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# MODELLING EVOLUTIONARY CYBERNETICS: ONTOLOGY, INVARIANTS AND DESIGN PRINCIPLES

*Evolutionary cybernetics (EC) is presented as a general discipline for steering change in technical, biological and socio-technical systems under uncertainty. Unlike classical control with fixed goals and architectures, EC assumes that goals, constraints and structures may themselves evolve. The paper contributes: (i) an ontology of EC with four levels (object, process, mechanism, meta-control) and a two-loop organization (operational vs. evolutionary); (ii) a set of cybernetic invariants-information, resource constraint, regulation, structural organization, temporality, integrity/openness, teleonomy — that summarize cross-domain regularities; (iii) a formal model of an evolutionary cybernetic system and operators for meta-level updates; (iv) methodological principles and functional requirements for engineering EC systems (modularity, guided diversity, pace orchestration, default safety, ex-ante verification*

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*and post audits); and (v) application tracks in socio-cybernetics, bio-/neuro-interfaces, infrastructure, and sustainability governance. Modern AI (safe RL, control-theoretic shields) and digital twins are positioned as one practical realization of the evolutionary loop rather than its essence. EC thus provides a coherent conceptual and engineering framework for the directed evolution of complex systems.*

***Keywords***: *evolutionary cybernetics; directed evolution; meta-control; two-loop control; cybernetic invariants; co-evolution; digital twins.*

## Introduction

The development of universal theories of control throughout the 20th century initiated the formation of an interdisciplinary approach to analyzing systems of different natures — from technical and biological to socio-technical and hybrid. A landmark event in this process was the emergence of cybernetics, formulated by Norbert Wiener as the science of control and communication in living and nonliving systems [1]. The methodological core of cybernetics was based on modeling information flows, feedback loops and invariant regulatory principles [2]. Classical cybernetic models effectively described processes of stabilization and optimization, but relied on a fixed controller architecture and predetermined objective functions [3]. In such models, changes in a system's structure were viewed as external influences rather than the result of its internal dynamics.

A significant contribution was made by Victor M. Glushkov, who developed the concept of automated control systems due to integration of cybernetic principles and algorithmic adaptation methods. His approach initiated a transition from deterministic schemes to flexible architectures. This made possible to make such systems capable of modifying their own configuration during operation. Even though this expanded the adaptive potential of technical systems, the question of evolutionary mechanisms of control structures was still outside the scope of systems analysis.

In parallel, biology formed an evolutionary paradigm based on the combination of Darwinian selection, genetics and population dynamics. This paradigm conceptualized the role of variation, heredity and selection in shaping the fitness of organisms, but it did not envision the possibility of purposeful management of evolutionary processes by the system itself. Biological models of evolution remained limited to the domain of living entities and did not account for the existence of goals in the cybernetic sense, which made their direct application to technical or socio-technical systems difficult.

An attempt to transfer evolutionary principles into the context of engineering and computer science [4–6] occurred in the second half of the 20th century thanks to the works of John Holland. The genetic algorithms he proposed and their subsequent modifications (evolutionary strategies, genetic programming) became a powerful tool for search and optimization in complex solution spaces, especially where analytical methods proved impractical and the topology of the space was highly complex. However, even in modern implementations these algorithms are oriented primarily toward solving fixed problems, not encompassing changes in the very principles of control or the evolution of a system's goals [7–8].

In the Ukrainian intellectual tradition, the ideas of Vladimir I. Vernadsky played a significant role [9]. He viewed the noosphere as a new state of the biosphere in which scientific and engineering activity become factors of planetary evolution. Despite its philosophical character, this concept created a methodological context for studying the interaction of biological and technical processes within a single system. A further step toward establishing the theoretical foundations of evolutionary cybernetics as a new, timely branch of general cybernetic science was taken by the followers of Glushkov's and Vernadsky's ideas — scientists of the world-renowned V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine — whose research in the field of intelligent systems and hybrid control models demonstrated the possibilities of integrating logical formalisms, artificial intelligence methods and cybernetic principles in order to create systems with a high level of autonomy and coadaptation [10–13].

All of these historical facts and theoretical positions form a rich but fragmented knowledge base regarding problems of control, adaptation and optimization of systems. At the same time, a methodological niche remained open: the specification and control of goal changes, architectures and regulatory principles of the controlling structures themselves in response to variability of the external environment and the controlled object.

Therefore, the knowledge accumulated over recent decades, that includes classical control models, natural evolutionary mechanisms and artificial optimization methods, shows high effectiveness in their individual domains. However, none of these approaches managed to provide a holistic theoretical and methodological foundation, where evolutionary changes of control structures, goals and regulatory principles would be integrated elements of system dynamics. This creates prerequisites for the formation of a new level of interdisciplinary synthesis capable of overcoming existing methodological gaps and ensuring the adaptability of systems in the context of uncertainty and long-term evolutionary interaction.

## 1. Interdisciplinary Synthesis and Methodological Limitations of Modern Approaches

Modern science is in a stage of deep integration, where traditional disciplinary boundaries between the natural, technical and information sciences are becoming less rigid. Modeling tools initially created for describing physical or technical systems today are successfully applied in biology, cognitive sciences and economics, and methods from bioinformatics, machine learning, and network theory are increasingly implemented in the design of engineering and socio-technical systems. This process can be characterized as structural convergence — not only the borrowing of individual methods, but also the convergence of research paradigms at the

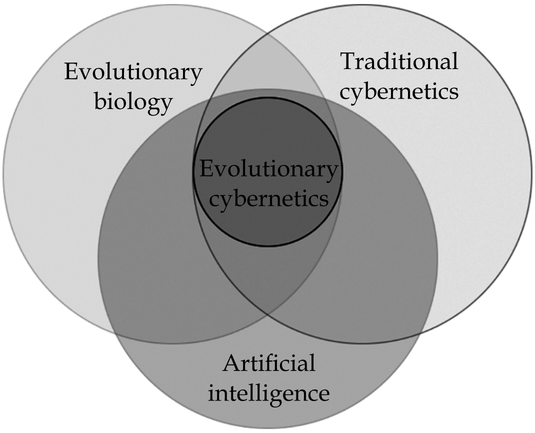

***Fig. 1.*** The interdisciplinary position of evolutionary cybernetics in the landscape of related sciences

level of models, ontologies and types of abstractions.

Despite an intensive exchange of ideas, there is an absence of a single formalism for describing systems, capable of changing their own goals, regulatory principles and control architectures in response to the environment. Existing approaches cover only separate aspects of this problem:

- Network models of complex systems effectively represent structural interconnections and the spread of influences, but for the most part ignore the dynamic change of the rules by which the network operates [14].
- Synergetics describes self-organization, interdisciplinary interaction and transitional processes, but does not include developed mechanisms for purposeful restructuring of system parameters [15–16].
- Evolutionary computation demonstrates high efficiency in searching for solutions in complex spaces, but its dynamics are usually constrained by predefined optimality criteria, a limitation by earlystructure-generating models of self-reproducing automata [17].

Fig. 1 illustrates the conceptual spot of evolutionary cybernetics among related disciplines. Evolutionary cybernetics located at the intersection of three fundamental fields: traditional cybernetics, which provides the theoretical apparatus for describing and controlling information processes; evolutionary biology, which provides mechanisms of variation, heredity and selection; artificial intelligence, which provides algorithmic and computational methods for realizing adaptive changes. The integration of these fields creates an unified formalism for modeling and controlling evolutionary processes in technical, biological, social, hybrid systems, stopping treating them as individual disciplines and forming a new scientific paradigm.

A comparison of the key characteristics of existing approaches versus the proposed direction of evolutionary cybernetics is outlined below in Table 1.

Thus, even in the interdisciplinary field of knowledge there is no unified approach that would consider the evolution of control structures as an independent, relevant scientific subject of research. This creates a methodological gap between control theories and theories of purposive change.

To fill this gap, a framework concept of directed evolution of systems is proposed, in which:

*Table 1.* **Comparison of key features of existing approaches**

| Category | Traditional cybernetics | Evolutionary biology | Evolutionary algorithms (AI) | Evolutionary cybernetics (emerging field) |
|---|---|---|---|---|
| Object of study | Control systems and feedback loops in technical, biological and social systems | Living organisms, populations and genetic and phenotypic changes | Algorithmic models of optimization and search | Evolutionary processes in control structures, information flows and regulatory loops of systems of any nature |
| Type of changes analyzed | Changes in system states under a fixed structure and fixed goals | Changes in genetic information and phenotype | Changes in parameters or solution structure for a fixed problem | Changes in the control architecture, principles of regulation and the system's own goals |
| Scale of application | Primarily technical or bio-technical systems. | The biosphere and individual populations | Algorithmic problems and computer simulations | Technical, biological, socio-technical, bio-hybrid systems within a unified formalism |
| Role of evolution | Secondary, as a factor of external changes | The natural mechanism of the development of life | A method of optimization | A central control process in cybernetic terms |
| Goal rigidity | Goals are usually specified in advance | Goals are absent as a cybernetic concept | The objective function is fixed | Goals can evolve together with the system |
| Methodological foundation | Control theory, information theory | Genetics, ecology, paleontology | Computational models and stochastic methods | Integration of control theory, network dynamics, informa-tion theory, concepts of directed evolution |
| Unique research problems | Stability, robustness, optimal control | Description and explanation of natural evolutionary processes | Search for an optimum in a given solution space | Meta-evolution of control algorithms, symbiotic cyber-biological systems, evolutionary resilience of control loops, evolution across multiple temporal scales |

- The object of research is the processes of intentional change of control structures in systems of any nature (technical, biological, socio-technical, hybrid).
- The subject is the mechanisms and algorithms for modifying control architectures, goal functions and principles of regulation under changing environments.
- The methodological basis is the integration of models from control theory, evolutionary algorithms, synergetics, network dynamics and information theory.

The key difference of this approach lies in embedding evolutionary operators (variation, selection, coadaptation, symbiosis) directly into the system's regulatory loops, making them instruments of purposeful design.

The practical implementation of this concept involves:

1. Developing a formal apparatus for describing and forecasting the dynamic change of control architectures and their goals.
2. Designing universal evolutionarily managed models suitable for technical, biological and hybrid systems.
3. Integrating with experimental platforms that allow hypotheses to be verified in multi-level environments.

Thus, the task of this new scientific field is to shift from the analysis and modeling of adaptation to the systematic design of processes of directed evolution, which opens possibilities for creating self-developing, autonomous and long-lived systems.

## 2. Structure and Research Trajectories of Evolutionary Cybernetics

Evolutionary cybernetics is emerging as a distinct interdisciplinary domain. Its primary objective is the synthesis of control methodologies, evolutionary mechanisms and adaptive algorithms into an unified body of knowledge. This comprehensive framework is designed to both model and facilitate the development of directed evolution across systems of diverse character. The discipline's theoretical foundation is established by integrating concepts from cybernetics, the theory of complex systems, evolutionary biology, artificial intelligence and synergetics. Unlike classical paradigms, evolutionary cybernetics regards variation, selection, coadaptation, and symbiosis as deliberately designed operators integrated into the regulatory loops of a system, rather than as spontaneous or external processes.

Structurally, the scientific field of "evolutionary cybernetics" can be presented as a set of interrelated subdivisions, each corresponding to a certain level or domain of controlled evolution:

1. Theoretical foundations of evolutionary cybernetics — the development of mathematical formalisms and conceptual models that describe the dynamics of goalchanges, architectures and principles of regulation in control structures. Particular attention is paid to informational-entropic criteria of efficiency of evolutionary processes.

2. Cognitive cybernetics — the management of processes of knowledge extraction, transformation, and use in artificial, biological, hybrid systems. Its tasks include simulating the development of cognitive architectures and decision-making protocols, harmonizing diverse knowledge streams and refining the cooperation between artificial and biological intellects. For example, the creation of intelligent agents that can learn and support during the decision-making is a part of cognitive cybernetics. Advances in this sphere allow purposeful influence on the evolution of knowledge and consciousness of both individuals and society as a whole.

3. Socio-cybernetics and organizational evolution — the study of the dynamics of social and socio-technical systems. Specifically, this research investigates the co-evolutionary patterns of agents operating in networks, the modification of governing frameworks and the use of algorithmic methods to manage collective thought processes. In terms of evolutionary cybernetics, social cybernetics is responsible for socio-cultural evolution: how societies change under the influence of new technologies, knowledge and values, and how these changes can be steered for the common good. Models of social dynamics, decision-support systems for governance, and scenarios of civilization development are developed to enable guided social transformations that take into account feedback between the economy, ecology, demography and other subsystems of society.

4. Bio-cybernetics with an evolutionary loop — the implementation of controlled evolutionary mechanisms in biological and bio-hybrid systems, including managing the evolution of microorganisms, adaptive biomedical technologies and modeling "human–machine symbiosis" systems. Bio-cybernetics also considers possibilities for the purposeful intervention in biological evolution and the development of living systems. This includes modeling processes in ecosystems, managing gene pools (through methods of genetic programming or selective breeding) and supporting the sustainable development of the biosphere. Bio-cybernetics forms the foundational basis for disciplines like synthetic biology and biomedical engineering. These applied fields, in turn, furnish the necessary instrumentation and methods required for exerting control over living systems. Additionally, this subdivision encompasses medical cybernetics — the application of cybernetic approaches in medicine and healthcare. Its contribution to evolutionary cybernetics is in managing the development of humans as bio-social systems. This involves monitoring and correcting the health state of populations, extending life expectancy and steering human evolution through medical technologies (from public health to human bioengineering). Medical cybernetics makes it possible to predict and ensure the formation of a healthy nation and to develop evolutionary strategies for human development (for example, adapting society to increasing longevity, implementing cyborgization technologies etc.).

5. Techno-cybernetics and robotic evolution is about the creation of technical systems, capable of changing their own architecture and goal functions. Directions include self-configuration of hardware and software

platforms, evolutionary design of robotic complexes and co-evolutionary learning of autonomous systems. Within the evolutionary paradigm, technical cybernetics is concerned with the evolution of the technosphere: controlling the development of network infrastructures, the Internet, artificial intelligence and technological platforms. Specifically, this involves steering the advancement of sophisticated technological platforms and AI systems. The aim is to ensure that these emerging technologies progress in alignment with pre-established objectives and rigorous safety parameters.

6. Network and infrastructure evolutionary systems involve guiding the long-term development of expansive distributed infrastructures. The core focus is on refining the topologies and functional linkages within systems like communication networks, energy grids and large transport complexes. This optimization is carried out while inherently factoring in principles of self-restoration and autonomous development.

7. Evolutionary computing in management focuses on designing algorithms specifically for implementing directed evolution. Key developments include multi-agent evolutionary methods featuring adaptive selection criteria, techniques for dynamically modifying objectives in real-time contexts, hybrid frameworks that fuse evolutionary, cognitive and network strategies. Ultimately, this area delivers the practical algorithmic instruments necessary to embed evolutionary mechanisms directly into system control loops.

8. Ethical and safety aspects involve crafting the guiding principles for the secure evolution of autonomous and hybrid systems. Key areas include developing ethical governance methods for agents whose objectives can change, alongside formulating strategies to avert scenarios of uncontrolled development. Since modifying the goals and architectures of autonomous systems presents profound ethical challenges, the work in this subdivision is dedicated to guaranteeing that system evolution remains under strict supervision and upholds elevated standards of human values.

The integration of all these sub-domains is crucial for establishing an unified field of research. Within this framework, evolutionary mechanisms are no longer merely subjects of description or simple optimization tools; they are transformed into controlled instruments for system design and progressive development. This convergence unlocks considerable potential for engineering systems that are autonomous, self-evolving and exceptionally durable. Such systems would be capable of operating successfully even when facing significant environmental uncertainty and high levels of structural change.

## 3. Theoretical and Methodological Foundations of evolutionary Cybernetics

**3.1. Formalization of the concept of "evolutionary cybernetics".** Evolutionary cybernetics (EC) is defined as an interdisciplinary scientific area dedicated to investigating the core principles, underlying mechanisms and various models of directed evolution within systems of diverse origins, including technical, biological, socio-technical and bio-hybrid entities. Its ontology comprises a structured system of concepts that articulates the essential entities, their properties (attributes) and the relationships required for a description and engineering of evolutionary processes. The goal of establishing this ontology is to develop an unified conceptual framework capable of harmonizing theoretical models, algorithmic methodologies and practical applications.

The multi-level structure of the EC ontology includes four interrelated levels:

- Object level — describes systems and their components (control structures, control objects, environment).
- Process level — captures the dynamics of change (operational, adaptive and evolutionary processes).
- Mechanism level — specifies the evolutionary operators (variation, selection, coadaptation, symbiosis, differentiation) and techniques used for their implementation.
- Meta-control level — outlines mechanisms for altering the rules, goals and control architectures (meta-evolution).

Within this structural framework, the central entity is thecontrol structure, which mediates the system's interaction with the control object and the environment through two primary channels:

- Functional loop — the implementation of objective functions under current conditions, oriented toward stability and performance.
- Evolutionary loop — the modification of goals, regulatory principles and the control architecture in response to changes in the external or internal environment.

A distinctive feature of EC is the presence of a meta-level of control that allows a system not only to adapt to conditions, but also to purposefully change its own control mechanism. At this meta-level four types of changes are possible:

- ■ Structural — involves re-architecting the system, specifically altering the organization and connections (topology) of its components.
- ■ Functional — modifying the algorithms and operational strategies by which the system operates.
- ■ Goal-oriented — revising or reinterpreting system's goals and criteria of optimality.
- ■ Ontological — updating the model of the environment and the system's own role within it.

The key classes and entities of the EC ontology include:

- System — an integral entity with a specific architecture, defined functions and clear goals that interacts with its environment.
- Control structure — the subsystem responsible for establishing goals, strategies and means of control.
- Control object — a component or external entity that is the target of influence.

- Environment — the external context that dictates possible states and influences the system's development.
- Evolutionary process — a sequence of modifications in the properties and structure of the system.
- Evolutionary operator — a formalized mechanism of change that implements variation, selection, recombination, symbiosis etc.
- Meta-evolution — the overarching process of altering the principles by which the system's evolution is conducted.

The relationships between these entities are formalized as follows:

- ▪ The system has a control structure.
- ▪ The control structure executes evolutionary processes through evolutionary operators.
- ▪ An evolutionary process changes the system's parameters, architecture and goals.
- ▪ The environment influences the evolutionary process and is in turn changed by it (co-evolution).
- ▪ Meta-evolution adjusts the evolutionary operators and determines new goals.

Attributes of the key concepts include:

- System: measured by the size of its state space (dimensionality), level of autonomy, time scales of response.
- Environment: characterized by the pace of change, stochasticity, structural complexity.
- Evolutionary operator: described by its operational speed, scope of changes, probabilistic characteristics.
- Meta-evolution: defined by the frequency of updates, degree of predictability, impact on system stability.

In essence, the ontology of evolutionary cybernetics functions as a conceptual blueprint for the entire subject area. It effectively integrates the description of system structures, processes and change mechanisms into a single, cohesive body of knowledge.The implementation of this ontology creates a basis for the mathematical formalism and algorithmic solutions that will be considered in subsequent sections.

**3.2. Paradigms of evolutionary cybernetics.** Establishing a new scientific direction requires clearly defining its methodological orientations. The paradigms of evolutionary cybernetics reflect fundamental tenets that outline its differences from classical cybernetics and related disciplines. They set the conceptual boundaries within which the analysis and design of directed evolutionary processes unfold.

- Directed evolution as a subject of control. Evolution is viewed not as an external backdrop, but as a target object of control: not only the states of the system change, but also its rules, architectures and goals. This extends classical cybernetics beyond stabilization/optimization to the construction of developmental trajectories for systems of different natures.
- Two-loop control. Besides the functional loop (operational implementation of current goals), there exists an evolutionary loop that read-

justs goals, architecture, criteria and control procedures. This organization provides closed feedback both at the level of action and at the level of changing the "rules of action".

- Meta-control (meta-level). Beyond parameter adaptation, there is a level for changing the rules of adaptation: selecting evolutionary operators, their intensity, update frequency and safety constraints. This enables the self-development of the control subsystem in response to changes in the object, environment and value-goal framework.
- Co-evolution with the environment. The system and the environment mutually shape one another. Therefore, appropriate goals and strategies should minimize structural misfit between the control architecture and the environment's dynamics, maintaining co-ordinated development.
- Multi-levelness and multi-scalability. Evolutionary changes occur at different levels of organization (components, architecture, goals, ontology) and on different time scales (operational, tactical, strategic, civilizational). The synchronization of these scales is a prerequisite for sustainable development.
- Informational adequacy and reflection. The effectiveness of evolutionary control depends on sufficient observations and the quality of ontologies. These ontologies represent the system's internal models of the external environment and its self-representation. Reflexive correction of the system's representations of the world is as important as changing its structure or goals.
- Built-in safety and ethics. Since the goals and rules themselves change, safety constraints and normative frameworks must be integrated into the evolutionary mechanisms (fail-safes, corridor constraints, prevention of undesirable attractor scenarios).

Thus, the paradigms of evolutionary cybernetics are not merely an expansion of the classical cybernetics toolkit. They form a holistic conceptual foundation that allows integrating heterogeneous mechanisms — from biological to socio-technical – into a single field of study. These principles guide researchers toward a long-term vision of system development and create the necessary conditions for a new scientific paradigm centered on directed evolution.

**3.3. Principles of evolutionary cybernetics.** The operation of any scientific discipline relies on a set of principles that establish its internal logic and define its scope of application. For evolutionary cybernetics, these tenets serve not only as regulative propositions but also as methodological benchmarks that consolidate approaches to describing, analyzing and designing systems with directed evolution. They reveal mechanisms for combining classic cybernetic ideas with the unique characteristics of evolutionary processes, establishing the groundwork for a cohesive scientific paradigm.

1. Principle of feedback (on three levels). Feedback loops function at the operational level (stabilization and deviation correction), at the evolutionary level (controlling the intensity of variation/selection, main-

taining diversity) and at the meta-level (revising rules and criteria when the gap between expected and actual evolutionary progress becomes significant). This three-layer closure ensures alignment of short-term and long-term behavior and reduces the risk of "jamming" in local optima.

2. Principle of shaping the evolutionary trajectory. The evolutionary trajectory is not merely observed but actively designed: desired properties of future states, corridors of acceptable evolution, milestones and a policy for the rate of change are specified. This includes (1) choosing the style of evolution (smooth incremental change vs. abrupt phase transitions), (2) controlling the speed (acceleration/deceleration) and (3) mechanisms to prevent undesirable attractors ("safety rails"). As a result, evolution ceases to be a "post-factum adaptation" and becomes a purposeful process with predictable navigation.

3. Principle of self-development of the control subsystem. The control structure evolves together with the object and environment: it revises goals, criteria, algorithms and architecture while maintaining operational functionality during reconfiguration ("graceful" evolution). Self-development requires: (1) internal modularity (to change parts without stopping the whole system), (2) metrics of meta-effectiveness (evaluating the quality of the changes themselves), (3) mechanisms for rollback and counterfactual testing of alternative designs.

4. Principle of co-evolutionary coherence. Any local optimization that ignores mutual feedback with the ecosystem produces global dysfunctions. Therefore, performance criteria should include the impact on the environment and the environment's feedback, and also support an ecology of diversity (diversification of strategies) that enhances evolutionary resilience under changing conditions.

5. Principle of multi-level goal alignment. Goals can and do evolve, but changes at lower levels (algorithms, modules) must be aligned with transformations at higher levels (architecture, value priorities, ontology). Otherwise, the system will generate goal conflicts and degraded performance.

6. Principle of informational sufficiency and reflection. Evolutionary decisions are made under uncertainty. It is necessary to maintain adequate sensory channels, models of the environment and self-models, as well as procedures for regular revision of ontologies (updating conceptions of relevant variables, relationships, constraints) in order to avoid systematic biases and the accumulation of evolutionary debt.

7. Principle of guided diversity. Resilience demands maintaining a controlled diversity of hypotheses, modules and strategies. Exploitation must be counterbalanced with exploration across time (through epochs) and across a population of agents/models. Diversity is not the ultimate objective, but a resource for successful adaptation and meaningful innovation.

8. Principle of default safety. Given that the evolutionary loop has the capacity to modify system's objectives, safety constraints must be robust-

lyintegrated in the rules of evolution (e.g., invariants, forbidden state spaces, ethical corridors), ensuring controllability even when the system undergoes radical reconfigurations.

9. Principle of trajectory verification. Any proposed evolutionary change should undergo preliminary verification for compliance with the desired trajectory and constraints (via scenario modeling, "sandbox" environments, A/B evolution experiments), with the possibility of safe rollback.

The above principles collectively form the methodological framework of evolutionary cybernetics. They deliver normative guidance for the development of formal models, algorithmic implementations and real-word applications, avoiding reduction to isolated technical tricks. In this way, evolutionary cybernetics can function as a coherent scientific discipline, combining systemic vision, forecasting tools and mechanisms of goal-directed development.

**3.4. Formal model of an evolutionary cybernetic system.** An evolutionary cybernetic system (ECS) is formally defined as an ordered tuple

$$E = \langle X, U, F, G, A, H, R, \Theta \rangle, \tag{1}$$

where $X \subseteq R^n$ is the state space of the system, describing its current configuration at a given moment in time; $X \subseteq R^m$ is the space of control inputs (signals) applied to the system; $F : X \times U \times \Theta \to X$ is the dynamic evolution operator, parameterized by a vector of internal parameters $\Theta$, that represents the change in the system's state under the influence of control; $G : X \to Y$ is the observation operator that projects the internal state into the space of output data available for analysis; $A$ is the set of admissible system architectures (the structural configurations of the control subsystem); $H : P \to U$ is the decision operator which, relying on the current state and/or the system's history $P$, determines the optimal actions; $R : X \times U \to R$ is the utility function (objective function) that specifies the criteria for evaluating effectiveness; $\Theta$ is the set of parameters that determine the behavior of both the operational and evolutionary levels of the system.

A key feature of an ECS is the presence of a two-level control structure:

- Operational level — carries out direct management of the system's current states in accordance with given goals and parameters.
- Evolutionary level — modifies system parameters $\Theta$ and architecture $A$ according to the mechanisms of controlled evolution (selection, variation, recombination, symbiosis etc.).

The evolutionary level is formally described by an update operator:

$$\Theta(t+1), A(t+1) = \Phi(\Theta(t), A(t), M(t), \Xi(t)), \tag{2}$$

where $\Phi(\cdot)$ is the evolutionary operator that implements changes to parameters and/or architecture; $M(t)$ is the set of candidate models of behavior at iteration$t$; $\Xi(t)$ represents random or environmental perturbations affecting the update process.

This formalism allows us to represent the integration of the evolutionary loop with the functional control loop, as outlined in subsection 3.1. It enables describing not only the stabilization of states $X \subseteq R^n$, but also the long-term transformation of the system's architecture, goals and regulatory principles.

At a conceptual level, an ECS can be viewed as a meta-system in which evolutionary operators are part of the regulatory mechanism, and the process of meta-evolution — changes in the rules and criteria of control — is integrated into the formal description. This provides the possibility of designing systems capable of autonomously modifying their own structure, which is a key prerequisite for their resilience in complex and unpredictable environments.

As a practical example, consider an adaptive relaxation protocol where a patient watches short, calming videos while sensors stream heart rate and facial EMG. The formal ECS tuple $E = \langle X, U, F, G, A, H, R, \Theta \rangle$, where $X$ is the patient's current physiological signals (e.g., heart rate, facial EMG) plus a latent stress index; $U$ is the parameters of the calming media (e.g., video scene selection, audio tempo); $F$ is the parameterized model of how the patient's state $X$ responds to the control inputs $U; G$ is the sensor and processing pipeline that translates raw biometric data into the formal state $X; A$ is the set of admissible control policies (e.g., a simple PID controller, a rule-based system, a deep reinforcement learning policy); $H$ is the currently active policy selected from $A$ that determines the next control $U$ based on the state history; $R$ is the objective function, e.g., «minimize the stress index quickly while respecting safety constraints"; $\Theta$ is the full set of parameters defining the current state of $F, H$ and $R$.

In this system:

The operational loop is the policy $H$ adjusting the control $U$ (video/audio) in real-time to minimize the objective $R$ (stress).

The evolutionary loop runs periodically (e.g., every $n$ sessions) to evaluate alternative architectures $A$ or parameters $\Theta$ using sandboxed "digital-twin" replays of past sessions. Promising variants are then promoted for live use.

The meta-control level enforces safety corridors (e.g., forbidden ranges of $U$), rate-limits structural changes and triggers an "ontology refresh" if the model's prediction error drifts significantly.

**3.5. Methodological guidelines for designing EC systems.** The development of evolutionary cybernetic systems is impossible without a clear methodological foundation that defines both the principles and the concrete approaches to their implementation. Methodological guidelines need to integrate architectural solutions, organizational mechanisms, normative principles and epistemic procedures, ensuring consistency between the operational and evolutionary levels.

- Architecturally. It is necessary to employ modular, version-controlled management structures with "hot" swappable components and separate telemetry channels for operational and evolutionary metrics.

This organization provides flexibility and fault tolerance, allows gradual integration of new elements without shutting down the system and creates conditions for tracking the effectiveness of both current actions and long-term transformations.

- Orchestrationally. Policies for the pace of evolution must be defined — determining when to change rules, at what speed and on which levels. This also includes managing diversity: establishing quotas or pools for experimental variants and balancing exploitation of current solutions with exploration of new possibilities. Such measures ensure the process remains controlled and prevent both stagnation and uncontrolled dynamics.
- Normatively. An ex-ante system of constraints and an ex-post audit of evolutionary steps should be in place. It is also important to provide protocols for halting evolution in case of anomalies or deviations from safe corridors. These measures guarantee that the system's development adheres to established safety, ethical and societal criteria.
- Epistemically. It is crucial to conduct regular revisions of ontologies and criteria that determine "progress dynamics." This avoids fixation on outdated goals, allows correction of assumptions about relevant variables and relationships and maintains coherence between the system's internal models and the dynamics of the external environment.

Thus, the methodological guidelines for designing EC systems form a multi-dimensional framework that combines technical engineering with organizational management, normative regulation and cognitive reflection. Their integration guarantees the system's integrity and resilience. This synergy makes it feasible directed evolution even under conditions of complexity, uncertainty and rapid change.

**3.6. Functional requirements for control tools.** Within the framework of evolutionary cybernetics, control tools must satisfy specific requirements that transcend the traditional paradigm of stabilization or optimization. These are instruments capable not only of maintaining system functionality within a dynamic environment, but also of ensuring its goal-directed development, the shaping of evolutionary trajectories and the integration of normative and epistemic demands. The key functional requirements derived from the paradigms and principles of EC are outlined below:

1. Ensuring multi-level controllability. Control tools should support functioning at the operational, evolutionary and meta-levels. This means being able to integrate short-term tasks with long-term objectives, as well as to coordinate parameter changes, structural modifications and the revision of value-goal orientations.

2. Flexibility and modularity of architecture. Control instruments should exhibit modularity, facilitate the "hot" swapping of components and offer detailed version tracking of elements. This permits the integration of new functional blocks without compromising the system's operability, thereby supporting dynamic updates in response to environmental changes.

3. Informational adequacy and telemetry. It is essential to have dedicated monitoring channels for both operational and evolutionary parameters. Control tools must collect and process data reflecting both the effectiveness of current task execution and the dynamics of the system's development. It is important to ensure regular revision of ontologies and models that represent both the external environment and the system's internal structure.

4. Orchestration of pace and diversity. Functional capabilities should include policies for the tempo of evolution: defining when rules change, the speed of transformations and the levels at which they occur. In addition, control tools should support maintaining a guided diversity of hypotheses and solutions, creating a pool of alternative strategies and balancing exploration and exploitation.

5. Built-in safety mechanisms. Given the potential for radical transformation of goals, control systems must have built-in safety mechanisms by default. This entails invariant constraints, forbidden regions of state space, ethical corridors, and emergency protocols for halting evolutionary changes in the event of threats to stability or to compliance with fundamental criteria.

6. Normative audit and control protocols. Control tools should incorporate ex-ante constraints that define the acceptable paths of development and ex-post audits to asses the advisability and safety of the changes made. Functionally, it is important to have protocols for halting or reversing evolutionary steps whenever anomalies or unforeseen risks are detected.

7. Support for reflection and self-learning. Functional requirements include the system's ability to conduct a reflective analysis of its own performance and maintain capabilities for self-learning. This means revising performance criteria, adapting models and accumulating knowledge about the results of strategies that have been applied.

Thus, the functional requirements for control tools in evolutionary cybernetics are defined by the integration of architectural flexibility, normative safety and epistemic reflection. Their fulfillment provides not only the ability to maintain the system's functionality in a complex, changing environment, but also creates conditions for its purposeful, controlled and safe development.

**3.7. Formalization of evolutionary processes via mathematical modeling.** Within the ontology of evolutionary cybernetics outlined in subsection 3.1, an evolutionary process is treated as an ordered sequence of changes in the parameters, architecture, goal functions and regulatory principles of a system's control structure. Unlike classical approaches, where evolution is regarded as an uncontrolled or external process, in EC it is an integrated element of the control mechanism, interacting with the functional loop and directed by the meta-level of management.

According to the formal model described in section 3.4, an evolutionary cybernetic system is represented by the tuple (1), where the operational level determines the dynamics of state $X \subseteq R^n$ in the functional loop and the evolutionary level governs certain variables Θ, $A$, $H$ and $R$ in the evolutionary loop.

Evolutionary processes in an ECS can be formalized as dynamics in an expanded state space:

$$S(t) = (X(t), \Lambda(t)), \Lambda(t) = (\Theta(t), A(t), H(t), R(t), E(t)), \tag{3}$$

where $\Lambda(t)$ is the vector of evolutionary parameters; $E(t)$ represents environmental parameters that influence co-evolution.

Within this space, the evolutionary process can be modeled as the composition of four interconnected sub-processes. These correspond to the categories of change previously outlined in subsection 3.1:

1. Structural changes:involve the reconfiguration of the architecture $A(t)$ and topology of connections.

2. Functional changes:entail the modification of control operators $H(t)$ and the related operational procedures.

3. Goal changes:focus on updating of the utility function $R(t)$ and associated priorities of its objectives.

4. Ontological changes:correction of the environment model $E(t)$ and the ways it is interpreted.

Formally, the evolutionary dynamics is described by the operator:

$$\Lambda(t+1) = \Phi_{evo}(\Lambda(t), E(t), \Xi(t)), \tag{4}$$

where $\Phi_{evo}(\cdot)$ is the composition of evolutionary operators (variation, selection, coadaptation, symbiosis etc.); $E(t)$ is the relevant slice of information about the environment; $\Xi(t)$ denotes random or uncontrolled disturbances.

The distinguishing feature of this approach is the integration of the operational and evolutionary loops: functional changes influence the immediate performance of the system, whereas evolutionary changes affect its long-term stability, innovative potential and ability to adapt to uncertainty. The meta-level of management plays a key role, determining which evolutionary operators $\Phi_{evo}(\cdot)$ will be activated, with what frequency and within what limits.

In light of the interconnection with the environment, it is advisable to include a co-evolutionary component in the mathematical model:

$$E(t+1) = \Psi(E(t), X(t)), \Lambda(t)), \tag{5}$$

which reflects the impact of the system's states and parameters on the environment and the feedback influence of the environment on the system. This allows one to formalize scenarios in which changes in the system are not only reactive but also proactively shape the conditions of its own development.

Thus, formalizing evolutionary processes within evolutionary cybernetics enables a shift from describing static or passively adaptive systems to models capable of designing their own evolutionary trajectory. This approach lays the foundation for developing the theory and practice of directed evolution, which is the defining feature of the new scientific field of evolutionary cybernetics.

**3.8. Universal laws and invariants of evolutionary processes.** Synthesizing universal laws of complex system development requires introducing the concept of cybernetic invariants. There are meta-parameters that retain their validity across different contexts, including biological, social and technical domains. They serve as a basis for formalizing evolutionary laws and constructing a unified model of directed evolution.

Key invariants include:

1. Information invariant — the preservation, transmission, and transformation of information as the fundamental requirement for any development to occur. This aligns with contemporary research in information complexity theory, where evolution is interpreted as a process of enhancing a system's informational capacity.
2. Resource constraint invariant — the dependence of evolution on energy, material, and informational resources [18]. This principle is supported by models of biospheric resilience and the theory of metabolic scaling.
3. Regulation invariant — the presence of control mechanisms and feedback loops that ensure a system's adaptability and viability.
4. Structural organization invariant — the tendency toward hierarchization and the emergence of new levels of complexity, consistent with principles of nonlinear dynamics and synergetics.
5. Temporality invariant — the rhythm and speed of evolutionary shifts [19, 20], including their acceleration due to the accumulation of knowledge and technology.
6. Integrity and openness invariant — the preservation of systemic unity and cohesion through the necessity of continuous interaction and exchange with the environment.
7. Teleonomic invariant — the directedness of evolution toward achieving new goals or maintaining a certain developmental course, especially important for social and cognitive systems.

Formalizing these invariants creates a foundation for constructing universal models of controlled evolution and integral metrics of sustainable development, which could form the basis of modern programs for global risk management.

**3.9. Artificial intelligence and agentic architectures as an evolutionary control layer.** Building on 3.1–3.8, an AI-driven agentic layer operationalizes the evolutionary loop and meta-control by (1) re-interpreting objectives, (2) recomposing control architectures and (3) proactively planning state-space trajectories under uncertainty. Unlike fixed-rule expert systems, agentic AI supports online model revision, hypothesis generation and coordinated decision-making across interacting agents.

- Architectural role. AI agents inhabit the evolutionary loop and meta-level: they select and schedule evolutionary operators (variation, selection, co-adaptation, symbiosis), tune their intensity and cadence, run counterfactual evaluations before promoting changes to the functional loop. Practically, this is realized by conversation-centric, tool-using multi-agent frameworks with human-in-the-loop checkpoints.

• Predictive modeling and digital twins. To verify evolutionary steps ex ante, the AI layer couples to digital twins and scenario simulators where agents explore candidate goals/architectures [21], stress-test safety corridors (invariants, forbidden regions of state space) and optimize multi-objective trade-offs prior to deployment.

• Safety and governance. As this layer can propose goal changes, safety must be enforced by design. Two complementary toolsets are used: (1) Safe reinforcement learning under explicit constraints (e.g., CMDP-style penalties, domain safety layers) to avoid unsafe policies [22, 23]; (2) Control-theoretic shields (control barrier/Lyapunov functions) to ensure real-time constraint satisfaction [24]. These mechanisms implement your doctrine of ethical corridors, fail-safes and emergency halts.

• Embodied/VLA control. Embodied agents and vision-language-action (VLA) models map high-level semantic goals to sequences of actions, enabling purposeful design inside regulatory loops [25]. This supports long-horizon planning, tool use and skill transfer in open-ended environments.

• Multi-agent emergence and oversight. Agent populations can demonstrate emergent conventions and unintended biases. Therefore, the meta-level is responsible for upholding norms, conducting audits, applying rate-limiters, enforcing minority-override checks and implementing diversity policies to steer collective dynamics toward desired attractors.

The practical realization of these principles requires the following functional components:

1. Dual telemetry: separate operational performance metrics vs. evolutionary metrics.
2. Gated promotion: structured deployment process, that moves agents or updates through distinct stages: from controlled sandbox/development environment → to limited staged rollout → into full production.
3. Controlled diversity: rotating agent/model portfolios.
4. Ex-ante rules & ex-post audits: invariants, forbidden states, rollback.
5. Periodic ontology/objective reviews to prevent goal drift.

Embedding an AI-driven agentic layer operationalizes the EC invariants from 3.8 in deployable form: information via world-models and persistent memory;resource constraints via compute/energy budgets and risk-aware policies; regulation via safe-RL and control-theoretic shields; structural organization via modular and population-based architectures; temporality via adaptive planning horizons and update cadence; integrity&openness via tool use and digital-twin coupling; and teleonomy via periodic objective reviews and drift metrics. With sandboxed DTs, gated promotion and ex-post audits, this layer provides a traceable path from universal laws to robust, responsibly autonomous systems across domains.

**3.10. Novel contribution of this work.** This paper's original contributions include: (1) The four-level ontology (object-process-mechanism-meta) unifying biological and technical evolution; (2) Formalization of cybernetic invariants as cross-domain evolutionary laws; (3) The two-loop control architecture with explicit meta-evolution operators; (4) Methodological principles for safe EC engineering (modularity, guided diversity, pace orchestration, default safety); (5) Integration framework positioning AI/DT as realization mechanisms rather than definitional elements of EC.

Prior work (Vernadsky, Glushkov, Holland) provided conceptual or algorithmic fragments; while this synthesis establishes EC as a coherent discipline with formal foundations and engineering guidelines.

## 4. Integration with Modern Fields

Evolutionary cybernetics (EC) has significant potential for integration with the leading areas of modern science and technology, since its methodological apparatus makes it possible to describe, model and control processes that unfold in systems of any nature. Such integration not only enriches the theoretical basis of EC itself, but also creates new application areas for the fields that already have well-established research traditions.

1. Global governance and sustainable development. EC can be applied to solving planetary problems and to strategic planning of humanity's development. In particular, its methods offer tools for scenario analysis and systemic forecasting to shape strategies for humanity's survival under conditions of ecological and biospheric crises. This includes the management of major issues such as climate change, resources, demographic processes and the formulation of long-term sustainability policies. For instance, EC models can help international organizations and governments to plan development multiple decades ahead, while accounting for the complex feedbacks between the natural environment and socio-economic systems.

2. Technological evolution and NBIC convergence. The current age is characterized by the convergence of nano-, bio-, information and cognitive technologies (NBIC convergence), a trend which leads to a radical acceleration of technological progress. EC considers coordinating the development of emerging technologies from the standpoint of directed evolution — from supporting innovation and scientific research to evaluating risks from the deployment of breakthrough technologies. For example, EC can propose models of innovation management in which the development of different fields (biotechnology, artificial intelligence, nanomaterials etc.) is coordinated to achieve socially beneficial goals. Such an approach ensures the purposeful emergence and convergence of new technologies according to predefined criteria of efficiency and safety.

3. Cognitive and neurotechnologies. In the realm of cognitive neuroscience, EC can be used to build multi-level models capable of simultaneously accounting for neurophysiological mechanisms, the dynamics of neural networks and adaptive-evolutionary processes in cognitive systems. Notably, an evolutionary approach makes it possible to model not

only the stabilization of brain functions, but also the purposeful reorganization of neural network architecture under the influence of learning, trauma, or environmental change. This provides the foundation for new strategies of neuro-rehabilitation, the development of artificial cognitive agents and hybrid bio-artificial systems. In addition, opportunities arise to guide the cognitive evolution of humans at individual and collective levels — for example, through adaptive educational systems that adjust to the learner, or through the co-evolution of humans and AI, ensuring the safe and ethical integration of AI into society.

4. Biotechnologies and genomics. EC methodology can be integrated into the analysis and modeling of genomic processes, where evolutionary operators (variation, selection, coadaptation) have direct biological analogues. Formalizing these processes in a cybernetic context allows designing controlled scenarios of evolution for genetic systems, creating models of organisms' adaptive responses to environmental changes and supporting engineering biotechnological applications, particularly in synthetic biology. In this way, EC methods can aid in steering the evolution of living organisms — from genetic engineering to ecosystem management — with the goal of enhancing the resilience of the biosphere.

5. Social transformations. Socio-technical systems are examples of complex evolutionary objects in which goals, management architectures and environment mutually transform one another. EC enables the description of processes of collective adaptation, the evolution of network interaction structures, and the purposeful shaping of behavioral patterns in communities. Using evolutionary-cybernetic models, one can analyze various scenarios of social change — from the transformation of political institutions to the evolution of culture under the influence of the internet. For instance, it is possible to model how the implementation of a universal basic income or other economic innovations would influence social structure over decades. An important task is managing social changes to minimize risks (conflicts, crises) and support harmonious development. Thus, within EC, social cybernetics addresses both the analysis of current trends and the design of new social systems (e-governance, e-democracy etc.).

6. Economic systems. In economic systems, EC can provide a theoretical foundation for constructing models of markets capable of changing their own "basic rules" in response to external challenges. The evolutionary perspective allows markets to be viewed as dynamic regulatory systems with multi-level feedback adaptation, where changes in goals, mechanisms, and management architectures can be purposefully designed to sustain efficiency and stability. For example, regulators might deploy evolutionary algorithms for adaptively adjusting financial rules in response to new global trends, thereby ensuring the economy's resilience over long-term cycles.

The interaction of EC with these fields creates prerequisites for the formation of interdisciplinary platforms in which mathematical models, algorithms, and experimental environments support a unified conceptual approach to controlled evolution. Such synergy opens the way for the creation of universal evolutionary architectures applicable in neuroengineering, biotechnology, social governance, and economic forecasting.

## 5. State and Prospects of Development

By 2025, evolutionary cybernetics is at the stage of forming itself as a scientific paradigm. It is still developing predominantly among systems thinkers and futurists, with initial publications appearing and conferences being held on this topic. Theoretical foundations are being laid, but ahead lies a great deal of work on the practical implementation of EC's ideas. There is growing awareness that humanity needs tools for collectively managing its own future, and evolutionary cybernetics aims to become a supplier of such tools.

To accelerate the development of this new field, steps toward its institutionalization and integration into the educational environment are important. It is proposed to establish specialized research centers and communities dedicated to evolutionary cybernetics, launch dedicated journals, and hold regular conferences. The accumulation of knowledge can be systematized by formalizing EC as a separate discipline within cybernetics or systems analysis. In parallel, there is the task of developing academic programs to train specialists of a new generation. It would be prudent for universities to introduce Master's specializations and doctoral courses in evolutionary cybernetics. Such programs could include courses in complex systems modeling, futurology, innovation management, technology ethics and more, to teach young researchers to think systemically and long-term, combining knowledge from cybernetics, ecology, sociology, IT and other fields.

An important direction for progress is deploying international research projects that demonstrate the practical value of EC approaches. For example, programs under the UN or EU could be initiated to model climate and socio-economic scenarios and projects such as a "Global Brain" (the concept of a planetary information network as a collective intelligence) or interdisciplinary studies on NBIC-technology convergence. Collaboration between scientists of different countries in such projects will lay an empirical foundation for EC and allow its approaches to be tested in practice. Moreover, closer integration of EC with the development of artificial intelligence and cognitive sciences is needed. AI can become both a subject of research (the evolution of artificial agents) and a tool for analyzing big data about system development. EC will increasingly account for the human factor — human cognitive limitations and the psychology of perceiving change — when designing strategies for directed evolution. This necessitates dialogue with the social and human sciences to address the ethical and cultural aspects of intervening in evolution.

The growth of evolutionary cybernetics calls for a comprehensive research program that integrates fundamental and applied areas. First, on the theoretical level, it requires discovering universal laws of evolution, formalizing invariants of complex systems and developing an ontology of developmental processes, drawing on the synthesis of ideas from Vernadsky, Glushkov, Prigogine, and contemporary cognitive science. In this context, it is promising to leverage methodologies drawn from information complexity theory, nonlinear dynamics and evolutionary computation. Secondly,the applied dimension of EC is centered on creating predictive models for natural-technical and socio-economic systems. This involves employing tools from AI and big data to analyze evolutionary scenarios, Additionally, the development "life safety" indicators as an integral metric of sustainable development is important as well. A crucial component is the cognitive aspect — taking into account the role of consciousness, collective intelligence and cognitive governance. In the future, forming international consortia and national programs for directed evolution may become the foundation for a global system for monitoring and managing evolutionary processes, addressing the challenges of the 21st century.

## 6. Tasks and Guidelines of Evolutionary Cybernetics

The initial stage of establishing evolutionary cybernetics requires identifying the areas of its practical application where the new methodology can demonstrate tangible advantages over classical approaches. This involves not only isolated experiments, but the creation of reference examples — demonstration testbeds to validate theoretical propositions. It is important to form a portfolio of application projects in various domains: from infrastructure networks and biomedical technologies to socio-technical systems. On this basis, a corpus of benchmark problems should be assembled, in which the primary criterion is not the achievement of static goals, but the system's ability to design and implement its own evolutionary trajectories.

Developing metrics of evolutionary resilience holds significant importance, as these allow one to distinguish mere adaptation from goal-oriented development. Examples of such metrics include the velocity and expense of system reconfiguration, the predictability of dynamics and the alignment of objectives across different organizational levels. Verifying these metrics is a prerequisite for establishing engineering standards and practices for subsequent application. In the future, this paves the way for projects such as "evolutionary digital twins" of energy systems, evolutionarily managed medical platforms, or two-loop artificial intelligence agents capable of generating and testing their own architectures.

At the same time, from the very beginning the global dimension must be considered, because evolutionary cybernetics cannot be confined to local problems. It is naturally oriented toward planetary-scale systems that unite the technosphere, biosphere and socio-cultural structures. A paramount objective involves establishing long-term goals aligned with the principles of sustainable development, life safety, ethical responsibility and intergenerational justice. It is necessary to harmonize the pace of transformations in diverse subsystems to avoid structural imbalances between technological innovations, institutional shifts and cultural processes. On a global level, effectiveness criteria include multi-level alignment of objectives, maintaining diversification of potential development trajectories and regular revision of ontologies that determine which changes should be qualified as progressive.

In this context, artificial intelligence and its use hold a special place. Modern breakthroughs in deep learning need to be complemented by evolutionary mechanisms that can ensure self-design capability, maintenance of diversity and safety by default. The combination of "deep learning + evolutionarity" opens the prospect of creating two-loop agents that can autonomously adapt not only their parameters but also their own rules of functioning, while remaining controllable and transparent to the user.

Problem formulation in evolutionary cybernetics reflects its transdisciplinary character and practical orientation. At the theoretical and methodological level, the key task is to construct a general concept of controlled evolution that synthesizes the principles of cybernetics, evolutionary theory and cognitive sciences. The analytical and prognostic dimension entails creating models for eventuality analysis and indicators of the state of global and local systems to forecast possible trajectories of civilizational development. The applied dimension is connected with developing mechanisms of influence on social, economic and ecological processes, integrating NBIC technologies and implementing "life safety" criteria as an universal measure of sustainable development. The cognitive-social dimension is of particular importance, focusing on the evolution of consciousness, knowledge, and collective intelligence, which determine humanity's ability to manage its own future in a coordinated way [26]. Finally, the organizational and managerial tasks are aimed at establishing national and international programs of controlled evolution, which should become a new institutional foundation for global society.

Thus, the initial tasks of evolutionary cybernetics are multi-faceted: they need to lay the theoretical foundation of this important branch of cybernetics while simultaneously being oriented toward creating applied research demonstration systems and shaping long-term global programs in which technological innovations are integrated into the broader context of civilizational evolution.

## Conclusions

Evolutionary cybernetics opens new horizons for science and practice, offering a holistic vision of the directed development of humanity, society and the planet. It combines the achievements of cybernetics, evolutionary theory and the cognitive and social sciences, forming a paradigm of directed evolution. Its ideas — from Vernadsky's noosphere to artificial intelligence — are aimed at harnessing knowledge and technology for the sake of a sustainable future [27].

At the same time, this new field requires broad interdisciplinary dialogue and a responsible attitude. Directed evolution raises serious ethical questions and necessitates accounting for diverse interests and risks. The further development of evolutionary cybernetics is feasible only through close collaboration among experts from wide spectrum of fields — including cyberneticists, biologists, ecologists, sociologists, philosophers, engineers — and requires the active support of society. If successfully realized, evolutionary cybernetics could become an intellectual tool that assist humanity consciously and responsibly steer its own evolution in harmony with nature and cutting-edge technologies.

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# МОДЕЛЮВАННЯ ЕВОЛЮЦІЙНОЇ КІБЕРНЕТИКИ: ОНТОЛОГІЯ, ІНВАРІАНТИ ТА ПРИНЦИПИ ПРОЄКТУВАННЯ

**Вступ.** Еволюційна кібернетика (ЕК) пропонується як загальна наука керування зміною у технічних, біологічних і соціотехнічних системах за умов невизначеності. На відміну від класичної парадигми зі сталими цілями та фіксованою архітектурою регулятора, ЕК виходить із того, що цілі, обмеження й структура також можуть еволюціонувати. Ця архітектура будується на двоконтурній організації управління: операційний контур оптимізує поточну поведінку, а еволюційно-метаконтур виконує функцію зміни та оновлення фундаментальних правил, архітектури та критеріїв ефективності системи.

**Мета:** (1) Сформулювати онтологію ЕК (об'єкти, процеси, механізми, метаконтроль); (2) визначити кібернетичні інваріанти (інформація, ресурсна обмеженість, регуляція, структурна організація, темпоральність, цілісність/відкритість, телеономія) як спільні закони еволюції; (3) надати принципи та функційні вимоги до систем ЕК; (4) подати формальну модель еволюційної кібернетичної системи та операторів мета-оновлень; (5) окреслити сфери застосування та дослідницьку програму.

**Методи.** Формалізація спирається на онтологічне моделювання та двоконтурну схему прийняття рішень. Онтологічне моделювання охоплює чотири рівні: «об'єкт — процес — механізм — метаконтроль». Крім того, запроваджуються оператори еволюційних змін, які застосовуються для модифікації параметрів, цілей та архітектури системи. Інваріанти задають загальні обмеження й критерії узгодженості через домени. Методологічні принципи охоплюють керування темпом і різноманітністю, багаторівневе узгодження цілей, рефлексивне оновлення онтологій, безпеку «за замовчуванням», а також перевірки *ex ante* і аудити *ex post*.

**Результати.** Запропоновано: (1) цілісну концептуальну рамку ЕК; (2) набір принципів і вимог до інженерії систем, що здатні змінювати власні цілі та архітектуру, зберігаючи контрольованість; (3) формальну модель та операторів мета-рівня для інтеграції еволюційного контуру з функційним; (4) дорожню карту застосувань у соціокібернетиці, біо-/нейроінтерфейсах, інфраструктурних мережах і політиках сталості. Сучасні інструменти (напр., безпечне підкріплювальне навчання, контрольні бар'єри, цифрові двійники) розглядаються як практичні механізми реалізації еволюційного контуру, а не як обмежувальна сутність дисципліни.

**Висновки.** ЕК надає метатеоретичний та інженерний каркас для керованої еволюції складних систем: поєднання двоконтурного керування, інваріантів та формальних операторів мета-оновлень забезпечує керовану зміну цілей і структури з гарантіями безпеки та узгодженості у довгих часових горизонтах. Це відкриває шлях до відповідальних практик розвитку в мінливих середовищах.

***Ключові слова:*** *еволюційна кібернетика; керована еволюція; метаконтроль; двоконтурне керування; кібернетичні інваріанти; коеволюція; цифрові двійники.*