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Modern Trends in Control Theory: Networks, Hierarchies and Interdisciplinarity

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Abstract: In this essay, we analyze some national priorities in control science and topics of largest recent conferences in control theory and its applications. What is seen that multiagent systems are considered as a canonical example of wide-spread object of control. And then the roles of interdisciplinarity and limits of science are stressed. The conclusion is that main modern trends in control theory are: NETWORKS, HIERARCHIES and INTERDISCIPLINARITY.

Keywords: Control theory, multiagent system, network, hierarchy, interdisciplinarity, scientific life-cycle

1. Some Priorities

National Science Foundation (USA) several years ago declared among others the following priorities in control: group control, combat control, control in financial and economic systems, control in biological and ecological systems, man and team in a control loop, unified theory of control, computation and communication (C^3), … .

Among European priorities are: man-machine symbiosis (modeling a man in a control loop and as a controlled subject), distributed and networked systems, production, safety and strategies of heterogeneous control, new principles of interdisciplinary coordination and control, … .

Russian Academy of Sciences established the following priorities for next five years: methods and means of communicational and networked control of multi-level and distributed dynamic systems under uncertainty, intellectual control, … .

Generally, one can state that today both in theory and in practice NETWORKS (as control objects) ARE CONTROLLED BY NETWORKS (as control subjects) OVER NETWORKS (as communication) – see Fig 1.

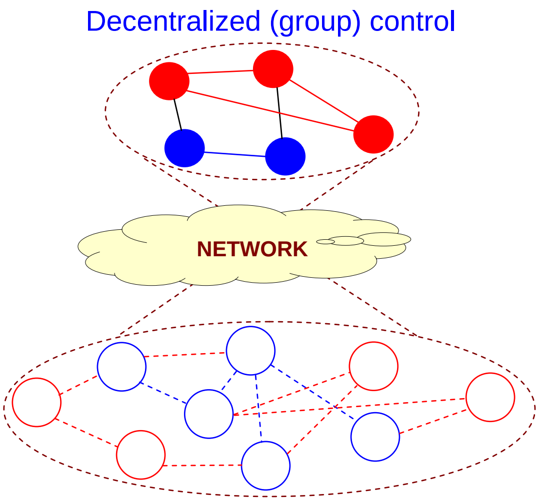

Fig. 1. Network Structures in Control Systems

2. Multiagent Systems: Networks versus Hierarchies

A paradigmatic example of network of controlled objects is a multiagent system (MAS). Such systems consist of numerous interacting autonomous agents having technical or informational nature (a classical example is a group of mobile robots). Multi-agent systems are remarkable for interaction decentralization and agents' multiplicity; these features lead to fundamentally new and important emergence properties (autonomy, lower vulnerability to adverse effects, etc.).

MAS could be subdivided by the classes of material («technical» - wheeled, UAVs, AUVs, controllers in industry, smartgrids, etc) and virtual (softbots – interacting computer programs, solving problems of distributed optimization, etc) – see Fig. 2.

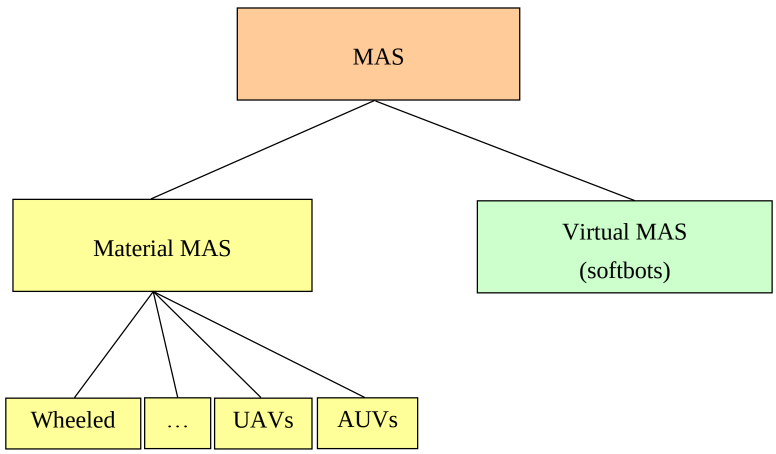

Fig. 2. Types of MultiAgent Systems

Specificity of MAS consists in following:

- Multiple components;
- Distributed, networked communications;
- Hierarchy;

- Intelligence (autonomy):
- Rationality (decision-making under uncertainty and cognitive restrictions);
- Autonomous goal-setting, goal-oriented behavior;
- Forecasting and reflection; and
- Cooperative and/or competitive interactions (the formation of coalitions, informational, and other types of confrontation).

On one hand any MAS "by definition" has a networked structure. On the other hand any intelligent agent has a complex (hierarchical) internal structure. The typical functional structure of an agent includes several hierarchical levels–see Fig. 3. Operational level (I) serves for implementing certain actions (e.g., stabilization of motion along a given trajectory). Tactical level (II) is intended for choosing actions (e.g., planning of actions–trajectories selection or solution of distributed optimization problems). Actions can be chosen taking into account interaction with other agents. Strategic level (III) is responsible for decision-making, learning and adaptivity of agents, as well as for control cooperativity (coordinated solution of a common task by a set of agents). An agent should have the capacity for strategic decision-making, adaptation, learning and reflexion. Finally, conceptual level (IV) corresponds to goal-setting principles. Each level employs a certain framework (as a rule, methods being applicable at a certain level can be used at higher hierarchical levels–see Fig. 3).

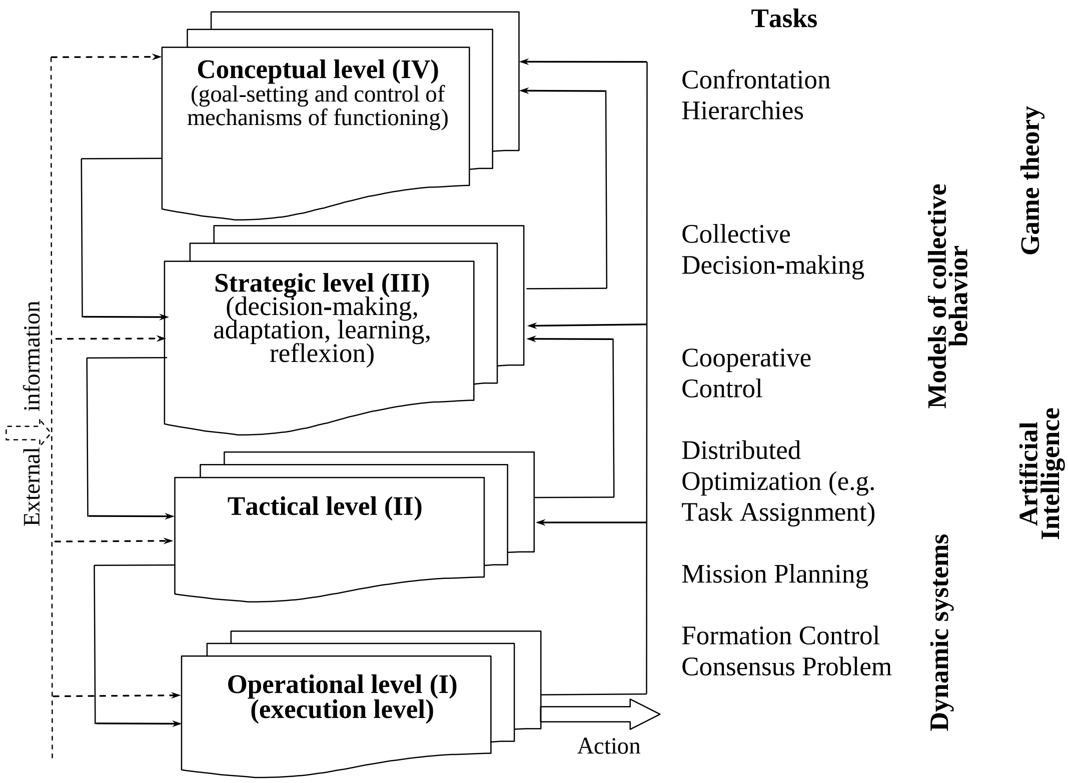

Fig. 3. MAS: The hierarchical architecture of an agent

One modern tendency of the theory of multi-agent systems, game theory (see below) and artificial intelligence theory lies in that researchers strive for integrating these scientific directions. Yet, game theory and artificial intelligence theory aim at higher levels of agent's architecture. Within algorithmic, computational and evolutionary game theories, one would observe “transition downwards,” i.e., from the uniform description of a game to its decentralization and analysis of the feasibility of implementing autonomously the mechanisms of equilibrium behavior and realization. In fact, similar “decentralization” trends can be found in operations research. On the other hand, the theory of MAS moves “upwards” in a parallel way due to the local character of scientific communities. The theory of MAS aspires after better consideration of strategic behavior and “intellectuality of agents”. These intellectual agents interact in a parallel fashion on their own different hierarchical levels. Thus a MAS should not be interpreted solely as a networked or hierarchical system – it is heterogeneous, i.e. networked, distributed and hierarchical (controlled object, control system and communications). Thus the new challenge to the control theory is HETEROGENEITY - a TRANSITION FROM NETWORKES AND HIERARCHIES TO HIERARCHIES OF NETWORKES AND NETWORKES OF HIERARCHIES (note, that heterogeneity usually additionally assumes that control system is multi-rate, multi-scale and different “languages” are used for the description of its components). Moreover, new trend matures – transfer from C^3 paradigm to C^5: addition to C^3 two global factors – Costs (of joint control system and object of control design and production) and Cycle (problems of lifecycle management):

$$C^5 = \text{Control} + \text{Computation} + \text{Communication} + \text{Cost} + \text{Cycle}.$$

In heterogeneous models problems of models «coupling», search for common language, generating and replicating typical solutions of control problems are actual. Intra-paradigmal problems also exists: «linearity» of development (self-isolation of different braches of control science), desire to reduce the problem to well-known, i.e. «internal» problems of any subject field. Requirements of real-time operation often cause need for «heuristical» applications (the concept of bounded rationality) – under the lack of time, ability or necessity instead of optimal pseudo-optimal solutions are heuristically searched.

As for MAS itself, one can conclude that:

1) The level of MAS’ “intellectualization” should be adequate to the problem in hand (taking into account various “costs” – computational, financial, cognitive, etc).

2) The intention to maximize the “intellectualization” at the higher levels of agent’s architecture leads to a centralized scheme of control.

3) Trend to the integration of networked MAS, game theory and artificial intelligence exists.

3. Control Conferences

One of the most efficient ways to analyze the modern state and trends in some science is to look at topics of corresponding well-recognized conferences. With this aim we have taken three main (its significance is authors’ subjective expert estimate) events in control science in 2011 (this year have been chosen as IFAC three-year Congress was held in 2011):

- IFAC (International Federation of Automatic Control) World Congress, 28 Aug – 2 Sept. 2011 more than 1500 papers;
- CDC (Conference on Decision and Control), held jointly with ECC (European Control Conference), 12-15 Dec 2011, organized by IEEE, Orlando, Florida, more than 1500 papers;
- ACC (American Control Conference), 29-30 June 2011, organized by IEEE, San Francisco, USA, more than 900 papers.

These World scientific events differ in theoreticity/applications, emphases, etc, but there is much in common:

1) ALMOST ALL "NON-CLASSICAL" AREAS ARE CONCENTRATED AROUND NETWORKS (see Fig. 4 – Fig. 6);

2) "Technical" problems of measurement, etc, become not a "science" (see Fig. 4 – Fig. 6) but a "trade" and are solved in R&D departments of industry;

3) Complex multiagent systems (with hierarchical organization of agents) require integration of traditional Control Theory areas (dynamic systems, stability, etc) with Artificial Intelligence, Game Theory, Decision Making, Collective Behavior, etc. But most attention of the researchers still is paid to lower levels of agents architecture (latin numbers on Fig. 7-9 and Fig. 3 are the same). One can expect in the nearest future the SHIFT OF ATTENTION TO STRATEGIC AND CONCEPTUAL LEVELS.

4) In applications there is an observed shift in emphasis from traditional IT, robots and aerospace to energetics and bio-med (see Fig. 11 – Fig. 12).

5) Etc (one can come to his own conclusions) – Fig.4 – Fig. 12 seem expressive and informative.

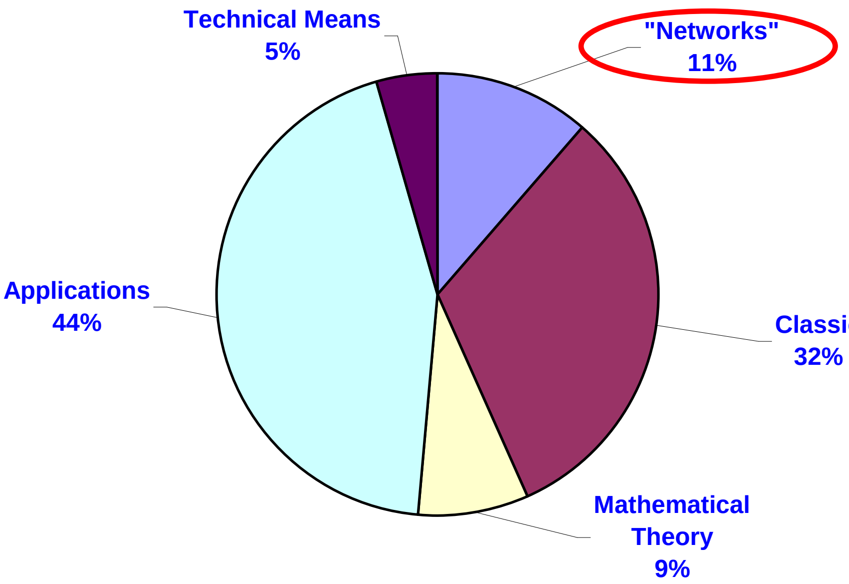

Fig. 4. General topics of IFAC-2011 World Congress

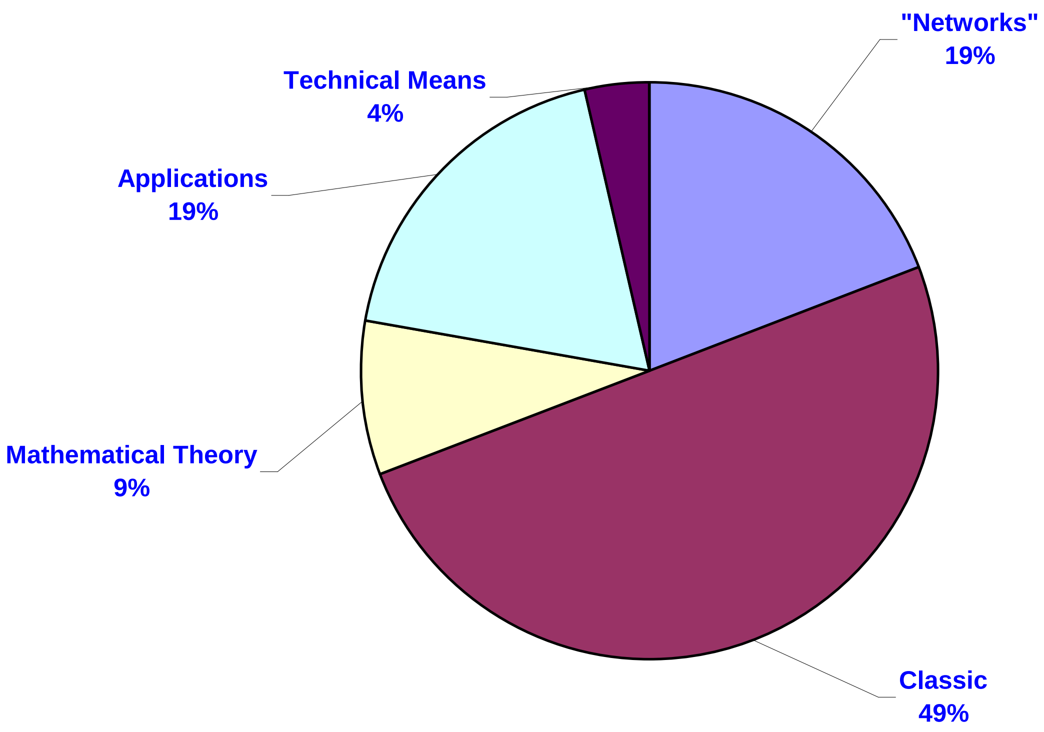

Fig. 5. General topics of CDC-ECC-2011 World Congress

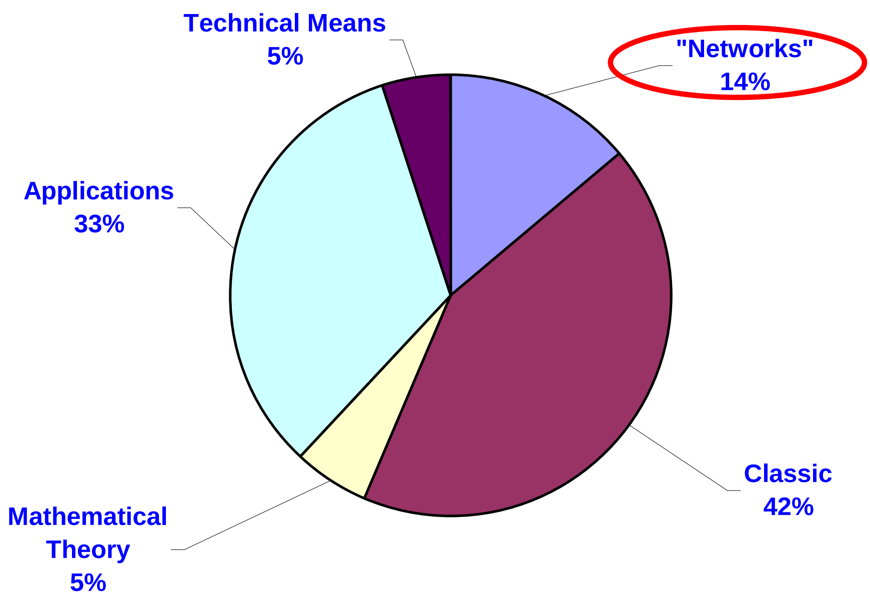

Fig. 6. General topics of ACC-2011

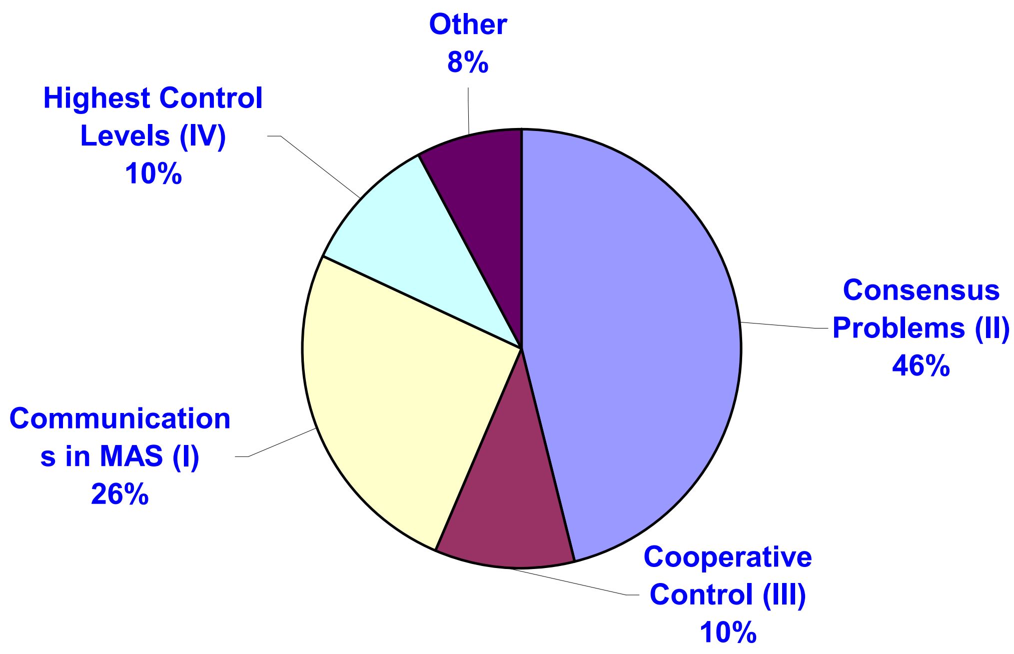

Fig. 7. “Networks” on IFAC-2011 World Congress

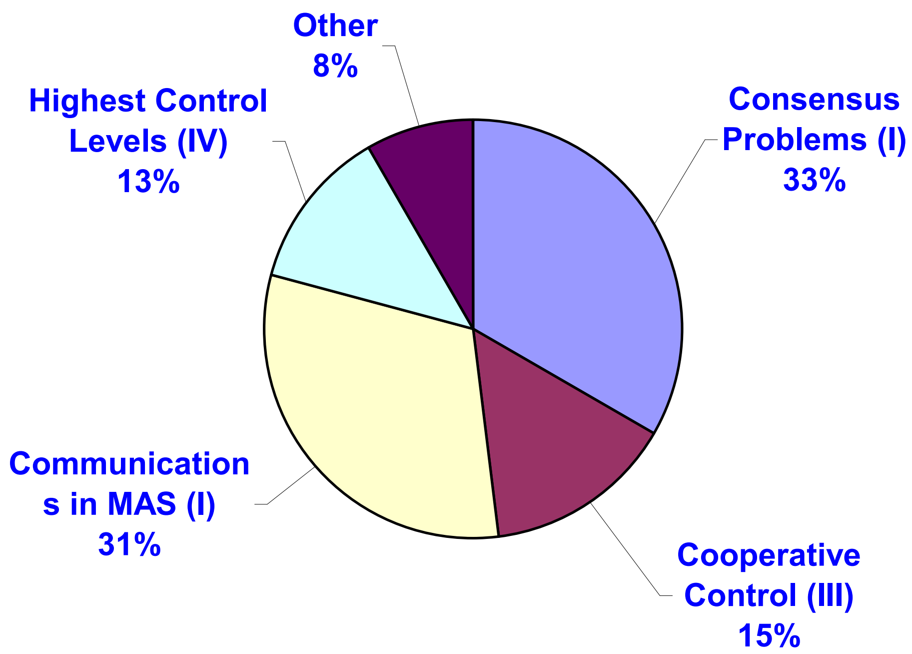

Fig. 8. “Networks” on CDC-ECC-2011 World Congress

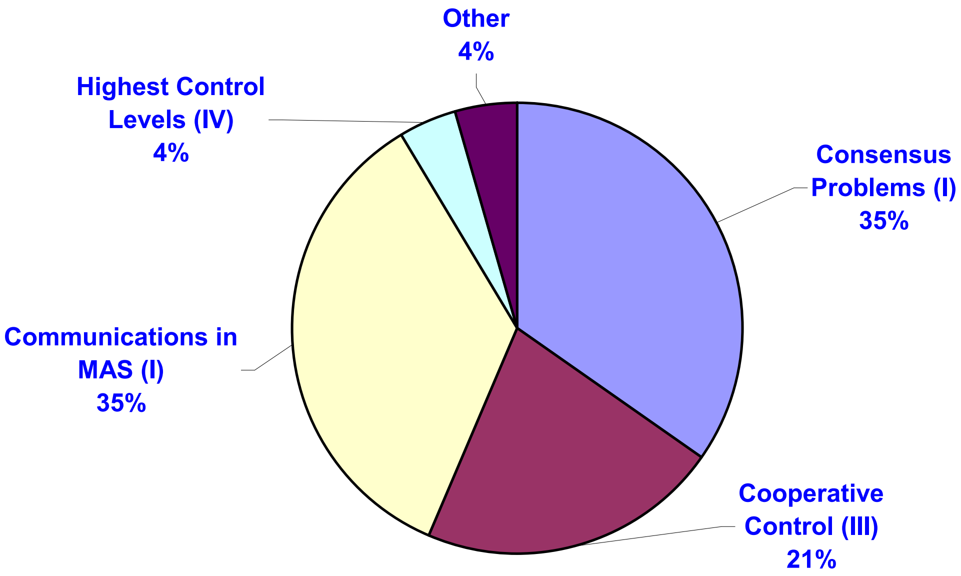

Fig. 9. “Networks” on ACC-2011

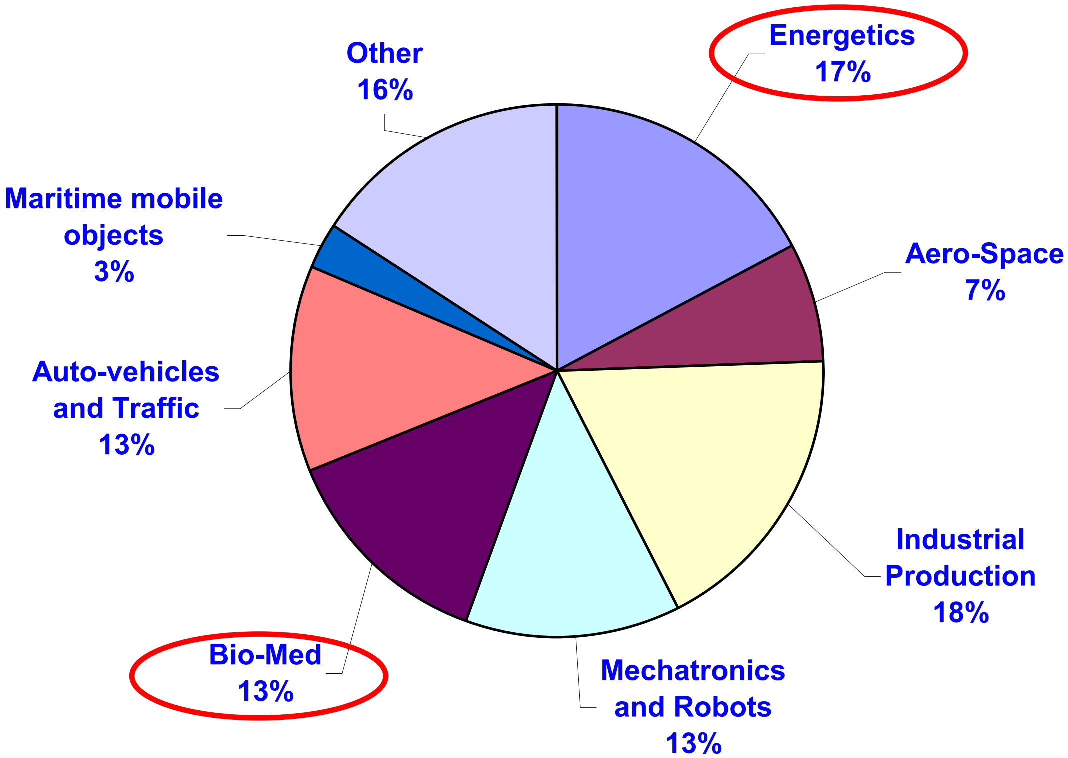

Fig. 10. Applications on IFAC-2011 World Congress

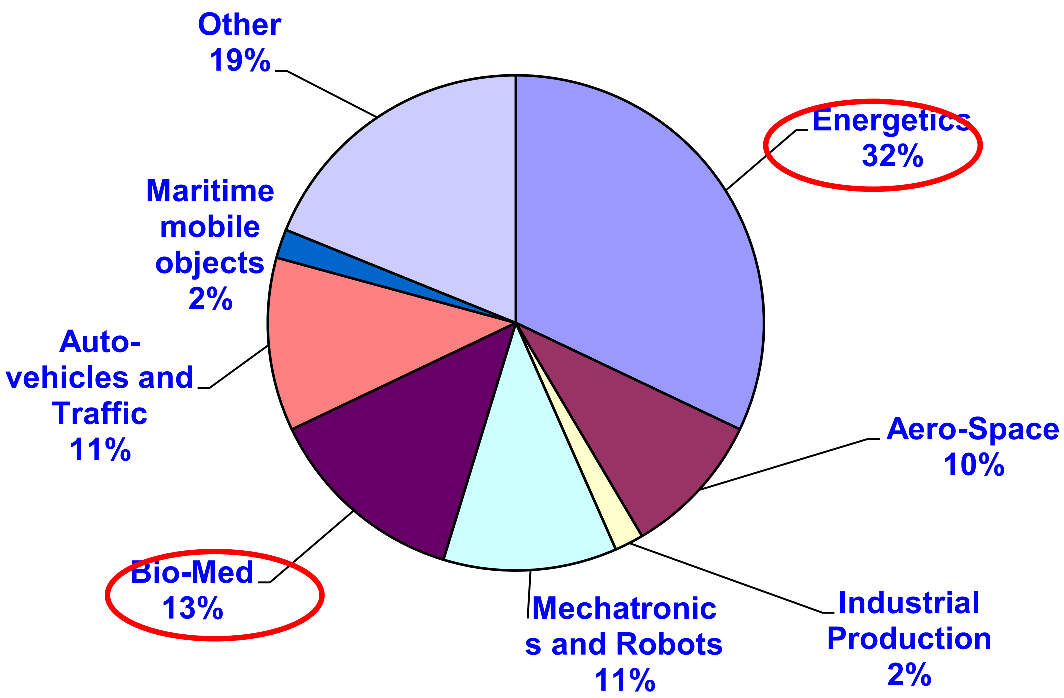

Fig. 11. Applications on CDC-ECC-2011 World Congress

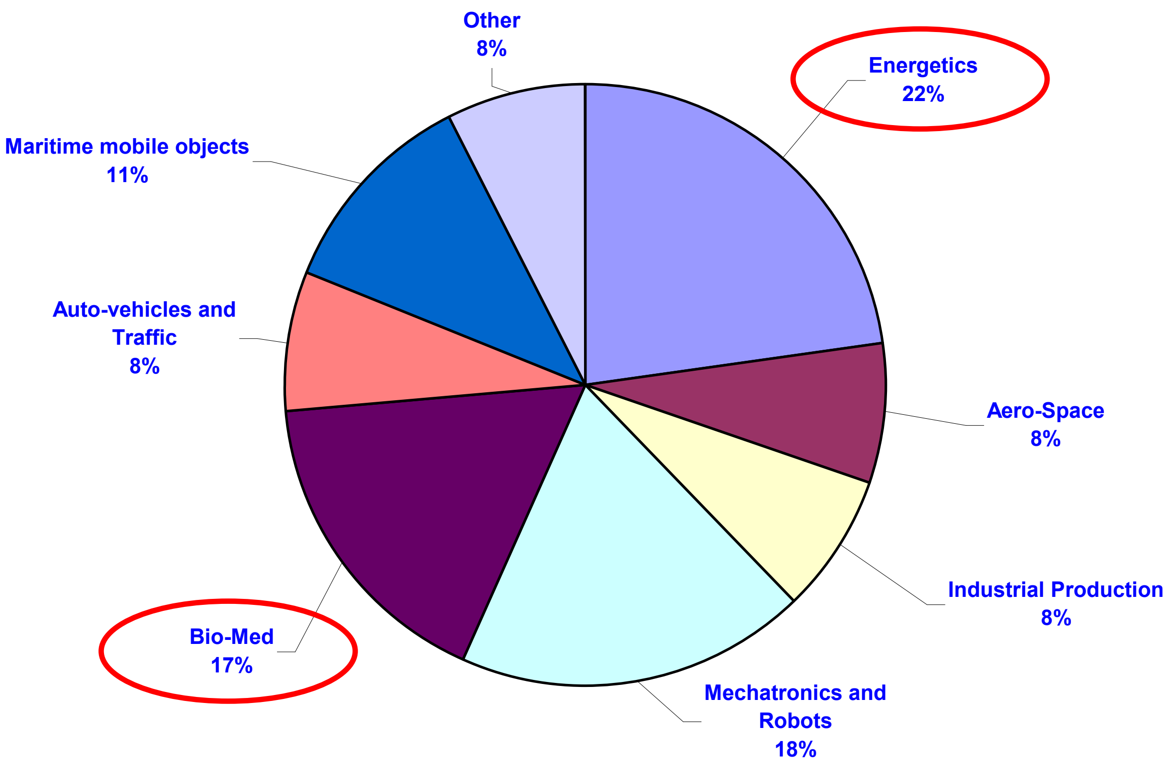

Fig. 12. Applications on ACC-2011

4. Interdisciplinarity

Control problems, generally (as first approximation), can be separated by the class of controlled object, used methods (mathematical apparatus) and applied means (measuring, computational and executive). To understand future, let's turn to recent history.

Methods. The late 1960s were remarkable for the rapid development of cybernetics and systems analysis, operational research, mathematical control theory (automatic control theory), later – various branches of decision-making models, distributed artificial intelligence, as well as for the intensive implementation of their results into technology. At the same time, many scientific research centers endeavored to apply general approaches of control theory to design mathematical models of social and economic systems (public choice theory, theory of mechanism design, etc). Nowadays, together with MAS-"technique" all this branches constitute the arsenal of modern control theory – see Fig. 13. MORE AND MORE REFINED AND COMPLICATED "MATHEMATICS" IS REQUIRED FOR CONTROL THEORY (in many fields, the necessity for new paradigm (adequate mathematical tool) is unanimously recognized, e.g. models of individual and collective decision-making).

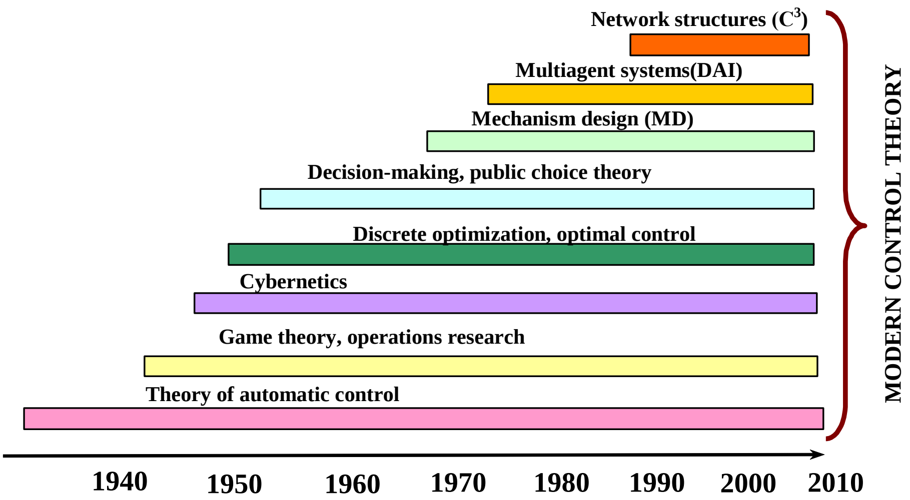

Fig. 13. Methods

5. Objects of Control

Consider the classification, which is based on the subject of human activity ("nature – society – production"). In this case, one may distinguish between

– Organizational systems (people);
– Ecological systems (nature);
– Social systems (society);
– Economic (technical) systems (production).

Different paired combinations, viz. systems of an interdisciplinary nature, emerge at the junction of these classes of systems (Fig. 14 shows the details). They are:

- Organization-technical systems;

- Socio-economic systems;
- Eco-economic systems;
- Normative-value systems;
- Noosphere systems;
- Socio-ecological systems.

It should be noted that THE LAST THREE CLASSES HAVE NOT YET BEEN INTENSIVELY STUDIED IN CONTROL THEORY.

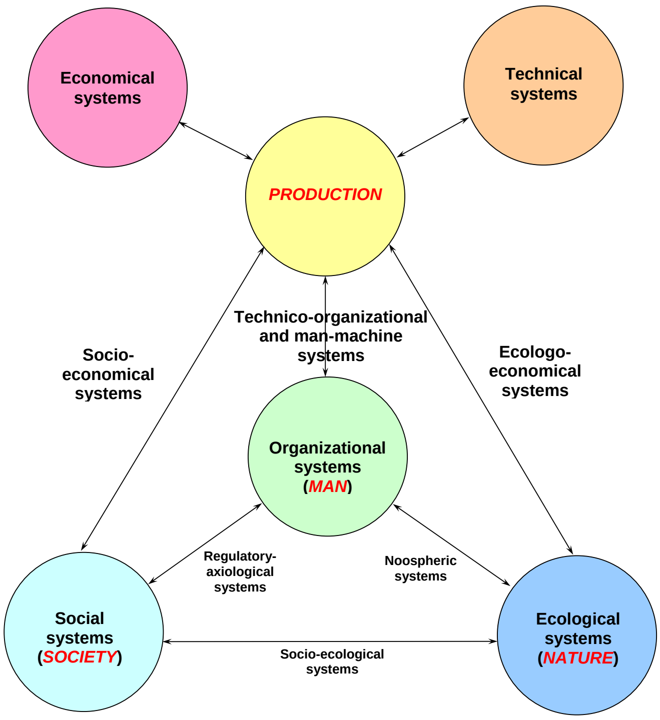

Fig. 14. Objects of Control

Scientific lifecycle. Any science, scientific domain and certain research has its own “lifecycle”. Control theory is not an exception - its typical “path” is given in Fig. 15.

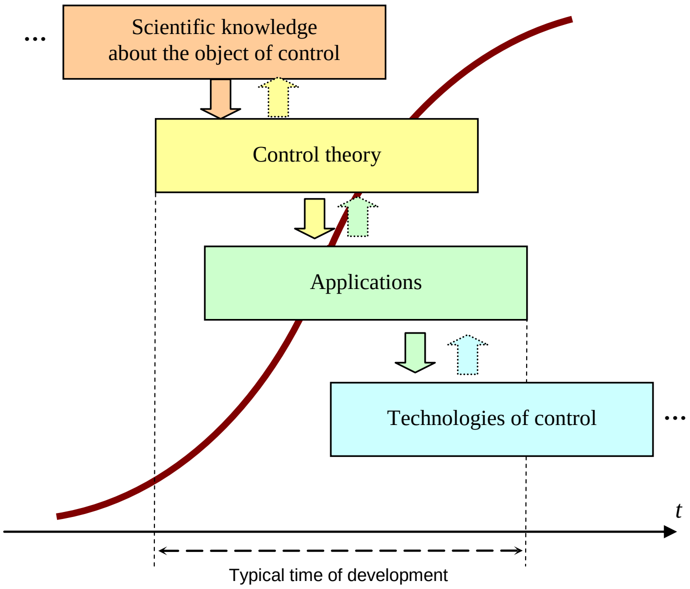

Fig. 15. “Lifecycle” of research in control theory

During the last 150 years of its development control theory had embraced many classes of controlled objects – see Fig. 16. In technical system in the last 10-15 years more and more trendy are decentralized intelligent systems. Parallely new and new objects of control appear in the focus of research – economical and ecological systems are well familiar to control theorists now. Future belongs to social and live systems (as objects of control). The “inflection point” (see Fig. 15) for technical systems was passed in XX century, now we observe rapid growth in economical applications. But, taking into account the lag of traditions and the need for forecasting, CONTROL THEORY SHOULD “SWITCH TO” THE PROBLEMS OF LIVE AND SOCIAL SYSTEMS CONTROL IN ADVANCE. This types of system are not well-explored themselves, thus CLOSE COOPERATION OF CONTROL THEORISTS WITH SPECIALISTS IN BIOLOGY, SOCIOLOGY AND OTHER BRANCHES OF SCIENCE IS INEVITABLE. On the other hand, this complex systems usually are decentralized, hierarchical and networked, hence, heterogeneity approach (mentioned above) in control models would surely be in demand.

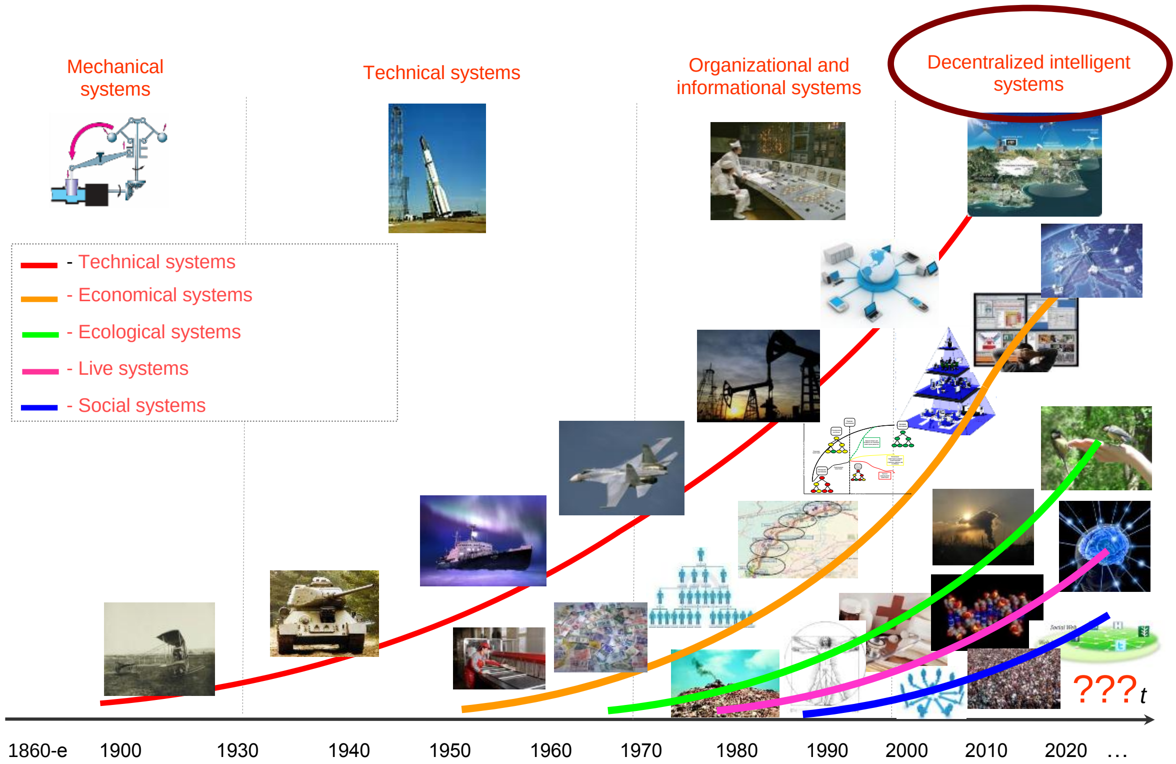

Fig. 16. General "lifecycles" of control theory

6. Limits of science

Interdisciplinarity has its advantages, but it leads to certain problems. The following law holds in epistemology: the wider is a problem domain, the more difficult is obtaining new common scientific results for it. This phenomenon vividly shows itself in mathematics. Notably, any formal assertion (e.g., a theorem) consists of two parts–suppositions ("Let…") and inferences ("Then…"). The stronger are suppositions (conditions, constraints), the simpler is the proof and the "precise" are the results.

Generally sciences are decomposed into epistemologically "strong" and "weak" ones. Accordingly, epistemologically weak sciences introduce the minimal constraints (or no constraints at all) and obtain the fuzziest results. Contrariwise, epistemologically strong sciences impose many limiting conditions, involve scientific languages, but yield more precise (and well-grounded) results. However, the field of their application appears rather narrowed (i.e., clearly bounded by these conditions).

Any suppositions (constraints) confine the domain of applicability (validity) of the corresponding results. For instance, in control of socioeconomic systems, mathematics (operations research, game theory, etc.) suggests efficient solutions; but the domain of applicability (adequacy) is appreciably limited by the explicit suppositions made to construct the corresponding models. On the other hand, social sciences and the humanities (also treating control problems in socioeconomic systems) introduce almost no suppositions and propose "universal remedies" (i.e., their domain of applicability is rather wide). But the efficiency of such "remedies" often coincides with that of sensus communis or the so-called best practices (the generalization of a positive practical experience). Without appropriate investigations one would hardly guarantee that a management decision (proved its efficiency in a certain situation) preserves the efficiency in another (though, a very "close") situation.

Thus, it is possible to draw different sciences using the coordinate axes "The Domain of Validity (relevancy)" and "The Domain of Applicability (application field)"; by analogy to the Heisenberg uncertainty principle), one can de bene esse formulate the following principle of uncertainty – see Fig. 17. The current level of science development is characterized by certain mutual constraints imposed on results' "validity" and results' applicability. That is, the "product" of the domains of results' applicability and validity does not exceed a constant (increasing the value of a "multiplicand" reduces the value of another "multiplicand").

An alternative explanation has the right to exist, as well. "Weakening" of sciences takes place as soon as the object of research gets complicated. Consequently, all epistemologically strong sciences can be called "simple," while the epistemologically weak ones can be referred to as "complex" sciences (based on the complexity their object of research). An imaginary "boundary" between them is biology (living systems). Analyzing separate systems of an organism (anatomy, physiology, etc.) still has a propensity for epistemologically strong sciences (the empirics is confirmed by reproducible experiments and is grounded by "simpler" sciences–biophysics, biochemistry, etc.). Thus, it may provide a base for formal constructions (similarly to physics and chemistry). Next, for living systems the experiments in their classical interpretation (reproducibility and so on) become difficult. Moreover, experiments are almost impossible for human beings and social systems.

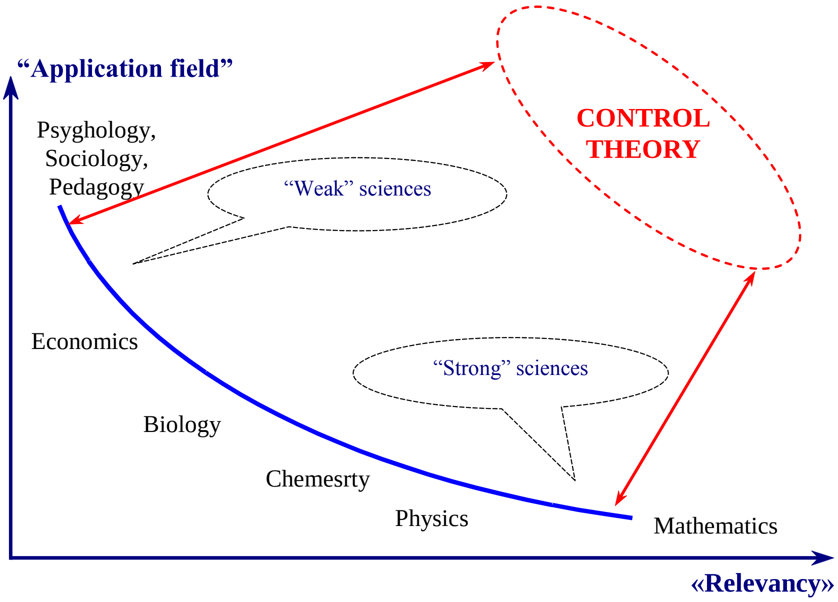

Fig. 17. Limits of science

Thus THE PROGRESS IN CONTROL THEORY IS CLOSELY CONNECTED TO THE LEVEL OF SCIENTIFIC KNOWLEDGE ABOUT THE OBJECT OF CONTROL. Moreover, sometimes requests of control theory stimulate researches in particular problem domains.

Meanwhile, authors hope that control theory, following the trends of NETWORKS, HIERARCHIES and INTERDISCIPLINARITY, will be able to overcome the afore-mentioned mentioned difficulties.