it possible to form an adsorbent with a balanced micro-mesoporous structure, acceptable mechanical strength and sufficient regeneration stability. In such a composite, bentonite acts as a mineral matrix, zeolite 4A provides selective microporous water adsorption, activated alumina improves thermo-mechanical stability, and silica gel supports fast moisture uptake in mesopores (Ruthven D. M., 1984; Yang R. T., 2003; Thommes M., Kaneko K., Neimark A. V., Olivier J. P., Rodriguez-Reinoso F., Rouquerol J., Sing K. S. W., 2015; Rouquerol F., Rouquerol J., Sing K. S. W., Llewellyn P., Maurin G., 2014; Breck D. W., 1974).

A central parameter for evaluating adsorbents in a flow system is dynamic adsorption capacity. Unlike static capacity, which is measured under equilibrium or quasi-equilibrium conditions, dynamic capacity characterizes the amount of water retained by a fixed adsorbent bed before breakthrough occurs. It is affected by mass transfer, pore accessibility, gas velocity, bed height, particle size, temperature, pressure and the regeneration history of the adsorbent. Therefore, determination of dynamic water adsorption capacity is essential for designing industrial adsorbers and for selecting a reliable adsorbent composition (Grande C. A., 2012; Ruthven D. M., 1984; Yang R. T., 2003; Thommes M., Kaneko K., Neimark A. V., Olivier J. P., Rodriguez-Reinoso F., Rouquerol J., Sing K. S. W., 2015).

The purpose of the study

The purpose of this study is to develop and describe a scientifically justified approach for determining the dynamic adsorption capacity of adsorbents for water vapor in the natural gas drying process. The study focuses on the KA-series composite adsorbents and especially on the KA-4 sample, which was selected as an optimal composition according to drying efficiency, dynamic capacity and regeneration stability. The specific objectives are: to define the main indicators used in dynamic adsorption tests; to describe the calculation procedure for dynamic water adsorption capacity; to analyze the influence of adsorbent composition and

operating parameters on breakthrough behavior; to evaluate KA-4 in comparison with other samples; and to propose criteria for using dynamic capacity as a practical design parameter for adsorption dryers.

The novelty of the approach lies in considering dynamic capacity as an integrated technological characteristic rather than as a single numerical value. The proposed evaluation combines the breakthrough curve, outlet moisture concentration, dew point, saturation time, pressure drop and residual capacity after regeneration. Such an approach gives a more realistic assessment of the adsorbent bed under cyclic operating conditions and provides a basis for pilot-scale design.

Literary analysis

The theoretical basis of adsorption processes is widely discussed in classical works on gas-solid adsorption. Ruthven described the principles of adsorption equilibria, mass transfer and breakthrough behavior in fixed beds (Ruthven D. M., 1984). Yang emphasized that the performance of adsorbents in gas separation and drying depends not only on equilibrium capacity but also on pore structure, diffusion rate, selectivity and cyclic stability (Yang R. T., 2003). These concepts are important because industrial gas drying is performed under dynamic flow conditions, where equilibrium capacity alone may overestimate the useful bed capacity.

In natural gas treatment, solid desiccant dehydration has been studied as an effective method for achieving a low water dew point. Gandhidasan and co-authors investigated the dehydration of natural gas using solid desiccants and showed the significance of breakthrough time, adsorbent loading and regeneration conditions (Gandhidasan P., Al-Farayedhi A. A., Al-Mubarak A. A., 2001). Handbook sources on gas processing and gas purification also indicate that molecular sieves and activated alumina are widely used for deep dehydration, especially before cryogenic units where very low water content is necessary (Mokhatab S., Poe W. A., Mak J. Y., 2015; Kohl A. L., Nielsen R. B., 1997; Kidnay A. J., Parrish W. R., McCartney D. G., 2011).

Zeolite molecular sieves are important for water removal because of their uniform microporous structure and strong interaction

with polar water molecules. Breck described the structure and adsorption properties of zeolite molecular sieves, including their high selectivity and crystallographic pore control (Breck D. W., 1974). However, the practical application of zeolite adsorbents can be limited by high cost and higher regeneration temperatures. Activated alumina and silica gel are less expensive and mechanically stable, but their deep dehydration capacity may be lower than that of molecular sieves. Therefore, mixed or composite adsorbents are often considered for balancing capacity, cost and regeneration performance.

The characterization of porous materials is another important part of dynamic capacity determination. BET surface area, pore volume and pore size distribution help explain why one adsorbent has a longer breakthrough time or higher capacity than another. Thommes et al. summarized the evaluation of surface area and pore structure by gas physisorption, noting the importance of micropores and mesopores for adsorption performance (Thommes M., Kaneko K., Neimark A. V., Olivier J. P., Rodriguez-Reinoso F., Rouquerol J., Sing K. S. W., 2015). Rouquerol et al. also emphasized the need for careful degassing and interpretation of adsorption-desorption isotherms in porous solids (Rouquerol F., Rouquerol J., Sing K. S. W., Llewellyn P., Maurin G., 2014). These methods are directly relevant to composite adsorbents, because micro- and mesoporous channels control both water uptake and diffusion inside granules.

The literature analysis shows that determination of dynamic water capacity must combine material characterization and fixed-bed testing. A material with a high static uptake may not always provide a long breakthrough time if its pores are poorly accessible, if granules are mechanically weak, or if the bed has excessive pressure drop. For this reason, the present work uses the dynamic adsorption capacity together with breakthrough time, dew point and regeneration recovery as main criteria for evaluating KA-series composite adsorbents.

Materials and methods

The investigated adsorbents were represented by KA-1 to KA-6 samples prepared from activated Navbahor bentonite and func-

tional additives. KA-1 consisted mainly of activated bentonite and served as a control sample. KA-2 included activated alumina to improve thermo-mechanical stability. KA-3 contained zeolite 4A and activated alumina for forming a selective microporous dehydration phase. KA-4 was a balanced composite containing bentonite, zeolite 4A, activated alumina and silica gel. KA-5 had a higher zeolite fraction to increase microporosity. KA-6 was selected for assessing regeneration resistance and mechanical stability. The granule fraction used for dynamic tests was 2–4 mm, which provides a compromise between diffusion path length and pressure drop.

Before the dynamic tests, the adsorbents were dried and regenerated to remove physically adsorbed moisture. The drying and regeneration temperature was selected according to the thermal stability of each composition. For KA-4, the recommended regeneration interval was 220–240 °C, while

the operating adsorption temperature was 25–35 °C. Dynamic tests were carried out by passing a humid gas stream through a fixed adsorbent bed. The inlet moisture concentration, outlet moisture concentration and dew point were recorded over time. The moment when outlet moisture increased to a defined fraction of inlet moisture was taken as breakthrough time.

The principal parameters used in the test are summarized in (Table 1). The most important indicator is dynamic adsorption capacity, because it shows how much water the adsorbent can retain under real flow conditions before breakthrough. Breakthrough time reflects the useful service period of the bed, whereas saturation time describes complete or near-complete filling of the bed with moisture. The outlet dew point is used as a practical quality indicator of dry gas, and pressure drop is used to assess hydraulic suitability of the bed.

Table 1. Main indicators used for determining dynamic adsorption capacity for water vapor

Indicator	Symbol	Unit	Determination method
Drying efficiency	η	%	$\eta = ((C_0 - C_t) / C_0) \cdot 100$
Dynamic adsorption capacity	qd	kg/kg or g/g	Water retained in bed per mass of adsorbent
Breakthrough time	tb	h	Time at $C_t/C_0 = 0.05-0.10$
Saturation time	ts	h	Time at $C_t/C_0 = 0.90-0.95$
Dew point	Td	°C	Measured at adsorber outlet
Pressure drop	ΔP	kPa	Difference between inlet and outlet pressure
Residual capacity after regeneration	Rq	%	Capacity retained after repeated cycles

For a constant volumetric gas flow rate, the amount of water retained by the adsorbent bed up to breakthrough can be calculated by integrating the difference between inlet and outlet moisture concentrations over time. In simplified form, dynamic capacity can be expressed as:

$qd = (Qg / mads) \cdot \int_0^{tb} (C_0 - C_t) dt$
where qd is dynamic adsorption capacity, Qg is the volumetric gas flow rate, mads is the mass of adsorbent in the bed, C₀ is the inlet moisture concentration, C_t is the outlet moisture concentration at time t, and t_b is breakthrough time. If the outlet concentration remains very low before breakthrough,

the expression can be approximated by the total removed water mass divided by the adsorbent mass. In industrial calculations, a safety coefficient is usually introduced to prevent premature breakthrough under fluctuating gas load and moisture content.

The determination procedure consisted of four steps. First, the adsorbent sample was regenerated and cooled to the adsorption temperature. Second, humid gas was introduced at a fixed flow rate, pressure and inlet moisture content. Third, outlet moisture and dew point were monitored continuously, and the breakthrough curve was obtained. Fourth, the water balance was calculated

from the area between inlet and outlet concentration curves. The same procedure was repeated after regeneration cycles to evaluate capacity recovery and long-term stability.

Discussion and results

The dynamic adsorption capacity of the KA-series adsorbents differs significantly depending on the composition and pore structure. The control sample KA-1, based on activated bentonite, showed limited capacity because bentonite alone does not provide sufficient microporous volume for deep water retention. Although activated bentonite has hydrophilic centers and can serve as a mineral matrix, its pore system is not enough to achieve a very low dew point in a dynamic gas stream. This confirms that activation improves the surface properties of bentonite but additional selective and mesoporous phases are required for effective natural gas drying.

The addition of activated alumina in KA-2 increased the mechanical and thermal stability of the granules. Activated alumina contributes to water adsorption due to hydroxylated surface sites and also improves resistance to attrition during gas flow. However, the absence of a strong molecular-sieve phase limited the deep dehydration performance. KA-2 therefore demonstrated better durability than KA-1 but did not reach the dynamic capacity of zeolite-containing com-

posites. This result illustrates that mechanical strength and adsorption capacity should be optimized simultaneously.

The introduction of zeolite 4A in KA-3 led to an increase in microporous water adsorption sites. As a result, breakthrough time and dynamic capacity increased compared with KA-1 and KA-2. Zeolite 4A is especially effective for water molecules because its microporous structure is suitable for selective uptake of small polar molecules. Nevertheless, a purely micropore-dominated system can suffer from diffusion limitations if mesoporous transport channels are insufficient. Therefore, the presence of a mesoporous component is beneficial for accelerating the movement of water vapor into internal adsorption sites.

KA-4 showed the most balanced performance among the investigated samples. In this adsorbent, bentonite provides the mineral framework, zeolite 4A provides selective microporous adsorption, activated alumina improves stability, and silica gel contributes to rapid moisture uptake in mesopores. The combination of these components forms a multi-level pore structure. Micropores are responsible for deep dehydration and low dew point, mesopores improve mass transfer, and the mineral binder phase maintains granule integrity. This structural balance explains the high dynamic capacity and long breakthrough time of KA-4.

Table 2. Representative dynamic drying results for KA-series composite adsorbents

Sample	Breakthrough time, h	Saturation time, h	Dynamic capacity, kg/kg	Dew point, °C	Efficiency, %
KA-1	3.1	5.8	0.061	−18	78.4
KA-2	4.6	7.4	0.084	−25	85.9
KA-3	6.7	10.2	0.119	−35	92.4
KA-4	8.6	12.8	0.146	−43	96.9
KA-5	8.1	12.1	0.149	−45	96.3
KA-6	7.5	11.5	0.137	−40	95.1

The representative results in (Table 2) show that dynamic capacity increased from 0.061 kg/kg for KA-1 to 0.146 kg/kg for KA-4. The corresponding drying efficiency increased from 78.4% to 96.9%, and the outlet dew point decreased from −18 °C to −43 °C. These changes demonstrate the effect of

component modification and pore structure development. KA-5 showed a slightly higher dynamic capacity of 0.149 kg/kg, but its higher zeolite content may increase regeneration demand and pressure drop. Therefore, KA-4 was evaluated as the optimal sample based on the total balance of capacity, dew

point, pressure drop, mechanical strength and regeneration stability.

The breakthrough curve is the key experimental output in determining dynamic adsorption capacity. At the beginning of the test, the outlet moisture concentration remains close to zero, indicating that the adsorbent bed retains almost all incoming water vapor. As the mass-transfer zone moves through the bed, the outlet moisture begins to increase. The breakthrough point is reached when C_t/C_0 becomes 0.05–0.10. At this moment, the adsorbent still contains unused capacity near the outlet, but the dry gas specification is no longer safely maintained. For process design, the bed should be switched to regeneration before full saturation to avoid water slip into the product gas.

The dynamic capacity is affected by gas flow rate. When gas flow increases, the contact time between gas and adsorbent decreases, and the mass-transfer zone moves faster through the bed. As a result, breakthrough occurs earlier and the useful capacity decreases. For KA-4, increasing the gas flow rate from 0.5 to 2.0 m³/h shortened the breakthrough time from 10.2 to 5.3 h and reduced dynamic capacity from 0.151 to 0.116 kg/kg. At the same time, the pressure drop increased from 4.2 to 18.9 kPa. This confirms that excessive gas velocity prevents full utilization of the adsorbent bed and increases energy consumption.

Bed height also has a significant effect. A higher bed contains more adsorbent and provides a longer mass-transfer zone reserve. Therefore, breakthrough time increases as bed height increases. However, an excessively high bed creates larger pressure drop and may require stronger compression. For KA-4, a bed height of 300 mm gave a breakthrough time of 8.6 h and a pressure drop of 7.8 kPa, which represents an acceptable balance. At 400 mm, breakthrough time increased further, but pressure drop became less favorable. Thus, the optimum bed height should be selected not only by maximum breakthrough time but also by hydraulic resistance and equipment limitations.

Temperature strongly influences physical adsorption. Water adsorption on solid desiccants is usually favored at lower temperature because adsorption is exothermic. As temperature increases, adsorbed water

molecules are more easily desorbed and the equilibrium capacity decreases. In the KA-4 data, increasing temperature from 20 to 50 °C decreased dynamic capacity from 0.152 to 0.111 kg/kg and worsened the outlet dew point from –46 °C to –29 °C. A practical operating interval of 25–35 °C was therefore recommended for adsorption, with 30 °C as a convenient laboratory regime.

Pressure can improve drying performance by increasing gas density and the contact probability between water molecules and adsorbent active sites. For KA-4, increasing pressure from 0.5 to 2.5 MPa improved breakthrough time and drying efficiency. At 2.5 MPa, the outlet dew point reached approximately –43 °C and the drying efficiency was 96.9%. At 4.0 MPa, the efficiency increased only slightly, while the equipment requirements became higher. This means that the most rational pressure should be selected by considering both technical performance and apparatus safety. For pilot and industrial operation, an interval of 2.5–4.0 MPa is acceptable for the proposed system.

Granule diameter is another important factor in dynamic capacity determination. Small granules reduce internal diffusion resistance and can improve mass transfer, but they also increase pressure drop and may cause bed compaction. Large granules lower pressure drop but slow down diffusion into the internal pore system. In the present technological assessment, 2–4 mm granules were selected as the recommended fraction. This size range provides an acceptable compromise between contact efficiency, mechanical stability and hydraulic resistance. It is also suitable for fixed-bed adsorbers operating in cyclic drying-regeneration mode.

Regeneration history must be considered when determining dynamic capacity. An adsorbent may show good initial capacity, but if regeneration is incomplete, residual water remains in the pores and the next cycle starts with partially occupied active sites. For KA-4, regeneration temperatures below 200 °C were insufficient for complete capacity recovery, while 220–240 °C provided a recovery level of about 94–96%. Regeneration at 260 °C gave only a small additional improvement but increased energy consumption and could affect long-term structural stability.

Therefore, a regeneration interval of 220–240 °C for 2–4 h is recommended.

The determination of dynamic capacity should also include reproducibility and mass balance control. The inlet moisture concentration must be kept stable, the flow rate should be measured accurately, and the outlet moisture analyzer must be calibrated. The mass of the adsorbent should be reported on a dry basis after regeneration. If the gas contains liquid droplets, heavy hydrocarbons or solid impurities, a separator and filter should be used before the adsorber, because contamination can block pores and distort the capacity value. Such precautions are necessary for obtaining reliable data and for transferring laboratory results to pilot-scale design.

The obtained results show that dynamic water adsorption capacity is a practical criterion for ranking adsorbents, but it must be interpreted together with dew point and breakthrough behavior. KA-5 can have slightly higher water uptake because of increased microporosity, but KA-4 has a better technological balance. The KA-4 sample provides a long service time, low outlet dew point, high efficiency and suitable regeneration behavior. Thus, KA-4 can be recommended as the main adsorbent for further studies on natural gas adsorption drying and for scale-up calculations.

Conclusion

1. Dynamic water adsorption capacity is one of the main criteria for evaluating adsorbents used in natural gas dehydration because it describes the useful amount of water retained under real flow conditions before breakthrough.

2. The determination of dynamic capacity should be based on breakthrough curves, outlet moisture concentration, dew point, saturation time, pressure drop and mass balance calculations.
3. The KA-series adsorbents show that modification of activated bentonite with zeolite 4A, activated alumina and silica gel significantly increases water uptake and drying efficiency.
4. KA-4 demonstrated the most balanced technological performance, providing a breakthrough time of 8.6 h, saturation time of 12.8 h, dynamic capacity of 0.146 kg/kg, dew point of about –43 °C and drying efficiency of 96.9%.
5. The optimal operating conditions for KA-4 include 2–4 mm granules, adsorption temperature of 25–35 °C, pressure of 2.5–4.0 MPa, adsorption cycle of 8–12 h and regeneration at 220–240 °C for 2–4 h.
6. Excessive gas flow rate decreases contact time and dynamic capacity, while excessive bed height increases pressure drop – P. Therefore, the optimum should be selected by balancing adsorption performance and hydraulic resistance.
7. Regeneration temperature strongly affects capacity recovery; for KA-4, 240 °C for about 3 h provides an optimal compromise between recovery efficiency and energy consumption.
8. The proposed dynamic capacity determination method can be used for comparing composite adsorbents and for designing pilot or industrial fixed-bed natural gas drying units.

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submitted 15.09.2026;

accepted for publication 29.09.2026;

published 30.09.2026

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Section 5. Technical sciences in general

DOI:10.29013/EJTNS-26-5-38-45



INTERLEAVED RECORDING OF FORMATTING MARKS IN THREE-DIMENSIONAL OPTICAL INFORMATION CARRIERS: REDUCING FORMATTING TIME FOR MULTILAYER STORAGE MEDIA

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Cite: Morozov A. V. (2026). *Interleaved Recording of Formatting Marks in Three-Dimensional Optical Information Carriers: Reducing Formatting Time for Multilayer Storage Media*. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-38-45>

Abstract

Formatting time scales with the number of independently addressed layers in a volumetric optical carrier, a relationship that recent gains in per-layer data density have made increasingly costly. This paper examines the interleaved formatting method disclosed by Polshchikov I., in which servo marks are recorded along radial and axial paths matched to a three-dimensional lattice, replacing the spiral track later used for reading. For a representative carrier with 37,000 spiral tracks, the disclosed method reduces recording-head travel distance from approximately 9415 m to approximately 22 m per formatted layer and reduces the required number of head rotations by a factor of roughly 66. Combined radial-axial interleaving raises recording rate by at least a factor of twelve over spiral-following formatting. The analysis identifies group-to-group transition distance, specified in the disclosure at 30 to 70 microns, as the parameter most likely to constrain further throughput gains, and proposes testing whether synchronous-movement recording strategies documented in holographic storage transfer to axial refocusing in discrete-layer carriers.

Keywords: *Three-dimensional optical storage, formatting time, multilayer recording, interleaved recording*

1. Introduction

The storage capacity in a volumetric optical carrier increases with the number of independently addressed layers. The servo infrastructure required to make each layer readable does not become cheaper to pro-

duce as the number grows. A carrier built to hold 20 formatted layers requires roughly 20 times the positional reference recording effort of a single-layer disc because conventional formatting scans a recording head along the full spiral track separately for

every layer (Polshchikov I., 2025). Materials research has pushed layer counts and per-site information density upward, making the relationship more consequential. Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) reported error-free five-dimensional recording across 100 layers in silica glass using anisotropic nanopore modification that preserves greater than 99 percent visible-range transmission through each preceding layer; this transmission figure makes deep multilayer stacks optically viable. Park *et al.* (Park C. H., Petit Y., Canioni L., Park S. H., 2020) demonstrated a distinct route to the same goal, encoding two independent 4-bit bitmap images within a single glass volume by multiplexing the ellipse orientation and fluorescence intensity against a 16-by-16 calibration matrix, so that each recorded site carries more information without requiring additional physical layers. Neither study reported the time required to produce the positional reference structure a playback system would need to locate and read these sites. Both treat data-layer capacity as the variable of interest and leave the layer-addressing cost unexamined.

This gap recurs across several studies in the same subfield. Gu *et al.* (Gu M., Zhang Q., Lamon S., 2016) surveyed metallic nanoparticles, graphene and graphene oxide, semiconductor quantum dots, and rare-earth-doped nanocrystals as optical storage media, organizing the field around capacity, lifetime, and energy consumption; formatting or servo-layer production does not appear as a design parameter anywhere in that framework. Yu *et al.* (Yu J., Luo M., Lv Z., Huang S., Hsu H. H., Kuo C. C., *et al.*, 2020) extended the same materials-first framing to luminescent nanomaterials, distinguishing upconversion, long-persistence, and downconversion mechanisms by their optical readout properties; the cost of writing the coordinate structure on which these mechanisms depend plays no part in that classification. Dai *et al.* (Dai D., Zhang Y., Yang S., Kong W., Yang J., Zhang J., 2024) reviewed rare-earth nanoparticles, graphene, and diarylethene compounds under the same organizing principle. Collectively, these three reviews show a developed vocabulary for comparing storage density and lifetime across chemically

unrelated media. No equivalent vocabulary exists for comparing the production cost of the addressing structures that media require once assembled into multilayer carriers. Yan *et al.* (Yan Z., Hu J., Xiao Z., Xie D., Cao Q., Gan Z., *et al.*, 2023) directly named this omission: their review noted that Blu-ray-derived multilayer storage remains capacity-limited by a fixed, predefined layer count precisely because each additional layer carries a fixed addressing cost. The review distinguishes multidimensional encoding, which packs more bits into each diffraction-limited voxel, from super-resolution encoding, which creates diffraction-unlimited voxels through controlled photoexcitation and photoinhibition. Both strategies increase the density per layer; neither changes the cost of addressing a layer once it exists.

The second branch of the field bypasses the discrete layers entirely. Chen *et al.* (Chen R., Wang J., Wu H., Song M., Yang Y., Lin D., *et al.*, 2026) recorded data holographically by jointly encoding the amplitude, phase, and polarization within a single data page, using a convolutional neural network to decode the three properties from intensity measurements alone. Information is distributed volumetrically through interference, with no fixed set of physical depths assigned; therefore, no layer count exists for a formatting pass to scale against in the sense that constrains the media reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022; Park C. H., Petit Y., Canioni L., Park S. H., 2020). Liu *et al.* (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) reported a holographic recording technique that increases the writing speed by synchronizing the movement of the recording medium with that of a spherical reference wave, a strategy that reduces the dead time between recording events without changing their number. Chen *et al.* (Chen X., Liu H., Zheng S., Wang J., Chen R., Ke S., *et al.*, 2026) achieved capacity gains through hybrid angle-polarization multiplexing within the same holographic framework, again without introducing additional physical layers. Wu *et al.* (Wu J., Peng L., Wu H., Xiong R., Huang J., Wu E., *et al.*, 2026) worked at the material level within this branch, addressing photopolymer

stability and repeatability constraints in PQ/PMMA media. The stability and repeatability constraints they address indicate that holographic storage carries a throughput bottleneck of its own, located in material degradation and reference beam alignment, separate from layer-by-layer addressing cost.

Anderson *et al.* (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025) described a third variant of this trade-off at the system scale. Project Silica writes data into quartz glass platters designed to remain untouched for their entire service life, eliminating the periodic media refresh that magnetic storage requires roughly every five years for hard disk drives (HDDs). The system's central design goal is that formatted media never need to be revisited once they are written. This goal is compatible with either branch of the materials literature. It changes the economic weight of formatting time: a system built around write-once, permanently archived carriers amortizes any fixed per-carrier formatting cost across the entire archival lifetime of the carrier. Therefore, a reduction in formatting time compounds differently at the data-center scale than for a single disc produced for consumer use.

Kazansky *et al.* (Kazansky P. G., Lei Y., Wang L., Yu Y., Wang H., Sarao B., 2020) and Zhou *et al.* (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) represent a fourth line of development, pursuing storage lifetime and density through material choice: quartz glass in the former case and diamond fluorescent vacancy centers in the latter, with Zhou *et al.* reporting a storage density of 14.8 terabits per cubic centimeter and a per-site write time of 200 femtoseconds. Neither paper addresses how positional reference information is produced across a growing number of storage centers within a fixed volume, the same omission identified above in the nanomaterials reviews, applied here to a defect-center medium.

Polshchikov (Polshchikov I., 2025) directly addressed this omission by treating the sequence in which formatting marks are recorded as a variable independent of the geometry of the servo pattern itself. Their disclosure identifies the transit time between locations

where consecutive marks are recorded as the rate-determining factor in conventional formatting, and the duration of an individual recording pulse contributes far less to the total formatting time. The disclosure proposes reordering the transit path to follow the coordinate axes of the underlying three-dimensional lattice, replacing the spiral track that would otherwise guide playback.

2. Materials and Methods

Polshchikov (Polshchikov I., 2025) described a carrier whose body could be monolithic or assembled from multiple plates bonded with an optically active adhesive. The active moiety responds to laser irradiation through two-photon absorption, allowing marks to be recorded at controlled depths without disturbing adjacent layers. Data occupy a series of virtual layers separated by roughly 10 to 15 microns; formatting marks occupy a sparser, separate set of layers interspersed among them. This physical separation between data layers and formatting layers makes the recording sequence for the latter an independent design variable, because a formatting layer need not be produced in the same pass or by the same path as the data it will later help address.

The spatial arrangement of the formatting marks follows a three-dimensional lattice defined by the intersection of three surface families: equidistantly spaced cylindrical spiral tracks, equiangular spaced radial planes, and recording planes substantially orthogonal to the radial planes. Each intersection point constitutes the lattice node. A mark is recorded within a tolerance zone around that node, which is sized to a fraction of the interlayer spacing, sufficient for servo positioning. This tolerance permits reordering: the addressable unit is a node, and any traversal that visits every node satisfies the formatting requirements.

Radial formatting exploits this freedom by exchanging the roles of the conventional formatting assigned to the head and carrier. The head executes a fast reciprocating motion along a radius, while the carrier advances in discrete angular steps, remaining static during each recording event (Polshchikov I., 2025). In contrast, conventional formatting holds the carrier's angular position fixed while

scanning the head along a spiral. The angular spacing between successive radii was set to intersect every mark on the outermost track at a fixed interval, producing a constant angular velocity servo pattern: linear mark spacing decreased toward the center, while the angular spacing remained uniform. The scheme can also be executed by the continuous rotation of both the head assembly and carrier. The head then traces radial arcs whose curvature a matched carrier rotation compensates, so recorded marks fall along true radii and not along the arcs that the head itself traces.

Axial formatting addresses the layer dimension by refocusing the recording beam along its optical axis while the carrier rotates continuously; thus, marks intended for different depths are recorded during a single pass along a track, replacing separate passes for each layer. Refocusing occurs through a differential-thread lens actuator, which shifts a movable lens by a fraction of a millimeter per rotation, or through an electro-optical refractive-index modulator that changes the beam divergence and, therefore, the focal depth within nanoseconds. Interleaving marks across several layers during one scan requires refocusing faster than any mechanical actuator can move, and this speed requirement makes the electro-optical route necessary: a modulator that changes divergence within the recording beam path avoids the inertial delay that a lens actuator would otherwise impose between successive layers. The carrier continues to rotate during refocusing; thus, marks recorded at successive depths are displaced angularly relative to each other, producing a lattice tilted with respect to the beam's optical axis. The disclosure specifies that after one complete carrier rotation, any nodes left unaddressed by this tilted pattern are filled in, restoring the intended grid without requiring the recording sequence to directly correct for the tilt.

The apparatus supporting concurrent multi-carrier formatting mounts a plurality of spindles, each carrying one carrier and rotating about its own axis, on a stage that is centered on a common central axis. A separate platform above it carries a corresponding array of recording units that rotate about the same axis. The platform and spindle rotation are synchronized so that the optical

axis of each recording unit traces radial arcs on the carrier beneath it, following the relationship $\alpha = 360^\circ k/M$, where α is the angle each spindle rotates during one platform revolution, k is the number of radial planes intersecting the layer being recorded, and M is the number of recording units in operation. This relationship allows the formatting throughput to scale with the number of recording units deployed, independent of any single unit's recording speed, because each additional unit constitutes an independent channel operating on its own carrier or depth range. A small compensating rotation, on the order of fractions of a micron in linear displacement, corrects for the continuously changing radius of the spiral tracks as marks are recorded on successive tracks, preventing the accumulation of radial drift across a full platform rotation (Polshchikov I., 2025).

3. Results

For a carrier with an average track diameter of 81 mm, bounded by a maximum recordable diameter of 118 mm and a minimum of 44 mm, and a track pitch of approximately 800 nm, the active recording area supports approximately 37,000 spiral tracks (Polshchikov I., 2025). Conventional spiral-following formatting requires the head to travel the full cumulative length of these tracks (approximately 9415 m) for each formatted layer. At a rotation speed of 100 Hz, the maximum sustainable centrifugal and vibrational constraints on the carrier correspond to a travel distance of approximately six minutes per layer.

Radial formatting replaces spiral traversal with radial traversal across an active area width of approximately 37 mm, using approximately 600 radii to match the mark count on the outermost track (Polshchikov I., 2025). The total head travel per formatted layer fell to approximately 22 m, a reduction by a factor of approximately 430 relative to spiral-following formatting. The number of head rotations required decreased from approximately 37,000 to 600, a reduction by a factor of approximately 66. Individual marks are recorded with pulses shorter than one microsecond, typically around 100 ns. The disclosure attributes the bulk of the time savings to reduced travel distance, and the

pulse duration remains the same between the two schemes.

The mark spacing changes accordingly. Conventional formatting records marks at spacings matched to data readout requirements, typically hundreds of microns along the track, with the carrier rotation speed limiting the recording rate to hundreds of kilohertz. Under radial formatting, consecutive marks along the radius correspond to adjacent spiral tracks. Therefore, intermark spacing falls to approximately one micron, permitting a higher recording rate without any increase in the pulse generation speed. When axial and radial interleaving are combined, for example, recording marks at three spiral radii and four depths within one coordinated scan, the disclosure reports a resulting recording rate at least 12 times higher than that achieved by spiral-following formatting, despite marks still being recorded in sequence (Polshchikov I., 2025).

This twelvefold figure is not directly comparable to the write-speed figures reported elsewhere in the optical storage literature because the two sets of numbers describe different processes. Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) reported a data-layer writing speed of 8 kilobytes per second for their 100-layer birefringent glass medium; this figure describes the user-data throughput after formatting is complete. It says nothing about the rate at which the formatting layers are produced. Zhou *et al.* (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) reported a 200-femtosecond write time per fluorescent vacancy center in diamond, describing the duration of a single data-bearing event. This figure likewise says nothing about the aggregate time needed to populate a positional reference grid across an entire carrier. Polshchikov's (Polshchikov I., 2025) twelvefold figure describes formatting throughput specifically, the rate at which the coordinate structure a subsequent data-recording pass depends on, is produced. This is the quantity missing from each capacity-focused paper discussed in the Introduction.

The depth range achievable within a single lens configuration constrains the number of layers that can be grouped together before the focal point must be repositioned by other

means (Polshchikov I., 2025). For two-photon absorption media recorded at a numerical aperture of 0.65, the interlayer distance between adjacent data-bearing layers falls between 4 and 10 microns. A single lens can focus without spherical aberration correction across approximately 100 μm of depth, supporting groups of approximately 20 layers recorded with a simplified single-lens optical system. The groups were separated from each other by 30 to 70 microns. This distance reflects the accuracy achievable when transitioning the focal point between groups, which is distinct from the interlayer spacing within one group. The group-to-group transition distance, which is an order of magnitude larger than the interlayer spacing, is identified in the Discussion as the most likely constraint on further throughput improvement.

Quality control following optical formatting verifies six parameters (Polshchikov I., 2025): axial distance between formatted layers, parallelism of the layers to each other and to the disc surface, accumulated axial position deviation error across the layer stack, distance between formatting marks within each layer and any differences in that distance between layers, distance between the first surface and the first recorded layer, and the distance between the last surface and the last recorded layer. These parameters target the principal failure mode of the interleaved method. A newly formatted layer group is referenced to a previously recorded layer, not to the original embossed reference; thus, positional errors can accumulate across successive groups. The disclosure specifies that after a bounded number of layers are formatted relative to one reference, the procedure resets, and a new group is formatted relative to a more recently verified reference. This reset limits the extent to which the accumulated error can propagate before correction.

4. Discussion

The travel distance reduction reported by Polshchikov (Polshchikov I., 2025) arises from reordering the path followed by the recording head. The mark density and mark shape remain unchanged, which is what makes the method complementary to the capacity-increasing strategies surveyed in the Introduction. A carrier formatted with 100 birefringent

layers using the approach reported by Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) still requires the same lattice of positional reference points, whether the lattice is produced by spiral-following or interleaved traversal. The interleaved method only changes the production cost of a servo structure whose geometry and function remain the same. The unchanged servo geometry is the reason why the twelve-fold formatting-rate figure and the 100-layer density figure reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) describe complementary quantities. The omission identified in the Introduction, that materials-focused papers do not report formatting costs, reflects separate development and reporting traditions between two lines of work that fit together without conflict.

The group-to-group transition distance of 30 to 70 microns constrains this fit more than the within-group interlayer spacing. This distance is set by the accuracy of the transition of the focal point between lens configurations, not by the optical properties of the recording medium; therefore, it applies independently of which capacity-increasing material occupies each group, whether nanograting-based glass (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), ellipse-orientation-encoded glass (Park C. H., Petit Y., Canioni L., Park S. H., 2020), or a defect-center medium such as diamond (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024). Reducing this transition distance would extend the number of layers a single group can cover before a reset to a new reference layer becomes necessary, and this extension would reduce the frequency of positional-error accumulation in the six quality control parameters exist to catch. The disclosure does not report whether the transition distance can shrink below its current range without degrading the axial position accuracy, which is the same accuracy that the quality control parameters verify (Polshchikov I., 2025). Whether further formatting-time gains beyond the twelvefold figure are achievable within the described apparatus or require a different refocusing mechanism remains open.

Liu *et al.*'s (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) synchronous

movement recording technique for holographic storage offers one candidate mechanism worth testing against this constraint. Their method increases the write speed by coordinating the motion of the recording medium with that of a spherical reference wave, reducing the dead time between recording events in a volumetric medium with no discrete layers for transition. Polshchikov's (Polshchikov I., 2025) apparatus already coordinates the spindle rotation, platform rotation, and beam refocusing toward the same end within a discrete-layer architecture. Whether the synchronization principle reported in (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026), applied to axial refocusing, would reduce the group-to-group transition delay is a question that the current disclosure does not address, since the two methods were developed for architecturally distinct storage modalities and have not been tested against each other.

The design goal of Project Silica, which is to eliminate media refresh (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025), reframes the importance of formatting-time reduction at the production scale. A storage system built around carriers that remain untouched for their entire archival life amortizes the fixed cost of producing each carrier's formatting layer across its entire life, not across a single read-write cycle. A reduction in per-carrier formatting time from minutes to seconds, therefore, compounds across the total number of carriers a data-center-scale archival deployment would require, not merely across the time to produce one disc. This connection concerns where formatting time savings accrue economically. This does not imply that silica glass platters use the interleaved formatting method described here; the disclosure examined in this paper concerns discrete spiral-track carriers, and nothing in the reports in (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025), indicates that Project Silica's addressing scheme follows the same lattice structure.

One limitation constrains how far the reported figures can be generalized. A 430-fold

and 66-fold reduction in the travel distance and rotation count, respectively, was computed for a single carrier geometry with an 81-mm average track diameter and 800-nanometer track pitch (Polshchikov I., 2025). (The disclosure does not report how these ratios change for carriers with substantially different track pitches or diameters, and both vary considerably across the nanograting, fluorescence, and defect-center media surveyed above. The ratio between the spiral length and radial-formatting travel distance depends on the track pitch through the number of tracks per radius. A carrier formatted at a finer pitch to support the 100-layer density reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) would require proportionally more radii per group, and this would reduce the travel-distance advantage that interleaved formatting provides relative to the example reported here.

5. Conclusions

Reordering the path along which formatting marks are recorded reduces the formatting time for three-dimensional optical carriers by more than two orders of magnitude in head travel distance and by a factor of approximately 66 in the required rotation count for the carrier geometry reported by Polshchikov (Polshchikov I., 2025). The mark geometry, mark spacing, and servo pattern of the encoded marks remain unchanged throughout this reduction. The gain addresses the cost of capacity-focused literature on multilayer and multidimensional optical storage, which has consistently been left unreported. Nanograting-based glass (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), fluorescence-encoded glass (Park C. H., Petit Y., Canioni L., Park S. H., 2020), luminescent nanomaterials (Gu M., Zhang Q., Lam-on S., 2016; Yu J., Luo M., Lv Z., Huang S., Hsu H. H., Kuo C. C., *et al.*, 2020; Dai D., Zhang Y., Yang S., Kong W., Yang J., Zhang J., 2024), and defect-center media (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) each increase the number of layers or the per-voxel information density that a production process must eventually address;

none of these papers report the cost of addressing the production.

The 30-to-70-micron group-to-group transition distance identified in this analysis as the binding constraint on further gains sets the practical ceiling on how many layers a single formatting pass can cover before a reset to a new reference layer becomes necessary. Reducing this distance would directly extend the ceiling. Whether the synchronization principles reported for coordinated medium-and-reference-wave motion in holographic recording (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) transfer to axial refocusing in a discrete-layer architecture remains untested; the two methods were developed for different storage modalities and have not been evaluated against each other. Testing this transfer would require measuring axial refocusing accuracy against reference-layer tracking error across transition distances narrower than the range specified in (Polshchikov I., 2025), and applying the same six-parameter quality control protocol defined there to each tested distance.

The second open question concerns the generalization across carrier geometries. The 430-fold and 66-fold reductions reported here apply to one-track pitch and one carrier diameter. Materials capable of supporting denser layer counts, such as the 100-layer birefringent glass reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), typically require a finer track pitch, which increases the number of radii required per formatting group and narrows the travel distance advantage provided by interleaved formatting. Establishing how far this advantage narrows as the track pitch decreases would require formatting trials across the pitch range that the capacity-focused literature has already established as viable for high-density media, rather than a single representative case.

Funding

This research received no external funding.

Conflict of Interest

This research received no external funding.

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submitted 15.09.2026;

accepted for publication 29.09.2026;

published 30.09.2026

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DOI:10.29013/EJTNS-26-5-46-54



**FORECASTING THE INVESTMENT CHARACTERISTICS
OF A SMART OBJECT ECOSYSTEM.
(Innovative Transformation of Processes for Forecasting
Investment Volume Characteristics in the Ecosystem and
Infrastructure of a Smart Object and Its Advanced Combined
Supersystem with Interconnected Subsystems)**

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Cite: Ahmadova M. (2026). *Forecasting the Investment Characteristics of a Smart Object Ecosystem. (Innovative Transformation of Processes for Forecasting Investment Volume Characteristics in the Ecosystem and Infrastructure of a Smart Object and Its Advanced Combined Supersystem with Interconnected Subsystems)*. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-46-54>

Abstract

The article examines the innovative selection of parameters for transforming the processes of forecasting investment characteristics in the infrastructure of a smart object that, in terms of its elements and novelty features, meets the required attributes and criteria of an invention. Particular attention is paid to the possibility of its comprehensive and detailed integration into an advanced combined supersystem with interconnected subsystems as an essential component of preparing a startup project aimed at the development of innovative technology.

The article analyzes modern techniques and algorithms for developing integrated innovative technical solutions based on the application of distinctive features of known inventions in a new capacity and within newly emerging smart technology domains, including the integration of basic distinctive features. This approach is considered an important factor in achieving technological success through timely, targeted, and dynamically coordinated investment throughout the development of the project.

Since the entire range of activities related to the development of project elements is primarily aimed at ensuring the achievement of the ideal final result, the article emphasizes the need to coordinate all stages and phases of the project with the timing and periodicity of the investment process. Particular attention is given to linking investment forecasting and technological development processes with the active application of artificial intelligence and artificial neural networks.

Keywords: *Investment Characteristics Forecasting; Investment Volume Forecasting Processes; Smart Investment Object Ecosystem; Smart Investment Object Infrastructure; Innovative Selection of Parameters for the Transformation of Forecasting Processes; Novelty Features; Advanced Combined Supersystem with Interconnected Subsystems; Analysis of Modern Techniques and Algorithms; Distinctive Features of Known Inventions Applied*

in a New Capacity; Integration of Basic Distinctive Features; Manufacturing of Original Components; Active Application of Artificial Intelligence and Artificial Neural Network Elements

Introduction

Innovative Selection of Parameters for the Transformation of Investment Characteristics Forecasting Processes in the Infrastructure of a Smart Object.

The innovative selection of parameters for transforming the processes of forecasting in-

vestment characteristics in the infrastructure of a smart object, which meets all the required attributes and criteria of an invention in terms of its elements and novelty features, provides the basis for its comprehensive and detailed integration into an advanced combined super-system with interconnected subsystems.

Figure 1. *Activating Dynamic Device: Scale Factor – Working Diameters of 20, 35, and 60 mm with the Same Application and Connection Concept*

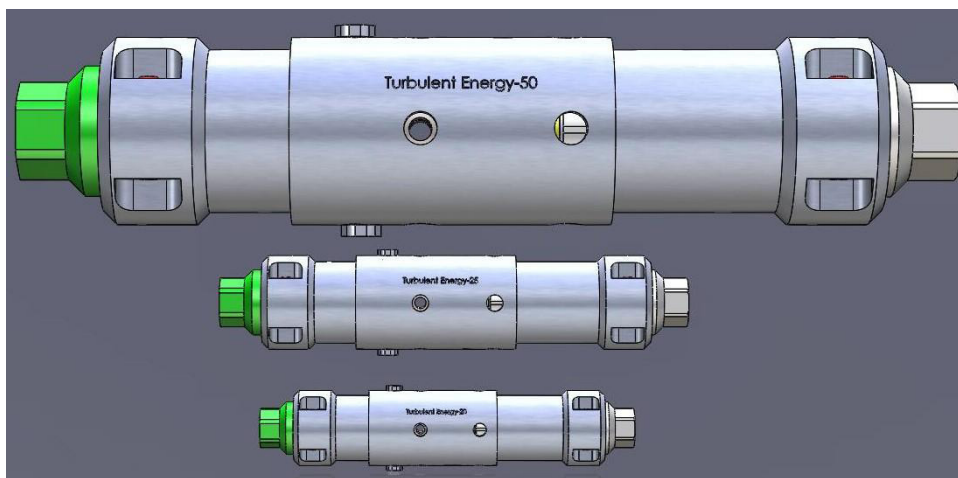
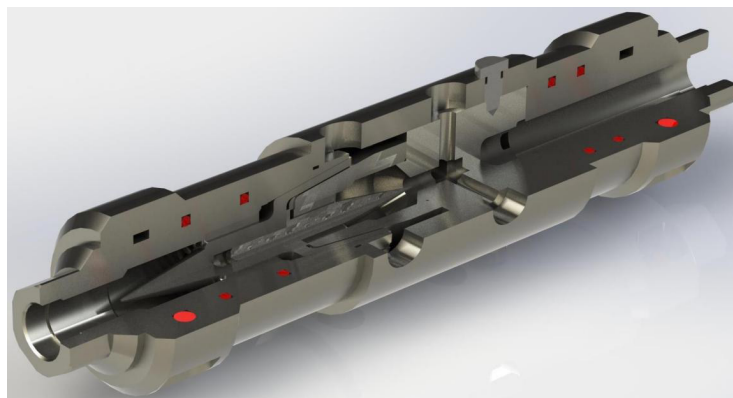


Figure 2. *Cross-Sectional View of the Activating Device*



Analysis of Modern Techniques and Algorithms for the Development of Integrated Innovative Technical Solutions Aimed at Applying the Distinctive Features of Known Inventions in a New Capacity and in Newly Emerging Smart Technology Domains (Integration of Basic Distinctive Features)

Technological Instruction

As an example, the processes for manufacturing original components of the Inte-

grated Device for Activating Fuel Mixtures, protected by 14 patents, are considered.

This technological instruction covers the manufacturing of original components, as well as the selection of standard parts, materials, and components required for the production of prototypes of the Integrated Device for Activating Fuel Mixtures designed for use in internal combustion engines, including conventional gasoline-powered engines and compression-ignition

(diesel) engines, primarily intended for use in vehicles.

1. Technical Requirements for the Manufacture of Original Components

1. All original components shall be manufactured in full compliance with the working drawings.
2. All conical surfaces of the components shall be experimentally verified using aluminum mock-ups. The mock-ups of mating components shall be used as reference templates and gauges.
3. Electrochemical polishing of the components after machining shall be performed only after all components included in the device have been checked for proper assembly and compatibility.
4. Heat treatment of the components shall be carried out at the workpiece stage in accordance with the requirements of the technical documentation.

Figure 3. *Components of the Activating Device*



Figure 4. *Components of the Activating Device*



2. Technical Requirements for Device Assembly

1. All sections of the device shall fit into the opening of the outer housing with a sliding fit.
2. During assembly, the manifold housing, which contains eight independent channels, four of which are intended for supplying compressed air, shall be aligned with the openings in the outer housing through which compressed air is supplied from the compressor.
3. After alignment, the retaining elements shall be screwed into the openings of the outer housing, after which the outer housing nut shall be tightened. Once tightened,

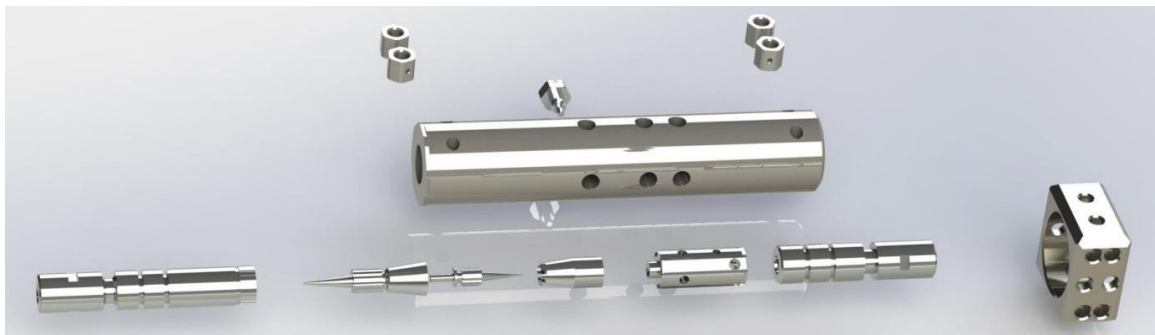
the retaining elements shall be unscrewed one at a time and replaced individually with fittings securing the compressed-air pipeline.

4. The assembly procedure shall be as follows:

- A nipple shall be fitted onto the fuel pipeline;
- The nipple shall be secured to the pipeline;
- The resulting connection shall be joined to the outer housing nut and, together with the nut, fitted onto the hydraulic section housing;

- The entire assembled connection shall be inserted into the opening of the outer housing and secured by means of the nut;
- From the opposite open side of the outer housing, the conical interface of the hydraulic section shall then be inserted. The interface of the pneumatic section shall be press-fitted into its central opening. The pneumatic section housing shall be mounted onto its splined portion, after which the manifold housing seat shall be installed inside it.

Figure 5. *Exploded View of the Activating Device*



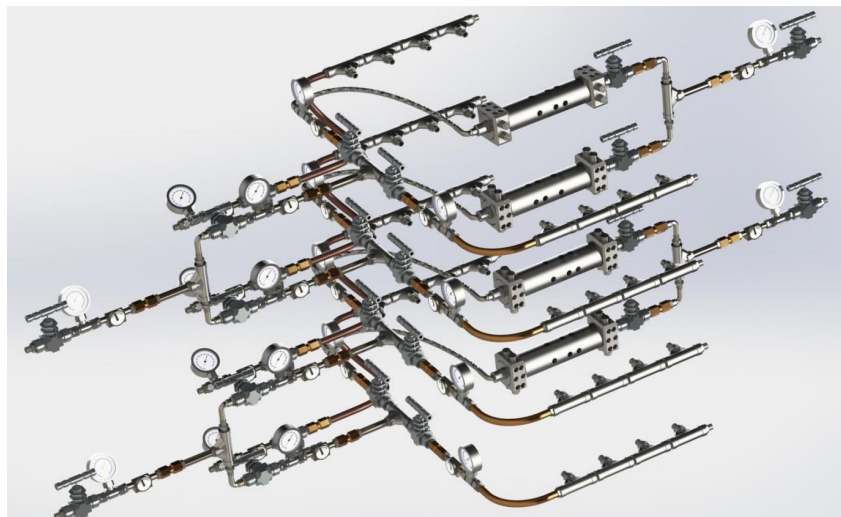
2.5. The manifold housing shall be oriented in accordance with Section 2.3.

3. Technical Requirements for Standard Fuel Pipeline Components

1. The standard components of the device include fittings for securing four pipelines supplying compressed air from the

compressor; four metal tubes selected in accordance with the dimensions of the fittings; and two tubes for the sections of the fuel pipeline located upstream and downstream of the device. The dimensions of the two nipples shall be calibrated according to these tubes, and the nipples shall be securely and leak-tight attached to them.

Figure 6. *System for Parallel Connection of the Activating Device*



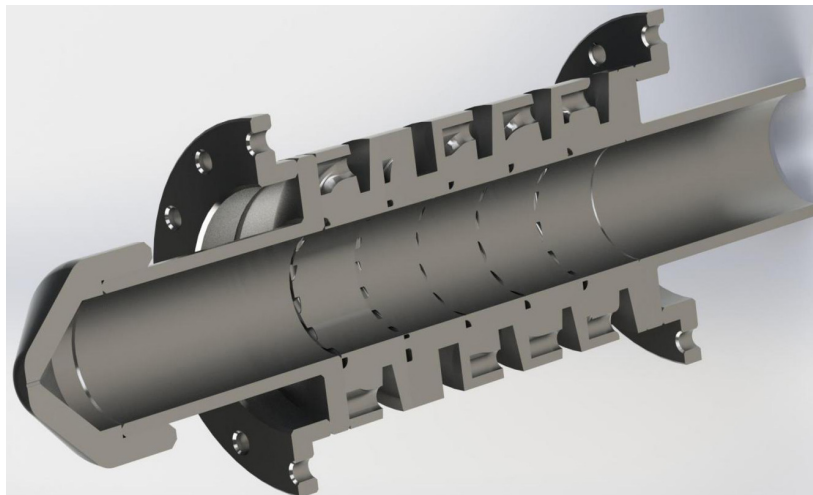
4. Technical Requirements for Compressed-air Pipelines From the Compressor

1. The pipelines used to supply compressed air from the compressor to the fuel-mixture activating device shall comply with the requirements specified in Section 3.1.

5. Technical Requirements for The Compressor

1. For the initial stages of testing, the specific type of compressor is not of critical importance.
2. The compressor shall provide a nominal operating pressure of at least 20 atmospheres.
3. An air filter with a liquid buffer shall be installed at the compressor air inlet.
4. The compressor shall have at least four compressed-air outlets or be equipped with a system ensuring uniform distribution of the compressed-air flow at the compressor outlet.
5. The pressure level shall be adjustable throughout the entire operating range of the compressor, from minimum to maximum.
6. The compressed-air flow rate at the compressor outlet shall be adjustable from maximum to minimum.
7. All connections between the outlet pipelines and the compressor shall use standard fittings and connections.

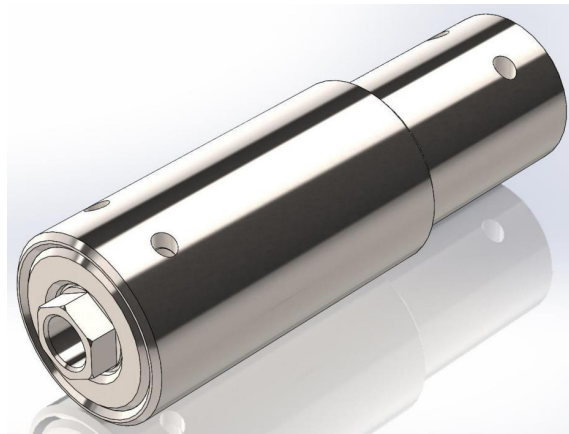
Figure 7. *System for Vortex Tube Formation*



6. Program and Procedure for Preliminary Testing at the Device Manufacturer's Facility

1. Each component shall be accompanied by a quality certificate.
2. Each component shall be accompanied by a conformity report confirming that its linear dimensions correspond to the dimensions specified in the engineering drawing.
3. All components shall be selectively matched for each individual assembly.
4. A separate inspection report shall be prepared for each assembly, confirming its assemblability and compliance with the general technical requirements for the product.
5. All connections of the device's hydraulic lines, both at the inlet and outlet, shall be tested for leak-tightness at a pressure **25% above the nominal operating pressure.**
6. All connections of the device's pneumatic lines shall be tested for leak-tightness at a pneumatic-system pressure **25% above the nominal operating pressure.**
7. The fully assembled device shall be tested for leak-tightness of both the hydraulic and pneumatic sections while operating simultaneously at a pressure **25% above the nominal operating pressure.**
8. A manufacturer's technical passport shall be prepared for each device, specifying the results of all preliminary tests performed.

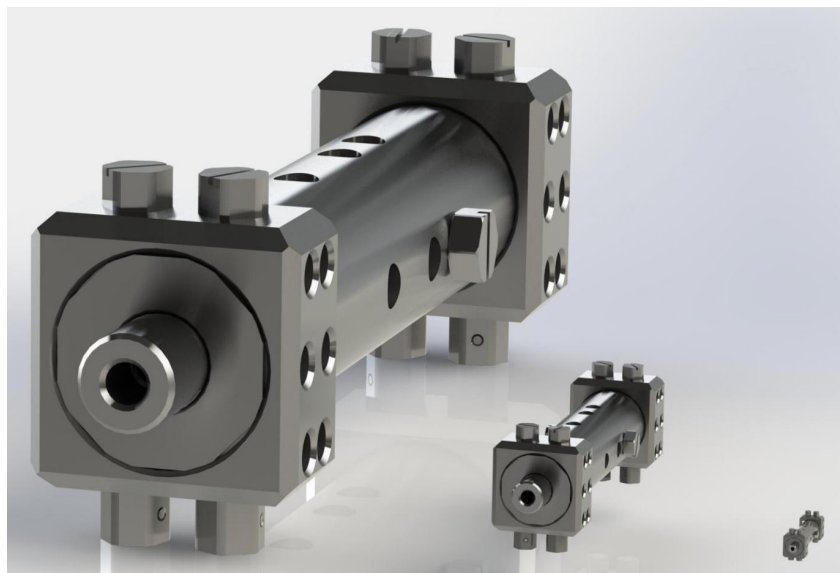
Figure 8. *Stabilization Device*



7. Technical requirements for the air filter installed at the inlet of the compressor connected to the fuel-mixture activating device

1. The compressor shall provide an operating pressure of at least 20 atmospheres.
2. The pressure shall be adjustable within the range from the minimum to the maximum value.
3. The air purification filter shall be capable of operating under the specified parameters.
4. The filter shall incorporate a system for directing the airflow through a liquid medium, such as light mineral oil or industrial alcohol.
5. Air shall be introduced into the filter through tangential inlet channels.

Figure 9. *Example of the Scale Factor*



Considering the relatively compact design of our device and its ease of integration into the fuel system of a modern engine, it is important to protect the formulated concept and its structural implementation as soon as possible, since it is expected to enter the intellectual property market simultaneously with the basic product – various types of biological fuel mixtures.

The scope of claims that may be declared includes:

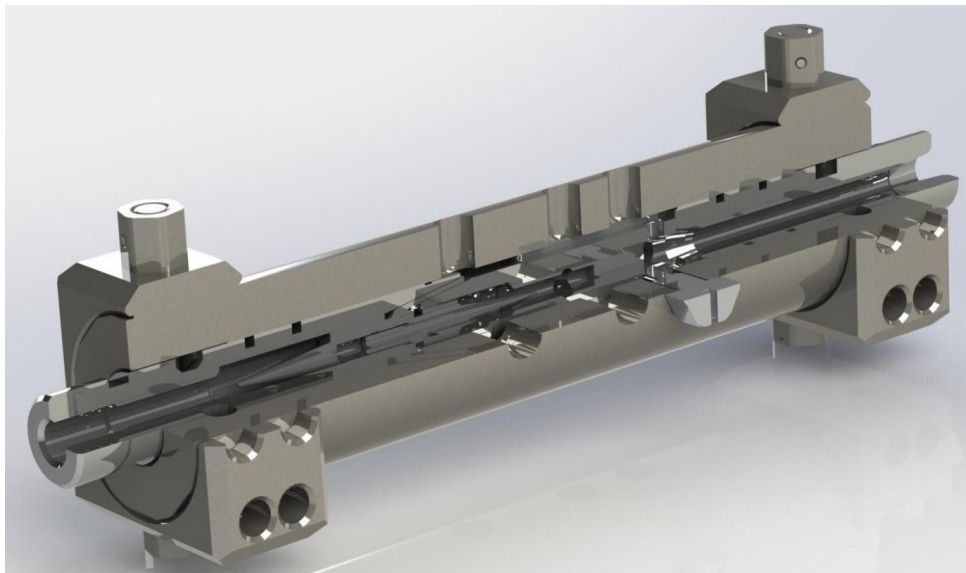
- A mixer integrated into a pipeline and utilizing pressure differentials arising or generated in different sections of the pipeline due to differences in the linear flow velocities of liquids moving through the pipeline;
- A hydrodynamic mixer;

- A hydrodynamic mixer integrated with a foam generator;
- A sequential mixing and foaming unit;
- A sequential mixing and foaming unit integrated into a pipeline and utilizing the kinetic energy of liquid flows moving through the pipeline to perform its technological functions;
- A hydrodynamic mixer designed to increase the level of turbulence;
- A hydrodynamic turbulence-enhancing mixer integrated with an aerodynamic turbulence-enhancing foam generator;
- A hydrodynamic generator designed to increase the turbulence level of liquid flows moving through a pipeline;
- Sequential hydrodynamic and aerodynamic turbulence-enhancing flow converters integrated into a pipeline for processing liquid flows moving through the pipeline;
- An aerodynamic foam generator;
- A compact aerodynamic foam generator designed for integration into a fuel pipeline;
- A hydrodynamic mixer for liquids with different viscosities and physicochemical properties;
- A compact hydrodynamic mixer integrated into a fuel pipeline, designed for mixing liquids with different viscosities and physicochemical properties without requiring additional energy consumption for the performance of its functional operations;
- An integrated hydrodynamic-aerodynamic compact unit designed for installation in a fuel pipeline and for preparing fuel mixtures prior to their injection into the combustion chambers of combined engines operating according to the Otto cycle.

Analysis of Modern Techniques and Algorithms for Developing Innovative Technical Solutions Based on the Application of Distinctive Features of Known Inventions in a New Capacity and in Newly Emerging Fields of Technology
(Use of Basic Distinctive Features in a New Capacity)

First, we will briefly consider the technology proposed as an example, as well as its specific features and elements of novelty:

Figure 10. *Cross-Section of the Fuel-Mixture Homogenization Device*



The device shall consist of an accelerating hydrodynamic section transitioning into a coaxially arranged second hydrodynamic section with an integrated vortex generator, which in turn transitions into a hydrodynamic turbulence-enhancing

unit connected to the inlet of a high-pressure pump.

All milk to be homogenized in the proposed device is divided into two streams. The first stream, representing **60% of the total flow**, enters the accelerating hydrodynamic

ic section at a pressure of **3 bar (45 psi)**, where acceleration occurs in accordance with **Bernoulli's principle**. The second stream, representing **40% of the total flow**, enters the second hydrodynamic section, arranged coaxially with the first section, at a pressure of **3 bar (45 psi)**.

The device provides a dynamic process of sequential milk-flow homogenization. During the first stage, homogenization is achieved by controlling the level of turbulence within the pipeline. This process is presented as the principal element of novelty and is described in the relevant intellectual property protection documents.

The homogenized milk flow is then transformed into a vortex flow by means of the integrated vortex generator and directed to a high-pressure pump operating at a pressure of **2,000–3,000 bar (29,000–43,500 psi)**. The second stage of dynamic in-flow homogenization takes place under these conditions, resulting in a reduction in the particle size of the emulsion – milk being an emulsion – to less than one micron, thereby producing a nanoemulsion.

The homogenization process takes less than one second and is designed to preserve the natural and biological relationships among the components of the milk. The process takes place at a stable temperature or, under certain operating conditions, with a reduction in milk temperature.

The entire dynamic homogenization process is based on the creation of specific turbulent hydrodynamic conditions within the milk flow without disrupting the biological equilibrium among its components.

Advantages of the Proposed Process Compared with Existing Technology

- Existing technology does not include a stage of dynamic homogenization based on the turbulence level and therefore does not provide for homogenization directly within the pipeline;

- In the proposed process, the second homogenization stage is performed at a pressure that is at least twice as high;
- The resulting fat particles (globules) are stated to have a uniform size within the range of **70–120 nm** and to show no tendency to agglomerate, whereas existing technology is described as producing a particle-size variation of more than tenfold, from **0.2 to 2 μm**;
- All homogenization processes can be performed directly within the pipeline, for example, during milk transfer from a tanker to the processing equipment of a dairy plant, without requiring dedicated production areas;
- The milk temperature does not increase during the proposed process;
- The device enables additional components, such as multivitamins or lysozyme, to be introduced into the milk during homogenization, including for the purpose of extending shelf life;
- The device has compact overall dimensions, is convenient to operate, and provides favorable conditions for sterilization;
- The device can also be used to perform fermentation either during or after homogenization without altering the parameters of the homogenized milk;
- The proposed device is described as significantly less expensive than existing equipment;
- The device can be used for technological homogenization before milk enters processing equipment for the manufacture of dairy products.

Based on the principles and methods of the Theory of Inventive Problem Solving (TRIZ) and the Algorithm for Inventive Problem Solving (ARIZ), a structural analysis of currently available milk homogenization technologies was performed.

The most probable systemic contradiction appears to be associated specifically with the application of high-pressure treatment to milk during the homogenization process.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-55-61



DESIGN OF SMART TRANSPORTATION SYSTEMS USING ARTIFICIAL INTELLIGENCE. (Development of Integrated Technical Systems Using AI-Enabled Computer-Aided Design Software)

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Cite: Benito Diaz. (2026). *Design of Smart Transportation Systems Using Artificial Intelligence. (Development of Integrated Technical Systems Using AI-Enabled Computer-Aided Design Software).* European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-55-61>

Abstract

This article examines the development of integrated technical systems using computer-aided design software incorporating elements of artificial intelligence.

To design specialized technological equipment complexes that meet modern requirements while preserving the applicability of the Theory and Algorithm of Inventive Problem Solving, it is necessary, at a minimum, to analyze the definitions and laws governing the evolution of technical systems in conjunction with AI-enabled computer-aided design systems.

The system under consideration is a higher-level integrated technical system comprising a number of technical systems interconnected through a common technological cycle and functioning as dual parallel local supersystems. Each supersystem includes two lines: a chemical line and a mechanical line incorporating electroplating operations.

Accordingly, each dual parallel local supersystem consists of multiple local technical systems, or subsystems, connected through local programmable processors to the central processor of the higher-level integrated technical system.

Keywords: *integrated technical system; dual parallel local supersystems; higher-level integrated technical system processor; law of technical system evolution; classical technical system; automated robotic production and assembly complex*

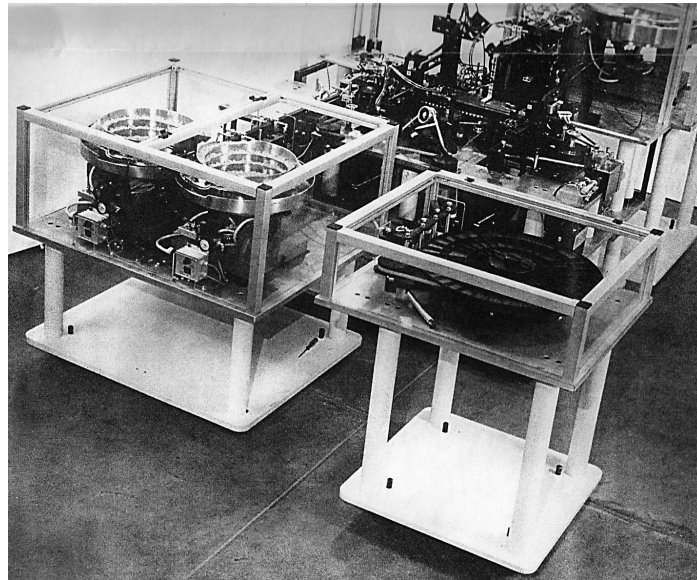
Introduction

The structure and interaction of local technical solutions within each subsystem are fundamentally determined by the laws of technical system evolution formulated within the Theory of Inventive Problem Solving (TRIZ).

For a more detailed analytical examination, it is appropriate to return to examples

of specific contemporary developments, taking into account the above comments on the laws of technical system evolution, as well as certain modifications to TRIZ definitions and classifications proposed in the well-known publications of Mykhailo Korobko.

Figure 1. *The figure shows the technological modules of an automated robotic production and assembly complex designed for the autonomous manufacture of contact blocks for telephone lines. As can be seen in the image, the complex contains four principal technological modules. Three of these modules prepare parts and components for assembly and are arranged around the assembly conveyor module*



The operating cycle of each module is synchronized with the indexing step, or operating cycle, of the assembly conveyor module. This applies both to the vibratory hopper modules traditionally used in such complexes, shown on the left side of the figure, and to the fundamentally new modules used to stamp the contacts and feed them

to the assembly and inspection conveyor, shown in the center.

This configuration of an automated robotic production and assembly complex may be classified as a technical system with a fixed production cycle, in which all technological modules are synchronized with the indexing step of the assembly conveyor module.

Figure 2. *The figure shows a configuration of a flexible photolithography processing module for thin-film microassembly boards. The module comprises two parallel process flows, each of which is fully autonomous, including independent integrated computer control systems. In addition to these systems, the module also includes a computer-based control and monitoring system for the operator robot, which is functionally connected to the integrated computer control systems*



In this configuration, the technological modules function as subsystems, while the assembly conveyor module functions as the governing supersystem. The subsystem modules operate in accordance with the production cycle of this supersystem.

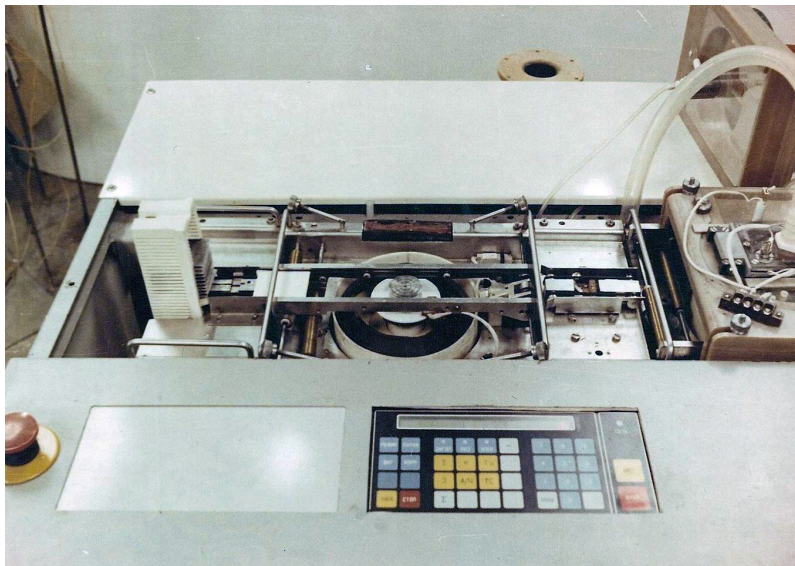
As can be seen in the figure, although the assembly complex contains numerous points of interaction and requires the coordination of its production cycles, it is not subject to any specific requirements governing increased flexibility or adjustment of the modules' production cycles.

This configuration is characteristic.

The module comprises several closely interconnected functional technical systems, each of which may be classified as a super-system.

Together, these systems include loading and unloading modules, local loading and unloading units, tracks, centrifuges, chemical reagent and photoresist metering and delivery units that supply these materials to the processing area on the centrifuge table, monitoring systems, and other associated components.

Figure 3. *The figure shows the processing track of a system used to apply electroplated coatings to thin-film microassembly boards. The processing track includes autonomous board loading and unloading devices installed at the process inlet and outlet*



The track comprises several centrifuges: a processing station for preparing surfaces for coating, a processing station for electroplating, and a processing station for the final treatment of the board after the coating has been applied.

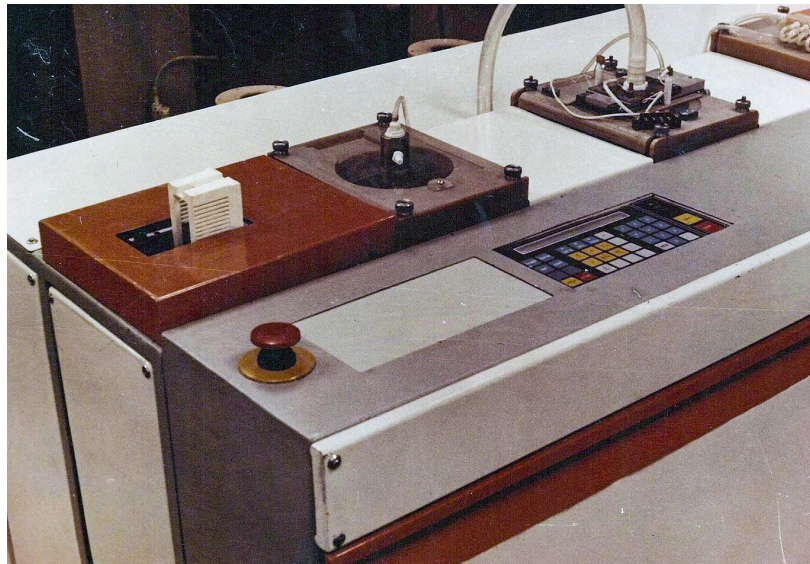
The system is fully automated and is controlled and monitored by programmable processors connected to the power supply for the electroplating process. The system provides flexible adjustment of the current density depending on the coating area and thickness.

The system has two process flows, one of which is shown in the figure. It is operated, regulated, configured, and monitored by several programmable controllers. Data, programs, and commands are entered into these controllers through a touchscreen.

It is important to note that each local technical system, even when functioning as a low-level subsystem, possesses considerable potential for integrative adaptation within technical systems at every level of the hierarchy due to its high degree of unification and standardization. This hierarchy determines the composition and functional characteristics of the supersystem at its highest level.

Because prototypes of such equipment are generally developed at the level of an invention in specific production environments, the accurate definition, systematic qualification, and classification of all new technical solutions and their combinations within technical systems at every level of the hierarchy are critically important.

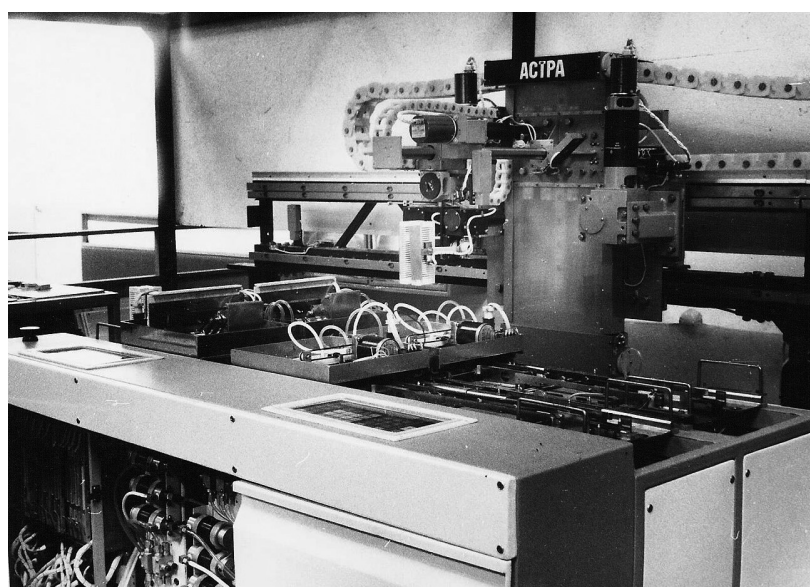
Figure 4. *The figure shows an automated system comprising two process flows, each equipped with flexible and independent control and monitoring. The system is designed to apply electroplated coatings to thin-film microassembly boards in a semiconductor manufacturing environment. It can be incorporated into flexible in-line processing modules, which, in turn, can be integrated into higher-level systems*



As shown in the figure, the thin-film microassembly board blanks, manufactured from a special ceramic material and measuring 48×60 mm, are held in cassettes positioned at the beginning and end of the process flow. Operator involvement in the process is therefore not required, since all

loading and unloading operations are performed by an operator robot. All operations and the sequence in which control commands are executed are monitored by a programmable processor, which is accessed through a touchscreen control panel.

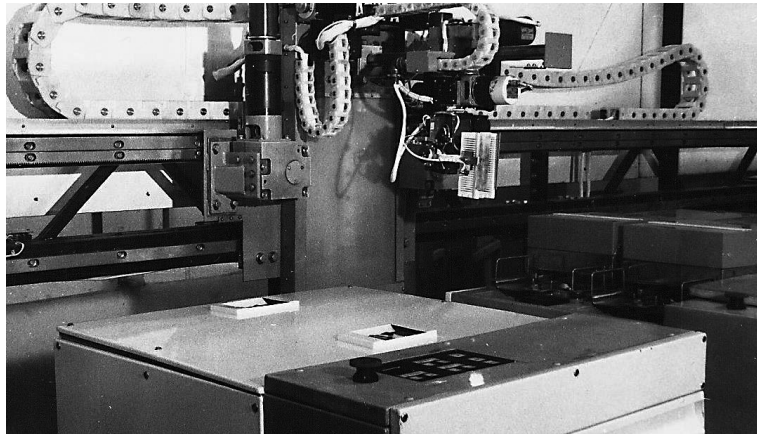
Figure 5. *The figure shows the technical solutions incorporated into and forming the transport systems at all levels of the flexible automated processing module. These range from transporting thin-film microassembly board blanks from the loading and unloading module to the processing stations to the integrated transport system of the robotic manipulator, which can be adapted for use with equipment designed for other technological processes and with computerized control and supervisory regulation systems*



Systems of this kind generally incorporate a wide variety of basic technical solutions. When these solutions are combined with technical solutions possessing world-

wide novelty, it is the resulting integrated technical solutions, in their various combinations and configurations, that may qualify as inventions.

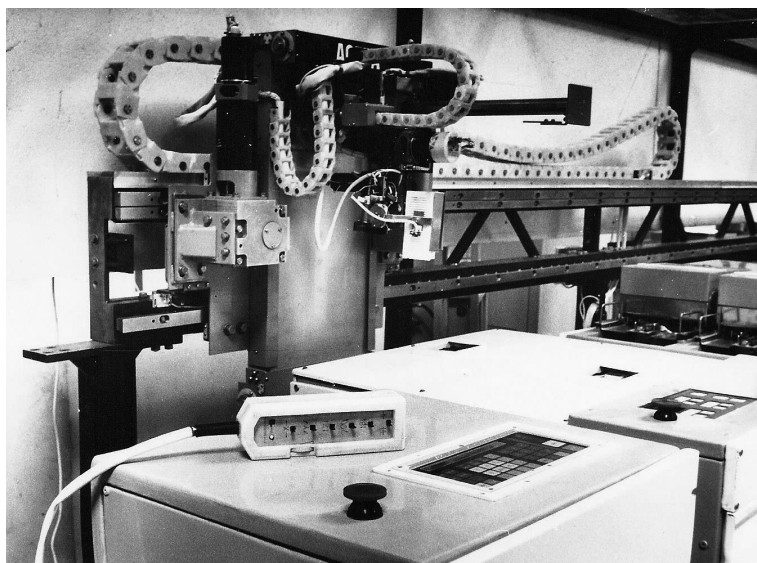
Figure 6. *The figure shows the integration of the transport systems of a flexible automated processing module with the transport and orientation systems of a buffer-storage module functioning as a universal supersystem*



In a configuration comprising technical solutions that extend upward and downward through the hierarchy of the highest-level supersystem, the strategy for patent protection from a technical perspective and licensing protection from a legal perspective depends heavily on the clear and technically accurate classification of the entire set of technical solutions and their functional interconnec-

tions. Of even greater importance are their relationships with the definitions and formulations applicable to the various categories and types of technical solutions incorporated into higher-level systems within the hierarchy, including subsystems and the technical solutions located at the interfaces of local and substantially autonomous technical systems that connect them into supersystems.

Figure 7. *The figure shows a section of a flexible photolithography processing module for thin-film microassembly boards, illustrating the fundamental method used to load and unload the processing stations by means of an operator robot. The robot retrieves a cassette containing substrates from the buffer-storage module and places it on the loading device table of the process flow. The same procedure is performed in reverse: the robot retrieves a cassette containing processed substrates and places it in the buffer-storage module*

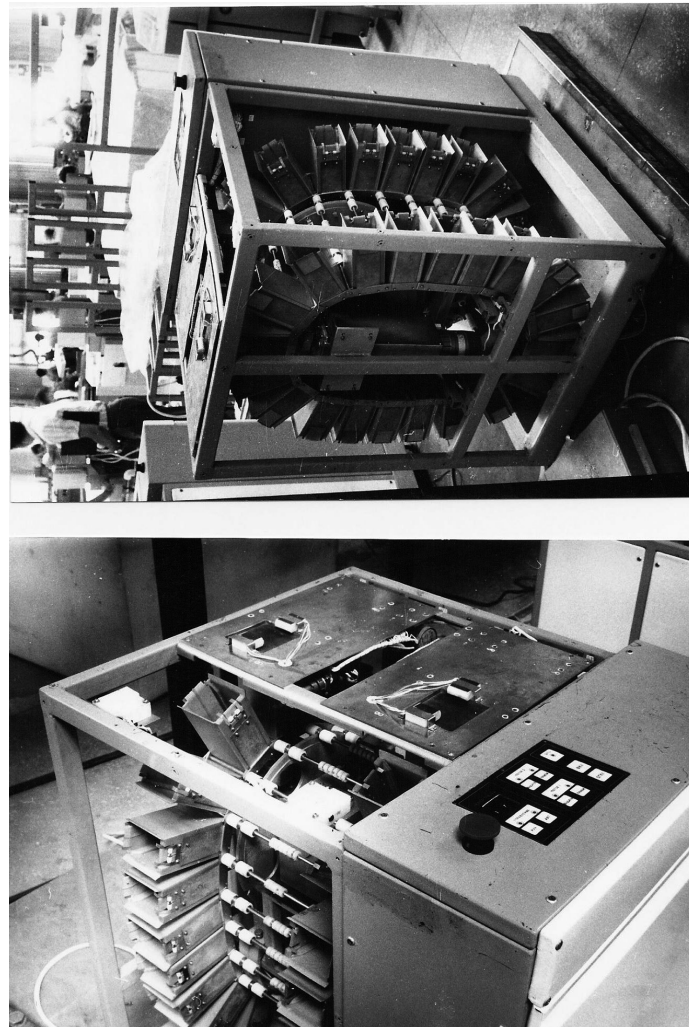


The presence of programmable control and monitoring controllers and processors naturally elevates the status of these technical systems from local technical systems to smart technical systems. The foregoing demonstrates the importance of the analytical work performed by Mykhailo Korobko in his pioneering research. His development of fundamental principles for classifying and systematizing the types and characteristics of technical systems, together with the definitions applicable to each level of such systems, is essential to the systematic continuation and further optimization of computer-aided design processes. This work enables the use of advanced computer-aided

design software in combination with the latest principles and methods of digital technology, while aligning them with the terminology and laws of technical system evolution established within the Theory of Inventive Problem Solving (TRIZ) and the Algorithm for Inventive Problem Solving (ARIZ).

As shown in the figure, the buffer-storage modules contain sealed cassette cells and are equipped with programmable control processors. These processors monitor the processing sequence and transmit signals to the conveyor of the buffer-storage module, identifying the cell that must either receive a cassette or be cleared of one.

Figure 8. *The figure shows the internal structure of the buffer-storage module. As can be seen in the figures, the module is equipped with a vertical conveyor to which cells are attached for inserting and removing cassettes containing workpiece blanks*



This technical system has undergone extensive testing. A detailed analysis demonstrates that virtually all layout, schematic, and structural technical solutions incor-

porated into the components of the flexible automated production module correspond – in terms of their design, functions, layout methods, and operating methods – to the

classification, terminology, and structure of modified technical systems, as well as to the definitions formulated in the works and publications of Mykhailo Korobko.

The analysis would be incomplete without examining the standard process for developing a new technical solution incor-

porated into a technical system at a higher level of composition and layout. It is also necessary to determine whether the relevant formulations and definitions correspond to the modified formulations and definitions for technical systems at all levels proposed by Mykhailo Korobko.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-62-69



**INTEGRATION OF STRUCTURAL AND TECHNOLOGICAL
SOLUTIONS IN INNOVATIVE PROJECTS.
(Fundamental Aspects of the Horizontal and Vertical
Integration of Structural, Engineering, and Technological
Solutions under Conditions of Complex Uncertainty Regarding
the Final Integrated Solution and the Ideal Final Result)**

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Cite: Drapii V. (2026). *Integration of Structural and Technological Solutions in Innovative Projects. (Fundamental Aspects of the Horizontal and Vertical Integration of Structural, Engineering, and Technological Solutions under Conditions of Complex Uncertainty Regarding the Final Integrated Solution and the Ideal Final Result).* European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-62-69>

Abstract

This article examines the growing importance, under conditions of increasingly intensive globalization, of ensuring comprehensive and robust protection of innovative technical ideas against unauthorized appropriation and even direct copying, with particular emphasis on maintaining a degree of non-obviousness of such ideas to an ordinarily skilled specialist within the technological field in which they originate. This issue becomes even more significant as an innovative idea undergoes concrete and comprehensive development and gradually evolves, step by step, from a purely conceptual idea into a set of specific, interrelated technical solutions. This evolution is accompanied by the integrative penetration and technological diffusion of such solutions from one technological field into adjacent fields. A fundamental prerequisite for such cross-field penetration is the shifting of boundaries between technological fields and the progressive blurring of the distinctive characteristics and properties defining those boundaries. As an example of the emergence and synthesis of an innovative idea of this kind, the author presents the development of the concept of non-contact remote control and online monitoring of the parameters and concentrations of a process solution. The initial concept was progressively developed into a sensor-capsule design principle and an algorithm for its application, followed by the serial production of such sensor capsules and their large-scale deployment in modern, complex, high-technology manufacturing environments, as well as their potential application in biotechnology, medicine, and agriculture. At this point, the author considers it necessary to make a brief analytical digression in order to examine macro- and micro-scale scenarios for the development and application of these technologies, taking into account the specific characteristics of applications at different scales and the corresponding differences in operating conditions. Since the author of this article initiates innovative startup projects and

is also engaged in restoring and further developing startup projects in which the **Ideal Final Result** has not been achieved, and, for a number of objective reasons, operates under conditions characterized by a micro-scale technological factor, the article proposes a method for the qualification and comparative analysis of innovative modifications to processes and materials.

Keywords: *Integration of Structural Solutions; Integration of Technological Solutions; Innovative Projects; Fundamental Aspects of Integration; Fundamental Aspects of Horizontal Integration; Fundamental Aspects of Vertical Integration; Final Integrated Solution; Complex Uncertainty Regarding the Feasibility of the Final Integrated Solution; Complex Uncertainty Regarding the Ideal Final Result; Comprehensive Protection of Innovative Technical Ideas; Comprehensive Development of an Idea and Its Gradual, Step-by-Step Transformation from a Concept into Specific Technical Solutions*

Introduction

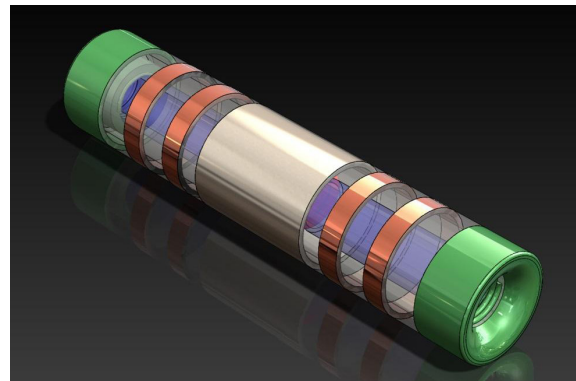
In the context of increasingly intensive globalization, ensuring comprehensive and robust protection of innovative technical ideas against unauthorized appropriation and even direct copying has become critically important. In this regard, the non-obviousness of an idea to a person of ordinary skill in the technological field in which the idea originated is of particular significance. This issue becomes even more important as an innovative idea undergoes concrete and comprehensive development and gradually evolves, step by step, from a purely conceptual idea into a set of specific, interrelated technical solutions. This evolution is accompanied by the integrative penetration and technological diffusion of such solutions from one technological field into adjacent technological fields. A fundamental prerequisite for such penetration is the shifting of boundaries between technological fields and the progressive blurring of the distinctive characteristics and properties defining those boundaries. As an example of the emergence and synthesis of an innovative idea of this kind, the author presents the development of a concept originating from the idea of non-contact remote control and online monitoring of the parameters and concentrations of a process solution. This concept was progressively developed into a design principle and an application algorithm for a sensor capsule, followed by the serial production of such sensor capsules and their large-scale application in modern, complex, high-technology manufacturing environments, as well as their corresponding application in biotechnology, medicine, and agriculture. At this point, the author considers it appropriate to make a brief analytical

digression in order to examine macro- and micro-scale scenarios for the development and application of these technologies, taking into account the specific characteristics of applications at different scales and the corresponding differences in the conditions under which such technologies are employed.

Since the author of this publication initiates innovative startup projects and is also engaged in the restoration and further development of startup projects in which the Ideal Final Result has not been achieved, and, for a number of objective reasons, operates under conditions characterized by a micro-scale technological factor, a method is proposed for the qualification and comparative analysis of innovative modifications to processes and materials. It is proposed to examine and compare different initial conditions that determine the baseline requirements for identifying and developing new innovations, both in the field of new materials and in the field of innovative technological methods and techniques. Ultimately, these factors determine the economic efficiency, technological and commercial effectiveness, and overall practical viability of the proposed innovations. For comparative purposes, two contrasting cases may be considered: at one extreme, the complex process of restoring, for example, a painting by a medieval artist that constitutes a museum treasure and may even form part of a nation's cultural heritage; and, at the other, the process of milk homogenization under modern industrial production conditions and within a globalized economy. Both processes require online monitoring; however, they are characterized by fundamentally different baseline parameters and conditions for assessing the need

to introduce innovative technical solutions for such monitoring. The principal distinction between these two processes lies in the respective levels of recoverable and irreversible losses that may arise in the event of a loss of control over the operation of monitoring devices. In the event of an accident or process failure in milk production, irreversible losses are quantifiable and subject to clearly defined limits. By contrast, if control over the quality of materials and the techniques used in their preparation is lost during a restoration process, the resulting irreversible material and non-material losses may exceed even the highest anticipated limits. Consequently, for an innovative project to be practically relevant and to generate the required material, commercial, and non-material benefits, the issues associated with the vertical and horizontal integration of an innovative solution – from the initial idea through to mass production – must be addressed with a sufficient degree of universality to ensure that the level of irreversible losses does not exceed the level of recoverable losses. The emergence of the idea and its subsequent innovative synthesis originate in techniques and methods for the active monitoring of liquid parameters in process vessels through the use of so-called control coupons. Such control coupons have a limited service life and must be replaced with new ones once that service life has expired. As a general rule, these elements are placed in the corners of process vessels and baths, where so-called dead zones tend to occur. In these zones, the level of turbulence is substantially lower than in the central regions of the vessels or baths. Typically, a control coupon of this kind contains a chemical reagent that interacts with the solution contained in the process vessel or bath and, under the progressive action of that solution, undergoes a change in mass. When the control coupon is removed, the nature and extent of changes occurring in the solution are determined by weighing its control element and assessing the corresponding change in mass. Clearly, this method does not provide active online monitoring. In this configuration, the control coupon performs the function of passive, periodic monitoring rather than continuous real-time process control.

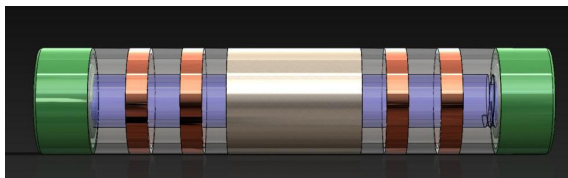
Figure 1.



The model depicts a module designed for active, non-contact monitoring of the parameters of a controlled fluid flow. The monitored medium may be a mixture, an emulsion, a fluid medium exhibiting compressible properties, an aerosol, or another type of liquid or multiphase medium. Let us consider the principles of horizontal and vertical integration of the fundamental technical solutions underlying a module intended for remote, non-contact monitoring of an object containing one of the above-mentioned types of media, including liquids, aerosols, chemical solutions, and similar media. As a starting point for a comprehensive analysis of the module's distinguishing features, the author proposes examining the design constraints applicable to the module and its constituent systems, particularly those arising from the requirements and limitations established by applicable standards. As a rule, these constraints comprise a set of interrelated parameters, including dimensions, materials and combinations of materials, as well as the fundamental principles governing the module's operating cycle and enabling it to perform its primary functions. One such function is continuous online monitoring – for example, monitoring the acidity (pH) of a cow's gastric fluid. Based on previous experience with modules of this type, it is known that one of the principal challenges is continuous energy supply. Experiments involving the use of conventional chemical power sources in such modules have generally encountered limitations that ultimately required termination of the experiments. This is primarily because the service life and energy capacity of chemical batteries are inherently limited, while the practical possibilities for retrieving and replacing an

implanted or internally deployed module are even more restricted. Accordingly, the key to solving this problem lies primarily in ensuring a continuous and sufficiently reliable energy supply for all measurement, data-processing, and communication functions of the module. Let us now consider the operating environment within the cow's stomach in which the module is located. The gastric environment is generally acidic. If the gastric fluid is assumed to perform, in parallel with its primary biological functions, the additional function of an electrolyte for an integrated electrochemical power source, electrodes may be incorporated into or arranged on the external surfaces of the module housing. Under these conditions, the module housing with its integrated electrodes, while remaining in continuous contact with the acidic gastric fluid, could perform an additional electrochemical function alongside its primary structural and protective functions. In this configuration, the external surface of the module would form a spatially distributed, three-dimensional planar electrochemical cell (or an array of interconnected cells) capable of generating electrical energy for the module's monitoring and communication systems.

Figure 2.

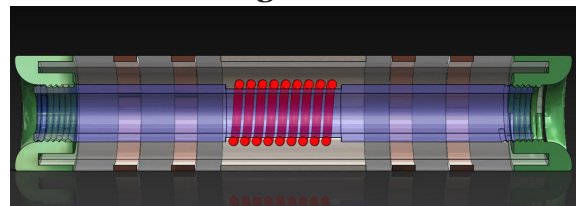


As can be seen in the following figure (3D model), a conductive shield is located at the center of the module's cylindrical structure. This shield provides electromagnetic shielding for the solenoid of the impedance-resonance sensor and is also designed to perform the additional function of one of the electrodes of the proposed innovative electrochemical power source.

Once the problem of electrical power generation is addressed through the use of a continuously replenished resource – namely, the gastric fluid acting as an electrolyte – the same medium can simultaneously perform several interrelated functions within the integrated system. Its acidity parameters are continuously monitored, while the gastric

fluid entering the module's internal channel interacts with structural elements of the module and is subjected to electromagnetic excitation generated by pulses from the sensor solenoid. Under this operating principle, the electrolyte – i.e., the gastric fluid – is exposed to the pulsed electromagnetic field generated by the solenoid sensor, producing a characteristic resonant response. At the peak of the corresponding response pulse, the maximum measured potential difference is obtained and used as an electrical parameter correlated with the acidity (pH) of the gastric fluid at the time of measurement. Simultaneously, along the external surface of the module housing, the same gastric fluid acts as an electrolyte and interacts electrochemically with the electrodes integrated into the module housing in the form of a system of circumferential ring electrodes.

Figure 3.

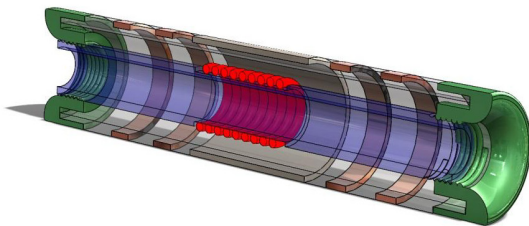


At the same time, these electrodes, in combination with the surrounding volume of electrolyte – the gastric fluid with which they interact – form a combined protective electromagnetic shielding system. This system shields the measurement zone and reduces electromagnetic and electronic noise, thereby improving measurement accuracy in real time. Thus, the module demonstrates a clear integration of functions, providing both horizontal and vertical integration through the continuous functional combination of the module's structural elements and the materials from which those elements are manufactured.

It is precisely this functional integration that constitutes a distinct innovative feature of the proposed technical solution: the same structural elements of the module simultaneously perform multiple functional roles within the overall system. It should be emphasized that all of the combined functions incorporated into the module are implemented using simple geometric configurations, straightforward combinations of structural

materials, and well-established manufacturing techniques that have been repeatedly applied in the fabrication of module prototypes and in the experimental verification of their operating parameters. The simplified geometry of the module's structural elements makes it possible to manufacture a prototype within a relatively short period of time and to conduct comprehensive testing of its operating parameters, as well as to evaluate the efficiency and effectiveness of the complete operating cycle. Figure 1.

Figure 4.

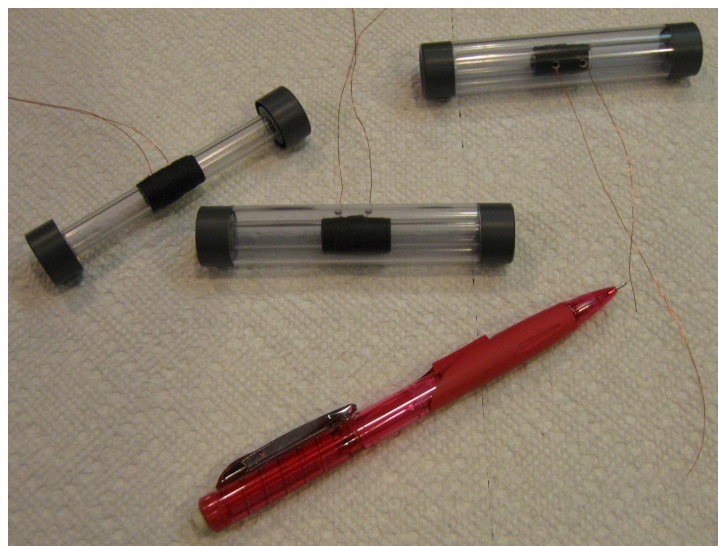


The figure presents a three-dimensional longitudinal sectional model of the module, providing a sufficiently clear representation of the feasibility of implementing the experimental module's vertically and horizontally integrated innovative operating functions.

This level of detailed engineering development of all structural elements of the module makes it possible to fabricate a fully functional experimental prototype incorporating all components and materials required for experimental verification and testing. The following photograph shows full-scale prototypes of the module, fabricated from standard, commercially available materials. The overall dimensions of the module have been established in accordance with the requirements of applicable standards and established requirements for dairy cattle applications. These requirements define dimensional parameters that allow the module to be swallowed by a cow without causing injury or adverse effects associated with its physical dimensions.

Preliminary testing of the modules, conducted under conditions simulating the relevant operating parameters and environment, has demonstrated that the selected materials and their combinations, the methods used to join and assemble the module components, and the specified functional dimensions of its structural elements collectively provide the required level of operational performance and functionality of the module.

Figure 5.



A particularly important aspect of the module development and modeling process was establishing a system-level correlation with the current state of the art in technical and technological equipment used in modern dairy production. The following photographs illustrate a dairy production facility operating at this technological level. Such an

advanced production environment requires a correspondingly high level of technical performance, reliability, and technological compatibility from all equipment components, instruments, auxiliary devices, and tooling employed within the production system. When analyzing the technical and technological level of the commercially manufac-

tured dairy-processing equipment shown in the photographs, it is appropriate to focus specifically on the concept of non-obviousness, considered in conjunction with other

fundamental characteristics of innovation, including novelty at the international level, technical operability, efficiency, and practical utility.

Figure 6.



First of all, it should be noted that the photographs depict standard, commercially manufactured technological equipment used in dairy production in a Western country. The technical and technological level of this equipment, which operates within a closed-loop production process and is controlled by a centralized monitoring and control system, also determines the required performance level of all associated technologies, instrumentation, and monitoring systems. Considering that, even on large-scale commercial dairy farms, an incorrect measurement of the acidity of a single cow's gastric fluid may result in milk of inadequate quality en-

tering the common milk collection system, such an error may subsequently require the affected batch of milk to be excluded from the production and processing cycle, potentially causing significant economic losses to the agricultural enterprise. Consequently, the principal requirements imposed on the proposed module are high operational reliability and the highest practically achievable level of measurement accuracy. If the module developers are able to demonstrate compliance with these stringent requirements, the concept of non-obviousness of the technical solution acquires an additional practical dimension.

Figure 7.



In this context, non-obviousness must be considered not only in terms of the originality of the technical concept itself, but also in relation to the ability of the integrated solution to achieve the required performance under actual operating conditions. Accordingly, the conclusion for the module's designers and engineers is clear: only by demonstrating the required levels of reliability and measurement accuracy can the practical feasibility of implementing this integrated technical solution be established within realistic technological and operational constraints.

Furthermore, the possibility of securing robust patent protection for the entire integrated set of technical solutions embodied, in one form or another, in the module – including its core hardware, software, signal

identification and decoding system, and the algorithms and procedures used to convert the acquired signals into specific quantitative measurement results – together with the demonstrable operability and reliability of all interconnected system components, determines the feasibility of integrating the proposed system into a modern dairy production environment. At the same time, the innovative nature of both the module itself and its associated operational system suggests considerable potential for the application of the module, as well as the integrated technology implemented through its use, across a broad range of industrial and agricultural sectors, and potentially in medicine, biotechnology, and biological research.

Figure 8.



The proposed technology is characterized by the flexibility to modify the design of the module and its principal components. The following models illustrate various design modifications of the module that have made it possible to incorporate a number of additional functional elements without altering its overall external dimensions. These innovations relate, in particular, to the composition, configuration, and geometry of the shielding elements, which simultaneously contribute to the functional characteristics and performance of the integrated electrochemical power source used to supply energy for the measurement process and for trans-

mitting measurement data to the system's central computer. In practical terms, the developments described above may be regarded as an example of the innovative development and refinement of one of the key elements of non-contact measurement technology, as well as the systematic formation of a distinctive combination of technical features characterizing both the technology itself and the devices, software, methods, and systems involved in its implementation. It is the integrated combination of these distinctive technical and system-level features, together with the required level of international novelty, technical operability, practical utility,

and non-obviousness, that can provide a basis for effective intellectual-property and patent protection and thereby help protect these technical solutions against unauthorized appropriation, reproduction, or copying.

Figure 9.

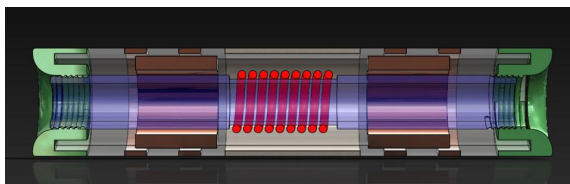


Figure 10.

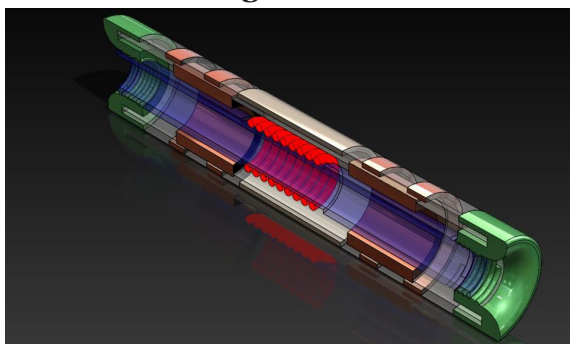


Figure 11.

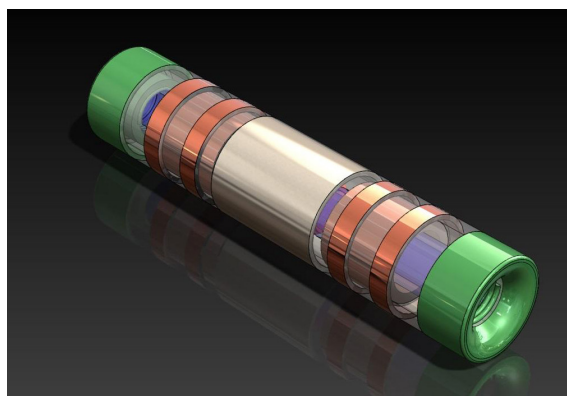
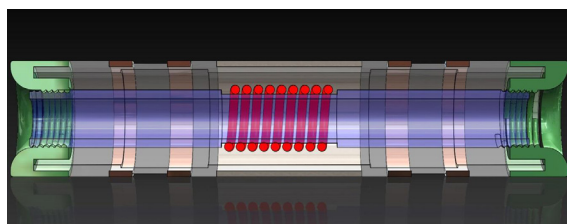


Figure 12.



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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-70-80



LASER TECHNOLOGY AND INTEGRATED TECHNICAL SYSTEMS. (Laser Technology and Integrated Technical Systems for Ophthalmic Devices and Instruments Utilizing Artificial Intelligence Elements Associated with Artificial Neural Networks)

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Cite: Efimova A. (2026). *Laser Technology and Integrated Technical Systems. (Laser Technology and Integrated Technical Systems for Ophthalmic Devices and Instruments Utilizing Artificial Intelligence Elements Associated with Artificial Neural Networks).* European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-70-80>

Abstract

This article examines the potential applications of the invention “Light Emitting Apparatus with Integrated Emitter” in medical technologies, machine vision, and related automated systems. The distinctive technical features of the proposed invention can provide significant technical and economic benefits across a wide range of applications. One of the prospective applications considered in the article is machine vision. A number of medical procedures, therapeutic processes, and automated manufacturing operations require uniform illumination of the operating or working area with monochromatic light. Under certain operating conditions, conventional laser systems produce localized and distorted light patterns and therefore are not suitable for generating a uniform monochromatic light flux across an operating or working area. Light-emitting diodes (LEDs) do not produce such distorted structures; however, they generally provide lower brightness, while their radiation may also exhibit non-uniformity in the far field. To provide a comprehensive solution to these technical limitations, the article considers a configuration of the “Light Emitting Apparatus with Integrated Emitter” incorporating a phosphor droplet at the end face of an optical fiber. In this configuration, the dimensions of the light-emitting region are determined either by the diameter of the phosphor droplet, approximately 100–150 μm , or by the diameter of the fiber core, approximately 30–50 μm . The proposed apparatus also incorporates a combination of engineering solutions intended to extend the operational lifetime of the laser diode, including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and protective coatings, including synthetic diamond films. The combined implementation of these technical solutions is expected to provide a laser diode operational lifetime of approximately 10,000 hours or

more, while enabling stable and uniform monochromatic illumination for medical, machine-vision, and automated industrial applications.

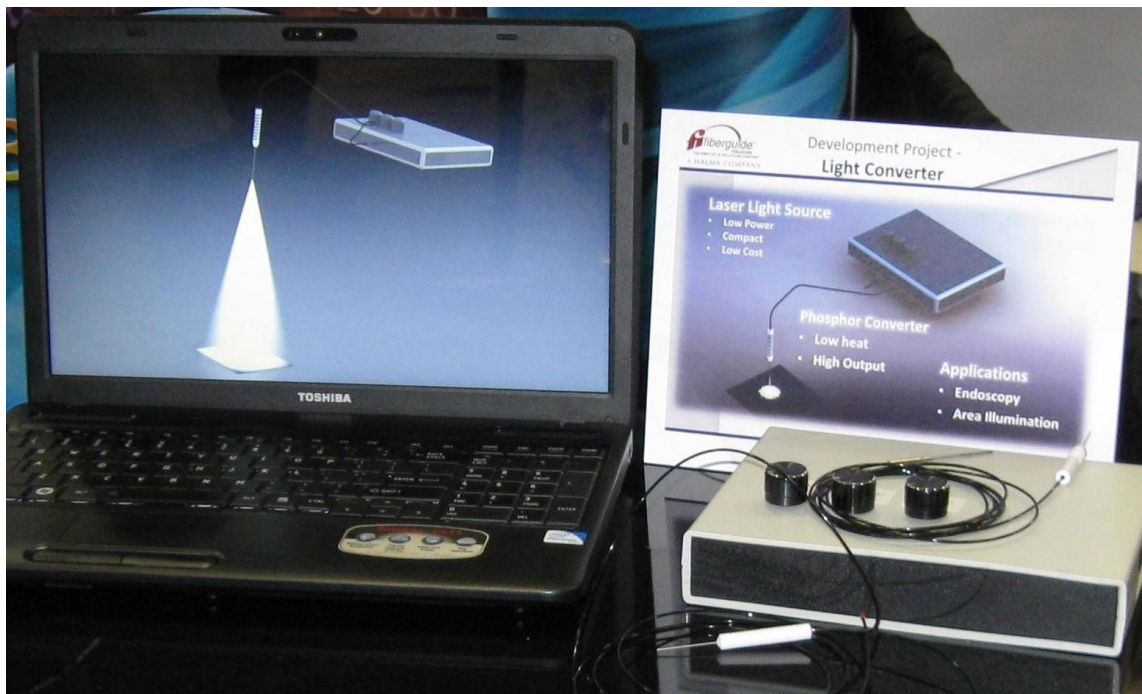
Keywords: *Laser Technology; Integrated Technical Systems; Light-Emitting Diodes (LEDs); Monochromatic Light; Laser Diodes; Standard Lasers; Monochromatic Light Flux; Machine Vision; General Technical Specifications of Microscopes; Modified Mounting Module; Laser Diode Lifetime*

Introduction

A wide range of medical technologies, as well as a number of technologies related to them to varying degrees, can benefit from the

distinctive features of the above-mentioned invention, providing a significant technical and economic effect.

Figure 1. *The figure shows an integrated laser illumination system for ophthalmic applications, implementing a product that utilizes artificial intelligence elements associated with artificial neural networks, under the general name “Light Emitting Apparatus with Integrated Emitter”*



Potential Applications of the “Light Emitting Apparatus with Integrated Emitter” Invention.

1. Machine Vision

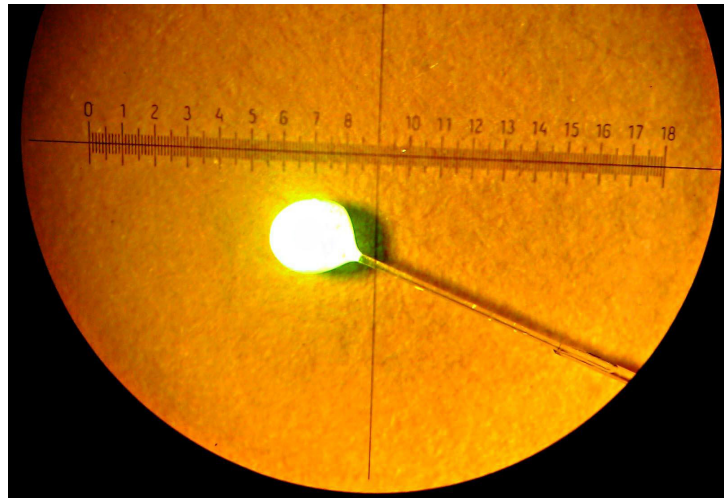
A wide range of processes, including medical treatment procedures and various automated manufacturing processes, require uniform illumination of the operating area with monochromatic light.

Under certain conditions, conventional lasers produce localized, distorted light patterns and are therefore unsuitable for generating a uniform monochromatic light flux within an operating area.

Light-emitting diodes (LEDs) do not produce such distorted patterns; however, they provide lower brightness. In addition, LED radiation is non-uniform in the far field.

For a comprehensive solution to this problem, a configuration of the above-mentioned invention incorporating a phosphor droplet at the end face of an optical fiber can be used. In this configuration, the size of the light-emitting region is determined either by the diameter of the phosphor droplet, approximately 100–150 μm , or by the diameter of the fiber core, approximately 30–50 μm .

Figure 2. The figure shows a droplet of phosphor mixed with a transparent optical coating applied to the end of an optical fiber inserted into a microscope. The system is shown at the lasing threshold with the microscope illumination lamp switched on



The application of the distinctive features of the above-mentioned invention makes it possible to fundamentally improve the existing technical configuration.

The dimensions of the phosphor droplet are approximately three times smaller than those of an LED (light-emitting diode). In addition, the resulting light output is expected to be more uniform and stable.

The cost of a conventional machine vision system typically ranges from approximately USD2,000–3,000 to USD25,000–50,000.

According to preliminary estimates, the proposed Light Emitting Apparatus is expected to be approximately 35–50% less expensive, regardless of its specific design or configuration.

The operational lifetime of the proposed apparatus is primarily determined by the operational lifetime of the laser diode.

Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime can be estimated at approximately 10,000 hours or more.

2. Illumination Systems for Microscopes

This application primarily concerns illumination systems for microscopes used in

various medical and biomedical laboratories.

First, it is necessary to compare the complexity and labor intensity involved in manufacturing the proposed technical system with those associated with conventionally used technical systems.

The proposed technology, when integrated into a larger technical system, is sufficiently flexible and adaptable to enable the incorporation of highly efficient and advanced local technical subsystems. These may include high-speed electronic circuit boards (so-called RITM boards) and advanced structural materials, including composite materials and, in particular, carbon–carbon composites produced by vacuum pyrolysis using viscose fabrics, as well as synthetic diamond films.

The implementation of these innovative subsystems makes it possible to obtain significant technical advantages arising from the specific characteristics of laser diodes.

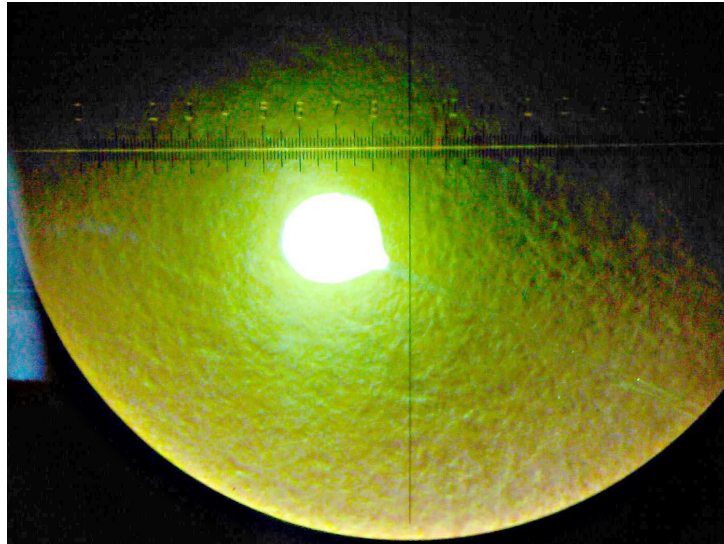
The monochromatic nature of the emitted light generated through the proposed invention makes it possible to reduce or eliminate chromatic aberration and thereby increase optical resolution.

At present, the cost of illumination systems used in various types of microscopes may reach approximately USD2,000–3,000.

When the proposed invention is implemented, energy consumption associated with illumination is expected to be reduced

by approximately 85–95%, while the cost of the proposed configuration is expected to be at least 50–60% lower than that of existing systems.

Figure 3. *The figure shows a droplet of phosphor mixed with an optically transparent coating, attached to the end of an optical fiber inserted into a microscope. The system is shown at the lasing threshold with the microscope illumination lamp switched off*

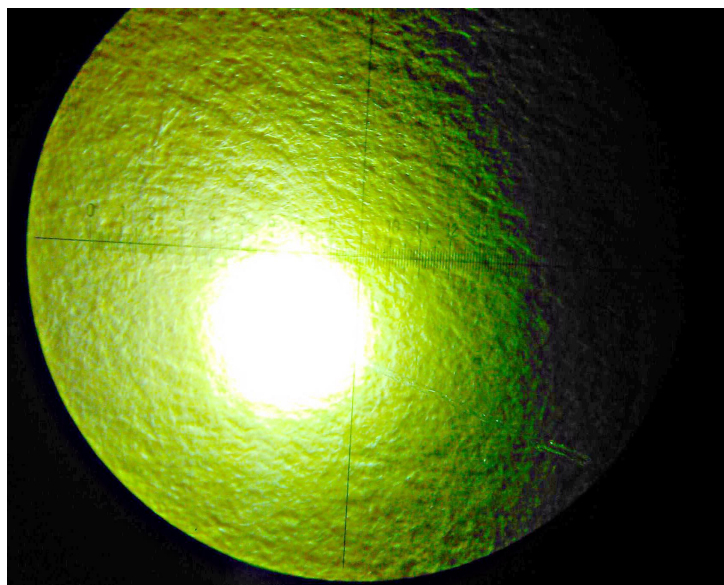


The application of the proposed invention fundamentally changes and improves the overall technical characteristics of microscopes, thereby expanding their potential applications across various fields of engineering

and technology, and particularly in medical applications.

The operational lifetime of the proposed configuration of the apparatus is also primarily determined by the operational lifetime of the laser diode.

Figure 4. *The figure shows a phosphor droplet at the end of an optical fiber inserted into a microscope, operating in a state equivalent to 2 mW of laser output, with the microscope illumination lamp switched off*



Since the proposed apparatus incorporates a comprehensive range of technical

solutions intended to extend the operational lifetime of the laser diode – including

intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime of the laser diode can be estimated at approximately 10,000 hours or more.

3. Application of the Proposed Apparatus in Medicine, Medical Technologies, and Medical Equipment

One of the primary areas of application of the proposed apparatus is endoscopy of various types.

An optical fiber equipped with a phosphor droplet makes it possible to illuminate the surrounding space in multiple directions, since the emitted light is distributed in all directions around the light-emitting region.

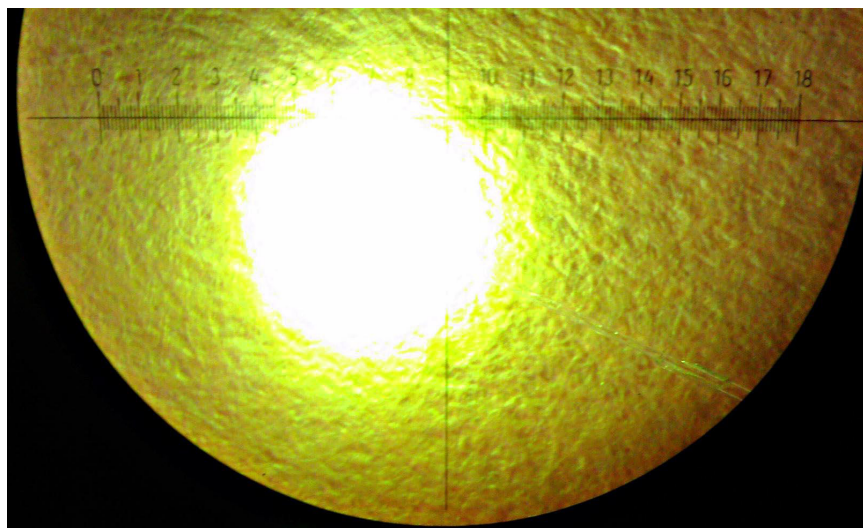
In conventional systems, one of the existing limitations is that only a relatively narrow area is illuminated, with the illuminated region being determined by the divergence of the radiation emerging from the optical fiber. In the proposed configuration of the invented apparatus, illumination can be generated in different spectral ranges and colors, includ-

ing white light. This also provides the possibility of performing, for example, photodynamic therapy and ultraviolet irradiation, thereby offering additional capabilities for both diagnostic and therapeutic procedures.

According to preliminary estimates, the cost of an endoscope illumination system designed in accordance with the proposed invention is expected to be approximately 35–45% lower, while the efficiency of the endoscope and the overall endoscopic procedure is expected to increase significantly.

The operational lifetime of the proposed configuration of the apparatus is primarily determined by the operational lifetime of the laser diode. Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime of the laser diode can be estimated at approximately 10,000 hours or more.

Figure 5. *The figure shows a formed phosphor droplet at the end of an optical fiber inserted into a microscope, operating in a state equivalent to 2 mW of laser output, with the microscope illumination lamp switched on*



4. Application of the Invention for Surgical Field Illumination

Another potential medical application of the proposed invention is illumination of the surgical field.

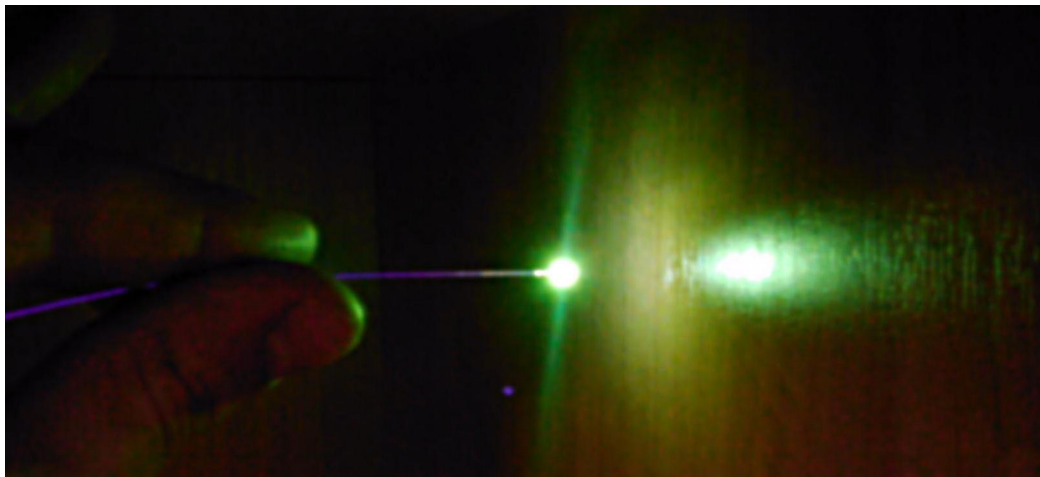
The optical fiber can be readily attached to a surgeon's finger or to a surgical instrument, such as a scalpel or clamp. This capability is of particular importance in ophthalmology.

In ophthalmic procedures, uniform illumination of the sclera of the eye is required. The optical fiber used for this purpose is very thin, with a diameter of approximately 100 μm . Its small diameter allows it to be introduced into the eye with minimal tissue trauma and to provide multidirectional illumination of the sclera. This is considered an important factor contributing to the successful performance of the surgical procedure.

The estimated cost of the proposed local surgical field illumination system may be approximately USD3,000.

The operational lifetime of the proposed configuration of the apparatus is primarily determined by the operational lifetime of the laser diode. Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime of the laser diode can be estimated at approximately 10,000 hours or more.

Figure 6. *The figure shows the characteristic light emission of the technical subsystem in a darkened environment*



As demonstrated by the initial experiments, even a module assembled from standard components operates effectively and confirms the initial theoretical and calculated assumptions.

The optical-to-optical conversion efficiency is very high, even when using a phosphor of relatively low quality that has not been selectively optimized for the specific application.

The image presented in Figure 6 immediately suggests a number of additional applications based on the obviously low weight and compact dimensions of the light-emitting unit, particularly illumination in hard-to-reach locations and localized illumination of specific areas. One of the primary fields for such applications is, once again, medicine.

In dentistry, the proposed technology can be used for illumination of the oral cavity by means of compact light-emitting units

integrated into standard medical and dental instruments. Such a localized illumination system can be incorporated into a dental mirror, saliva suction system, and other dental instruments and devices.

In laboratory and medical examinations, the technology can be used to provide illumination during endoscopic procedures. It can also be combined with fluorescence-based diagnostic techniques, including methods used for vascular examination. Localized procedures involving photochemical reactions can be performed by delivering illumination at the required wavelength.

In surgery, the technology can also be applied to illuminate poorly illuminated or otherwise difficult-to-access areas during diagnostic laparoscopy.

Furthermore, when developing new applications of the proposed technology, it should be taken into consideration that phosphors

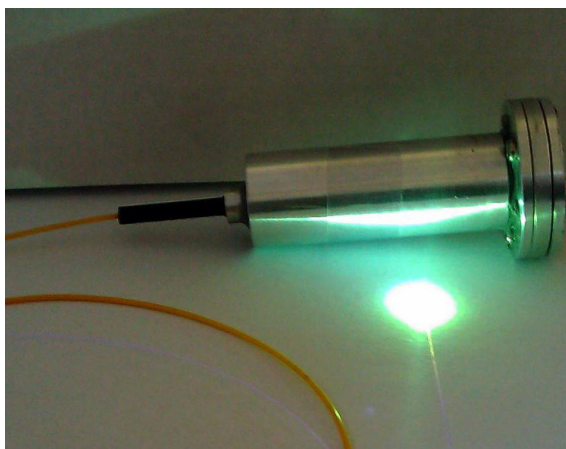
can retain their luminescent properties at temperatures of approximately 600 °C. This makes it possible to develop applications for localized or specialized illumination of high-temperature areas. For example, an optical fiber incorporating a phosphor-based emitter could be integrated into the tip of a heated soldering iron to provide visual feedback and real-time monitoring of soldering conditions and soldering quality.

The developers subsequently obtained additional photographs of the same module using the same phosphor. In this configuration, a phosphor-containing droplet was formed at the end of an optical fiber with a diameter of 125 μm . The droplet consisted of an optically transparent coating mixed with the required type of phosphor.

During the initial phase of the experiment, in order to obtain a comparative indication of the efficiency of the proposed technical solution, the phosphor was simply placed adjacent to the end of the optical fiber.

The experimental results showed that the re-emitted optical power reached 1 mW at a laser pump optical power of 2 mW. This represents an exceptionally high result, particularly considering that the phosphor had not been specifically or selectively optimized for this application.

Figure 7. *The figure shows the external appearance of the same module – an optical fiber with a phosphor droplet mixed with an optically transparent coating – with the laser operating in the lasing state*



Other configurations of the proposed system are also possible.

The diameter of the optical fiber is 125 μm .

The emitter may have various geometrical configurations. The emitter material may consist of a phosphor or a mixture of phosphors combined with an optically transparent adhesive that becomes optically stable after polymerization or curing.

A particularly preferred configuration involves mixing a phosphor, or a combination of phosphors, with a monomer of an optically transparent and chemically resistant polymeric material, such as polymethyl methacrylate (PMMA), polycarbonate, or other suitable polymers, followed by polymerization using non-contact heating under vacuum or microwave-assisted processing. The outer diameter of the emitter must not exceed 0.45 mm.

As demonstrated by the results of a comprehensive analysis, the same technical system, in various design configurations, can be effectively applied in numerous other technological fields, including applications at the intersection of different technologies.

For example:

5. Online Inspection System for Nuclear Reactor Containment Structures and Systems Located in the Vicinity of Nuclear Reactors

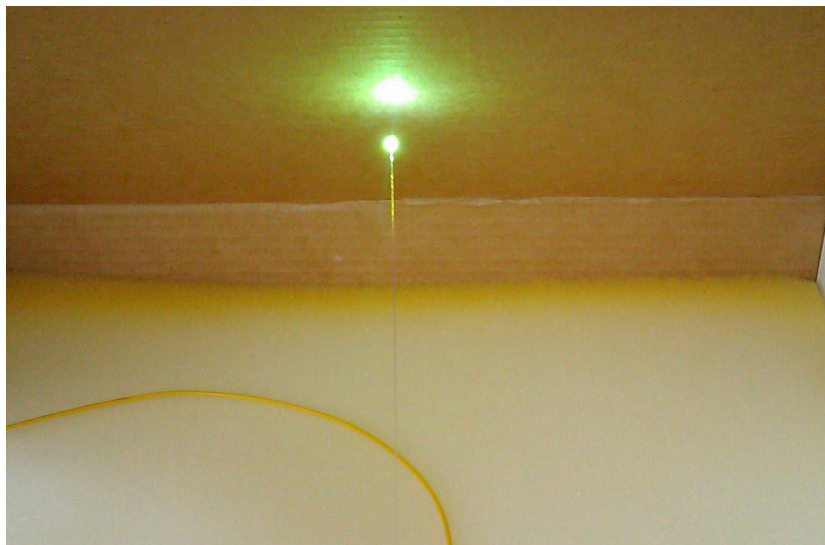
The proposed configuration of the invention could potentially be used for the online inspection and monitoring of nuclear reactor containment structures and systems located in the vicinity of nuclear reactors. The estimated cost of the proposed configuration of the invention may amount to several hundred thousand U.S. dollars.

Several hundred such devices may potentially be required worldwide. In addition, several hundred similar devices may be required for the inspection of nuclear reactors installed on submarines and other facilities equipped with nuclear propulsion or nuclear power systems. The operational lifetime of the proposed configuration of the apparatus is primarily determined by the operational lifetime of the laser diode. Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use

of specialized materials and coatings, including synthetic diamond films – the expected opera-

tional lifetime of the laser diode can be estimated at approximately 10,000 hours or more.

Figure 8. *The figure shows how the light emitted by the phosphor is projected onto a screen*



6. Underwater Illumination Systems, Particularly for Bathyscaphes and Divers

The proposed technology can also be applied to underwater illumination systems, particularly illumination equipment designed for bathyscaphes, submersibles, and divers.

The estimated cost of such a system may reach approximately USD100,000.

There are also several possibilities for developing standalone products based on the same technological principle.

One such standalone product is a light source.

For a single-use configuration, the estimated demand may exceed 5,000 units per month. A disposable version of the product may be commercially feasible provided that its price remains relatively low and below the cost of comparable products currently manufactured and used.

For a reusable configuration, the projected demand is approximately 3,000 modules per month. There is also significant potential for the development of numerous specialized applications based on the proposed product and technology.

Another standalone product based on the same technological principle may have a current estimated demand of at least 5,000 units per month. The potential market demand

may exceed 1,000,000 units per month for a single-use version of the product. One of the principal limitations of comparable products currently manufactured and available on the market is insufficient light intensity.

Figure 9. *The figure shows how the light emitted by the phosphor is projected into the corner of the box*



The operational lifetime of the proposed apparatus depends on a number of individual components; however, the operational lifetime of the illumination system itself is

primarily determined by the operational lifetime of the laser diode. Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime of the laser diode can be estimated at approximately 10,000 hours or more.

If there is specific interest in this application, the system can be developed and analyzed in greater detail.

7. Underwater Communication Between Divers, Surface Vessels, and Submarines

Another potential application of the proposed technology is an underwater optical communication system between divers, surface vessels, and submarines.

Green light may be used in coastal waters, while blue light may be used in the open ocean. The communication range between underwater users may reach approximately 100 m, while communication between a surface vessel and a bathyscaphe or other submersible may reach approximately 10,000 m.

The estimated cost of an integrated system of this type may be approximately USD1 million, particularly when the system is intended for operation under military conditions, emergency situations, or technological and industrial disasters.

The operational lifetime of the proposed apparatus depends on a number of individual components; however, the operational lifetime of the illumination system itself is primarily determined by the operational lifetime of the laser diode.

Since the proposed apparatus incorporates a comprehensive range of technical solutions intended to extend the operational lifetime of the laser diode – including intensive cooling, a modified mounting module equipped with control and regulation electronics operating in the radio-frequency range, selective use of specialized materials and coatings, including synthetic diamond films – the expected operational lifetime of

the laser diode can be estimated at approximately 10,000 hours or more.

If there is specific interest in this application, the system can be developed and analyzed in greater detail.

Other Design Configurations

Configuration 1

The diameter of the optical fiber is 125 μm .

The outer diameter of the tube is 0.6 mm. The tube is made of stainless steel, such as 12Kh18N10T stainless steel. The inner diameter of the tube is 0.45 mm. The length of the tube may vary; however, this does not impose a limitation on the product, since variations in tube length can be compensated for by adjusting the length of the optical fiber.

The emitter may have various geometrical configurations. The emitter material may consist of a phosphor or a mixture of phosphors combined with an optically transparent adhesive, which becomes solid after polymerization or curing.

A particularly preferred configuration involves mixing a phosphor, or a mixture of phosphors, with a monomer of an optically transparent and chemically resistant polymeric material, such as polymethyl methacrylate (PMMA), polycarbonate, or other suitable polymers, followed by polymerization using non-contact heating under vacuum or microwave-assisted processing.

The outer diameter of the emitter must not exceed 0.45 mm.

Configuration 2

The diameter of the optical fiber is 125 μm .

The emitter may have various geometrical configurations.

The emitter material may consist of a phosphor or a mixture of phosphors combined with an optically transparent adhesive, which becomes solid after polymerization or curing.

A particularly preferred configuration involves mixing a phosphor, or a mixture of phosphors, with a monomer of an optically transparent and chemically resistant polymeric material, such as polymethyl methacrylate (PMMA), polycarbonate, or other suitable polymers, followed by polymerization using non-contact heating under vacuum or microwave-assisted processing.

To provide complete chemical neutrality and enhanced chemical resistance, it is proposed that the emitter and the adjacent section of the optical fiber be coated with a 5 μm -thick synthetic diamond film.

The outer diameter of the emitter, including the diamond coating, must not exceed 0.45 mm.

Configuration 3

The proposed diameter of the optical fiber is 125 μm .

The outer diameter of the tube is 0.6 mm. The tube is made of stainless steel, such as 12Kh18N10T stainless steel. The inner diameter of the tube is 0.45 mm.

The length of the tube may vary; however, this does not impose a limitation on the product, since variations in tube length can be compensated for by adjusting the length of the optical fiber.

The emitter may have various geometrical configurations. The emitter material may consist of a phosphor or a mixture of phosphors combined with an optically transparent adhesive, which becomes solid after polymerization or curing.

A particularly preferred configuration involves mixing a phosphor, or a mixture of phosphors, with a monomer of an optically transparent and chemically resistant polymeric material, such as polymethyl methacrylate (PMMA), polycarbonate, or other suitable polymers, followed by polymerization

using non-contact heating under vacuum or microwave-assisted processing.

The outer diameter of the emitter must not exceed 0.45 mm.

Configuration 4

The diameter of the optical fiber is 125 μm .

The outer diameter of the tube is 0.6 mm. The tube is made of stainless steel, such as 12Kh18N10T stainless steel. The inner diameter of the tube is 0.45 mm.

The length of the tube may vary; however, this does not impose a limitation on the product, since variations in tube length can be compensated for by adjusting the length of the optical fiber.

The emitter may have various geometrical configurations.

The emitter material may consist of a phosphor or a mixture of phosphors combined with an optically transparent adhesive, which becomes solid after polymerization or curing.

A particularly preferred configuration involves mixing a phosphor, or a mixture of phosphors, with a monomer of an optically transparent and chemically resistant polymeric material, such as polymethyl methacrylate (PMMA), polycarbonate, or other suitable polymers, followed by polymerization using non-contact heating under vacuum or microwave-assisted processing. The outer diameter of the emitter must not exceed 0.45 mm.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-81-85



AUTOMATION COMPONENTS BASED ON THE INVERSE PIEZOELECTRIC EFFECT. (Further Development of Innovative Applications Based on the Inverse Piezoelectric Effect)

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Cite: Kavinskyi V. (2026). *Automation Components Based on the Inverse Piezoelectric Effect. (Further Development of Innovative Applications Based on the Inverse Piezoelectric Effect).* European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-81-85>

Abstract

The article examines the application of piezoelectric motors operating on the principle of the inverse piezoelectric effect in advanced automation and precision engineering systems, with particular emphasis on their use as precision miniature stepper motors. As requirements for higher accuracy, lower motor weight, and reduced overall dimensions become increasingly stringent, the integrated use of specialized composite materials as the primary materials for motor components and structures is becoming an important direction in the development of such motors. Testing of these types of piezoelectric motors and attempts to use them as stepper motors have raised a number of technical issues. These are largely related to the incompatibility between modern control processors and their software functions and the design limitations resulting from the use of conventional structural materials that performed well with earlier generations of components. The mechanical transmission chain extends from the plain bearing to the piezoceramic ring, then through the spring-steel fingers soldered to the ring, to the friction ring and, finally, to the motor rotor. Design limitations in this chain have shown that the principal cause of the wide variation in motor output parameters is the insensitivity of its components to changes and fluctuations in control and monitoring pulses. Analytical studies have shown that the main problem is the system's inability to distribute or dissipate the pulses applied to the piezoelectric ring virtually instantaneously. As the first step in optimization, it was decided to replace the conventional piezoceramic material of the piezoelectric ring with a piezoceramic composite containing components that do not respond to the pulses applied to the ring. Previous practical experience has shown that this can be achieved by uniformly incorporating synthetic diamond microspheres into the piezoceramic material.

Keywords: Automation; automation components; direct piezoelectric effect; inverse piezoelectric effect; innovative applications; piezoelectric motors; piezoelectric motors operating on the principles of the inverse piezoelectric effect; a foundation for advanced automation and precision engineering systems; systems and configurations for precision

miniature stepper motors; virtually instantaneous distribution or dissipation of pulses applied to the piezoelectric ring; the insensitivity of the components in the mechanical transmission chain to changes and even fluctuations in control and monitoring pulses as the principal cause of the wide variation in motor output parameters

Introduction

Practical experience has shown that piezoelectric motors operating on the principles of the inverse piezoelectric effect can provide a foundation for advanced automation and precision engineering systems incorporating elements of artificial intelligence and artificial neural networks.

Developers and designers are particularly interested in the potential to use the inverse piezoelectric effect to develop systems and configurations for precision miniature stepper motors.

Figure 1. *Piezoelectric motor*

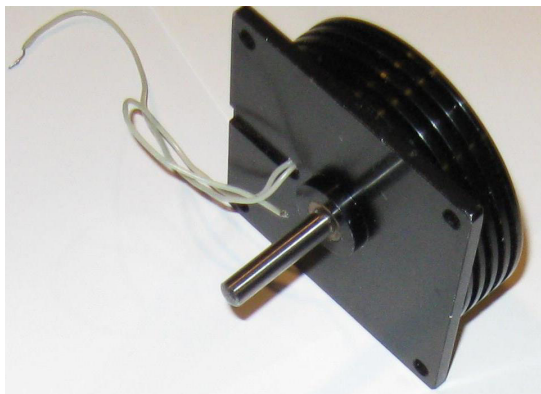
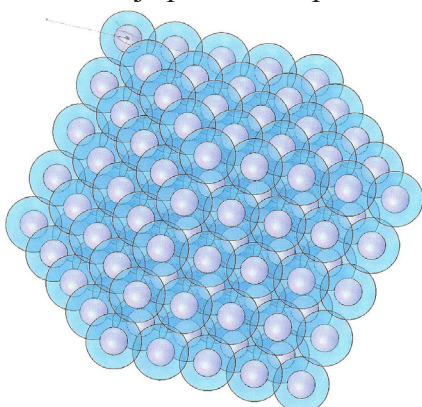


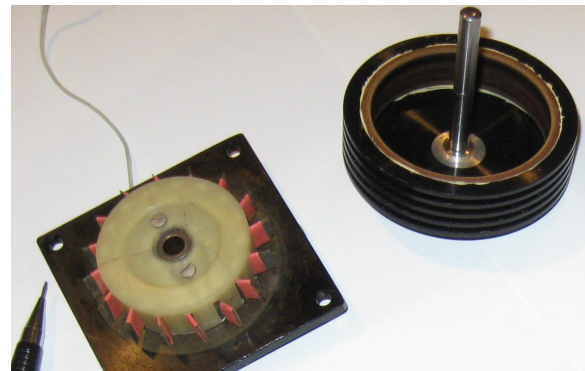
Figure 2. *Three-dimensional model of spherical capsules*



As requirements for greater accuracy and lower motor weight become more stringent, including through reductions in overall dimensions, an increasing number of designs and engineering solutions propose the inte-

grated use of specialized composite materials as the primary materials for motor components and structures.

Figure 3. *Piezoelectric motor with the rotor removed*



Optimization Process

The accuracy required of piezoelectric stepper motors, together with software-based monitoring and control, requires a consistent relationship between motor output parameters and the characteristics of the signal pulses applied to the piezoceramic ring.

The mechanical transmission chain extends from the plain bearing to the piezoceramic ring, then through the spring-steel fingers soldered to the ring, to the friction ring and, finally, to the motor rotor. Design limitations in this chain have shown that the principal cause of the wide variation in motor output parameters is the insensitivity of its components to changes and even fluctuations in control and monitoring pulses.

Analytical studies have shown that the main problem is the system's inability to distribute or dissipate the pulses applied to the piezoelectric ring virtually instantaneously.

As the first step in optimization, it was decided to replace the conventional piezoceramic material of the piezoelectric ring with a piezoceramic composite containing components that do not respond to the pulses applied to the ring.

Previous practical experience has shown that this can be achieved by uniformly incorporating synthetic diamond microspheres into the piezoceramic material.

Figure 4. *Piezoelectric motor beside
a mechanical pencil for scale*



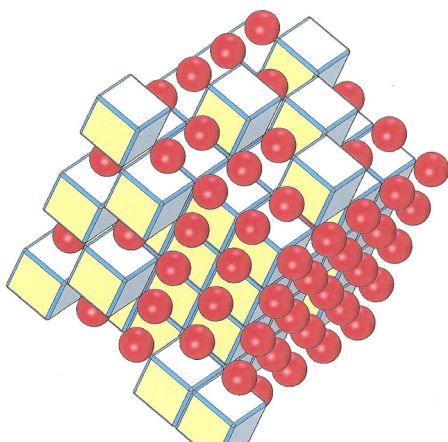
Pseudoporous Structure

The model of this material shows its three-dimensional structure, comprising numerous spherical capsules with at least two constituent levels.

The first level consists of synthetic diamond microspheres, which can now be produced with very high precision at minimal manufacturing cost and with minimal raw-material costs.

Unlike gem-quality crystals, these synthetic diamonds do not need to meet transparency or purity requirements.

Figure 5. *Schematic model of
a composite with spherical inclusions*



The illustration shows the structure of this composite material.

After manufacture, the diamond spheres are coated with a moist ceramic mixture and placed in a mold. Under pressure, the ceramic surrounding the diamond spheres under-

goes bulk deformation, forming numerous cubic microstructures, each with a diamond sphere at its geometric center.

This structure is pseudoporous: the diamond spheres, which are virtually unresponsive to the pulses, cause signals or pulses to be distributed almost uniformly throughout the volume of the ceramic cubes. This provides exceptional stability and uniformity of signal propagation within the pseudoporous piezoceramic ring.

Figure 6. *Three-dimensional
model of the capsule structure*

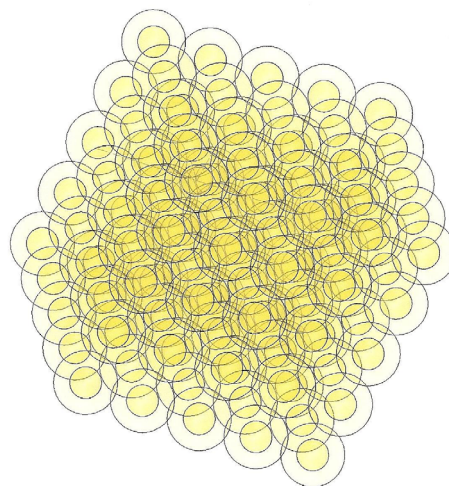
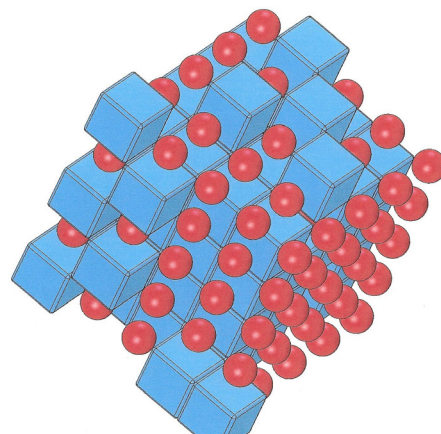


Figure 7. *Schematic model with cubic
regions and spherical inclusions*



Because spring fingers are soldered to the ring's outer cylindrical surface, a signal pulse distributed uniformly within the piezoelectric ring can satisfy all the principal requirements for the stability and uniformity of the driving vibratory pulses transmitted from the fingers to the rotor in contact with them.

It is now necessary to return to the question of rotor wear resistance.

The tips of the spring fingers remain in continuous dynamic contact with the rotor's inner surface. If pulses are distributed unevenly throughout the three-dimensional volume of a rotor made of conventional piezoceramic material, it can be assumed that the force transmitted by the finger tips to the rotor's inner surface is nonuniform. This would cause uneven wear of that surface and, consequently, radial runout of the motor's output shaft.

Replacing the piezoelectric ring material with a pseudoporous piezoceramic composite will significantly reduce the dependence of rotor wear on the uneven distribution of pulses in the piezoceramic material. This should have a positive effect on the piezoelectric motor's output parameters and operating characteristics.

The relevant parameters and improvements include:

- Radial runout of the motor shaft;
- Synchronization of all mechanical contacts between the motor's structural components;
- Longer motor service life;
- Easier simultaneous synchronization of the operating output parameters of multiple motors in systems that convert motor rotation into linear carriage motion;
- Uniform and consistent rotor speed.

In the existing motor design, all motor systems are also affected by vibrations arising from the uneven and cyclic transmission of mechanical forces from the piezoceramic material to the rotor and, ultimately, to the output shaft.

Systems analysis and computer modeling have shown that it is also reasonable to replace the rotor material with a material analogous to the pseudoporous composite used for the piezoceramic ring.

In this case, the structural arrangement of the composite remains unchanged; only its constituent materials change.

For example, to improve the durability of the motor's structural components, the diamond core could be replaced with beryllium, with aluminum forming the surrounding shell.

Aluminum is sufficiently ductile to provide the cold flow required when sizing the geometry of motor parts and components by bulk plastic deformation.

Many material options and combinations can be selected for the capsules, providing maximum flexibility in the design of monitoring and control systems that use piezoelectric motor drives.

The spring fingers also warrant discussion in this article.

Soldering the fingers to the piezoceramic ring introduces a further set of problems: the required levels of accuracy, strength, and durability cannot be assured. The reasons are well known and arise from dependence on the specific properties of materials conventionally used for soldering.

Preparing the outer surface of the piezoceramic ring for soldering is particularly difficult, as is applying a metallic or equivalent layer to which the spring fingers can be soldered.

The author proposes solving this problem by eliminating soldering and optimizing the spring-finger assembly as a spring strip with the fingers stamped into it.

The strip is clamped around the outer circumference of the piezoceramic ring, providing several additional benefits for the optimization of the motor's systems:

- Uniform spacing of the fingers around the piezoceramic ring;
- Adjustment of the force pressing the spring strip against the surface of the piezoceramic ring;
- Easy, reliable, and rapid replacement of the strip when the fingers wear out;
- A substantial reduction in motor cost, together with improved efficiency and quality.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-86-95



GENTRIFICATION OF THE INNOVATIVE STARTUP ECOSYSTEM

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Cite: Mehtiev A.L. (2026). *Gentrification of the innovative startup ecosystem*. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-86-95>

Abstract

The article examines conceptual and organizational approaches to the formation and development of an innovative startup ecosystem located within production facilities in industrial areas that have undergone gentrification, comprehensive reconstruction, and systemic revitalization. Particular attention is paid to the horizontal and vertical integration of technical, structural, and technological solutions, as well as to the organization of the startup company's research, consulting, and educational activities. *The article discusses Kseniia Kaplieva's concept of the functional structure of an innovative startup, including technological project support, selection of standards and components, preparation of technical documentation, development of patent and licensing strategies, and the application of artificial intelligence and artificial neural networks in monitoring and control systems.* Using an optics-focused startup as an example, the article analyzes potential applications of a light-emitting apparatus with an integrated emitter in machine vision, microscopy, endoscopy, surgical illumination, nuclear facility inspection, and underwater illumination systems. The importance of using standard components in the development of initial prototypes is emphasized as a means of reducing costs, identifying structural and circuit design errors at an early stage, and improving investment efficiency. The article demonstrates that the integrated application of scientific and technological developments, intelligent monitoring systems, prototyping, patent and licensing strategies, and modern production infrastructure is an important prerequisite for the successful development of an innovative startup and the achievement of the desired final result.

Keywords: *Gentrification of startup production facilities, revitalization of startup production facilities, industrial territory ecosystem, industrial territory infrastructure, optical specialization of the startup, fundamental issues of horizontal and vertical integration of technical, structural, and technological solutions, final integrated solution, production facilities as part of the industrial territory ecosystem, comprehensive reconstruction and systemic revitalization, development of a licensing strategy, supporting targeted training in the detailing of materials and processes*

What are the conceptual and organizational solutions for a startup company proposed by Kseniia Kaplieva, a well-known specialist in smart home and smart production facility technologies.

1. The company should have a scientific and research division with additional functions of interactive consulting and scientific and technological training.
2. The startup's clients may include startups, for example, those specializing in the chemical and pharmaceutical fields, that require professional support and accompanying targeted training in the detailed aspects of materials and processes that are the subject of development by each specific startup.
3. At the request of its clients, the startup company develops and models the technological route in the necessary detail, after which, on the basis of the development, it prepares a program and methodology for interactive training sessions, as well as technical requirements and conditions for finding the most suitable partner to manufacture the necessary semi-finished products and materials.
4. The startup company prepares all the necessary technological instructions for the client to implement the project.
5. The startup company selects the necessary applicable standards for the client to control and support the project development process.
6. Based on the developed technical requirements and conditions, as well as the requirements of the standards, the startup company prepares a draft agreement with the manufacturer, including a protocol and methodology for the handover and acceptance of completed orders.
7. If the client is interested, the startup company prepares basic materials for patent protection of the project and the development of a licensing strategy.
8. At the request of clients, the startup company prepares scientific and technical reports on conducted research and experiments, laboratory studies, and experimental technological work.

Fundamental issues of horizontal and vertical integration of technical, structural, and technological solutions under conditions

of the complex uncertainty of reality and the success of the final integrated solution are particularly relevant for startups located in production facilities as part of the ecosystem of industrial territories that have undergone all stages of gentrification, comprehensive reconstruction, and systemic revitalization. In this situation, conceptual and organizational solutions for building their functional structure, aligned with the classical principles of startup ecosystem theory, acquire exceptional importance.

What are the conceptual and organizational solutions for an innovative startup company proposed by Kseniia Kaplieva, taking into account systemic options for control and management with elements of artificial intelligence and artificial neural networks.

9. The company should have a scientific and research division with additional functions of interactive consulting and scientific and technological training.
10. The startup's clients may include startups, for example, those specializing in the chemical and pharmaceutical fields, that require professional support and accompanying targeted training in the detailed aspects of materials and processes that are the subject of development by each specific startup.
11. At the request of its clients, the startup company develops and models the technological route in the necessary detail, after which, on the basis of the development, it prepares a program and methodology for interactive training sessions, as well as technical requirements and conditions for finding the most suitable partner to manufacture the necessary semi-finished products and materials.
12. The startup company prepares all the necessary technological instructions for the client to implement the project.
13. The startup company selects the necessary applicable standards for the client to control and support the project development process.
14. Based on the developed technical requirements and conditions, as well as the requirements of the standards, the startup company prepares a draft agreement with the manufacturer, including a protocol

and methodology for the handover and acceptance of completed orders.

15. If the client is interested, the startup company prepares basic materials for patent protection of the project and the development of a licensing strategy.
16. At the request of clients, the startup company prepares scientific and technical reports on conducted research and experiments, laboratory studies, and experimental technological work.

As an example, Kseniia Kaplieva proposed “Possible applications of the invention Light Emitting Apparatus with Integrated Emitter”.

1. Machine vision. Automated production requires the operating area to be illuminated with uniform monochromatic light. Lasers and laser diodes produce speckle patterns during operation and are unsuitable for use in devices for illuminating production facilities, especially those presented as part of the innovative startup ecosystem.

Speckle (from the English word *speckle* – spot, fleck) – a random interference pattern that is formed by the mutual interference of coherent waves having random phase shifts and/or a random set of intensities. In such a pattern, as a rule, light spots and speckles separated by dark areas of the image can be clearly observed.

It is necessary to note Kseniia Kaplieva’s original innovative concept for selecting standard components for the electronic parts of prototypes. This makes it possible to assemble circuit solutions at all stages of testing the operability of technological and structural solutions and to avoid additional expenditure of funds and time until the feasibility of achieving the ideal final result of the prototype has been verified.

Figures 5–11 show, as an example of component selection, housing and basic components for circuit variants of control and monitoring systems in electronic units and modules of the electrical and electronic parts of prototypes.

This possibility of developing circuit solutions for prototypes at the earliest stages of innovative projects makes it possible to eliminate schematic and structural errors and thereby ensure maximum investment efficiency in the project.

The development of prototypes from standard components also makes it possible to create experimental and control samples for comparative evaluation of the results of each stage, which makes it possible to select the optimal option for the next stage of testing, determining the best possible solution for achieving the ideal final result already at the initial stages of project development.

Figure 1. *The figure shows a spectrometer that is widely used by startups specializing in optics as a monitoring instrument when testing prototype variants of innovative technologies*



A speckle pattern – a pattern that is formed, for example, when randomly inhomogeneous objects, such as a rough surface, are coher-

ently illuminated, or when coherent radiation passes through a transparent medium with a spatially fluctuating refractive index.

Coherent radiation can be produced both by lasers and by conventional broad-spectrum light sources with an extended luminous body emitting partially coherent light with a short temporal coherence length and a small spatial coherence area.

Due to the inhomogeneity of the Earth's atmosphere, as well as its turbulence, speckle patterns are clearly visible, for example, in highly magnified photographs of stars taken with ground-based telescopes, which may reduce the quality of the resulting images.

Figure 2. *The figure also shows a spectrometer that is widely used by startups specializing in optics as a monitoring instrument when testing prototype variants of innovative technologies*



Thus, waves from observed cosmic objects entering a telescope have random phase delays, while the interference pattern in the focal plane (a mosaic of spots) continuously changes – the image of the object appears to “boil”.

Nevertheless, speckle patterns can also serve as a source of additional measurement information.

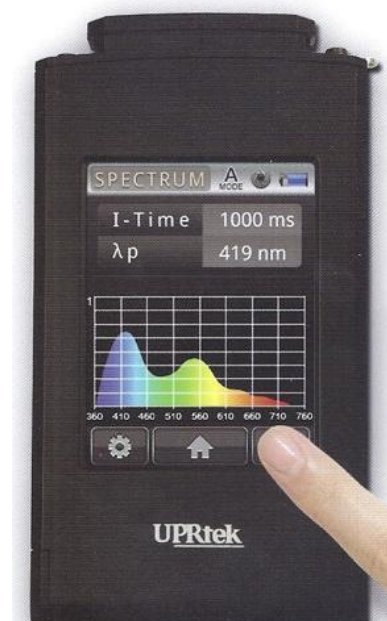
The analysis of speckle patterns is successfully used to study close binary stars.

While spectroscopic measurements provide the orbital dimensions of stars in a binary system in linear units (in AU), the analysis of speckle patterns provides them in angular units (in arcseconds).

Comparing these data makes it possible to determine the distance to the system. Moreover, since the main result of studying the orbits of stars in a binary system is the determination of the masses of their components, the analysis of speckle patterns makes it possible to significantly increase the number of stars for which the mass has been determined.

When studying a surface, the speckle pattern contains information about the microrelief and shape of the object, the near-surface layer, and the distribution and movement of scatterers within it.

Figure 3. *The figure also shows a spectrometer in operation, which is widely used by startups specializing in optics as a monitoring instrument when testing prototype variants of innovative technologies*



Thus, statistical processing of speckle patterns can provide information about

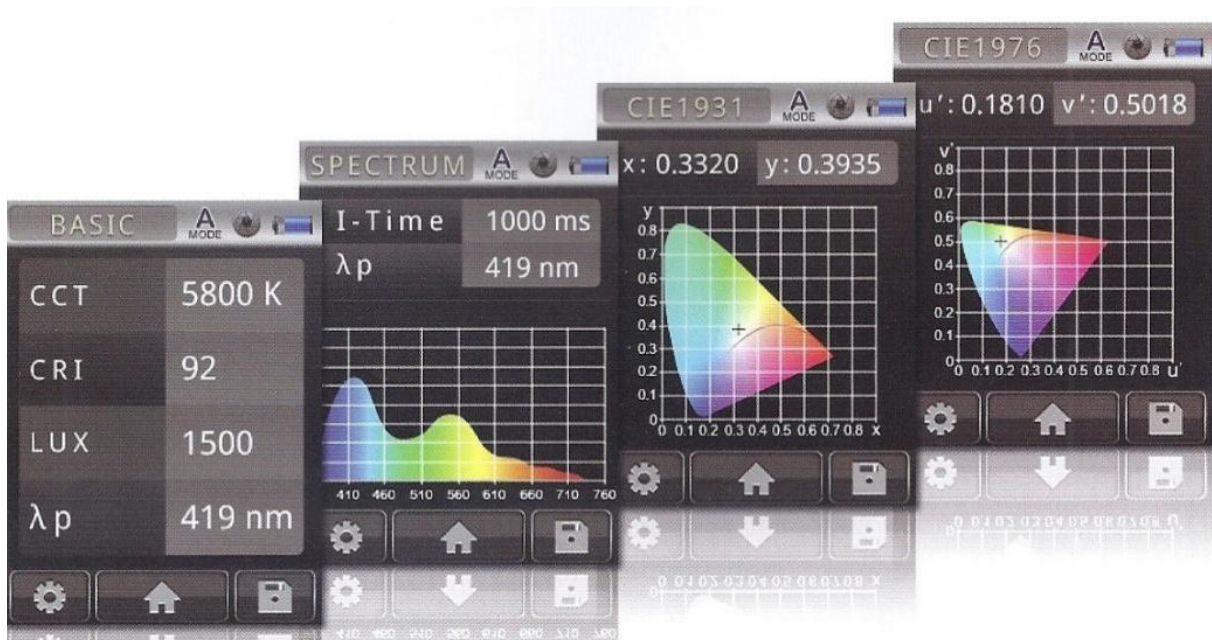
such parameters as displacement, velocity of movement, including that of scatterers in the near-surface layer, amplitude and frequency of vibrations, etc., changes in which may be caused both by controlled deformations, displacements, and internal mass transfer, as well as by random processes such as chemical transformations and phase transitions, abrasion resulting from friction, deposition, condensation or evaporation of particles on the surface, heating, etc.

According to Kseniia Kaplieva, the speckle pattern can be used for the subjective assessment of visual defects.

When radiation containing a speckle pattern enters the human eye, a granular image is formed on the retina.

Movement of the observer's head produces different effects depending on the condition of the visual system.

Figure 4. The figure shows, as an example, a system of monitoring modules that, during online real-time monitoring and control of a prototype of a startup's innovative product, assess its actual ability to achieve the ideal final result, which determines the level and nature of the project's success



Thus, an observer with normal vision sees a changing speckle pattern perceived as chaotic flickering of spots. An observer with hyperopia sees the spots of the speckle pattern moving in the same direction as the movement of the head, while an observer with myopia sees them moving in the opposite direction. The perceived speed of movement of the spots is directly proportional to the degree of refractive error.

Light-emitting diodes used to form speckle patterns do not provide uniform illumination, their brightness is lower, and, in addition, LED radiation is non-uniform in the far field. A suitable option here is the version of the specified invention with a droplet

of phosphor at the end of the fiber, in which case the size of the luminous body will be determined by the diameter of the droplet – 100–150 μm , or by the diameter of the fiber core – 30–50 μm .

This is three times smaller than that of an LED, and, in addition, the light will be more uniform.

The cost of a machine vision system ranges from 2–3 thousand dollars to 25–50 thousand dollars. According to preliminary estimates, the proposed light-emitting apparatus should be 35–50% less expensive in any design and any configuration version of the apparatus.

Figure 5. *The figure shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*

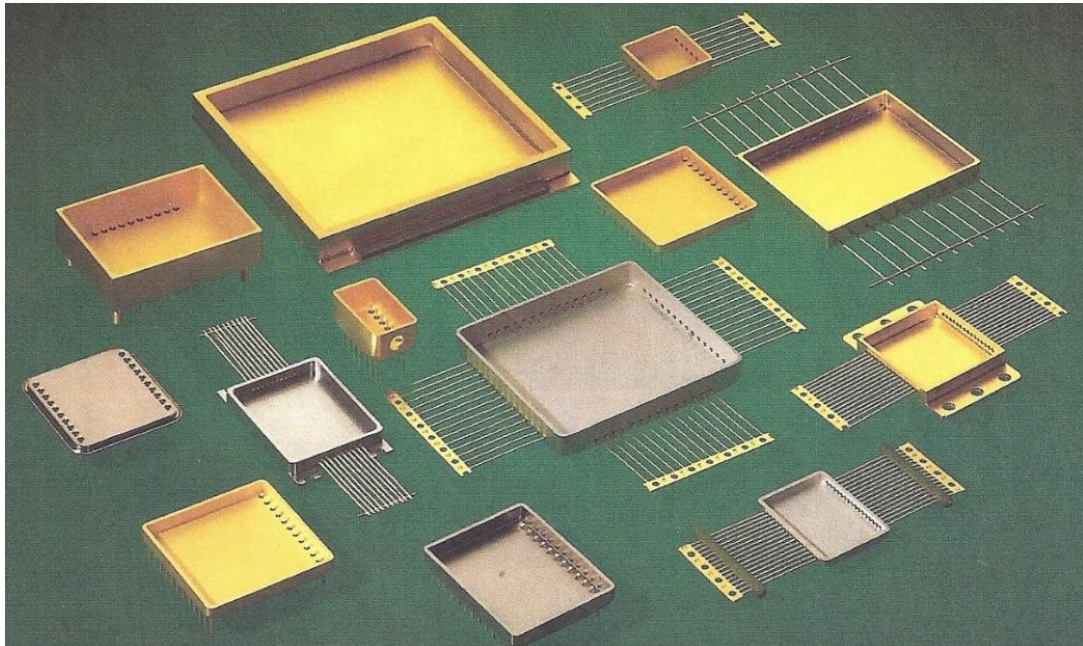
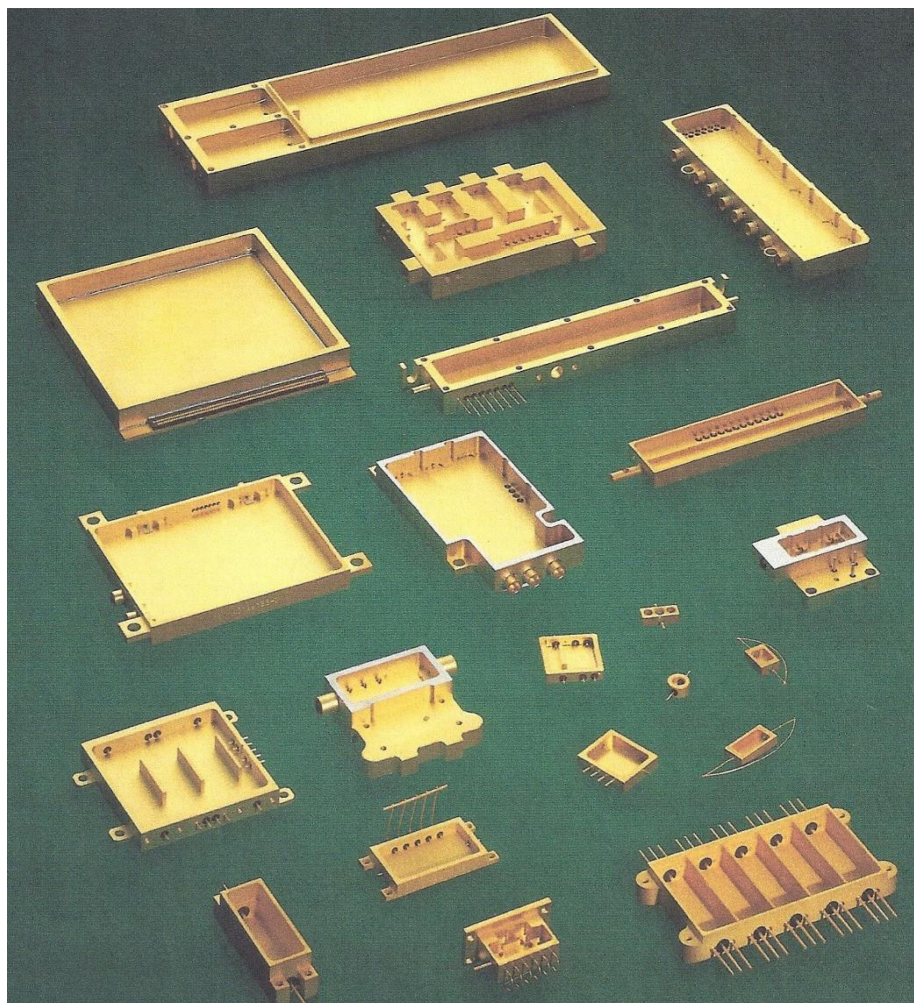


Figure 6. *The figure also shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*



The service life of the proposed apparatus is determined by the service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the proposed apparatus – intensive cooling, a modified mounting module with control and regulation electronics operating in the radio-frequency range, selective material selection, and special coatings, including synthetic diamond films – the service life can be estimated at 10,000 hours or more.

2. Illumination systems in microscopes. The monostructure of light radiation when using the proposed invention makes it possible to eliminate chromatic vibration and increase resolution. The cost of an illumination system currently used in various types of microscopes may range from 2–3 thousand dollars.

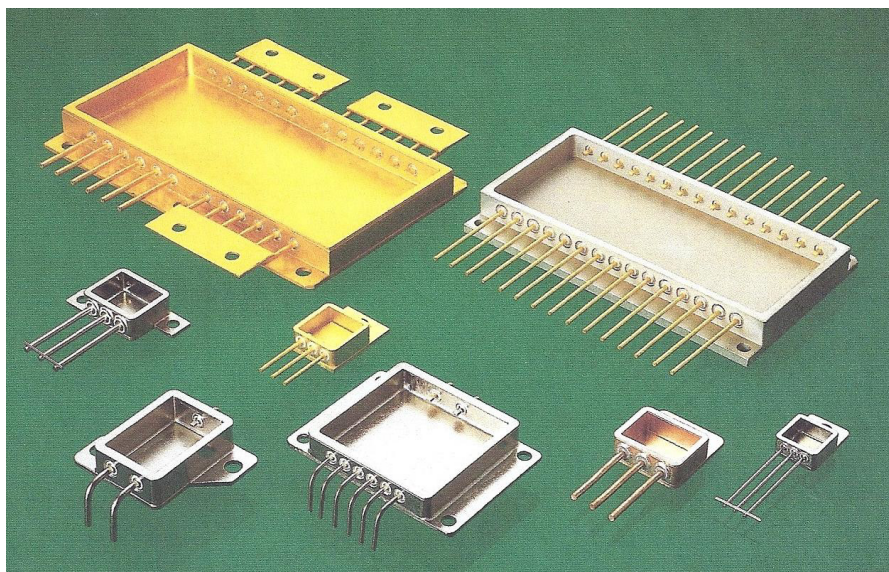
When using the proposed invention, energy consumption for illumination should

be reduced by 85–95%, while the cost of the proposed version of the invention is at least 50–60% lower than that of existing solutions.

The application of the proposed invention fundamentally changes and improves the overall technical characteristics of microscopes, which expands their range of use across all fields of engineering and technology.

The service life of the proposed version of the apparatus is also determined by the service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the proposed apparatus – intensive cooling, a modified mounting module with control and regulation electronics operating in the radio-frequency range, selective material selection, and special coatings, including synthetic diamond films – the service life can be estimated at 10,000 hours or more.

Figure 7. *The figure also shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*



3. Use of the proposed apparatus in medicine. This is, first and foremost, endoscopy.

An optical fiber with a droplet of phosphor makes it possible to illuminate the entire surrounding space, as the rays will propagate in all directions. Currently, there is a problem because only a narrow area determined by the divergence of radiation from the fiber is illuminated.

In our case, when using a version of the invented apparatus, illumination can be provided in all colors, including white, that is,

for example, photodynamic therapy and ultraviolet irradiation can be performed – these are additional possibilities for diagnosis and treatment.

According to preliminary estimates, the cost of an endoscope illumination system designed using the proposed invention will be 35–45% lower, while the efficiency of the endoscope and the entire endoscopic procedure will increase significantly.

The service life of the proposed version of the apparatus is also determined by the

service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the proposed apparatus – intensive cooling, a modified mounting module with control and

regulation electronics operating in the radio-frequency range, selective material selection, and special coatings, including synthetic diamond films – the service life can be estimated at 10,000 hours or more.

Figure 8. *The figure also shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*

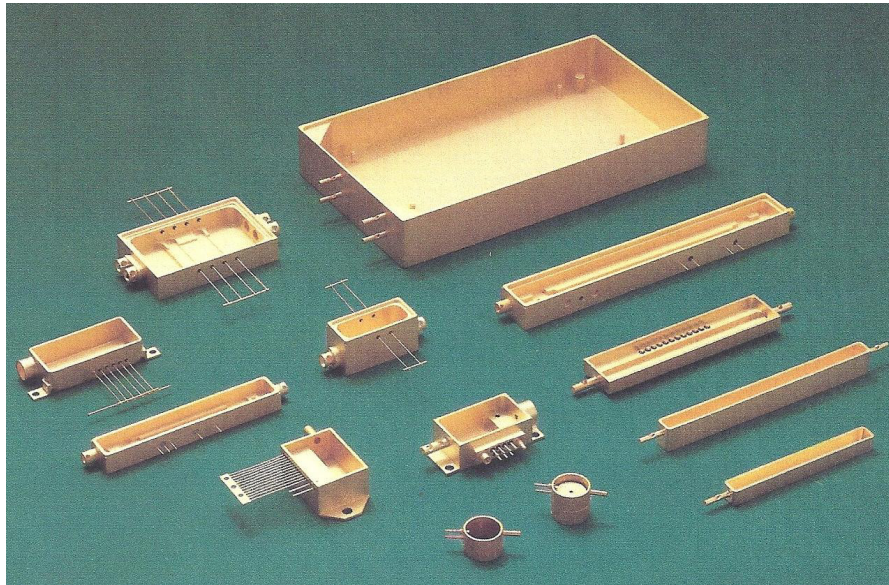
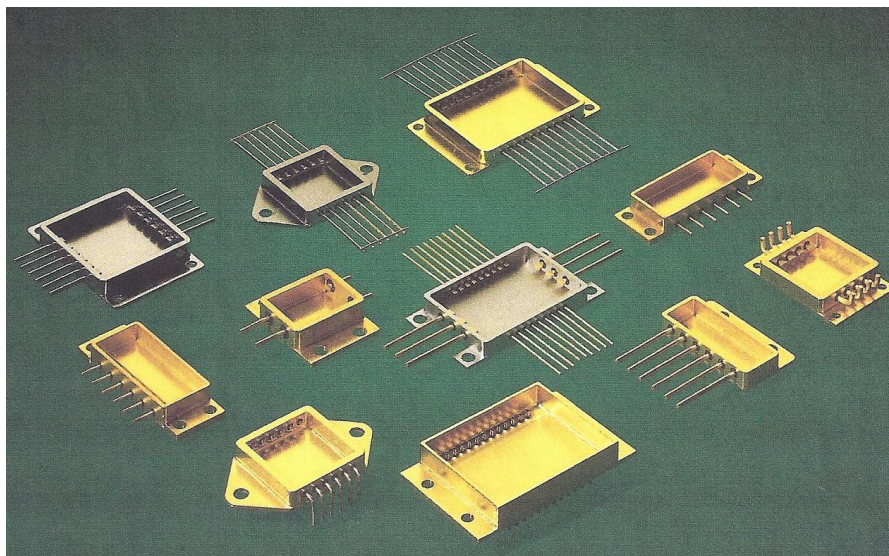


Figure 9. *The figure also shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*



Another application of the invented apparatus in medicine – illumination of the surgical field.

The optical fiber can easily be attached to a finger or an instrument (scalpel, clamp). This is particularly important in ophthalmology, where it is necessary to illuminate the

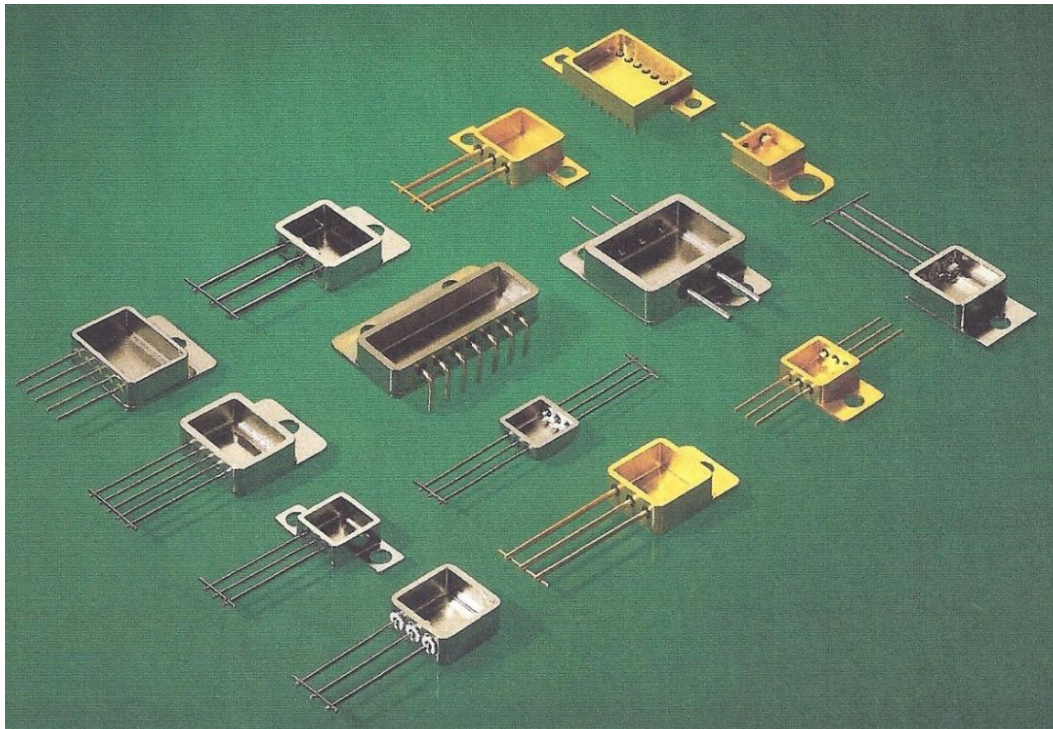
sclera of the eye uniformly. The fiber used for this purpose is thin, with a diameter of 100 μm . It can easily be inserted into the eye without causing injury and can illuminate the sclera in all directions. This is considered a very important factor in ensuring the success of the operation.

The cost of the proposed local surgical field illumination system may be approximately 3,000 dollars.

The service life of the proposed version of the apparatus is also determined by the service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the

proposed apparatus – intensive cooling, a modified mounting module with control and regulation electronics operating in the radio-frequency range, selective material selection, and special coatings, including synthetic diamond films – the service life can be estimated at 10,000 hours or more.

Figure 10. *The figure also shows the concept of selecting basic components for the first prototypes developed by an optics-focused startup*



4. Online inspection system for monitoring the condition of nuclear reactor containment structures and systems located near nuclear reactors.
5. Presumably, the proposed version of the invention may cost several hundred thousand dollars.
6. Several hundred such devices are required worldwide; several hundred such devices are also needed for the inspection of nuclear reactors on submarines and other facilities with nuclear power systems.

The service life of the proposed version of the apparatus is also determined by the service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the proposed apparatus – intensive cooling, a modified mounting module with control and regulation electronics operating in the radio-

frequency range, selective material selection, and special coatings, including synthetic diamond films – the service life can be estimated at 10,000 hours or more.

7. Underwater illumination systems, particularly for bathyscaphes and divers.

The estimated cost may reach 100,000 dollars.

The service life of the proposed version of the apparatus depends on numerous components, but the service life of the illumination system itself is also determined by the service life of the laser diode. Since all possible measures to extend the service life of the laser diode are provided for in the proposed apparatus – intensive cooling, a modified mounting module with control and regulation electronics operating in the radio-frequency range, selective material selection, and special coatings, including synthetic diamond films – the

service life can be estimated at 10,000 hours or more.

In the event of specific interest, this system, based on Kseniia Kaplieva's concept, can be developed in greater detail.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-96-108



**CONTACTLESS MONITORING TECHNOLOGIES IN SMART
MANUFACTURING FACILITIES.
(The Development and Advancement of Real-Time Online
Contactless Monitoring Technologies Based on the Fundamental
Principles of Electromagnetic Resonance Spectroscopy)**

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Cite: Nikolov K. (2026). *Contactless Monitoring Technologies in Smart Manufacturing Facilities. (The Development and Advancement of Real-Time Online Contactless Monitoring Technologies Based on the Fundamental Principles of Electromagnetic Resonance Spectroscopy)*. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-96-108>

Abstract

This work examines contemporary approaches to the development of the ecosystem and infrastructure of smart manufacturing facilities designed to accommodate startups and innovative enterprises engaged in the development and implementation of advanced intelligent manufacturing technologies. Particular attention is given to the creation of a specialized technological environment that takes into account the characteristics, functional requirements, and interrelationships of the supersystems and subsystems of modern smart manufacturing. Contactless monitoring systems are considered one of the key elements of such infrastructure, enabling the acquisition, processing, and analysis of information on the condition of manufacturing equipment and ongoing technological processes without direct physical interaction with the monitored components. The work examines the prospects for the development of real-time online monitoring technologies based on the fundamental principles of electromagnetic resonance spectroscopy. Particular emphasis is placed on the integration of contactless monitoring systems with advanced processor-based systems incorporating elements of artificial intelligence and artificial neural networks for automated data processing, detection of deviations, and improvement of manufacturing process control. Special consideration is given to the potential application of these technologies in high-technology manufacturing processes, including the production of printed circuit boards, thin-film microassemblies, and high-speed electronic components, where the speed, accuracy, and contactless nature of monitoring may be essential for maintaining stable technological parameters and ensuring the quality of manufactured products. The proposed approach is aimed at the further development of intelligent manufacturing ecosystems that integrate contactless monitoring methods, digital data processing, artificial intelligence, and automated control systems within a unified technological infrastructure of a smart manufacturing facility.

Keywords: *Technology; Contactless Monitoring; Smart Manufacturing Facilities; Printed Circuit Board Manufacturing; Thin-Film Microassembly Manufacturing; Printed Circuit Boards; Thin-Film Microassemblies; High-Speed Electronic Components*

Introduction

Under current conditions, the establishment of manufacturing facilities intended to accommodate startups developing new smart technologies creates a need for a specialized ecosystem that takes into account the characteristics and requirements of smart-technology supersystems. One of the essential subsystems within such an ecosystem comprises contactless monitoring elements and their associated processors, which, in turn, incorporate elements of artificial intelligence and artificial neural networks.

This field is relatively new, and Kateryna Vorobiova has made a significant contribution to its development through her fundamental publications and books.

In her developments, Kateryna Vorobiova has successfully integrated concepts relating to the preparation and optimization of manufacturing-facility interiors with the development of infrastructure components for smart manufacturing complexes, as well as with advanced technological solutions aimed at increasing the processing speed of electronic systems in order to meet the anticipated requirements associated with quantum computers and their processor-based equivalents.

RITM Technology (Dimensional Selective Metal Etching)

Printed Circuit Board Module

A module for the installation, cooling, management, and monitoring of high-energy optoelectronic systems, and a method for manufacturing the same, comprising:

- at least one double-sided printed circuit board having, on one side thereof, geometrically aligned and mutually electrically insulated electrically conductive and thermally conductive topological structures;
- at least one integrated heat-conducting pad arranged on the opposite side of the printed circuit board and thermally connected to the heat-conduct-

ing structures located on the first side of said printed circuit board;

- thermally conductive channels connecting each of the heat-conducting structures on one side of said printed circuit board to the integrated heat-conducting pad located on the opposite side of said printed circuit board;
- wherein said integrated heat-conducting pad and said thermally conductive channels are electrically insulated from the electrically conductive topological structures.

High-Speed Jet Electrochemical Deposition

High-speed jet electrochemical deposition is a **galvanic process performed within a selectively oriented, directed electrolyte flow incorporating a continuous recirculation system that continuously renews the electrolyte.**

The system comprises:

1. **An electrolyte reservoir** operating under specified electrolyte-maintenance parameters, including: nickel and copper concentrations;
 - temperature;
 - acidity or alkalinity level (pH);
 - density;
 - electrical conductivity.
2. Due to the technological advantages of the proposed process, the use of **organic brightening additives is not required.**
3. **A pump equipped with a filter.**
4. **An anode for jet electroplating**, comprising a component soluble in the particular type of electrolyte and a component insoluble in that electrolyte, arranged sequentially in the direction of electrolyte flow.

The insoluble component is made of a **composite conductive carbon-graphite fabric**. It is positioned parallel to the surface being metallized and is arranged downstream of the soluble component, immediately upstream of the surface to be coated (the cathode).

Both components are connected to a **positive electrical potential** and have selectively adjustable permeability to the electrolyte. The anode incorporates a system for the uniform distribution of electrolyte across the surface of the soluble component. This distribution pattern is subsequently reproduced across the insoluble component and, consequently, across the surface being metallized – the cathode.

The manufacturing process further comprises:

- removal of the photoresist;
- etching of the iron from one side to a depth corresponding to one-half of the thickness of the steel strip;
- removal of etching products from the surface, first by aerodynamic treatment and subsequently by hydrodynamic treatment;
- encapsulation with a flowable polymer composition, performed in the following sequence:
 - filling with a monomer;
 - subsequent polymerization;
 - thermal stabilization;
- etching of the iron from the opposite side using the same technological principles;
- encapsulation from the opposite side using the same technological principles;
- application of a protective coating to the electrically conductive structures;
- vacuum deposition onto all thermally conductive structures of a multilayer system comprising semiconductor nanostructured polycrystalline diamond films.

Integration with Contactless Monitoring Technologies

A significant contribution made by Kateryna Vorobiova consists in combining and integrating contactless monitoring technologies and systems with the technologies used for manufacturing specialized circuit boards by means of dimensional selective metal etching.

Given that this technological combination and integration were implemented within a relatively short period of time, it is appropriate to examine in greater detail the

resulting concepts and potential applications of contactless monitoring technologies in modern smart manufacturing environments.

Inventions in the Field of Contactless Monitoring of Drinking Water and Cow's Milk Quality

The quality of drinking water is one of the fundamental factors determining the quality of human life. In conventional water-quality monitoring methods, electrical conductivity is generally regarded as an important indicator of water purity.

The higher the concentration of contaminants in water, the lower its electrical resistance tends to be; conversely, the purer the water, the higher its electrical resistance.

For a long time, this approach was considered sufficient. However, increasing concerns associated with intentional contamination risks, together with the unprecedented scale of environmental pollution, have created a need for more comprehensive and reliable methods of water-quality monitoring.

These are by no means the only factors determining the urgent need for more comprehensive water-quality control, but they represent important considerations.

Many existing technologies, instruments, and systems for water-quality monitoring have a relatively limited range of technical capabilities and do not simultaneously cover all parameters that may require continuous monitoring. Consequently, there is a need for technologies capable of detecting potentially hazardous changes in water quality before contaminated water reaches the end user and poses a potential risk to human health.

Milk is one of the important components of a balanced diet and, since water constitutes a substantial proportion of its composition, it likewise requires mobile, reliable, and accurate monitoring technologies adapted both to increasingly stringent quality requirements and to evolving regulatory standards.

In milk-quality monitoring, particular importance is also attached to the ability of monitoring systems to adapt to new technological conditions and industrial processing methods.

Based on these considerations, it is reasonable to conclude that there is a need for continuous monitoring of the quality and

condition of both drinking water and milk prior to their use or consumption.

Technologies intended to address these requirements have been developed, and a brief description of the proposed technological solutions is provided below:

1. Device for Real-Time Monitoring of the Current Quality Status of Drinking Water

The device is designed for the real-time monitoring and assessment of the current value of a comprehensive digital indicator characterizing the dynamic quality status of drinking water. The device may also be adapted for use in process-water quality monitoring systems at the inlet to an industrial process, as well as for monitoring wastewater quality prior to discharge into a sewerage system or prior to its return to the technological process following regeneration.

The Comprehensive Digital Indicator of the Dynamic State of Water and Aqueous Solutions is an integral parameter that, based on frequency, amplitude, electrical resistance, resonance characteristics, inductance, and a set of dynamic characteristics of the water flow, provides an integrated representation of the current content and concentration of components present in the water, as well as the relationships, including biological interactions, between these components and the measured parameters.

The device for real-time selective identification of the current value of the Comprehensive Digital Indicator of the Dynamic Quality Status of Drinking Water is a compact system designed for integration into water-supply pipelines and water-flow meters. It may also be configured for operation under field conditions using solar power.

The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the water flow. The water-flow transformation system incorporates an aerodynamic mechanism for removing gases from the water flow.

The device may be configured both for stationary operation and for rapid on-site analysis.

Neither operation of the device nor the associated monitoring procedure requires specialized training of the operator or end user.

2. Device for Real-Time Monitoring of the Current Quality Status of Cow's Milk

The device is designed for the real-time monitoring and assessment of the current value of a Comprehensive Digital Indicator characterizing the dynamic quality status of cow's milk.

The Comprehensive Digital Indicator of the Dynamic State of Cow's Milk is an integral parameter that, based on frequency, amplitude, electrical resistance, inductance, and a set of dynamic characteristics of the milk flow, provides an integrated representation of the current content and concentration of components present in cow's milk, as well as the relationships, including biological interactions, between these components.

The device for the real-time selective identification of this Comprehensive Digital Indicator is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels.

The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow. The milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured both for stationary operation and for rapid on-site analysis.

3. Comprehensive Integrated Water and Aqueous Solution Quality Indicator and a Device for Its Real-Time Identification

The Digital Indicator of the Dynamic Quality Status of Drinking Water is an integrated parameter determined by comparing a signal pulse transmitted to the sensor with the corresponding parameters generated within the pipeline as a result of resonance phenomena occurring in the water flow. The comparison is performed on the basis of frequency, amplitude, electrical resistance,

and inductance, in combination with a set of dynamic characteristics of the water flow. Taken together, these parameters provide an integrated representation of the current content and concentration of components present in the water.

The device for the real-time selective identification of this indicator is a compact system designed for operation within municipal or main water-supply pipelines, as well as under field conditions, including configurations powered by solar panels.

The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the water flow being analyzed. The water-flow transformation system incorporates an aerodynamic mechanism for removing gases from the flow.

The Comprehensive Integrated Water Quality Indicator also incorporates a Comprehensive Integrated Sensor Indicator, which represents a constant value for each specific sensor type, its design parameters, and the parameters of the signal supplied to the sensor. According to the presented experimental data, the constancy of this indicator has been confirmed by a series of tests comprising more than 1,000 test cycles performed using four different types of sensors.

The device may be configured both for stationary operation and for rapid on-site analysis.

4. Comprehensive Integrated Cow's Milk Quality Indicator and a Device for Its Real-Time Identification

The Digital Indicator of the Dynamic State of Cow's Milk is an integrated parameter that, based on frequency, amplitude, electrical resistance, inductance, and a set of dynamic characteristics of the milk flow, provides an integrated representation of the current content and concentration of components present in cow's milk.

The device for the real-time selective identification of this indicator is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels.

The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow. The milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured both for stationary operation and for rapid on-site analysis.

5. Dynamic Indicator of the Current Somatic Cell Count in Cow's Milk and a Device for Its Real-Time Selective Identification

The Digital Indicator of the Dynamic State of Cow's Milk is a parameter that, based on frequency, amplitude, electrical resistance, inductance, and a set of dynamic characteristics of the milk flow, provides an integrated representation of the current content and concentration of somatic cells in cow's milk.

The device for the real-time selective identification of this indicator is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels.

The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow. The milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured both for stationary operation and for rapid on-site analysis.

Dynamic Comprehensive Indicator of the Current Fat Concentration in Cow's Milk and a Device for Its Real-Time Selective Identification

The Digital Indicator of the Dynamic State of Cow's Milk is an integrated parameter that, based on frequency, amplitude, electrical resistance, inductance, and a set of dynamic characteristics of the milk flow, provides an integrated representation of the current content and concentration of fat or fatty acids in cow's milk. The device for the real-time selective identification of this indicator is a compact system designed for operation on dairy farms or under field conditions,

including configurations powered by solar panels. The device is characterized by minimal energy consumption. The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow. The device may be configured both for stationary operation and for rapid on-site analysis.

Dynamic Comprehensive Indicator of the Current Lactose Content in Cow's Milk and a Device for Its Real-Time Selective Identification

The Digital Indicator of the Dynamic State of Cow's Milk is an integrated parameter that, based on frequency, amplitude, electrical resistance, inductance, and a set of dynamic characteristics of the milk flow, provides an integrated representation of the current lactose content in cow's milk. The device for the real-time selective identification of this indicator is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels. The device is characterized by minimal energy consumption. The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow. The device may be configured both for stationary operation and for rapid on-site analysis.

Comprehensive Integrated Indicator of Mastitis in Cows and a Device for Its Real-Time Identification

The Digital Indicator is an integrated parameter that, based on frequency, amplitude, electrical resistance, and inductance, serves as an integrated equivalent or indicator of the occurrence of mastitis in a cow. The device for the real-time identification of this indicator is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels. The device is characterized by minimal energy consumption.

The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow. The device may be configured both for stationary operation and for rapid on-site analysis.

Device for Real-Time Selective Identification of Cow's Milk Quality During Its Transfer to a Collection Tank Following Milking

The device is a compact system designed for operation on dairy farms or under field conditions, including configurations powered by solar panels. The device is characterized by minimal energy consumption. The device comprises functionally interconnected systems for the inlet, outlet, monitoring, and transformation of the milk flow, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

Device for Contactless Monitoring of Cow's Milk Condition Parameters

The device comprises systems for introducing milk into the monitoring zone and removing the milk flow from the monitoring zone, as well as an integrated electronic sensor monitoring module equipped with an interface. The device may further comprise a signal identification system and a device for accelerated comparison of identified signals with a reference signal or reference value.

Device for Simultaneous Monitoring of Multiple Cow's Milk Condition Parameters During Transportation

The device may be implemented in two configurations. The first configuration is designed for installation on milk transport tanks for monitoring milk quality during transportation and during the transfer of milk for subsequent processing into dairy products. The second configuration is designed for installation on flexible or rigid pipelines through which milk is transferred to storage tanks. This configuration may additionally provide real-time temperature measurement functionality.

Device for Rapid Analysis of Cow's Milk Quality

The device is a compact portable instrument comprising an internal chamber into which milk, or another liquid, is introduced for analysis. A sensor is positioned around the chamber and is selectively configured to monitor a specific parameter of the milk or other liquid. The device requires no adjustment or calibration and incorporates several levels of protection.

Device for Selective Rapid Analysis of Cow's Milk Quality Parameters

The device is a compact portable instrument comprising an internal chamber into which milk, or another liquid, is introduced for analysis. A sensor positioned around the chamber is selectively configured to monitor a specific parameter of the milk or other liquid. The device requires no adjustment or calibration and incorporates several levels of protection.

Contactless Sensors for Monitoring Milk Levels in Tanks

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The device may be implemented in several configurations. It may be positioned inside the liquid-containing tank or externally to the tank and may incorporate different sensor configurations.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of the Integrated Milk Quality Indicator at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor and assess the integrated milk quality indicator and as a liquid-level sensor. The device may simultaneously monitor physical characteristics of milk or another liquid, including electrical conductivity, density, and acidity level.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of the Somatic Cell Count in Milk at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor the somatic cell count and as a liquid-level sensor. The device may also simultaneously monitor physical characteristics of the milk or other liquid, including electrical conductivity, density, and acidity level.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of Milk Fat Content at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor fat concentration and as a liquid-level sensor.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of Lactose Content at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor lactose concentration and as a liquid-level sensor.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of Blood Traces in Milk at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor the concentration of blood traces and as a liquid-level sensor.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Sequential Assessment of the Concentrations of Basic Milk Components at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensor configured to monitor selected parameters and as a liquid-level sensor.

Device for Comprehensive Monitoring of Milk Levels in Tanks with Simultaneous Assessment of the Concentrations of Multiple Basic Milk Components at the Monitored Level

The device monitors the level of milk, or another liquid, within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored. The specified pipeline section simultaneously functions as a resonant sensing system configured to monitor parameters and concentrations of components in milk or another liquid and incorporates multiple sensors, each configured to monitor an individual parameter. Each sensor simultaneously functions as a liquid-level sensor.

Device for Modifying the Turbulence Level of a Milk Flow

The device is designed for the dynamic transformation of a turbulent milk flow, creating a localized region of laminar flow in which the milk is monitored using a resonant sensor. During flow transformation, the device additionally releases air from the milk flow and stabilizes its hydrodynamic characteristics.

Device for Preparing a Milk Flow for Real-Time Monitoring of Its Condition Parameters

The device is designed for the dynamic transformation of the milk flow with the formation of a localized region of laminar flow in which milk monitoring is performed using a resonant sensor.

Device for Real-Time Monitoring of Gas Content in Milk

The device comprises a resonant sensor configured to detect changes in a set of milk

parameters depending on the concentration of air or another gas present in the milk. The device may simultaneously monitor the degree of filling of the pipeline through which the milk flows and the turbulence level of the milk flow within the pipeline.

Milk Aeration Process Control System with Real-Time Monitoring of Air Content in Milk

The system is designed to control the milk aeration process while monitoring the level of air content in the milk. The system incorporates feedback from a resonant sensor and adjusts the parameters of the compressed-air supply according to the concentration of air in the milk. The system comprises a resonant sensor, an interface, and a signal converter configured to transform signals received from the sensor into control signals transmitted to the compressed-air source, thereby enabling adjustment of the pressure and flow rate of the compressed air. The system further incorporates an aerodynamic function for introducing air into the milk.

Information on the Verification and Testing Results of a Method for Selective Separation of Various Materials Dissolved in Water or Aqueous Solutions and Subsequent Monitoring of Their Concentrations Using Resonance Technologies

When analyzing water contaminated with dissolved metal ions and other substances, significant difficulties arise in accurately determining the actual concentration of each individual material or metal. In addition to the technology presented previously, a new invention has been developed that enables high-precision selective separation of substances contaminating water or other liquids into groups characterized by specific resonance frequencies. The sensitivity of the measuring instrument makes it possible to distinguish resonance frequencies with an accuracy down to the microhertz range. According to the presented results, this accuracy makes it possible to distinguish materials and chemical-mechanical complexes contained in water or aqueous solutions with a precision of up to 0.00001 grams. Preliminary testing demonstrated that measurement

accuracy does not depend on the presence or absence of organic compounds or combinations of such compounds and other materials in the water or aqueous solution. The preliminary verification results confirm the possibility of real-time active monitoring of liquids to determine the concentrations of individual substances without direct contact with the monitored liquid and without additional or auxiliary procedures. The concentration of each component is determined separately, providing an independent result with the required accuracy using the same measuring instrument.

A digital monitoring and control system was developed to manage the measurement process. According to the presented materials, the system underwent a complete testing cycle in cooperation with one of the leading Japanese companies in the course of practical monitoring tasks. The results were assessed as exceeding the capabilities of the referenced existing technologies by 1,000 times or more. The tested technology is characterized by substantial technological flexibility and may be implemented using only those capabilities required for a particular application, where appropriate, thereby also allowing the cost characteristics of the technology to be adjusted according to the requirements of the specific application site.

Brief Description of the Resonance Method

The method involves generating an alternating electromagnetic field within the space containing the sample under examination. This field serves as an intermediary between the resonant circuit and the test sample. On the one hand, the resonant circuit functions as an emitter of this field and, on the other hand, as a receiver or sensing element responsive to changes introduced into the electromagnetic field by the test sample. Even in the absence of a test sample, the alternating electromagnetic field generated by the solenoid represents the superposition of two electromagnetic fields varying in opposite phase. One field is generated by changes in the magnetic induction of the solenoid and produces a vortex electric field in accordance with the Maxwell–Faraday equation. The other field is generated by changes in the electric field re-

sulting from the potential difference between the outermost, most widely separated turns of the solenoid when the sample is positioned inside the solenoid, or by the potential difference between the turn closest to the surface of the sample and the sample itself when the sample is positioned opposite the end of the solenoid. This produces a vortex magnetic field in accordance with Ampère’s circuital law with Maxwell’s correction.

Under the influence of an external alternating electromagnetic field, various electrical phenomena may be induced in the test sample, depending on its nature, including linear and eddy conduction currents, linear and eddy displacement currents, as well as linear and eddy ionic currents representing the ordered motion of ions. In accordance with the principle of field superposition, these electrical phenomena introduce distortions into the external alternating electromagnetic field. These distortions are detected by the solenoid of the resonant sensor. The resonant circuit incorporating this solenoid changes its behavior in a manner analogous to the addition of supplementary circuit elements, namely a capacitor, an inductor, and a resistor. The combination of the additional capacitive, inductive, and resistive components constitutes an additional impedance introduced into the system by the test sample. This is the parameter measured by the resonant sensor.

Changes in the parameters of the resonant circuit are reflected in changes in its amplitude and frequency characteristics, specifically in its resonant frequency and resonant amplitude. By analyzing these changes, the impedance characteristics of the test sample can be evaluated.

Interference Immunity

Mechanical parameters such as viscosity, density, transparency, and pressure, provided that the medium is incompressible, should not directly affect the measured electrical parameters of the substance. Flow velocity within a pipeline and turbulence represent processes occurring on time scales substantially slower than the megahertz-frequency processes involved in impedance measurement and therefore are not expected to exert a significant influence on the measurement process. Hardness is a chemical characteris-

tic determined by the components present in the substance. Temperature generally affects impedance; however, measuring temperature and compensating for its influence during impedance measurements does not represent a particularly complex technical task.

Selective Monitoring of Component Concentrations in Water and Aqueous Solutions

In simplified terms, the selective measurement and monitoring of concentrations of metal salts and other substances dissolved in water can be explained as follows. Water has an anomalously high dielectric constant, which is associated with the large dipole moment of water molecules. Consequently, the overall polarization response in an alternating electric field will depend substantially both on the concentration of nonpolar impurity molecules and on molecules having dipole moments different from that of water.

This difference provides the basis for the resonant method of selectively measuring impurity concentrations in water or aqueous solutions. When water is introduced into an oscillatory circuit, it determines the position of its characteristic resonance and corresponding resonance line. Each impurity introduced into the water or aqueous solution within the oscillatory circuit causes a shift in this resonance and its corresponding resonance line. Different impurities, depending on their concentrations, produce different resonance shifts.

A family of such dependencies, each corresponding to a particular metal or other component, makes it possible to selectively determine the magnitude of the resonance-line shift and, accordingly, the concentration of each impurity in the water or aqueous solution. The family of dependencies is established through chemical calibration using conventional chemical analytical methods.

For solutions and liquids that are not aqueous, the methodology and underlying logic of selective component-concentration measurement are similar. The principal difference is that one of the components of the solution or liquid whose molecules exhibit the highest dipole moment within that particular system is selected as the reference component for measurement.

Preliminary Investigation of the Sensitivity of Resonant Monitoring Technology for Milk Analysis

At the preliminary stage of testing and evaluating the sensitivity of the resonant monitoring technology, samples representing several fundamentally different types and conditions of milk were examined. These included samples of whole natural milk obtained during morning manual milking and divided into three principal groups: samples collected at the beginning of milking, characterized by the lowest concentration and an acidity value of 6.7 units; samples collected during the main phase of milking, characterized by an intermediate concentration, an average optimal concentration of the constituent components, and an acidity value of 6.8 units; and samples collected during the final phase of milking, characterized by the highest concentration of the principal components and an acidity value of 6.9 units.

The investigation also included samples of the same milk after 24 hours of storage at room temperature; samples of the same milk after 24 hours of refrigerated storage at +3 °C; samples of four types of commercially available milk having different characteristics; samples of all milk types supplemented with preserved blood; samples supplemented with sucrose; samples supplemented with glucose; samples supplemented with sugar; and samples supplemented with milk fat followed by mechanical mixing.

Objectives of the Preliminary Investigation

The preliminary investigation was intended to determine the degree of contrast in the reflected resonant signals obtained when comparing all of the milk samples described above. Another objective was to demonstrate the possibility of selectively identifying, from the multiple combinations of signal parameters obtained, those groups of parameters for which the differences and signal contrast between different types of milk are maximal, thereby providing the level of assessment and measurement accuracy required by leading European manufacturers of integrated technological equipment for dairy production and consistent with the requirements and limitations of applicable European Union standards.

1. Demonstration of the Possibility of Selectively Identifying Indicators and Assessing the Somatic Cell Count in All Types of Milk, with Comparison Against the Readings of Somatic Cell Counting Instruments Developed and Marketed Internationally by Recognized Leading Manufacturers Complying with the Highest Technical Standards and Requirements.
 2. The workstation prepared by the company conducting the development for the preliminary studies was integrated into the infrastructure of a specialized and optimized standard clean-room environment intended for research activities.
 3. General Characteristics of the Measurements and Studies Conducted.
 4. The acidity of all prepared milk samples was measured using standard measuring instruments, and corresponding measurements were performed using the experimental resonance-monitoring unit.
 5. The somatic cell count in all milk samples was measured using standard equipment manufactured by DeLaval, and the corresponding integral signal from the same milk samples was measured using the experimental resonance-monitoring unit.
 6. A precisely defined quantity of blood was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 7. A precisely defined quantity of milk fat was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 8. A precisely defined quantity of urea was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 9. A precisely defined quantity of glucose was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 10. 10. A precisely defined quantity of sucrose was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 11. A precisely defined quantity of fructose was added to a measured milk sample, after which the resulting integral signal was measured using the experimental resonance-monitoring unit.
 12. *1Conclusions Based on the Results of the Preliminary Experimental Verification, Drawing on the Publications and Developments of Kateryna Vorobiova.*
 13. The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process on the basis of an integrated comprehensive indicator.
 14. The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process and of differentiating between the same samples after different periods of storage at room temperature.
 15. The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process and of differentiating between the same samples after different periods of storage at room temperature when specified quantities of blood have additionally been introduced.
 16. The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process and of differentiating between the same samples after different periods of storage at room temperature when specified quantities of glucose have additionally been introduced.
- The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process on the basis of an integrated comprehensive indicator. It is also capable of differentiating between the same samples after different periods of storage at room temperature when specified

quantities of urea have additionally been introduced.

Figure 1. *The figure shows a startup researcher's workstation located in a clean room within a restored industrial facility*



The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process on the basis of an integrated comprehensive indicator. It is also capable of differentiating between the same samples after different periods of storage at room temperature when specified quantities of milk fat have additionally been introduced.

The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process that have different somatic cell concentrations. It is also capable of differentiating between the same samples after different periods of storage at room temperature.

The resonance-monitoring technology is capable, with the required degree of accuracy, of distinguishing whole-milk samples obtained during the initial, middle, and final phases of the milking process that have different somatic cell concentrations. It is also capable of differentiating between the same samples after different periods of storage at room temperature while simul-

taneously assessing and distinguishing the acidity levels of the same milk samples. The experiments confirmed the validity of the strategy selected for the preliminary testing, which is based on an at least two-stage calibration system for the resonant sensor. At the first stage, calibration is performed at the level of the integral signal based on the characteristics of phenomena occurring in the milk. At the second stage, calibration is performed using a selectively identified combination of resonant responses exhibiting the most pronounced contrast in frequency, capacitance, and amplitude characteristics in the milk samples under investigation, specific to each monitored parameter and characteristic.

Overall, the system demonstrated high sensitivity to the applied signals, high selectivity in signal discrimination and comparison, a sufficient level of repeatability of the results, stable operation in accordance with the adopted methodology, sufficient accuracy in determining the integral components of the signals, sufficient autonomy and resistance to external influences and interference, as well as the ability to be operated in a stable, reliable, and controlled manner by an operator without formal specialized professional training.

The results of the preliminary studies provide a basis for proceeding, at the next stage of the project, to the development of applications for the selective monitoring of all required milk parameters and to the fundamental design and development of the necessary resonant-sensor configurations.

The results obtained from the adjustment and modification of the sensors' operating parameters, together with the overall characteristics of the sensor control and digital testing processes and the associated infrastructure, support the conclusion that reliable remote control of individual sensors and groups of sensors can be implemented, including synchronization of their principal measurement and analytical functions. The results also indicate the possibility of adapting the sensors to the specific operating requirements and varying conditions encountered on dairy and commercial farms and at dairy-processing enterprises.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-109-115



INTEGRATIVE MODULES FOR ELECTRONIC SYSTEMS. (Integrative Modules for Electronic Systems, Including Laser Diodes, with an Intensive Cooling System Based on Diamond–Copper Composite Materials)

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Cite: Akilbekova Sh.K. (2026). *Integrative Modules for Electronic Systems. (Integrative Modules for Electronic Systems, Including Laser Diodes, with an Intensive Cooling System Based on Diamond–Copper Composite Materials). European Journal of Technical and Natural Sciences 2026, No 5.* <https://doi.org/10.29013/EJTNS-26-5-109-115>

Abstract

The article examines integrative modules for complex electronic systems, particularly those incorporating laser diodes, with a focus on reliable and efficient thermal management. As demonstrated by practical developments in recent years, effective cooling remains one of the key challenges affecting the performance, reliability, and operational efficiency of such electronic devices.

Particular attention is given to the development of integrative technical solutions aimed at minimizing energy losses and increasing useful energy output, especially in various lighting systems. The proposed approach focuses on achieving efficient cooling without introducing additional structural elements or requiring additional energy consumption for thermal management, including through the application of diamond–copper composite materials.

The article also considers technical solutions intended to increase the output optical power of lighting devices while maintaining a compact and structurally simple design. The objective is to achieve higher light output at relatively low operating power and, consequently, reduced energy consumption, while providing the thermal conditions required for the stable operation of laser diodes and other electronic components.

Keywords: *Integrative Modules; Electronic Systems; Laser Diodes; Optical Power; Diamond Spheres; Ductile Material; Composite Material; Pseudo-Porous Structure; Optical Cable; Laser Radiation; Lamp with a Flat Light-Emitting Element*

Introduction

In order to minimize energy losses and increase useful energy output, particularly

in various lighting systems, considerable attention is currently being devoted to the development of integrative technical solutions

that provide efficient cooling without requiring additional structural elements or additional energy consumption for thermal management.

In parallel, research and development efforts are focused on technical solutions that make it possible to increase the output optical power of lighting devices while maintaining a compact, simple, and efficient design. Such solutions are intended to achieve higher light output at relatively low operating power and, consequently, reduced overall energy consumption.

Figure 1.



The image shows one of the innovative developments designed to convert laser radiation into light within conventional and commonly used spectral ranges.

The author of this publication considers the integrated solutions proposed in the scientific and technological publications and books by Aleksandra Efimova, a recognized innovation specialist in this field, to be among the most suitable approaches.

One of the principal features that distinguishes Aleksandra Efimova's proposals and developments from similar solutions presented by other authors is the extensive platform for experimental computer modeling. This platform has emerged from her broad and in-depth knowledge of the fundamental techniques and methods of systemic and combinatorial computer modeling applied to related innovation processes, including those at the intersection of fundamental scientific and technological disciplines.

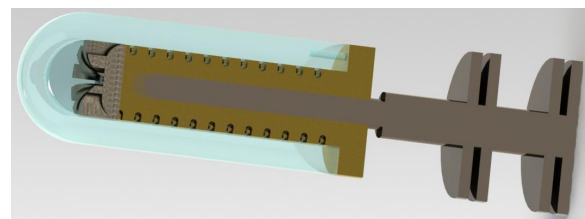
In analyzing the innovative technologies proposed in her publications, Aleksandra Efimova advances a concept of particular importance for addressing the problem

under consideration: the combinatorial structure of each solution, understood as a harmonious combination and mutual complementarity between conventional technologies and materials, on the one hand, and innovative technologies and materials – primarily composite materials – on the other.

Of particular significance in Aleksandra Efimova's proposals is the tendency toward the integration and comprehensive adaptation of new materials and technological approaches within the environment and operating conditions of existing, well-established technologies and materials. This approach creates a foundation for transforming their properties and capabilities and bringing them to a new level of technological innovation.

The following image presents an axial cross-sectional view of such a device, providing a more convenient representation for its detailed examination and analysis.

Figure 2.



As can be seen, the design of the innovative lamp integrates the functions of several basic structural elements within a single system.

The lamp holder incorporates a **vortex-type heat sink**, the shaft and discs of which are manufactured from a **diamond–copper composite material** that constitutes one of the key components of the lamp's cooling system.

Each component of this system is multifunctional. In addition to performing heat-transfer and heat-accumulation functions, the structure of these components, formed from numerous composite microglobules, simultaneously performs the essential function of dissipating heat flows. This effect is achieved due to the **pseudo-porous structure of the composite material**.

Particular attention should be given to the innovative structure of the diamond–copper composite.

The original manufacturing process for the composite globules begins with the formation of synthetic-diamond spheres with a diameter of 5–7 microns. This dimension may vary depending on the profile and dimensions of the component, as well as its operating conditions.

The spheres are subsequently coated with copper using specialized equipment and an original innovative technology (Appendix 2).

The thickness of the copper coating is selected so that, during the formation of the lamp component in a mold, a sufficient amount of ductile material remains on the diamond spheres to enable the metal to flow and fill the spaces between the synthetic-diamond spheres.

As a result, a pseudo-porous structure is formed in which diamond spheres are uniformly distributed throughout the material. Diamond provides exceptionally high thermal conductivity while remaining electrically non-conductive.

This structure enables heat to be rapidly dissipated and uniformly distributed across the cross-sectional area of the heat-sink discs.

An optical cable is positioned within the spiral grooves of the lamp housing and receives a laser beam from the laser module. The optical cable is arranged in a spiral and positioned within the housing grooves at a diameter that causes the cable to emit light across its entire cylindrical surface. This configuration is significantly more efficient than light emission transmitted solely through the end face of the cable.

In order to separate the laser radiation from the lamp's output radiation, a phosphor layer designed for a specific emission spectrum is applied to the optical cable.

As a result, the final radiation emitted by the lamp is completely non-toxic. Furthermore, because the emitting surface area is thousands of times greater than the area of the optical cable end face, a 1–2 W laser diode provides a lamp output equivalent to approximately 60–75 W.

The presented models demonstrate that, based on the general principles of innovative design proposed by Aleksandra Efimova, it is possible, within a conventional form and structural configuration – for example, that of an ion-exchange filter – to

use natural and completely safe materials to achieve an almost ideal final result characterized by unusual parameters and properties:

- complete elimination of chemical reagents from the process;
- use of naturally occurring ion-exchange properties;
- exceptionally high potential ion-exchange capacity, including the capacity required for the purification of liquids contaminated with radioactive substances.

Under such design approaches, the requirements imposed on the design process itself also change fundamentally. This makes it possible to extensively incorporate computer modeling methods and techniques, as well as methods and techniques aimed at achieving the ideal final result, into the development process.

Figure 3.

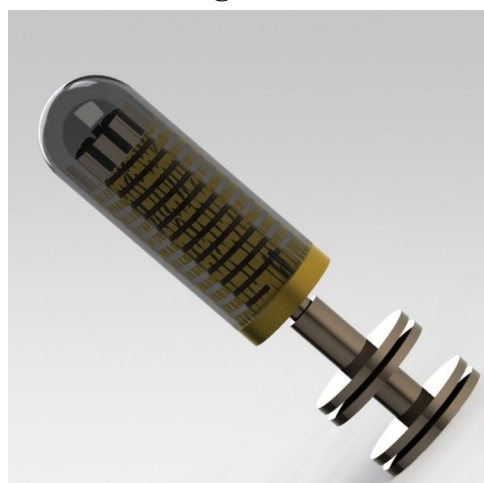


Figure 4.

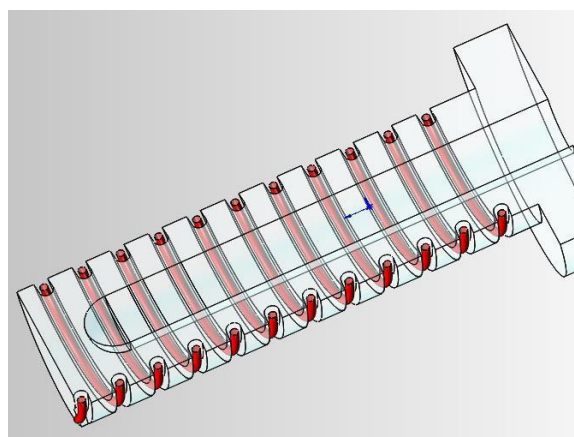
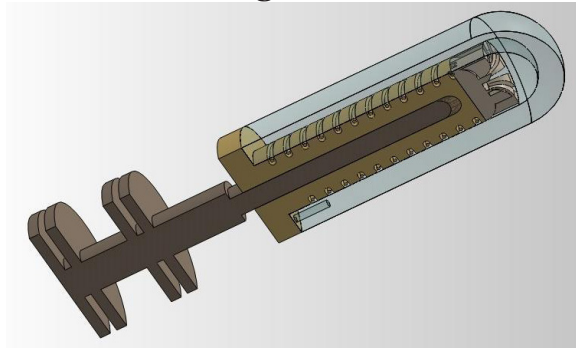
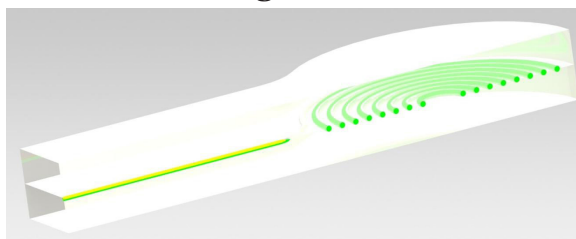


Figure 5.



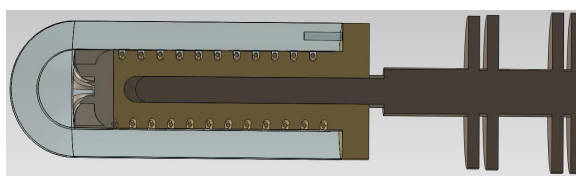
The formation of light emission resulting from the luminescence of an optical cable bent to a specific radius can be achieved through a variety of alternative configurations. One such example is the emitter shown in cross-section in the following image, in which the cylindrical surface of the optical cable begins to emit light when the cable is bent to a predetermined radius.

Figure 6.



The following image presents a structural diagram of the lamp in longitudinal cross-section, clearly illustrating its individual technical components. Each of these components has a specific functional and technical purpose and performs defined technological and conceptual functions within the overall design of the device.

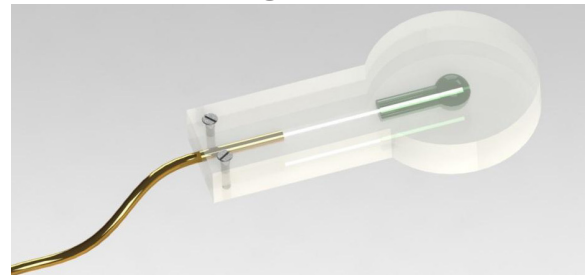
Figure 7.



The proposed design incorporates numerous innovative elements and, most importantly, is fully prepared for serial and mass production. Furthermore, the particular configuration of the lamp, together with the combination of technological principles

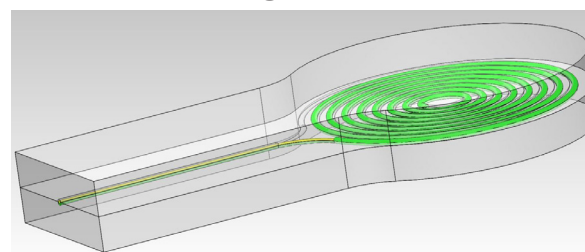
and structural materials employed in its design, provides significant potential for further technological development. The design allows new technical solutions to be integrated into the innovative product as they emerge through the continued advancement of laser technologies, composite-material technologies, and new energy-efficient control and cooling systems.

Figure 8.



The following image shows a miniature lamp in which a phosphor mixture is applied to the end of the optical cable according to a specific geometry within a three-dimensional coordinate system. This configuration provides light emission within the white region of the visible spectrum. The diameter of the optical cable is only 120 microns, making it possible to create micro-miniature light sources for use in highly compact optoelectronic systems.

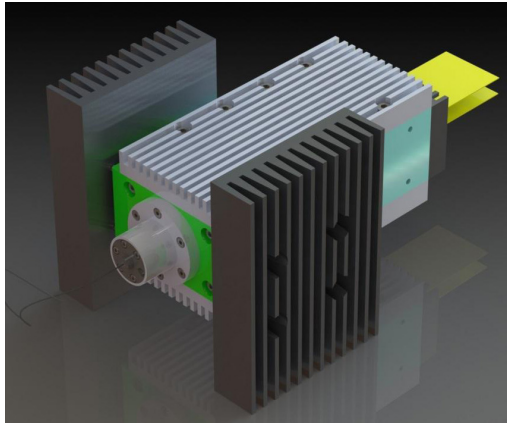
Figure 9.



The following image shows a lamp with a flat light-emitting element connected to a single optical cable. In addition to its overall energy efficiency, this system makes it possible to achieve the required level of illumination over a specified area with minimal resource requirements and maximum structural simplicity. The same system also allows virtually any combination or mixture of phosphor materials to be applied to the flat spiral section at the end of the optical cable,

thereby making it possible to obtain the required spectral and optical characteristics of the emitted light.

Figure 10.



The following image shows a laser diode module designed on the basis of active cooling principles utilizing the heat-dissipation effect of components manufactured from a pseudo-porous diamond–copper composite material.

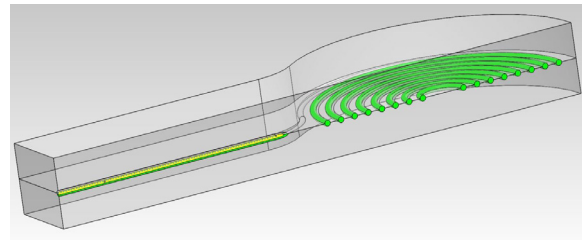
One of the innovative integrative features of the proposed design is the use of **thermo-electric coolers** in combination with the thermally conductive and heat-dissipating structural elements of the module housing.

The thermoelectric coolers are positioned between the external heat sinks and the module housing. The thermally conductive structural elements transfer heat from the printed circuit board (PCB) to the housing walls on which the thermoelectric coolers are mounted. The base surfaces of the heat sinks are, in turn, pressed against the thermoelectric coolers. Where necessary, additional module components requiring continuous cooling may also be mounted on these heat sinks.

Practical experience has demonstrated that reliable cooling makes it possible to achieve a high degree of stability in the output parameters of laser radiation. This, in turn, significantly expands the range of possible module output configurations and, where required, enables the laser radiation to be distributed among several optical cables, each of which supplies light to an individual lighting device.

The most important consideration remains the primary removal of heat directly from the laser diode.

Figure 11.



The image shows models of such devices.

Figure 12.

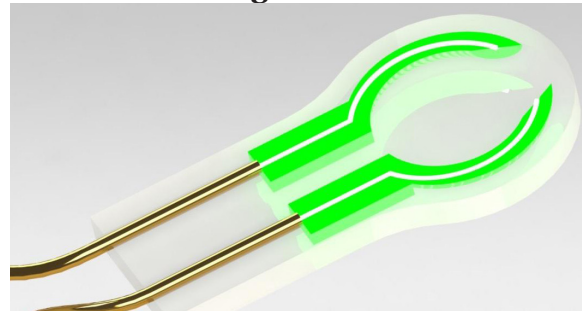
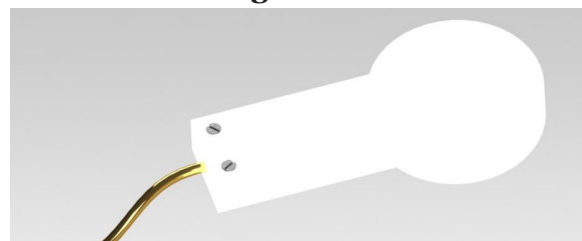


Figure 13.



The presented three-dimensional models show the thermally conductive structural elements that simultaneously serve as the primary mounting components for securing the laser diode within the module housing.

As can be seen from the models, despite its structural simplicity and manufacturability, the laser-diode support disc (highlighted in red in the models) provides comprehensive protection of the laser diode against overheating through a combination of thermal-management factors. As noted above, this significantly improves the operational stability of the module while reducing the amount of energy required for lighting.

The models also illustrate a coding and decoding system that makes it possible to identify the optical cables and corresponding lighting devices connected to the module.

In addition to its primary operating functions, such a system provides a platform for the implementation and control of various

computer-based models for energy management and distribution.

These functions depend entirely on the intended application and operating conditions of the module. Of particular importance for the further development of the proposed concept is the possibility of integrating the software component of the system directly at its most critical functional point.

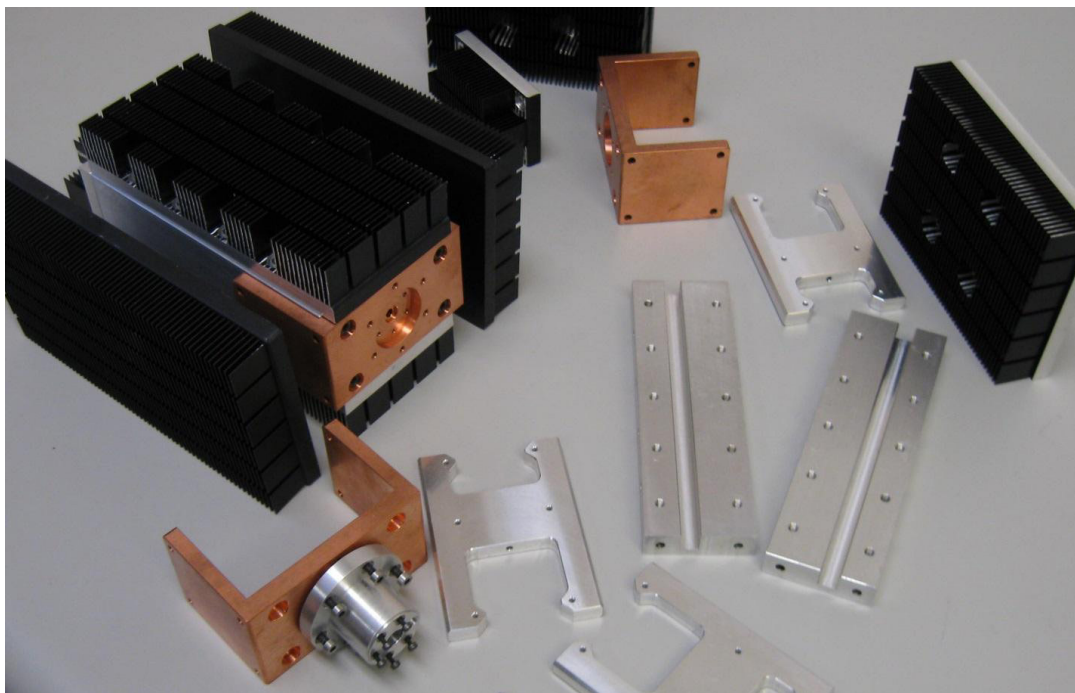
Furthermore, this fundamental approach to the application of new composite materials in novel applications, characterized by unconventional properties and performance characteristics, makes it possible to develop new lighting devices and instruments with parameters that meet the requirements of modern technologies.

It should also be noted that, in addition to advanced composite materials, nature

provides exceptionally valuable natural materials. The application of the approaches described in the publications of Aleksandra Efimova therefore makes it possible to establish a harmonious combination of long-established natural materials with proven engineering and manufacturing techniques.

The conceptual solutions proposed by Aleksandra Efimova also provide opportunities for further technological development. One example is the advancement of carbon – carbon composites, initially produced in fabric form, into solid components manufactured by compressing such fabrics. Components produced in this manner may exhibit highly unusual properties and open up new innovative possibilities in lighting technology and related technological processes.

Figure 14.



The image shows the actual structural components of the innovative laser diode module, including its cooling system and a laser diode holder manufactured from a diamond–copper composite material.

As can be seen from the image, all other components of the housing and cooling system of the laser module are manufactured from standard profiles and conventional materials and do not require any specialized materials or dedicated technological equip-

ment. The components can also be manufactured using standard cutting and measuring tools.

This design can be considered an example of the integration and combination of innovative technical solutions aimed at the efficient and safe conversion of laser diode radiation into safe, high-intensity phosphor emission, while providing virtually complete heat dissipation and minimizing both thermal and optical losses.

All principal output parameters of this integrated lighting system fully comply with the applicable standards and safety requirements.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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DOI:10.29013/EJTNS-26-5-116-125



THE IMPACT OF DIGITAL TECHNOLOGIES ON MODERN TECHNICAL SYSTEMS. (The Impact of Digital Technologies Incorporating Elements of Artificial Intelligence and Artificial Neural Networks on the Form and Characteristics of Modern Technical Systems as Components of Smart-Object Infrastructure)

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Cite: Zhdan A. (2026). *The Impact of Digital Technologies on Modern Technical Systems. (The Impact of Digital Technologies Incorporating Elements of Artificial Intelligence and Artificial Neural Networks on the Form and Characteristics of Modern Technical Systems as Components of Smart-Object Infrastructure)*. European Journal of Technical and Natural Sciences 2026, No 5. <https://doi.org/10.29013/EJTNS-26-5-116-125>

Abstract

The article examines the impact of the intensive development of digital technologies, artificial intelligence, artificial neural networks, and computer-aided design methods on the nature, structure, and principles underlying modern technical systems. As engineered objects become increasingly complex, the number of technical, technological, structural, and functional features defining a particular innovative solution and its subsequent development – from a local subsystem to an integrated technical supersystem – also increases substantially.

Particular attention is given to the classification and identification of innovative technical solutions. The parallel emergence of spontaneously identical or closely related ideas within different development teams, including teams operating in different countries, increases the importance of accurately defining the boundaries of a particular technical solution, its distinctive features, its relationships with other system components, and its position within the overall hierarchy of a technical object. Such identification is directly related to the possibilities for effective and systematic protection of existing and newly created intellectual property.

Keywords: *Modern technical systems; digital technologies; artificial intelligence elements; artificial neural networks; form and characteristics of modern technical systems; component of smart-object infrastructure; spontaneously identical ideas; classification of innovative solutions; classification and identification of innovative solutions; patent protection issues as an increasingly significant element in project development; technical and technological decision-making process; number of facts and distinctive features characterizing a technical solution and its comprehensive development up to the level of a technical supersystem*

The article considers an approach to the classification of modern technical solutions based on the distinction between local technical solutions, subsystems, and technical

supersystems. *Particular attention is paid to the conclusions and definitions presented in the publications of Aliaksandr Achapouski, in which an optimized classification of various types of technical solutions is proposed, taking into account the combination of classical design methodology with modern computer software development methods. The author seeks to correlate the fundamental principles formulated by Aliaksandr Achapouski with the methodology and system of conceptual decision-making used in modern machine design involving digital technologies and elements of artificial intelligence.*

The article emphasizes that the increasing complexity of tasks associated with the development, modernization, and optimization of engineering and technological systems is progressively reducing the practical effectiveness of isolated local solutions. *Achieving the required final result increasingly requires compositional, integrative, and comprehensive solutions that combine individual technical elements and subsystems into a unified, functionally interconnected supersystem. In this context, the terminology proposed by Aliaksandr Achapouski is considered in relation to contemporary processes of integrated technical design.*

Special attention is also given to the influence of computer-aided design methods on the development of technical solutions. Modern engineering software, including the SolidWorks family of design tools, significantly expands the possibilities for analyzing, modeling, and integrating numerous parameters and characteristics of a designed object. As a result, a technical solution increasingly represents not an isolated structural element but a component of a complex multilevel system incorporating mechanical, electronic, software, materials-engineering, optical, and other interconnected components.

The article further addresses issues associated with assessing the novelty, obviousness, and non-obviousness of modern technical solutions. The interdisciplinary nature of contemporary technologies complicates the application of traditional approaches to expert evaluation because innovative developments may simultaneously incorporate achievements in electronics, microelectronics, advanced materials science, fiber optics, laser technology,

software, and other interconnected fields. Under these conditions, a comprehensive assessment of a technical solution requires not only specialized expertise in individual disciplines but also professional competence in their integrated technological implementation.

The article also analyzes the influence of psychological, technological, and structural stereotypes on the innovation process. New technical and technological solutions are often evaluated through established concepts and principles governing the development of industrial technologies, machines, and mechanisms, many of which originated before the emergence of modern materials, electronic components, digital control systems, and laser technologies. This creates a need to improve methods for classifying and identifying technical solutions in accordance with the current level of technological development.

Thus, the systematic classification of technical solutions – from individual local elements and active subsystems to integrated technical supersystems – is considered an important instrument for organizing the modern innovation process, supporting the comprehensive development of technical systems, and establishing effective mechanisms for intellectual property protection. *The approach discussed in the article links the concepts and definitions developed by Aliaksandr Achapouski with contemporary methods of digital design, artificial intelligence, and the comprehensive integration of technologies within the infrastructure of smart objects.*

As can be seen from the figure, the current capabilities of the SolidWorks family of design software make it possible to present a development not only as an assembly unit, but also as a complete set of individual components required for assembling that unit, with visualization of both the individual parts and the complete assembly, taking into account the selected structural materials.

Where a development is conceived as a basic technical solution for a future invention, these capabilities require full coordination with the applicable laws and regulations.

This legislative framework was conceived in the post-war period as a kind of “exact science,” despite the fact that even at that time the inventive community was already addressing an important question concerning

the fundamental importance, for achieving the declared Ideal Final Result (or its equivalent), of having at the core of the development and selection of a new technical solution an individual capable of generating useful and

practically viable ideas. Today, there are sufficient grounds to state that an individual can play a significant role only when equipped with appropriate intellectual tools, primarily software-based tools.

Figure 1. *The figure presents an example of a modern design solution for a system intended for the real-time homogenization of liquids in a pipeline without the use of chemical reagents or stabilizing mixtures*



At that time, it was widely believed that any qualified professional or skilled worker, provided with a coherent and workable theory for solving inventive problems, could generate new ideas and develop them into an actual final result. The Theory developed on this scientific, technical, and, to a certain extent, psychological foundation was therefore received with considerable interest by the professional community.

For a certain period, its principles and methods generally corresponded to the existing level of technological and engineering development. The first significant discrepancies became apparent with the introduction of automated production lines into practical manufacturing processes, followed by computer numerical control (CNC) machine tools and, ultimately, digital technologies combined with innovative materials science and composite materials.

Returning to the optimized and modified definitions and classification terminology for technical solutions and the technical systems

of all levels incorporating such solutions, developed by Aliaksandr Achapouski, it should be emphasized that, even apart from the importance of this work for the various stages of project development, the clear and unambiguous definitions proposed by Aliaksandr Achapouski have significantly systematized the preparation of documents that are essential for new engineering and design projects. These include Technical Specifications, Technical Requirements, and, based on their content, Technical Assignments for new and innovative developments, while maintaining the highest possible degree of compliance with applicable standards at all levels.

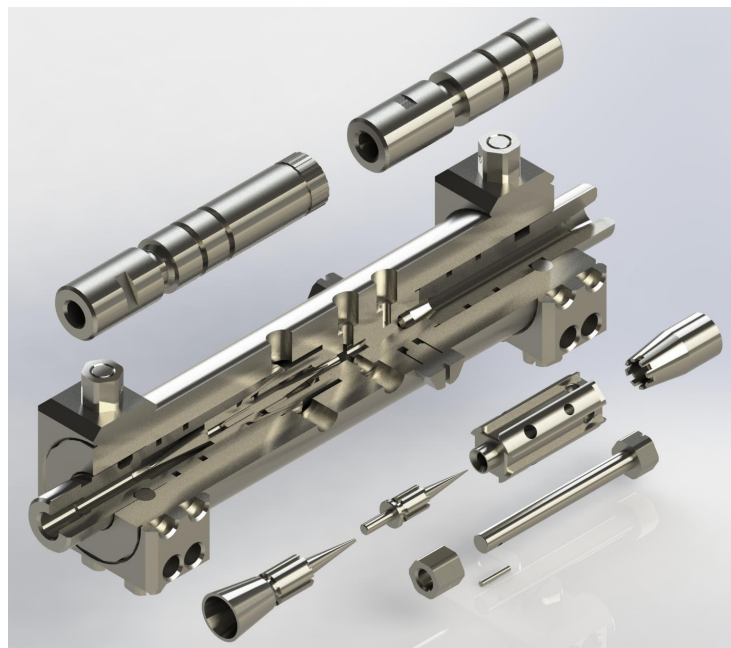
What does this legislation actually represent in contemporary development practice? How have modern high technologies and processor-based technologies influenced its compositional and integrative capabilities?

These are not the only questions that need to be clarified. One important factor that should be noted is the widespread practice of conducting detailed and in-depth search-

es within biological systems and biological and related medical objects for relevant and workable analogues of future inventions, particularly on the basis of biological aspects

of mechanical research. How does this approach correspond with the laws, methods, and techniques applied today?

Figure 2. *The figure presents the same project as shown in Figure 1, but with sectional views providing a complete representation of the internal structure of the technical solution and the geometric requirements for its components. These are, of course, not all the capabilities of modern computer-aided design software; however, the application of appropriate principles, definitions, and methods in combination with such software can further enhance the efficiency of new innovative developments, while simultaneously significantly reducing design costs and the time required for the development process*



At present, many interesting and effective inventions arise from discoveries and the systematic analysis of particular elements of living nature, which inspire and encourage inventors to develop increasingly sophisticated, comprehensive, and integrative technical solutions. Such solutions address unusual problems through unconventional methods and techniques, often derived from the principles governing the development of living systems and, owing to the capabilities of today's digital technologies, modeled and subjected to systematic simulation before the initial technical requirements and technical specifications are formulated and the inventive task is assigned.

Today, numerous examples of this kind can already be cited. Most importantly, the process of developing new methods and approaches to computer-aided design continues to evolve and expand in accordance with

the constantly increasing capabilities of computer hardware and corresponding software.

For inventors and developers, it has proved both extremely important and particularly difficult to clearly define numerous parameters and relationships, since work of this kind was being performed for the first time and no relevant preliminary developments existed.

The application of methods recommended and regulated by the applicable legislation, despite the fact that this type of integration had not been implemented in previous developments, made it possible to create a fundamentally new product that came close to achieving the Ideal Final Result.

This, in turn, immediately resolved a number of technical, innovative, and integration-related problems and made it possible to achieve complete autonomy of the object under development.

At the same time, the autonomous operating time of the object proved to be practically unlimited.

Thus, overcoming a multidisciplinary conglomerate of technical problems, combined with a certain psychological barrier, made it possible to proceed to the remaining design tasks through comprehensive, integrative, modified, and optimized methods and techniques.

The integration methodology described above, as applied to the synthesis of an innovative technical solution, is currently the focus of a range of organizational, technical, technological, scientific, and engineering activities.

To a certain extent, answers to these questions are provided by the latest methods for utilizing the capabilities and advantages of modern computer-aided design software.

Such depth and detail in engineering development, even at the preliminary design stage, make it possible to use initial exploratory versions of models to perform a complete cycle of computer modeling and simulation of the device's operating cycle, without the need to manufacture physical prototypes for testing.

Moreover, eliminating the need for a dedicated budget to verify a conceptual model can significantly reduce development time and make substantially greater resources and time available for the synthesis of innovative technical solutions aimed at developing and optimizing all project characteristics.

Within the framework of these capabilities, the system of psychological relationships between technology and equipment developers and investors also changes significantly. The fear of making a mistake is largely removed from these relationships because modeling and simulation of all processes occurring within a device make it possible not only to identify and analyze errors, but also to suggest alternative and potentially more effective directions for further project development.

For analytical consideration, let us adopt the following formulations of the laws of technical system evolution according to the modern classification:

1. Law of Completeness of the Parts of a System.

2. Law of Increasing the Degree of System Ideality.
3. Law of Displacement of the Human Being from the Technical System.
4. Law of Coordination of the Rhythms of System Parts.
5. Law of Energy Conductivity of a System.
6. Law of Uneven Development of System Parts.
7. Law of Transition from the Macro Level to the Micro Level.
8. Law of Increasing the Degree of Substance-Field Interactions.

Let us also adopt the modified classification of technical systems proposed by Aliaksandr Achapouski in his publications:

1. Technical System.
2. Local Technical System.
3. Developed Technical System.
4. Global Technical System.
5. Smart Technical System.

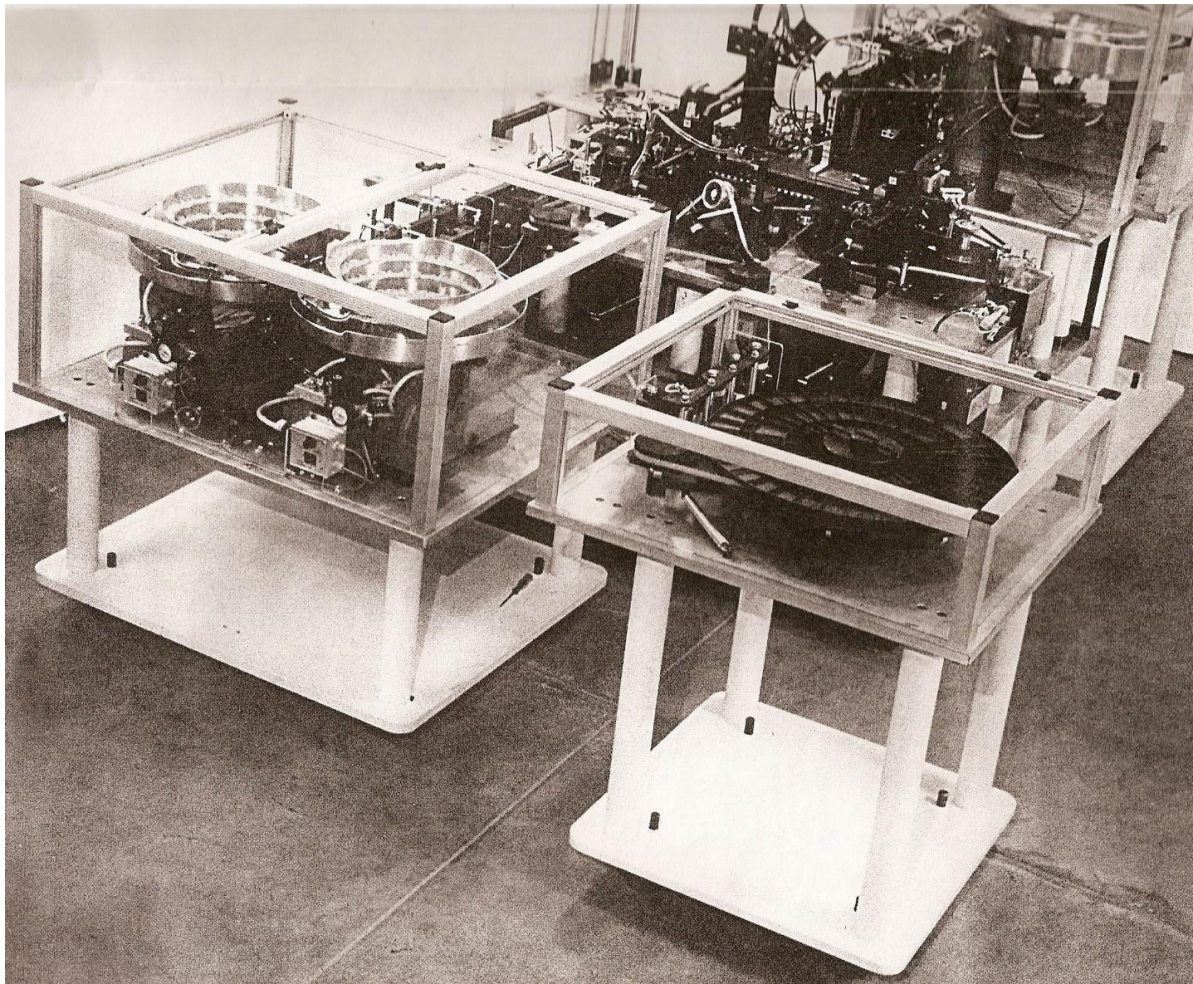
It is now appropriate to return to examples of specific contemporary developments, taking into account the above comments concerning the laws of technical system evolution, as well as the modifications to the definitions and classifications proposed in the publications of Aliaksandr Achapouski.

The operating cycle of each module is synchronized with the step (operating cycle) of the assembly module – the conveyor. This applies both to the vibratory hopper modules traditionally used in such systems (shown on the left in the figure) and to fundamentally new modules for stamping contacts and feeding them to the assembly and inspection conveyor (shown in the center).

This configuration of an automated robotic production and assembly complex can be classified as a Technical System with a fixed production cycle, in which all technological modules of the complex are synchronized with the operating step of the assembly module – the conveyor.

Within this configuration, the technological modules perform the functions of subsystems, while the assembly module – the conveyor – performs the function of the principal supersystem, with the production cycles of the subsystem modules being synchronized with its production cycle.

Figure 3. *The figure presents the technological modules of an automated robotic production and assembly complex designed for the autonomous manufacture of contact blocks for telephone lines. As can be seen in the photograph, the complex comprises four main technological modules, three of which are modules for preparing parts and components for assembly and are arranged around the assembly module – the conveyor*



As can be seen in the figure, although the assembly complex contains a considerable number of points of interaction and requirements for synchronizing production cycles, it does not incorporate any specific regulatory requirements aimed at increasing the flexibility or adjustability of the modules' production cycles.

Such a configuration is characteristic of integrated technological solutions operating with a constant working cycle that does not need to be adjusted or modified during the production process.

Accordingly, such complexes do not inherently require computerization and can operate successfully within an automated production cycle involving the mass production of standardized products.

For a Technical System performing tasks of this kind, all definitions applicable to a classical Technical System remain unchanged. The definitions and classification methods applicable to the components of such a system – the supersystem and subsystems – also remain unchanged.

With regard to the specific structure and characteristics of the automated robotic production complex, it is necessary to note certain elements of fundamental novelty in both the overall technological configuration of the complex and the characteristics of the product manufactured by it.

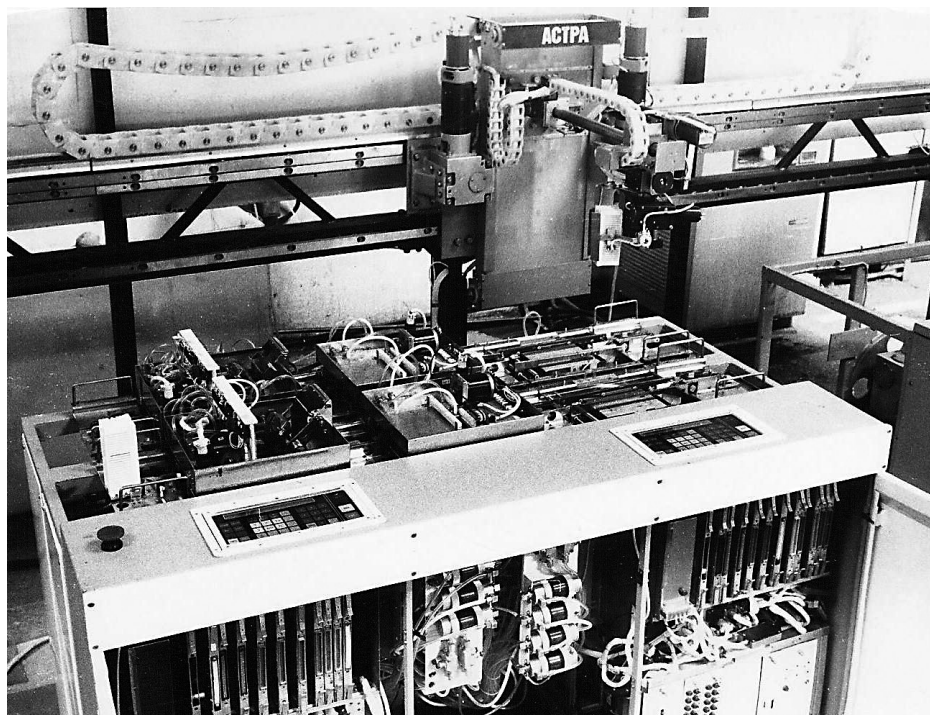
This primarily concerns the specific design and production of the contacts used in the contact blocks.

As can be seen in the figure, a strip made of a special bronze alloy with a high beryllium content is not immediately stamped into finished contacts within the stamping module. Instead, it is initially formed and partially cut along the contour of the contact. The strip is then transferred to another module, located on the opposite side of the assembly module – the conveyor – where it is finally formed into paired contacts and inserted into the corresponding conveyor cells in which the plastic components of the contact block have already been positioned.

For complexes of this type, this represents a fundamentally new technical solution that makes it possible to maintain a constant production rate for the contact blocks without requiring intermediate real-time inspection.

For the classification of a modern automated robotic production and assembly complex designed for the autonomous manufacture of contact blocks for telephone lines, the updated definitions of Technical Systems and their constituent elements, developed and proposed by the well-known researcher and innovation specialist Aliaksandr Achapouski, may be applied.

Figure 4. *The figure presents a version of a flexible photolithography processing module for thin-film microassembly substrates. The module includes two parallel technological process lines, and it should be noted that each process line is fully autonomous, including the independence of their integrated computer control systems. In addition to these systems, the module also includes a computer control and monitoring system for the robot operator, which is functionally connected to the integrated computer control systems*



The specified module comprises several closely interconnected functional technical systems, each of which can be classified as a supersystem. The combination of these systems includes loading and unloading modules, local loading and unloading units, tracks, centrifuges, dispensing and delivery units for supplying chemical reagents and photoresist to the processing zone on the centrifuge table, control systems, etc.

The track comprises several centrifuges: a processing station for surface preparation prior to coating, a processing station for electroplating, and a processing station for final treatment of the substrate after coating deposition.

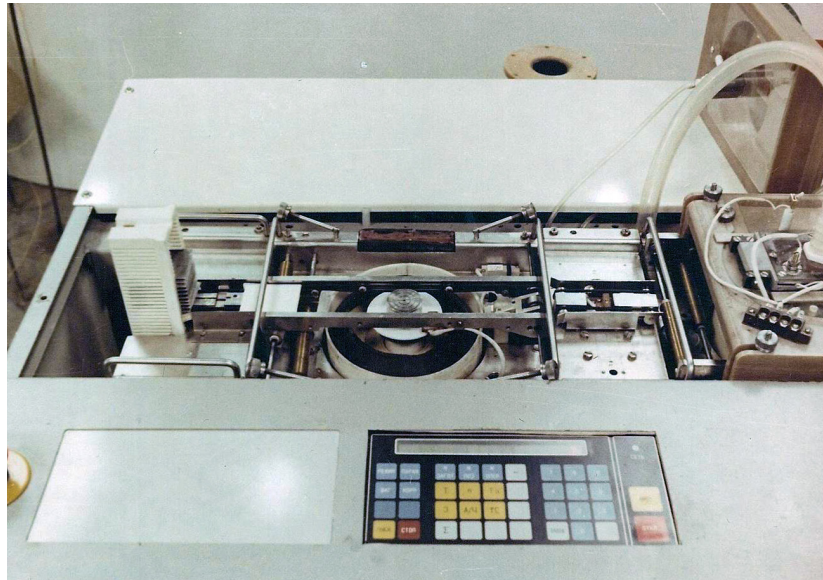
The system is fully automated and is controlled and monitored by programmable processors connected to the power supply for the electroplating process, with flexible reg-

ulation of the current density depending on the coating area and thickness.

The system has two processing lines, one of which is shown in the figure. The system

is operated, regulated, configured, and monitored by means of several programmable controllers, with data, programs, and commands entered via a touchscreen interface.

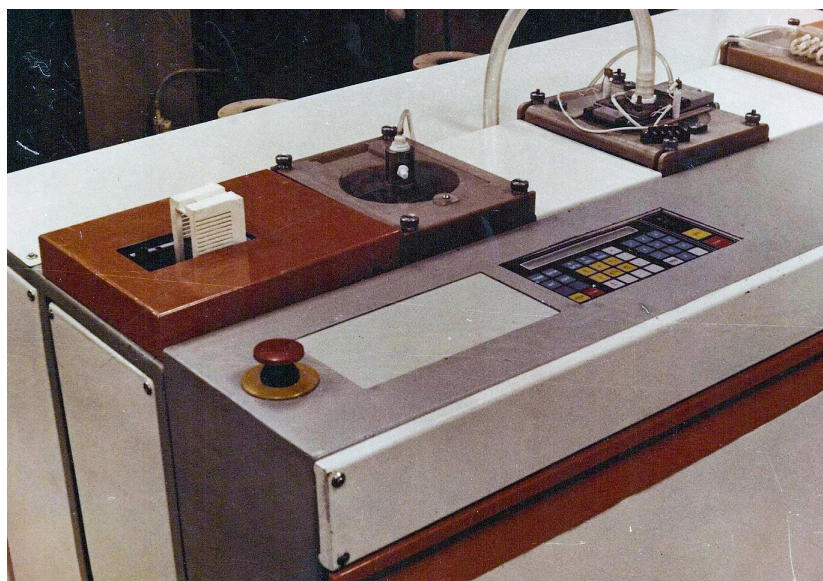
Figure 5. *The figure shows the processing track of an electroplating system for thin-film microassembly substrates. The processing track includes autonomous substrate loading and unloading units installed at the process inlet and outlet*



It should be noted that similar engineering solutions are implemented throughout the specialized process equipment used in the photolithography production line for thin-film microassembly substrates. These

solutions are based on technical systems of the same general type, with fundamental differences primarily in their software infrastructure.

Figure 6. *The figure shows an automatic electroplating system for thin-film microassembly substrates used in semiconductor manufacturing. The system consists of two process lines and provides flexible and independent control and monitoring of each line. The system is designed for integration into flexible in-line processing modules, which, in turn, can be integrated into higher-level systems*

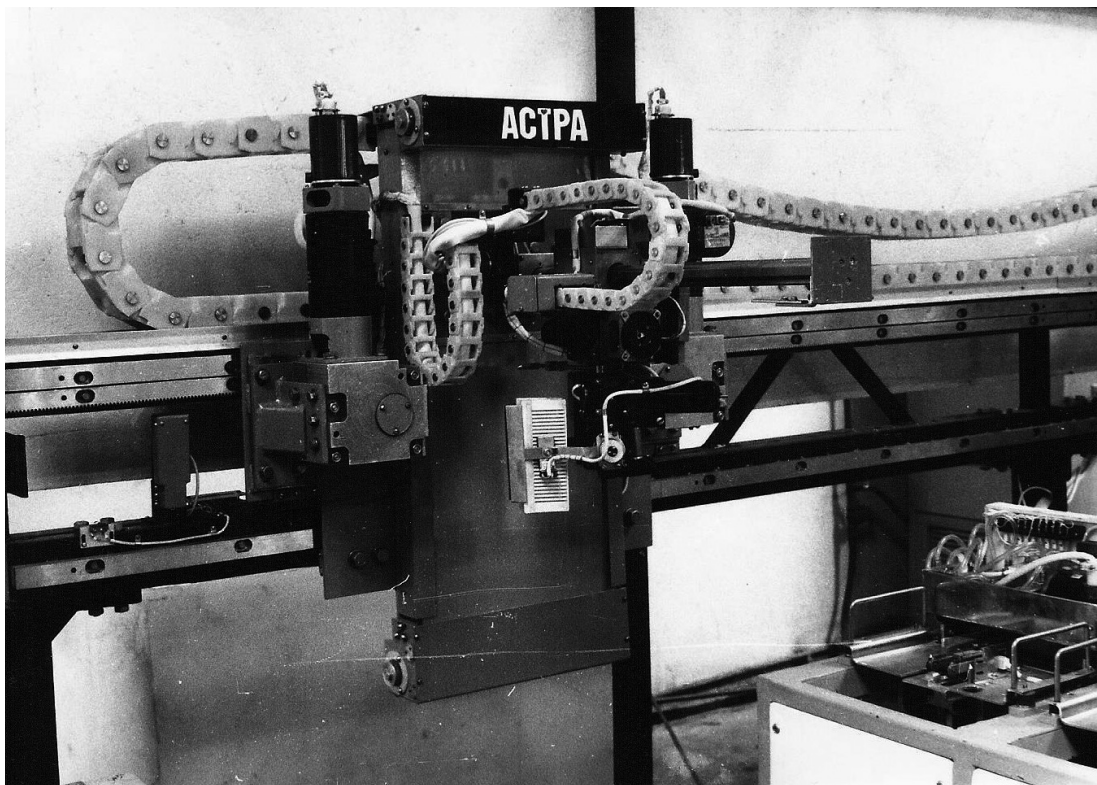


As can be seen in the figure, thin-film microassembly substrate blanks made of special-purpose ceramic material, measuring 48×60 mm, are contained in cassettes positioned at the beginning and at the end of the process line.

Thus, no operator involvement in the process is required, since all loading and un-

loading operations are performed by a robot operator, while all operations and the sequence of control commands are monitored and controlled by a programmable processor, which is accessed through a touchscreen control panel.

Figure 7. *The figure shows a flexible automated processing module viewed from the side of the input units, onto which the loading/unloading robot places a cassette containing thin-film microassembly substrate blanks*



The robot manipulator grips the cassette from a storage cell, transfers it to a position aligned with the table of the input unit, then lowers the cassette until it comes into contact with the table and secures it in position.

The combination of local technical systems shown in the figure can be classified as a combination of subsystems interconnected within a local, yet nevertheless integrated, supersystem by means of a specific flexible algorithm governing the entire integrated and sequential process: locating the cassette,

identifying and gripping the cassette, transferring the cassette, orienting its position in three dimensions, vertically aligning the cassette, identifying the cassette on the table of the loading/unloading input unit, and finally securing the cassette on the table, followed by the transfer of operational functions to the conveyor track.

All of the above operations simultaneously constitute the technical requirements for the development of the corresponding software.

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submitted 15.09.2026;
accepted for publication 29.09.2026;
published 30.09.2026
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