INTELLIGENT CONTROL OF SYSTEMS APPLIED IN WALKING VEHICLE CONTROL

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ABSTRACT. *The paper presents a contribution to an intelligent control problem solving. The most important features of the intelligent control are discussed and the application of this intelligent approach to control synthesis is presented here. The control of the complex system - walking vehicle - is an objective example of intelligent control utilizing.*

1. INTRODUCTION

According to the present paradigm of the control theory, usually named the *Control of the extraordinary complex systems,* new approaches and methods are being sought and used for the synthesis of control laws. Although every new paradigm takes over all tried approaches and methods from the previous paradigms (the Bohr's correspondence principle), the present one could be characterized namely by using of artificial intelligence (AI) methods and by the evolutional approach to the control synthesis.

The intelligent control as a part of the modern (automatic) control theory can be taken as its regular extension, that have been forced by the complexity, extent, and specific structures of the systems to be controlled.

2. INTELLIGENT CONTROL

The terms of intelligent control is used in two senses. The first one is the mentioned part of the control theory (or cybernetics). The second meanings of this term is a way of control performed by the man-made "intelligent" control systems, that are being able to solve the "intelligent" control tasks. The attribute "intelligent" is derived from the common definition of artificial intelligence, based on the comparison of the tasks and ways of task solving by the man, that uses his natural intelligence.

The intelligent tasks just correspond to the activity of the man, as an intelligent being, and they are characterized: by knowledge manipulation, by their own complexity, by complicated algorithmisation, by processing of different kinds of information, etc.

The examples of typical intelligent tasks are: collection and processing various kind of information, its transformation to form of knowledge; creating an *internal model of world* as a structured knowledge base; *decision making* and *problem solving* over created world model; *communications* with other intelligent subject - exchange of information and prefabricated knowledge; *understanding* and synthesis of natural language, etc. It is evident that these tasks correspond to parts of AI, e.g. *knowledge representation, general problem solving, tasks planning, machine learning, pattern recognition,* etc. Therefore the intelligent control can be characterized by the following features:

- taking advantage of AI - methods, in the phase of control synthesis well as in control process;
- it is usually based on the evolutional approach to the control law of synthesis; based on the adaptation and machine learning; to get the desired behaviour of the system;
- manipulation with various kinds of knowledge;
- the implementation of the control law on the computer system being capable to handle symbols.

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- the accent on the parallelism of tasks solving, that is connected with hierarchy and decentralization of the control structures. It is supported by construction of adequate computer systems and means (multi-processor systems, transputers, etc).

3. INTELLIGENT CONTROL PROBLEM REPRESENTATION

Taking into account common structure of the feedback cybernetic system, we can use very general set-representation of the control problem, where all objects (controller, controlled system, enviroment of the system...) and their connections are described by means of sets of variables and by relations between them, Fig 1.[9]

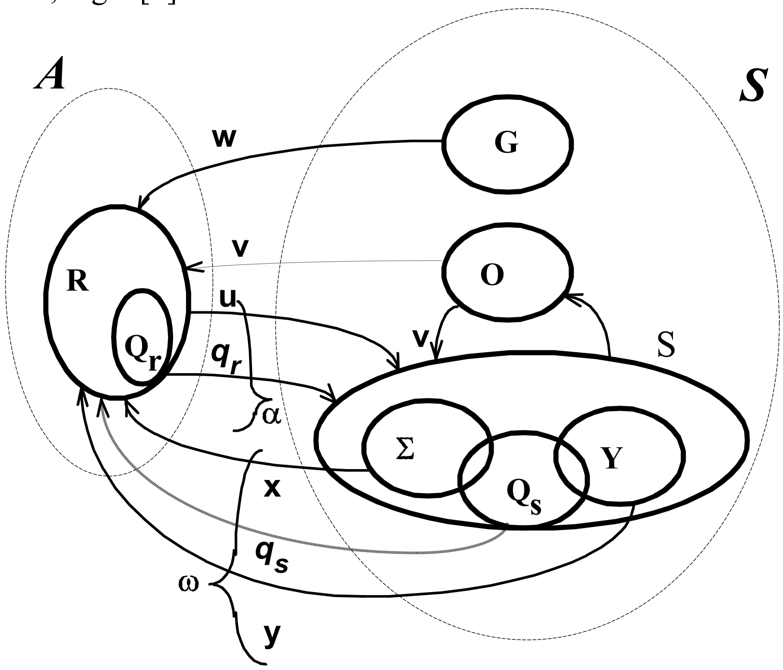

Fig. 1. The set - representation of the control problem

There are two main sets of variables in this scheme. First of them - *situation set* **S** - includes other sets (subsets): set of system states Σ, and/or set of system outputs **Y**, the set of variables specifying the influence of the system environment **O** and the goal set **G**, that expresses the demanded system behaviour. The second main set is called *action set* **A** and it represents the set of permissible acting values **R**. Both sets involve subsets $Q \equiv Q_R \cup Q_S$ of other auxiliary variables, that are used namely for qualitative evaluation of the system activity.

The action set A is given by the Cartesian product

$$A \equiv (R \times Q_R) \tag{1}$$

and the situation set S is expressed

$$S \equiv (G \times O \times \Sigma \times Y \times Q_S). \tag{2}$$

The situation σ and the action α are expressed like vectors of attributes

$$\sigma = (w, v, x, y, q_S) \qquad \text{resp.} \qquad \alpha = (u, q_R), \tag{3}$$

where $\mathbf{w} \in \mathbf{G}$ is demanded system behaviour, $\mathbf{v} \in \mathbf{O}$ is a vector of environment values, $\mathbf{u} \in \mathbf{R}$ is a vector of acting values, **x**, **y** are vectors of state and output, **q** and $\mathbf{q_S}$ are variables evaluating the behaviour of the controller and controlled system. The ω denotes the (generalized) behaviour of the system, α is an action.

The *system universe* is determined by Cartesian product of **A** and **S**

$$U \equiv (A \times S) \tag{4}$$

and the control law **R** could be expressed like relation defined over the **U**, i.e. its own subset

$$R \subset U. \quad (5)$$

The main constraint for the control law is the *controlled system relation* **S**

$$S \subset (R \times O \times \Sigma \times Y) \equiv U_S, \quad (6)$$

that is subset of the controlled system universe $\mathbf{U_S}$. Let the generalized behaviour $\boldsymbol{\omega}$ is an element of system activity set $\boldsymbol{\Omega}$, then the goal set is expressed as a subset of $\boldsymbol{\Omega}$. The goal of control is reached, when the control law **R** ensures satisfying the relation

$$\omega \in G \subset \Omega. \quad (7)$$

According to time-varying values (the system is dynamic) the control process can be interpreted as a sequence of control task solutions and the time-dimension of control representation must be taken into account.

4. THE APPROACHES TO THE CONTROL LAW DESIGN

The relation (1) can be expressed as a mapping, i.e. the control law is a mapping from the **S**-set to the **A**-set, Fig. 2.

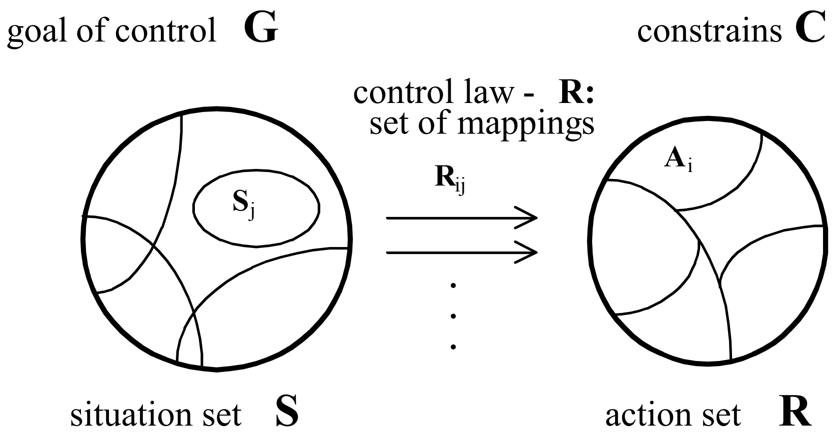

Fig. 2. The set representation of the control law.

The problem of control laws determinig can be interpreted using set representation as follows: Having some set $\mathbf{S}$ of possible situations σ of controlled system and its environment the control law determination means to find some mappings $\mathbf{R_i}$ from subsets $\mathbf{S_i}$ of $\mathbf{S}$ to the action set $\mathbf{A}$ of all possible actions α, taking into account the goal of control $\mathbf{G}$. Each mapping expresses some partial control law defined on some subsets $\mathbf{S_i}$ subsets.

To design the controller or to form its control laws the common used *direct algorithmic approach (DAA)* can be used. It is based on inspecting some useful admissible action of legs for any possible situation by means of a set of predeterminated numerical procedures and algorithms. In case of direct algorithmic approach the subsets $\mathbf{S_i}$ and the form of mappings $\mathbf{R_i}$ are determined a priori as a result of system analysis. The DAA is based on: a priori articulation of the **S** set; determining of partial mapping from $\mathbf{S_i}$ to **A** in a form of deterministic function or computational procedure. But, in case of a complex system to be controlled (like a walking machine, par.4) some marked disadvantages occur in DDA control law forming. To achieve satisfactory manner of the control system the situation set is to be covered by its own subsets $\mathbf{S_i}$ and for all of them some mapping to the action set is to be predetermined.

- To ensure it well, a lot of subsets $\mathbf{S_i}$ and partial control laws must be determined, it leads to complex control, a lot of algorithms must be incorporated
- In practice, it is usually difficult to ensure the admissible action for all of possible situation, and always we can expect that some new situation without predetermined action will occur.
- In articulation of set **S** a priori and in mapping **R** (partial control law) determination some important relations between attributes could be lost and it could cause collapse of control process.
- Performed control laws are fixed and any improving of the robot behaviour must be realized by reprogramming, and others.

Because of these negative properties this way is very unconvenient and unflexible. That is the reason for suggesting another *evolutional learning approach* (ELA) to reactive controller design. It is based on using of consecutive learning of an appropriate controller structure and it is aimed to get demanded control laws step by step in well organized training process. The main goals of learning process are:

- to precise borders of $\mathbf{S_i}$ subsets,
- to specify and precise control law formulation according to control experience,
- to satisfy good situation set covering.

The evolutional learning approach supposes that the boundaries of subsets $\mathbf{S_i}$ and the form of mappings $\mathbf{R_i}$ are being precised in course of well organized training process to get desired behaviour of the system (goal $\mathbf{G}$). To improve the system manner by learning process some information about previous actions and their consequences is recorded and processed and stored in a form of knowledge for the next utilization. In common cotrollers knowledge is distributed in control algorithms and other computational procedures. For learning is more useful to operate with explicit knowledge represented in some standard form, e.g. production rules or theorems, etc.

To determine convenient control laws some important characteristics of the system must be specified:

- structure of controlled system (subsystems, elements, couplings,...) their possibilities and limitations; structure and influence of environment of the system; i.e. an adequate simulation model of the controlled system and model of its environment must be constructed;
- structure of necessary information to be provided by the sensoric subsystem for control;
- control tasks to be solved in controler and other important functions;
- supposed participation of human operator;
- quality criteria for evaluating of controlled system behaviour and of a level of meeting the demanded $\mathbf{G}$;
- supposed structure and properties of the controller to be designed.

For the synthesis of the control laws using mentioned evolutional learning approach it is necessary to suggest:

- underlying strategy (strategies) of learning to get desired behaviour in course of training process;
- the way of the knowledge representation, storing and processing in learning process organization;
- some appropriate learnable structures as a backgroung of the controller activity evaluation and learning process orientation;

- an effective algorithm for multi-level learning process coordination if more learning algorithms and learnable structures are utilized;
- appropriate computer environment for diverse dynamic structures modelling and algoritms implementation, because, to carry out the controller design using the evolutinal approach the computer simulation methods are usually used;
- a set of qualitative criteria of the controller behaviour evaluation and learning process orientation.

5. SYTHESIS OF WALKING MACHINE CONTROL LAW

The system to be controlled is the locomotion subsystem of the walking robot, i.e. *walking vehicle* [5]. As to both construction and control the walking vehicle is complex nonlinear multidimensional dynamic system. For example, six legged vehicle - hexapod has 24 degrees of freedom at minimum and 18 leg-element-servosystems must be driven to control main six values of the robot body position and their derivatives. Motion of the walking vehicle (especially in complicated and unknown terrain with obstacles) necessitates such way of control, that exceeds common used methods of automatic control. To get desired robot motion and to overcome great redundancy and indeterminateness of control very complex tasks must be continually solved in controller. Efficient solutions of these tasks can be found using some appropriate methods pertaining to artificial intelligence. Therefore the control system of the walking vehicle must have so properties that (comparing with similar human activities) can be taken as intelligent ones and so walking vehicle represents cognitive robotic system by itself.

To achieve desired walking vehicle behaviour means to incorporate such control laws, that are able to find and to realize some useful action in any situation of the vehicle, to determine solution of all control tasks taking into account general motion quality criteria.

The situation set **S** is structured one and it involves dynamic state variables of vehicle, coupling terrain body attributes, group of operational control values expressing desired body motion and other useful characteristics. An element of **S** represents some situation of robot and it is determined by an ordered sequence of attributes. The action set **A** involves admissible actions of the vehicle, especially time instances of situating of a leg (lifts or puts), coordinates of a support point of a leg and, of course, acting values for continuos motion of legs and other.

Conditions of control are given especially by dynamic equation of walking vehicle, by construction, control and energetic limitations by actual terrain shape and by external couplings. The goal of locomotion control is to provide the continuous motion of the robot body in space by stable mechanic walking in the intention of given operational values (desired motion) and complying with motion quality criteria (stability, energy consumption, robustness).

6. LEARNING PROCESS ORGANIZATION

Teaching the walking machine to march is the task when a human operator can not be in role of example. Man is not able to control so complex system directly and his requirements and recommendations could be only given to the machine indirectly, off line. Therefore the main strategy of learning is *self-learning,* i.e. system learns without an intervention of the operator.

In the learning process the system can use only some amount of information or knowledge incorporated by man before. This knowledge belongs to *background knowledge* and it is involved in the model of the system, in the learnable control structure, in auxiliary computational procedures and, of course, some part of background knowledge explicitly formulated (e.g. like a rules or theorems) in useful knowledge representation. It is clear that for the beginning of the training process (experiment with the model) any controller being able to generate some reasonable (not always optimal) control values must be used. It need not be neither intelligent nor learnable nor too efficient but it must be capable to find satisfactory solution of control tasks and then this controller can serve as a teacher for other learnable structures. This system will obviously be designed like a state-space searcher. In our case this teacher system (denoted $\mathbf{R_1}$) is based in the dynamic programming procedure and it is supplemented with auxiliary algorithms for reducing a number of states that are to be generated and tested. We use backtracking (in limited form), heuristic functions and for this purpose other *rule - based controller* ($\mathbf{R_2}$) is used.

The rule - based controller has in our concept two main rules:

- it helps to increase effectiveness of the first system; using some rules the most helpful state trajectories are generated;
- in many situations $\sigma \in \mathbf{S}$ this system is able to provide action $\alpha \in \mathbf{A}$ directly without initialization of searcher $\mathbf{R_1}$.

Rule base of $\mathbf{R_2}$ is created by a set of rules. Some of them are formulated by operator before. The other rulres origin in mentioned training process, i.e. $\mathbf{R_2}$ is learnable and for learning of it two main algorithms are being specified. First of them is an algorithm of *statistic learning.* All good (a posteriori evaluated) control task solutions are processed to precise antecedents $\mathbf{S_i}$ of situation - action rules and to correct the reliability of rules $\mathbf{w_j}$. The second algorithm is simplified *inductive logic procedure* of learning from examples based on decision tree construction and it makes possible to formulate new rules.

To articulate situation σ by this simple way (according to antecedents of rules) is very advantageous but the absence of more complex relations between attributes that could be necessary to precise borders. The third used control subsystem **Chyba! Objekty nemohou být vytvořeny úpravami kódů polí.** is an *artificial neural network.* It is three-layer feedforward neural network with backpropagation learning procedure. We are trying this structure in a role of *student*, that is to be able to utilize its own natural learning property and to induce from examples. As input stimuli are applied some attributes of **S**, especially desired motion characteristics and state vector of walking machine. The pattern to be taught is the actual response of the *teacher system* $(\mathbf{R_1} + \mathbf{R_2})$, i.e. actual control values $\mathbf{u_T}$. For adaptation loop the difference between desired response $\mathbf{u_T}$ and student reaction $\mathbf{u_S}$ is used. The using of the neural network controller is aimed to precize borders of $\mathbf{S_i}$ according examples of control values $\mathbf{u_T}$ and to give good answer (admissible control value) when some new situation $\sigma \in \mathbf{S}$ occurs in control process.

7. CONCLUSIONS

Mentioned approach to controller design using machine learning seems to be perspective due to ability to solve more complex situations and nonstandard states of robot behaviour. It is possible to utilize the advantages of both of learning structures [7],[8] and their (well managed) cooperation could lead to better results, then simultaneous activity of both of them. It is the way how to reach the intelligent behaviour of the walking robot and the example of intelligent control application.

For control process simulation the walking machine model described in [5] is used.

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