RIGA TECHNICAL UNIVERSITY

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HYBRID INTELLIGENT SYSTEM DEVELOPMENT AND IMPLEMENTATION

Summary of Doctoral Thesis

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1. General Description

1.1 Motivation of the research

Artificial intelligence is one of the youngest branches of modern science. Its main sphere of studies is problem solving and knowledge representation. During the last few decades plenty of methods, technologies and approaches in both these directions developed that more or less successfully allow solving certain classes of problems.

Methods of artificial intelligence are applied practically in all economic sectors, but particularly widely in medicine, military sphere, manufacturing, businesses, etc. Systems that use methods of artificial intelligence become more and more complex from year to year, allowing to solve an ever increasing range of problems.

Intelligent systems in the context of this work fall into two groups - autonomous and supervised. The autonomous systems unlike the supervised ones can operate using their own experience without human (supervisor) intervention or help [1]. The development of autonomous systems faces with wide range of problems from concerning decision making, knowledge acquisition and representation because these systems have to acquire, organize knowledge and make a decision on their own. Therefore there are necessarily situations in when decision has to be made on incomplete knowledge and limited information about the system's environment [1]. As regard knowledge representation the autonomous systems are specific because they link units of the knowledge unaided and unassisted by humans (supervisors). So the development of the autonomous systems is usually more complex than the development of supervised systems or systems with limited autonomy. The development becomes even more complex if the system is developed for operation in sophisticated environments which are highly dynamic, hardly predictable, includes larger number of elements and links connecting them, etc [1, 2, 3]. It means that knowledge representation schema and decision making process become more sophisticated from structural as well as from control aspects.

Numerous methods and techniques in artificial intelligence have been developed, all of them are subdivided into two main groups - symbolic and subsymbolic (in some sources *emergent)* methods. Symbolic methods are usually based on a centralized management and operate with strictly defined symbols, for instance, expert systems [4, 5], Subsymbolic methods are based on a decentralized structure where its elements are interlinked with each other. Methods of both groups have their advantages and disadvantages, usually symbolic methods are selected for developing generally intelligent systems [4]. As it is easy to perceive the usage of the symbols the represented knowledge may be used on different levels of specification as well. Therefore knowledge-based (symbol-processing) systems are under close watch.

In order to implement an autonomous intelligent system (or any other information system) the necessary functionality based on the environments characteristics has to be defined [6, 7]. While the environment's complexity is increasing, the functional requirements towards the system are growing as well. Therefore the implementation of the system by making use of one appropriate method is difficult or even impossible.

One of the most promising directions of artificial intelligence is hybrid intelligent systems. The limitations of individual techniques is the central driving force behind the creation of intelligent hybrid systems .where two or more methods are combined into one systems that overcomes these limitations [8, 9], There is a special interest in combining several reasoning techniques thereby increasing reasoning and adaptation abilities of the system [8, 10].

1.2 Goals and Tasks of the Thesis

The goal is to develop and to implement a structure of autonomous intelligent system for operation in sophisticated environments satisfying all requirements as well as to experiment with the system to evaluate performance of the developed structure. The most important methods of artificial intelligence that are analyzed do not support all the necessary functions. Therefore on the basis of the analysis of the supported functionality and the corresponding summary the structure has to combine inductive, deductive, associative and case based reasoning techniques, thereby providing all of the required functions. On the ground of the hybrid structures analysis the most appropriate structure has to be selected and implemented. In order to validate performance and structural individuality of the developed structure and functionality compliance with the selected methods a series of experiments have to be accomplished. The sphere of possible applications has to be analyzed as well.

The doctoral thesis involves the following tasks:

- In order to define the necessary functionality of the system characteristics of complex environments have to be analyzed;
- description of the defined necessary functionality that is essential for successful operation of the system in complex environment has to be supplied;
- analysis of the most widely applied knowledge based methods has to be described and examined in order to estimate the possibility to use existing solutions for the development of the system for operation in complex environments;
- development of the kernel structure of the autonomous intelligent system via applying knowledge based techniques;
- implementation of the autonomous intelligent system using the developed structure;
- series of experiments has to be accomplished in order to evaluate the performance of the system, its advantages and weaknesses, as well as analysis of the application of the system;
- evaluation of the system's performance and possible application has to be supplied;

The used research methods:

- theoretical research is based on the analysis of:
  - characteristics of complex environments;
  - functionality of inductive, deductive and case based reasoning methods;
  - functionality of artificial neuron nets, associative reasoning, evolutionary theory based approach and properties of the hybrid structures;
- Experimental research is based on the analysis of the changes in the system's performance according to the parameter changes of the used methods (algorithms);

1.3 Novelty of the work and author's contribution

The most important **novelty of the doctoral thesis** is the developed structure of an autonomous intelligent system which is implemented as software and a robotic system. The developed structure and its implementation are based on the results of the complex environments properties and appropriate autonomous intelligent system functionality analysis resulting in a summary of the functionality of the investigated artificial intelligence methods. The thesis involves the analysis of hybrid intelligent systems structures and their application specifics for the development of the autonomous intelligent system for operation in complex environments.

The most important practical value of the thesis is the developed structure of the intelligent system and implemented prototype that combines inductive, deductive, case based and associative reasoning methods. This combination allows the system to operate effectively in sophisticated environments without outer (human) assistance. The elaboration of the thesis enabled to achieve the following **practical results:**

- Information about complex environment properties and their implications on functionality of the autonomous intelligent system was analyzed and summarized;
- The necessary functionality of the autonomous intelligent systems based on characteristics of the complex environments was defined and summarized;
- Properties of the most widely applied artificial intelligence methods in a strict accordance with the defined required functionality for effective operation in complex environments were analyzed;
- A summary of the properties of the analyzed methods correspondence with the required (defined) functionality.
- Hybrid intelligent systems structures compliance with the defined necessary functionality for operation in complex environments was analyzed as well as the recommendations on their application in autonomous intelligent systems were provided.
- Based on of the properties of the complex environments, the emergent functionality requirements and the results of the analysis of artificial intelligence methods, a structure of the intelligent system providing the necessary autonomy and flexibility for operation successfully in sophisticated environments is developed and implemented.
- The developed structure combines inductive, deductive, case based and associative reasoning methods in a common hybrid system, resulting in the ability to learn with an empty knowledge base (bottom-learning), i.e. to acquire and represent knowledge using appropriate representation schema, to apply the

knowledge in order to achieve goals as well as to adjust the existing knowledge in correspondence with respective feedback.

- It was experimentally proved that the combination of deductive, inductive, case based and associative reasoning techniques in one system provides the necessary flexibility for successful operation in complex environments.
- Recommendations are formulated for employment of autonomous intelligent systems in control and diagnostic tasks.

The results are included in the following publications:

1. A.Nikitenko, J. Grundspenkis, Combining of inductive, deductive and case-based reasoning: towards the development of hybrid intelligent system. Scientific Proceedings of Riga Technical University: 5th series "Computer science, Applied Computer Systems", Riga, RTU Publishing, 2001, Vol. 8, pp. 116 - 123.
2. A.Nikitenko, J.Grundspenkis, The kernel of hybrid intelligent system based on inductive, deductive and case based reasoning. KDS2001 Conference Proceedings, St. Petersburg, 2001, pp. 138. - 146.
3. A.Nikitenko, The structure of an intelligent system for complex environments. Proceedings of Riga Technical University: 5th series "Computer science, Applied Computer Systems (Special Issue)", Doctoral consortium, The 11th International Conference on Information Systems Development, Riga, RTU Publishing, 2002, Vol. 9, pp. 46 - 52.
4. A.Nikitenko, Inductive reasoning algorithms from the perspective of autonomous intelligent systems. Scientific Proceedings of Riga Technical University: 5th series "Computer science, Information Technology and Management Science", Riga, RTU Publishing, 2003, Vol. 14, pp. 10 - 17.
5. A.Nikitenko, A proposed structure for knowledge based hybrid intelligent systems for sophisticated environments. Varna, Bulgaria, KDS 2003 Conference Proceedings, 2003, Vol. 1, pp. 25-31.
6. A.Nikitenko, Robot Control Using Inductive, Deductive and Case Based Reasoning. Varna, Bulgaria, KDS 2005 conference proceedings, 2005, Vol. 2, pp. 418 - 427.
7. A.Nikitenko, Intelligent Agent Control Using Inductive, Deductive and Case Based Reasoning. Riga, Latvia, ECMS 2005 Conference Proceedings, 2005, pp. 486 - 492.

The results are included in the Latvia Science Council report in 2003 (In 19.05.2003. resolution Nr. 4-2-1 of the LSC Doctoral program committee of the doctoral grants).

The author's personal contribution is all of the research results presented in the thesis. The results are acquired in unaffiliated research carried out by the author of the thesis using scientific methods.

1.4 Structure of the document

The thesis document includes introduction, five sections, conclusions and bibliography.

The introduction contains motivation of the research. Its topicality and the research goals are formulated as well as the novelty, significance and practical value of the research are described.

The second section is devoted to the formulation of the problem. The section introduces the terminology used and analyzes the current situation, dealing with the description of the most important methods as well as the description of application guidelines. The section provides descriptions and definitions of the terms *complex environment* and *autonomous intelligent system.* Properties of the complex environment and requirements of the autonomous intelligent system that operates there are defined. The analysis of the application of the described methods is made regarding both general application and application in autonomous systems. The summary of the analysis enables to conclude that none of the described methods is fully compliant with the defined requirements. The summary clearly outlines that only a combination of the described methods can provide the necessary functionality.

The third section is devoted to the description of hybrid structures. It introduces two general classifications of hybrid structures. The summary at the end of the section provides a characteristic analysis of the structures in order to determine correspondence with the defined requirements. On the ground of the analysis the most appropriate structure is selected.

The fourth section is devoted to a general description of the developed structure of the autonomous intelligent system that is implemented as a robotic system. The section's summary provides an analysis of the developed structure and its functionality in order to determine its correspondence with the defined requirements. The analysis clearly demonstrates full correspondence.

The fifth section is devoted to a detailed description of the implementation of the developed structure. The section involves a description of the used algorithms and data structures.

The sixth section is devoted to the description of the experiments and their results. The experiments are made to estimate the following characteristics of the system: the ability to learn, efficiency of learning with growing knowledge base (the knowledge base is updated during the system's runtime), performance with different attribute values of the used algorithms and different combinations of the used methods (not all methods are used) as well as performance in a complex environment with selected attribute values (the selection is made on the ground of the previous experiments). The results allow to conclude that particular attribute values have considerable impact on the overall performance of the system, i.e. the number of examples used for learning, maximum plan length, plan, rule and case reliability values. The performance is considerably decreasing if the case based reasoning method is not employed. Nevertheless, the results outline that even when the performance is low (for instance, case based or associative reasoning is not involved), the system can adapt in dynamic environment by using the rest of the methods.

The conclusions present the most important conclusions, which are based on the experimentation results. The results are used to make this analysis of the advantages and disadvantages as well as analysis of the implementation correspondence with the defined requirements. This section provides analysis of the possible applications of the structure in control and diagnostic tasks.

The section provides a description and motivation of the future research directions. The main directions are:

- to advance the structure in order to reason about longer periods of time;
- to carry out deeper investigation of possible alternative implementations of the used methods in practical tasks;
- to investigate the possibilities to use more complex (precise) sensors in practical implementations.

The doctoral thesis is written in Latvian and consists of introduction, 5 sections and conclusions. The work includes 36 tables and 50 figures, in total 180 pages. The bibliographical list contains 80 references.

2. Thesis Composition

The introduction introduces classification of the artificial intelligence methods, i.e. *symbolic* and *subsymbolic* methods [4, 5]. In the thesis the main stress is put on symbolic methods because they are usually selected for the development of generally intelligent systems. Symbolic methods support knowledge representation in an easy-to-understand way for the user (researcher) [4]. The introduction outlines the key difference between autonomous and supervised systems, that is, autonomous system operates using its own experience (without human assistance) [1], When the complexity of the environment is increasing, the functionality requirements (demands) are increasing as well. Therefore the implementation of the functionality with one particular method is hard attain or even impossible.

Today one of the most promising directions of artificial intelligence is "hybrid intelligent systems". They are founded on the idea of combination of several methods (approaches) in one common system [8]. The thesis topicality is supported by the advantages of the hybrid intelligent systems that allow to eliminate drawback of one approach by means of the advantages of some other method, new qualities or functional abilities are obtained too [8, 10].

2.1 Goals, tasks and structure of the thesis

In the first section goals and tasks of the thesis are defined. The goal is, first, to develop and to implement the structure of an autonomous intelligent system for operation in sophisticated environments that satisfies all of the requirements, and second, to experiment with the system in order to evaluate performance of the developed structure. Analysis of the supported functionality obtained by the described methods and the correspondent summary the structure has to combine inductive, deductive, associative and case based reasoning techniques, thereby providing all of the required functions. On the ground of the made hybrid structures analysis the most appropriate structure has to be selected and implemented. In order to validate performance and structural individuality of the developed structure and functionality compliance with the selected methods a series of experiments have to be accomplished. The sphere of possible applications has to be analyzed as well.

A detailed description of the thesis goals and task is provided in section 1.2. "Goals and tasks of the thesis".

2.2 Definition of the problem

The second section "Definition of the problem" introduces the terminology that appears in the used sources, including definitions of the autonomous system, environment and its characteristics. On the ground of the used sources requirements for autonomous intelligent systems for operation in complex environments are defined. Properties of the most widely applied methods are analyzed in strict correspondence with the defined requirements and the characteristics of sophisticated environments. The result is outlined as a summary table that clearly shows the necessary functionality and the supplied functionality achieved by appropriate methods. In the thesis context the intelligent system is defined as an artificial system that can perform actions requiring an intelligent behaviour if they would be performed by a human [1]. In the thesis a more accurate definition is used, describing characteristics of an intelligent system [11]. The characteristics are:

- Reactivity - the ability to sense and to react to changes in the environment in accordance with the system's goals;
- Pro-activeness - the ability to demonstrate initiative in order to achieve goals considering changes in the environment;
- Social behaviour - the ability to communicate with other systems (natural or artificial);

According to the sources used [1, 10, 12, 13] in the thesis, an autonomous intelligent system is any artificial intelligent system that can achieve its goals using its own knowledge, experience and available decision alternatives as well as without any using outer assistance. It is stressed that the development of an autonomous intelligent system usually is much more complicated because it requires mechanisms for making decisions about system's behaviour without outer assistance [12].

This section defines complex environment according to the structural and behaviour characteristics of the environment [1]. In order to better characterize a sophisticated environment from the point of view of its behaviour, the environment is described as a complex system, because anything that can be assumed as one whole can be described as a system [2, 3, 14]. Thereby, on the ground of definition of the complex systems [3], any complex system can be described as a system having the following features: - Complex systems are hardly predictable or even unpredictable;

- Complex systems are unique or the number of similar systems is insignificant;
- Complex systems tend to preserve their main processes - they can resist outer influence in order to preserve the processes unchanged;

On the ground of the features of autonomous systems and the analysis of complex environment properties, the necessary functionality of the autonomous intelligent system for successful operation is defined. The defined functions are:

- Ability to sense the environment. The function requires a special sensing mechanism in order to supply the system with necessary input for decision making process [11, 15, 16].
- Ability to act. Actions are any kind of operations that may be used in order to lead the system to the goal [10, 17, 18];

It is an essential necessity to decide about the outputs if the inputs are known [10, 17]. The source [1] points out that the most important feature of the autonomous system is the ability to use its experience and "knowledge in order to make decisions. Obviously, if there is a mechanism that uses the experience, than the mechanism of experience acquirement (learning) is essential;

- Ability to learn. In accordance with the features of the complex environments a learning and adaptation mechanisms are essential [19];
- Ability to infer logically (deductively or sequentially). If the system can obtain regularities, then it is necessary to use them. The main singularity of the deductive reasoning is the provided formal mechanism, which allows deriving new knowledge from the existing knowledge and sensed (acquired) facts [5, 18]. On the most common applications of the deductive reasoning is action planning [5, 15, 16, 18, 20];
- Ability to apply experience in previously unknown situations. Complex environments are very varied and dynamic. It is likely that the system may not face situations that are identical with previously experienced. Therefore the system needs to apply experience in unknown environments. **This function is added, substantiated and its necessity is experimentally proved by the author.**
- Ability to reason associatively. Associative reasoning is based on the links that bind objects into a single net. Each link binds only those objects that are similar in some degree. In order to find a similar object to the given one the links which activate the similar objects are used. Similarity is determined by the number of attributes that have the

same value assigned (similarity measure) [21]. Usually the similarity measure calculated in accordance with the following formula:

$$yi = \begin{cases} 1, if \sum_{j=1}^{n} \partial(w_{ij} x_j) \geq Ti \\ 0, if \sum_{j=1}^{n} \partial(w_{ij} x_j) < Ti \end{cases} , where \quad \partial(x) = \begin{cases} 1, if \quad x > 0 \\ 0, if \quad x = 0 \end{cases}$$

In the formula:

- $\vec{X}$ - the question vector, i.e. the given (observed) object, that is described with attributes xj;
- $\vec{Y}$ - the answer vector with elements yi, which shows if the object (its description) i in the knowledge base is similar to the given one;
- wij - the weight of the attribute value j in the object description i;
- Ti - the similarity threshold - the similarity measure minimum for the object i;

The described mechanism allows to reason about the environment utilizing similarity [21, 22, 23]. **This function is added, substantiated and its necessity is experimentally proved by the author.**

- Ability to sense a sequence of events. This function is essential for determining the exact place of a particular event among other events [5] as well as for learning causalities that exist in the environment.
- Ability to be goal driven. The system has to be goal driven in order to adjust its actions according to the goals. This property is one of the characteristics that describe autonomous systems [4, 5, 10].

On the ground of the defined functionality, properties of the most widely used symbolic and subsymbolic methods were analyzed. On the basis of the analysis a summary table of the methods properties is made up:

Table 2.1. Properties summary

Property / Method	Deductive reasoning	Inductive reasoning	Case based reasoning	Artificial neuron nets	Associative reasoning	Evolutionary algorithms
Environment sensing	X	X	X	X	X	X
Action performing	X		X	X	X	X
Learning		X	X	X	X	X
Deduction	X			X2*		
Knowledge application in unknown	X		X	X	X	X
Associative reasoning				X3*	X	
Sensing event sequence		X				

Being goal driven	X	X1*	X4*	X4*	X5*

The analyzed methods are outlined in the column headers, and the appropriate functions in the line headers. "X" designates functions that can be implemented using the appropriate method. "*" designates functions that can be implemented with certain limitations or usage specifics.

1* - the functionality is achieved by finding the most appropriate case that includes the solution (or other means of achievement) of the given goal.
2* - deductive (sequential) reasoning can be done by selecting a specific net structure, learning rule and activity spreading conditions [24], Usually the limited ability of the neuron nets of high level sequential (deductive) decision making is stressed in contradiction to their ability to process low level signals [6].
3* - the associative reasoning can be done using a specific topology of the net.
4* - the goal is defined with a set of examples that have to be classified.
5* - the goal is defined with the fitness function.

The analysis results in a conclusion that none of the described methods can support all of the necessary defined functions. However, if several methods - inductive, deductive, case based and associative reasoning techniques are combined, then the necessary functionality can be acquired thus implementing a hybrid intelligent system. Therefore the next section focuses on hybrid structures, in order to determine the most appropriate structure.

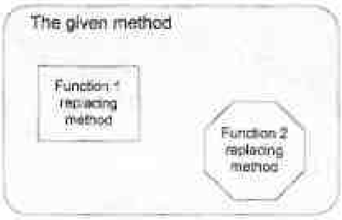
2.3 Hybrid intelligent systems

The third section **"Hybrid intelligent systems"** defines the term "hybrid intelligent system", namely hybrid intelligent systems are systems that combine more than one technique of artificial intelligence [6], **The** thesis presents two classifications, which do not **limit** methods that may be included into the structure.

Function replacing hybrids

Function replacing hybrids implement a functional composition, that is, a function of a single technique is implemented using some other technique. This kind of structure is motivated by the necessity to enhance the method in order to decrease or eliminate unwanted properties of the method.

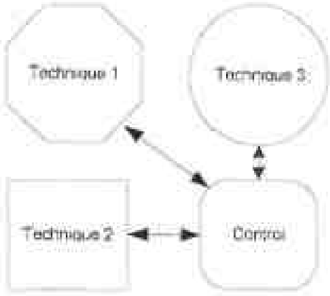
The architecture is depicted in the following schema:



2.1. figure. Function replacing architecture

Intercommunicating hybrids

Intercommunicating hybrids consist of self-contained processing units that communicate with each other in order to realize certain behaviour, which leads to the goal. Each unit implements one method. The units sequentially perform certain actions. If the units are competing then they may operate simultaneously. The structure is depicted in the following figure:



2.2. figure. Intercommunicating hybrid structure

Polymorphic hybrids

Polymorphic hybrids are used if functionality of different methods is necessary within the same system. These structures are also called "chameleon structures". The motivation is the demand for multifunctionality.

These structures can demonstrate different behaviour and change it as necessary during the runtime. The structure is depicted in the following figure:

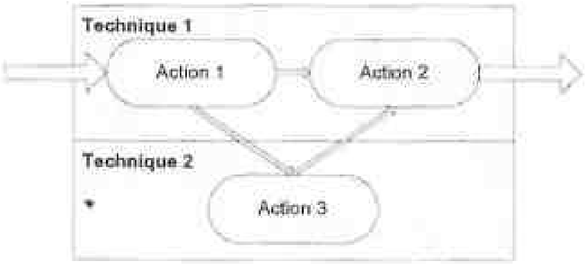
2.3. figure. Polymorphic hybrid structure

Besides the previously given classification the doctoral thesis presents one more classification of the hybrid structures [25], which includes additional structures thus enhancing the described classification.

Combined hybrid intelligent systems

The combination architectures (combined architectures) are sets of independent self-sufficient processing units that integrate symbolic and subsymbolic methods in one system, for instance, expert systems in combination with artificial neuron nets.

The combined structure is depicted in the following figure:

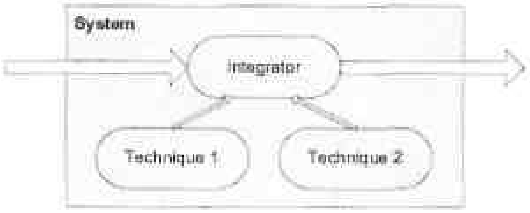


2.4. figure. Combined structure

As it is shown in figure 2.4. the system is implemented combining several techniques. This architecture is consistent with the described intercommunication architecture, and states that symbolic and subsymbolic methods have to be combined.

Integrated hybrid intelligent systems

This kind of architectures is characterized by the persistence of the so-called integrator, which depending on the given task and actual situation involves the appropriate units (each unit implements a different method of artificial intelligence). Schematically it is depicted in the following figure

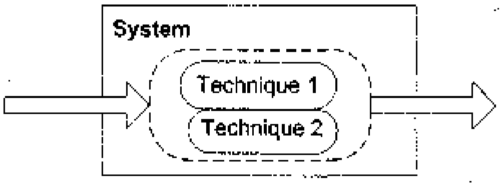


2.5. figure. Integrated hybrid architecture

This architecture is consistent with the described intercommunication architecture.

Merged hybrid intelligent systems

In this type of structures a particular function of one method is implemented by means of some other method. For instance, an explanation component of the expert system may be implemented using a neuron net that classifies the acquired decisions. Schematically, the merged architecture is depicted in the following figure:

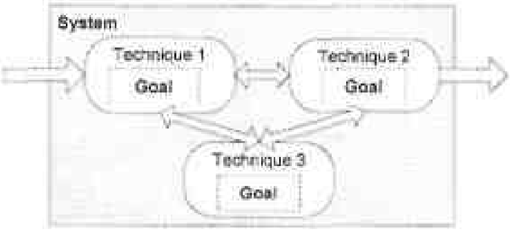


2.*6. figure. Merged architecture*

Figure 2.6. shows a system that supplies two functions. Each of them is implemented using a different method "Technique 1" and "Technique 2".

Associative hybrid intelligent systems

This structure is organized in such a way that each of the involved units can work in a combination with other units as well as autonomously. The decisions about cooperation among the units are made by the appropriate units thereby allowing to distinguish whether to cooperate or not for the achievement of a certain goal. Schematically, the architecture is depicted in the following figure:



2.7. figure. Associative architecture

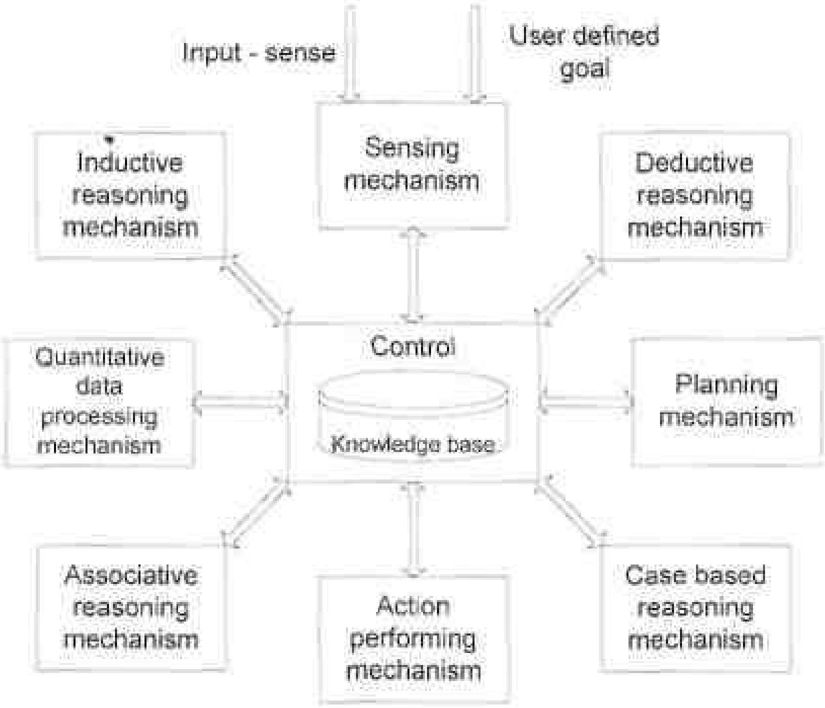
Figure 2.7. shows that each unit contains knowledge about the goal, which determines the way of cooperation among the units. It is pointed out in [25] that these structures have not found wide implementation thereby it is not possible to make conclusions about the efficiency of those structures.

On the ground of the analyzed properties of the described structures and defined necessary functionality an intercommunicating structure is selected that satisfies all of the requirements for combination of inductive, deductive, case based and associative reasoning without limiting the used techniques.

2.4 Kernel of the intelligent system

The fourth section "Kernel of the intelligent system" describes the **structure of an autonomous intelligent system developed by the author** of the doctoral thesis, and each module and its purpose is described as well.

The structure's kernel consists of inductive, deductive, case based and associative reasoning modules, which in a certain combination supply the defined necessary functions. The developed structure schematically is outlined in the following figure:



2.8. figure. The developed structure of the system

According to figure 2.8. the central element *control* provides an access to the common knowledge base as well as supplies and organizes communication among the mechanisms (modules). The depicted structure provides the following most important functions:

- capability to learn, using the inductive reasoning mechanism;
- capability to reason sequentially, using the deductive reasoning mechanism;
- capability to apply the acquired knowledge in unknown situations using case based reasoning mechanism;
- capability to reason associatively using associative reasoning mechanism;

- capability to follow the given goal, using deductive, case based and associative reasoning mechanisms;
- capability to sense the environment and perform actions that lead to the goal;

The structure involves the following modules:

- inductive reasoning module, that generates rules from the observed (sensed) input information;
- deductive reasoning module that is used for sequential reasoning. In the implemented system this module is mainly used for forecasting attribute values of the next situation if particular action is accomplished;
- case based reasoning module, which allows to collect behaviour patterns - plans that lead to the goal in particular situation;
- associative reasoning module, which allows utilization of similarity among different situations in order to reduce the overall amount of knowledge.
- sensing mechanism, which senses the environment. In the implemented robotic system this mechanism consists of different sensors whose measurements are used to describe the current situation.
- planning mechanism. Although deductive reasoning may be used for planning [21], it does not provide the following capabilities:
    - selection of actions in accordance with the required time limits;
    - splitting the goal into subgoals and planning actions for each subplan separately (divide and conquer);
    - stopping the execution of the plan if the further execution is not possible or is not reasonable for the goal achievement;
    - to recognize replanning necessity if the plan's further execution is not possible or is not reasonable;

  Therefore the structure involves an additional module for planning.

- action performing mechanism, which executes the generated plans;
- Quantitative data processing mechanism, which processes the quantitative data that is collectively used in other modules, for instance, certainty factor value calculation and so on. In the implemented robotic system, this module processes the following data:

- similarity measure of the situations - a numerical value that defines the similarity degree of two particular situation descriptions. The similarity degree and similarity calculation procedure is built in such a way that it is available for any other module in the system. The procedure implements the following formula:

$$yi = \begin{cases} 1, if & \sum_{j=1}^{n} \partial(x_j) \geq T \\ 0, if & \sum_{j=1}^{n} \partial(x_j) < T \end{cases}$$, where

$$\partial(x) = \begin{cases} 1, if & x > 0 \\ 0, if & x = 0 \end{cases}$$

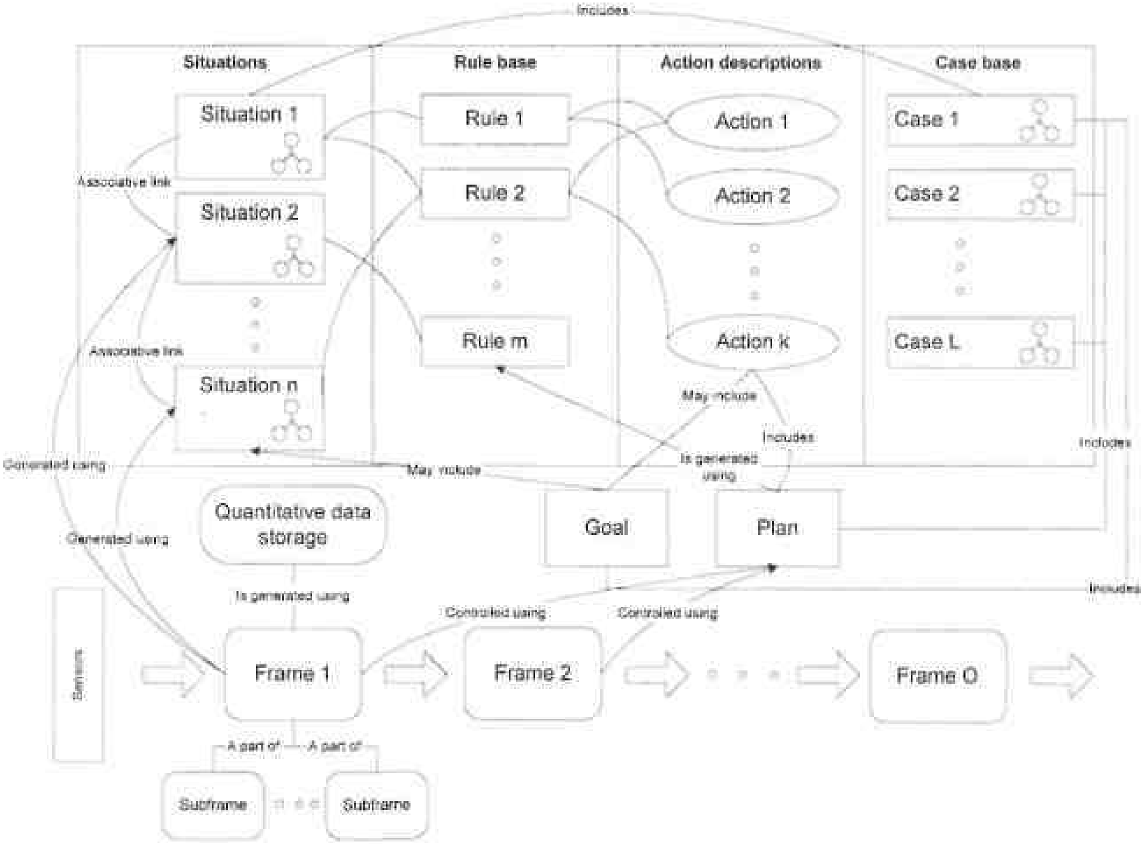
T - a similarity threshold value that is common for all situations;

Yi - an element of the answer vector $\vec{Y}$ that shows if the particular situation i is similar to the given one;

Xj - an element of the question vector $\vec{X}$ that shows if the values of the attribute j are equivalent;

- Plan value - a numerical value that describes forecast accuracy of the result of the last action in the given plan.

Knowledge is stored in the knowledge base. In order to support all the necessary manipulations with the stored knowledge the appropriate structure of the storage is required. Figure 2.10 outlines the **developed knowledge base structure,** which is used by all modules:



2.9. figure. Knowledge base structure

The structure includes the following elements:

- Situations are descriptions, which store knowledge about experienced different situations and are used to bind other units (plans, rules, cases, etc.) of the system's knowledge;
- Rules are descriptions that allow to represent causalities existing in the environment. Rules usually are represented in widely used n notation **If (condition) Then (conclusion)** [1, 20]. They are used in deductive reasoning mechanism and generated by inductive reasoning mechanism. The above mentioned notation can directly map certain actions in the conclusion or condition parts as well. For instance: "IF situation 1 and action 2 THEN situation 2" - if the action "action 2" is performed in the situation "situation 1" the situation "situation 2" will acquire. Thereby the links among rules and situations or rules and actions are defined;
- Actions are symbolic representations that can be translated by the system in order to perform certain operations. Actions are performed by the action performing

mechanism. For example, in the implemented robotic system action "Action 1" will cause the system to turn its right driving wheel for one round;

- Cases form case base. Cases are obtained and used by the case based reasoning mechanism. Each case involves the situation description, in which it may be applied, the goal, which may be achieved by applying the case, and the plan, which contains action sequence that leads to the goal. The case mathematically is interpreted as follows:

$$Case = \{E, Pl, G\} ,$$ Where

Case - description of the particular case;
E - description of the situation;
P1 - plan that leads to the goal;
G -.the goal;

- Frames are snapshots of the input that comes from the sensors. Frames are obtained using the sensing mechanism. Each frame includes knowledge about the state of the environment and the system itself. Each frame may be split into subframes in order to describe some dynamic features of the environment -trajectory, velocity, etc. Frames are inputs for the inductive reasoning mechanism (learning examples), deductive and case based reasoning mechanisms;
- Quantitative data storage supplies numerical data for modules of the system. Data is acquired and processed by the quantitative data processing mechanism and frames are a source of the feedback information;
- Plan is a sequence of actions that should be accomplished or is currently executed by the system. Plan is generated by the planning mechanism and its execution is controlled by the action performing mechanism;
- Goal is the task defined by the system's user. The goal is defined using the sensing mechanism. It can be defined in the following ways:
  - as a particular state that has to be achieved;
  - as a sequence of actions that has to be accomplished;
  - as a combination of the previous two definitions;

The mathematical interpretation is as follows:

$$G = \{S, M, C\} ,$$ where

G-goal;

S - a set of states that have to be achieved;

M - a set of actions that have to be accomplished;

C - a set of order conditions that defines an order of elements from the sets M and S;

The main functions that are supported by the system and the appropriate mechanisms are as follows:

- the ability to sense the environment and the system's inner state. This function is supported by the sensing mechanism that stores the sensed data in frames and subframes;
- the ability to perform actions allows to accomplish certain operations. It is supported and controlled by the action performing mechanism;
- the ability to learn allows to generate rales (generalizations, regularities) using the sensed knowledge about the environment and the system's inner state. This ability is supported by the inductive learning mechanism;
- the ability to reason deductively allows to make sequential decisions using the regularities generated by the inductive reasoning mechanism and the knowledge stored in the frames (facts). The result is new facts or actions, thereby realizing forward-chaining reasoning [21, 26];
- the ability to apply existing knowledge in unknown situations. This function is supplied by the case based reasoning mechanism and deductive reasoning. In addition, the associative reasoning mechanism is involved in order to reason utilizing similarity among situations;
- the ability to reason associatively increases flexibility of the system via utilizing similarity among different situations. In the implemented robotic system the associative reasoning is mainly used to determine similar situations during the deductive or case based reasoning processes;
- the ability to sense a sequence of events allows to record the current state storing the appropriate information in the frames. The frames are ordered according to their record moment (time stamp) thereby allowing to unambiguously determine the place of each frame in the frame queue;

- the ability to plan. Function is closely related with the requirement of being goal driven because the planning process itself is goal driven, during which a sequence of actions that leads to the goal is generated [21]. This function is supplied by the planning mechanism and involves the usage of the deductive and case based reasoning mechanisms for the plan generation;

The most important properties of the developed structure are described in close correspondence with the defined requirements and characteristics of the complex environments. The developed structure as well as its main properties is more or less general because each of the used mechanisms (inductive, deductive, etc. reasoning mechanisms) may be implemented applying different methods (algorithms) [1, 21, 27]. Hence, the developed structure is open, it can be implemented using different methods. This allows to achieve particular behaviour of the system.

2.5 Implementation of the autonomous intelligent system

The fifth section "Implementation of the autonomous intelligent system" describes both implementations of the developed structure, namely software and robotic system.

2.5.1 Software system

The software system is built as a world of *wolf and rabbits,* where the wolf is the intelligent system but rabbits are moving objects. The wolf has the aim to catch a rabbit. In addition, the user may place extra objects (obstacles) that are stationary and hinder movements of the other objects. At the beginning the wolf has an empty knowledge base that includes only action descriptions with precondition description for each action (without descriptions description of the action results). During the run, the wolf collects frames (input snapshots) that are used as example set for inductive learning. The learned rules are used by the deductive reasoning mechanism for planning future actions.

The mechanisms involved are implemented using the following algorithms:

- Inductive reasoning mechanism - algorithm ID 3 [28, 29]. This algorithm was selected in spite of its weaknesses because it is well understood, easily predictable thereby facilitating the study of the system.
- Deductive reasoning mechanism is based on certainty theory [30]. This method (certainty theory's practical model) was selected because it provides means for collecting and

distributing subjective, i.e. acquired by the system truth evaluations of the rules and facts - certainties.

Certainty factor values CF (Rule) to each rule are assigned. When a rule generated the value CF (Rule) = 1.0 is assigned stimulating the system to use the newly generated rules. For example, if there is a rule IF A THEN B CF (Rule), then CF(B) is calculated as follows: CF(B) = CF(Rule)*CF(A). If A is obtained from system's input then its CF value is equal to 1.0. According to the properties of the used inductive reasoning algorithm, like in the robotic system, only conjunctive rules are generated. For example, IF A and B THEN C CF(Rule). In this case CF(C) is calculated using the following expression: CF(C) = Min{ CF(A); CF(B) }*CF(Rule).

- Case based reasoning is implemented as a mechanism that allows to bind situation descriptions and action evaluations in this particular situation [4, 21, 31].
- Planning mechanism is implemented using POP algorithm [1]. Although this algorithm cannot generate uncertain plans, it can work with more than one plan, it can evaluate more than one alternative using the partial order of the plan alternatives.

A general guideline for the selection of algorithms consists of choosing the most classic ones that are well understood and predictable thus allowing forecasting and explaining the system's behaviour at certain situations.

The system is implemented, using RAD tool Delphi4 and data base management system Interbase (desktop edition), which are well integrated thus reducing overall development time. The main results of the implementation:

- The system demonstrated that the methods involved can be used for the development of an autonomous intelligent system;
- Cooperation mechanism among deductive, inductive and case based reasoning methods is developed;
- Mechanism of frame queue that is tailored for inductive learning is implemented and verified;
- Cooperation mechanism POP and deductive reasoning algorithms is implemented and verified, that is, the implemented mechanism allows POP to call deductive reasoning in order to forecast results of a certain action in the given situation;

- Mechanism of certainty factor calculations for the evaluation of rules and cases is implemented. It allows to maintain even contradictory rules in the rule base thus increasing system's flexibility;

The software system also revealed disadvantages of the developed structure. The most important of them are:

- Ability to process only discrete events resulting from the use of the frame mechanism where each frame is discrete snapshot of the system's and its environment's states.
- Complexity of the structure that evokes time consuming testing process;
- Plenty of symbolic information that has to be processed during the planning causing a considerable time consumption;

However the implementation revealed the following main advantages of the developed structure:

- The use of symbolic knowledge representation allowed to easily understand contents of the knowledge base that can be updated by the user as necessary.
- Flexibility and adaptation. The most important characteristics of the developed structure created mainly by the learning mechanism.
- Comparatively handy goal definition mechanism that allows to define or adjust goal during the runtime. Thereby the system demonstrated the ability to adapt in dynamic environment and goal conditions.

The observed advantages proved the validity of the necessity of learning mechanisms. Although the system demonstrated an adaptation in dynamic environment it did not have all mechanisms implemented that the developed structure requires. That's the reason why the robotic system was implemented. It is described in the next section.

2.5.2 General description of the robotic system

The robotic system is built as a differential driving platform [32] that is equipped with certain sensors and a driving mechanism. The platform contains appropriate electronic circuits that control mechanics and sensors. The steering is carried out using the so-called differential driving, which is based on two symmetric driving wheels and a few casting wheels that maintain balance of the platform.

Technical characteristics of the platform:

- Driving - two constant magnet direct current motors with appropriate gears and wheels, which supply the necessary mobility.
- 8 infrared range finders that can sense obstacles within the range 0.3m - 2.0m split into 5 sectors - 5 possible values.
- 2 bumping sensors - one rear and one front. They can sense collision with obstacles;
- Compass that can sense an orientation in accordance with the Earth's magnetic field with precision of 1 degree against North direction.
- Driving wheel positioning sensors (each wheel is equipped with two sensors). They determine the precise position of each wheel.
- Two BX24 microprocessors [33] control the mentioned sensors. One of them processes the distance measurements while the other controls the rest of sensors and maintains communication with the user's PC.
- User PC that supports user interface as well as runs most of the implemented mechanisms (except action performing mechanism);

Software solution:

- The system is implemented (except action performing mechanism) using the programming tool Delphi 7.
- Action performing mechanism is implemented using a simplified Basic programming language distributed by the manufacturer of the BX-24 microprocessors.
- Inductive learning mechanism is implemented using the C 4.5 algorithm [34].
- Deductive reasoning mechanism is implemented using the certainty theory based approach [30].
- Case based reasoning is implemented using approach described in [31], where each case is the description of the situation and appropriate solution. The utility of each case that is included in the case description depends on the goal and situation in which it is applied. Therefore the case description I complemented with the goal description:

$$Case = \{E, Pl, G\} \quad , \text{ where}$$

Case - description of on particular case;
E - description of the situation;
Pl -plan that leads to the goal;
G - the goal;

- Associative reasoning mechanism is implemented using an algorithm **developed by the author:**

```
        Gets an array X with its elements {xl,x2,x3,x4,x5,x6,x7,x8}
        List of similar situations = Ø
        With each element xi from the X perform the following operations:
        Number of identical elements = 0
        All of the situation descriptions yj in the knowledge base are scanned
            IF element of xi is identical with the correspondent element of yj
            THEN
                Number of identical elements = Number of identical elements +1
            IF Number of identical elements >= Threshold value, THEN List of similar situations = List of similar situations + yj
      Result = List of similar situations Y
```

This algorithm essentially implements formula previously defined and simplified by the author:

$$yi = \begin{cases} 1, if & \sum_{j=1}^{n} \partial(x_j) \geq T \\ 0, if & \sum_{j=1}^{n} \partial(x_j) < T \end{cases}$$

- Planning mechanism is implemented using a well known POP algorithm [1]. It is quite similar to the particular implementation of the software system;
- The sensing mechanism is implemented using the sensors of the robotic system. The input data from sensors is preprocessed using an algorithm that was **developed by the author.** Every measurement is automatically transformed into an integer value. Because of the considerable error of distance measurements an additional processing is made. Mathematically this processing can be described by the following formula:

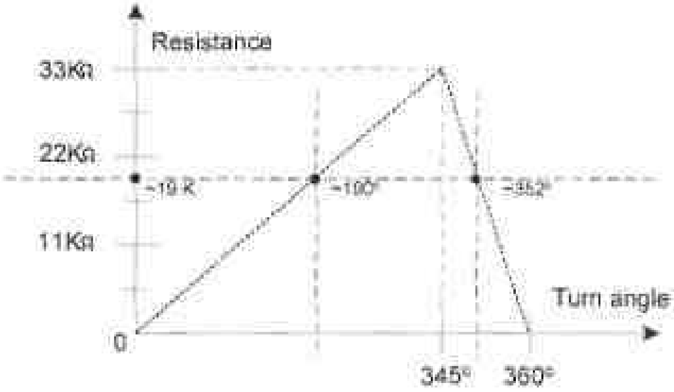
$$si = \frac{\sum_{j=1}^{n} aj}{n}, \qquad \text{where}$$

si - resulting distance. There are 8 of them, where each value corresponds with the appropriate range sensor.

aj - distance measurement j of the sensor i.

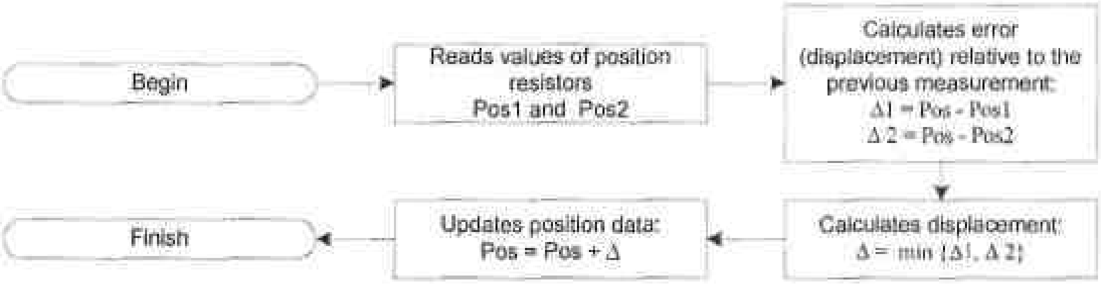
n - constant number 10, which is defined by the author in order to supply approximately 10 raw (unprocessed) measurements per second.

- The action performing mechanism is implemented using the platform, its mechanical components and appropriate controlling circuits as well as a controlling algorithm that was **developed by the author.** For the determination of driving wheel position two resistors are used for each wheel. Each of the resistor can encode (with particular resistance value) 345°. The remaining 15° are a very rapid transition from maximum resistance of 33 KΩ to minimum resistance of 0Ω, thus forming so called "blind" sector. It is depicted in the following figure:



2.10. figure. Resistor characteristic

Figure 2.10 shows that each wheel turn angle corresponds with two different resistance values. In order to determine the exact angle two resistors fixed in opposite directions are used. In other words, the blind sectors are in diametrically opposite positions. Therefore if the wheel is turned the resistance value is changing identically for both resistors (the error is insignificant ±0.5%). If one of the resistors is in the blind sector, then its value is changing considerably faster than the value of the other one. By constantly reading the values of the resistors the controlling algorithm determines the resulting change in the values. If any value is changing faster than the other then it is not used for wheel position calculations. It is shown in the following chart:



2.11. figure. Displacement calculation

- Quantitative data processing mechanism is implemented using an algorithm **developed by the author.** The most important expression used in the system is:

$$CF = \frac{Nv}{N}, \qquad \text{where}$$

CF - Certainty measure of the rule or case,

Nv - number of successful applications - when the forecast situation attribute value (one or many) was identical with the observed values. For the case - number of applications when the goal was achieved;

N - overall number of applications;

The largest part of the processing is done by the PC side software. A RS232 connection is used in order to communicate between PS and the platform controlling microprocessors.

2.6 Experiments and their results

The sixth section "Experiments and their results" is devoted to the description of the experiments made and the analysis of their results. The main goal of the experiments was to demonstrate the ability to adapt and to provide information for the analysis of the contribution of each of the involved mechanism.

Several experiments were carried out where the following properties were changed: amount of examples in learning set (values of the parameter {10;15;20;25}), reliability (certainty) factor value for case (values {0,3; 0,5;0,7;0,9}), similarity threshold (values {5,6,7,8}), maximum plan length (values{l,2,3,4,6}) and minimum plan reliability factor (values {0,2;0,4;0,6;0,8}). The values were changed in such a way that they could describe the influence of the particular values and the appropriate mechanisms on the system's overall performance.

The performance is calculated using the following expression:

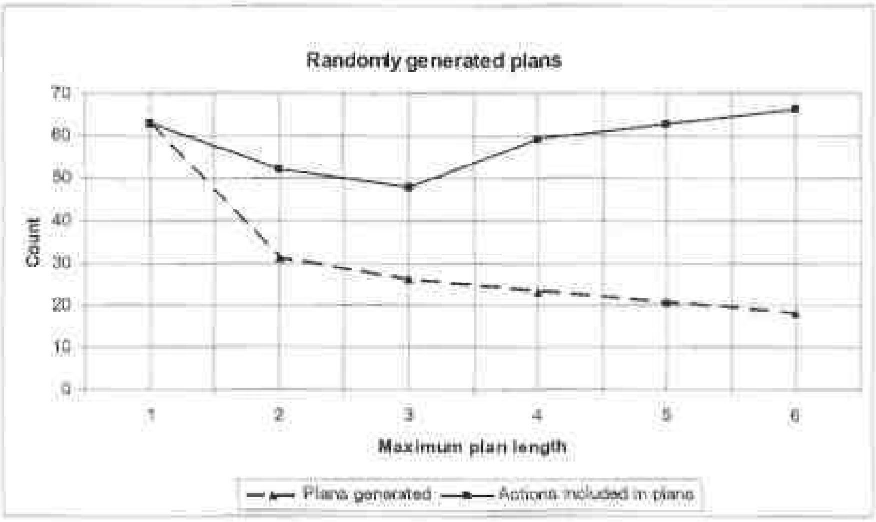
$$E = \frac{M}{P} \times 100\%, \qquad \text{where}$$

E - Efficiency expressed in per cents;

M - Number of achieved goals;

P - Number of generated plans for all goals;

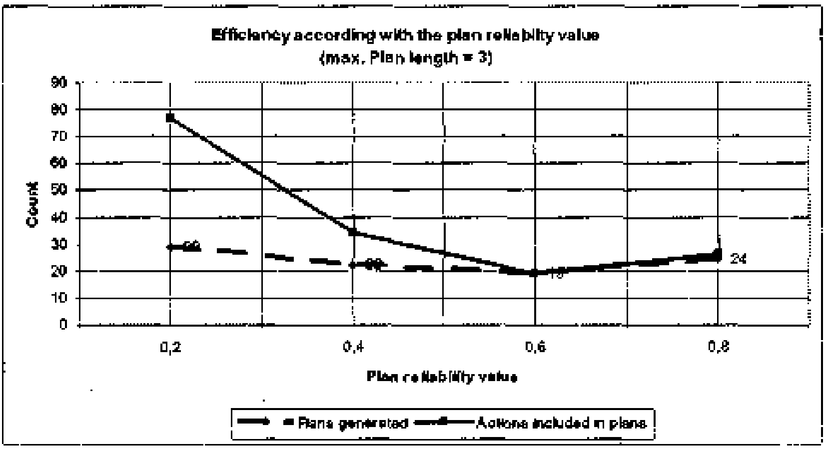
The experiment with a random plan generation shows that increase of the maximum plan length decreases the number of plans generated, i.e. the more actions are performed the higher possibility that one of the action leads to the goal. But the number of actions involved in plans reaches its minimum with maximum plan length 3. Graphically it is shown in the following figure:



2.12. figure. Number of generated plans and included actions

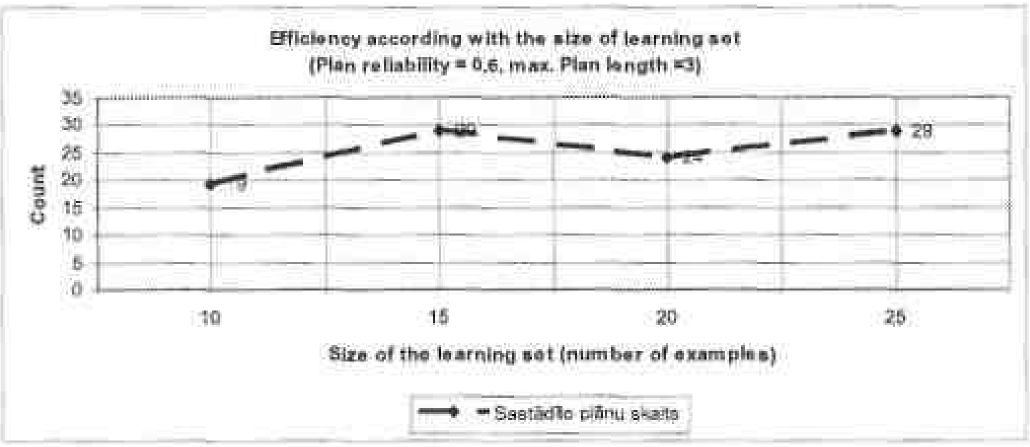
This enables to conclude that too long plans include repeating actions (the same action more than once), which decreases the utility of a particular action. It also enables to conclude that too short plans cause the system to generate many plans thus decreasing the utility of a single plan.

Experiments with alternating plan reliability minimum value show that with too low reliability value the system behaves similarly to the previous experiments. On the other hand too high reliability value causes the system to reject potentially good plans as being "unreliable" thus increasing the number of generated plans. Graphically it is depicted in the following figure:



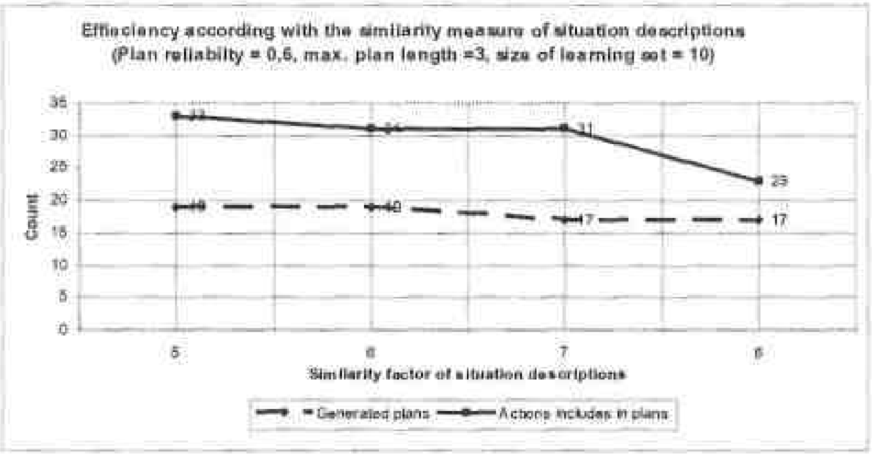
2.13. figure. Number of generated plans and included actions according to the plan reliability value

The experiment with the maximum amount of learning examples set shows correspondence between the amount of learning set and the efficiency of the system. On the ground of experiment results it is concluded that too large example set causes decrease of overall efficiency. While the learning set is collected, the system is operating with the existing knowledge or without it if the base is empty. With an empty knowledge base the system randomly generates plans that cause decrease of the efficiency. It is depicted in the following



2.14. figure. Number of plans generated in accordance with the learning set size.

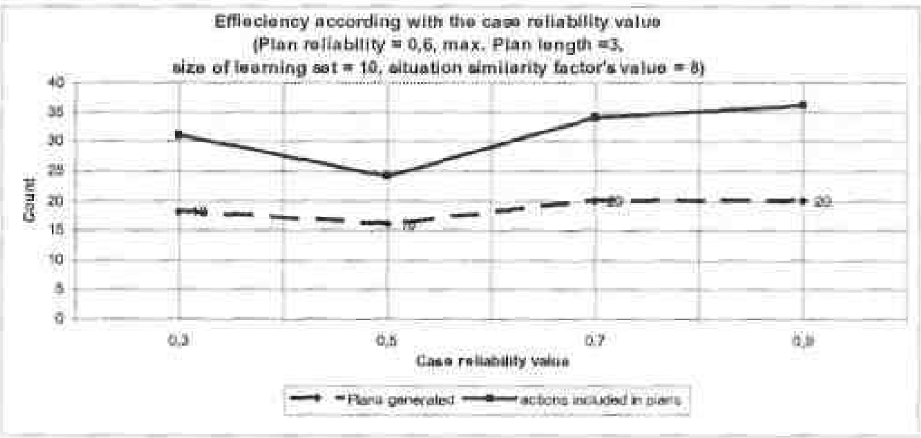
The experiment with the change of similarity factor in associative reasoning mechanism shows its impact on the system's efficiency. The experiment confirms the statement made by the author that associative reasoning can remarkably decrease overall amount of knowledge processed by the system because the number of situation descriptions and generated rules is decreased while the system's efficiency is increased. The results are depicted in the following graphic:



2.15. figure. Number of generated plans and included actions according to the similarity factor of the situation descriptions

Consequently, the experiment proves associative reasoning necessity in autonomous intelligent systems.

The experiment involving the case based reasoning shows efficiency dependence on the case reliability value. It is shown in the following figure:



2.16. figure. Number of generated plans and included actions according to case reliability value

The results confirm the conclusion that if a too high reliability value is required, then the system's efficiency is decreasing because if potentially good case's reliability is falling slightly, it is excluded from further usage thus decreasing the system's efficiency. On the other hand, a too low reliability value requires numerous usage times in order to exclude weak cases from further applying. Therefore some average value has to be selected in order to achieve high efficiency. Unfortunately, this experiment does not show remarkable efficiency increase compared with the previous experiment. The author states that it is caused by short operation time of the system (only 10 goals were given) thus limiting the possibility to acquire and apply more cases. Therefore the following experiment was carried out.

2.6.1 The system's adaptation abilities

Goal of the experiment

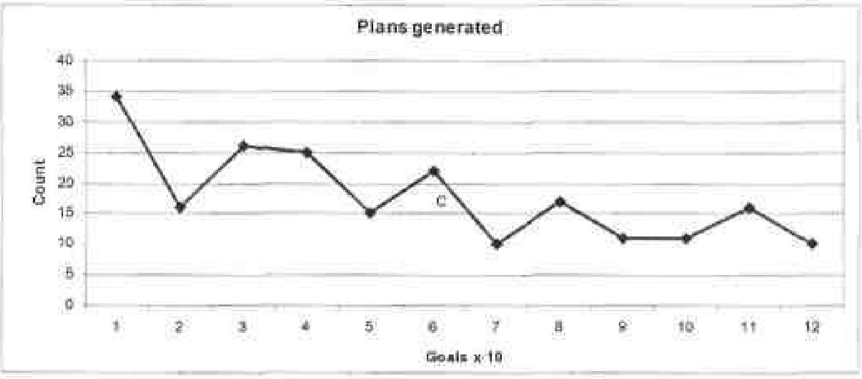
The main goal is to determine the ability of adaptation in a complex environment and to compare it with the data from previous experiments. In order to eliminate the disadvantage of previous experiments, the fact that a too short operation period can not reveal contribution of the case based reasoning, the goal is to run the system for a much longer period, thus giving an opportunity to collect larger knowledge base.

Experiment implementation

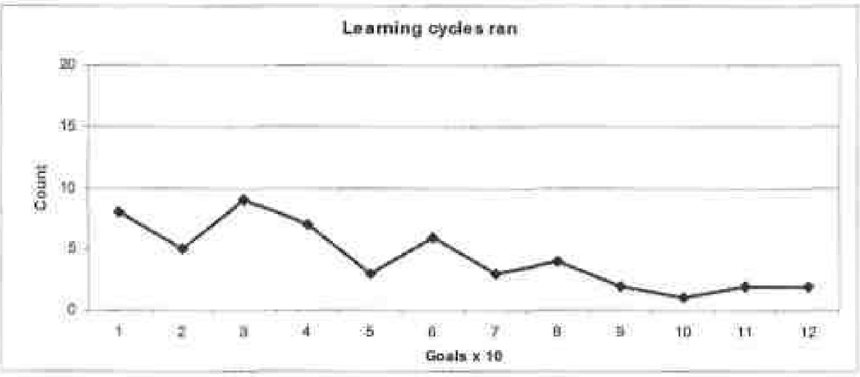
A 3 x 3 m arena is built, in which the system can move but it is not able to move outside the arena. Thus the system is able to gather more varied information about its environment. This brings the environment much closer to the real one. In order to observe the system's behaviour in dynamic conditions, stochastic events are generated involving the operator (human), that is, the operator unexpectedly moves around the arena or turns the platform in unexpected directions, thus causing stochastic state transitions. During the experiment 120 randomly generated goals are sequentially given to the system. Each of the goals may be more difficult to achieve than in previous experiments. For instance, certain directions that are defined by the compass state have to be achieved, thus pushing the system to plan more than one or two actions in order to achieve the goal.

Experiment results

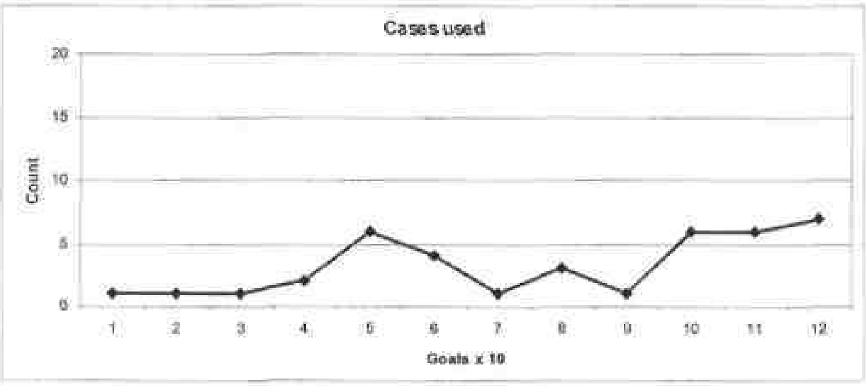
The system's operation is outlined in the following graphics:



2.17. figure. Number of generated plans during the runtime



2. 18. figure, number of learning cycles during the runtime



2.19. figures. Number of applied cases during the runtime

Table 2.3. Complementing data

	Rules	**Generated cases**	**Generated situation descriptions**
	1261	80	64
		18 of them involve more than one action	

Average planning time (last 20 goals)	8 s

Average case search time	0.005 s

Figure 2.17 shows the number of plans generated by the system. For example, the goals from 31th to 40th were achieved using 25 plans. Making use of the previously defined expression:

$E = \frac{10}{25} \times 100\% = 40\%,$ the efficiency of the system is 40 %.

Whereas the last 10 goals were achieved with using only 10 plans:

$E = \frac{10}{10} \times 100\% = 100\%$, t he system has achieved 100% efficiency.

A slight decrease in the generated plan count shows the adaptation process of the system. For example, a sharp decrease during the achievement of the 2nd and 5th plan decade shows the adaptation in certain conditions. When the system runs into new situations it has to adapt to those conditions and therefore it is less effective during the adaptation process. This can be observed during the achievement of the 3rd, 4th, 6th, and 8th goal decades.

The second graphic outlines executed learning (induction) cycles. The number of learning cycles is decreasing with the system becoming more experienced. It is caused by the reduction of time required to achieve of instant goal. Therefore the number of achieved goals is increasing while the same amount of learning examples is collected.

The third graphic shows the number of applied cases for plan generation. As it is depicted in the graphic the number of applied cases is growing together with system's experience. 39 out of 120 goals were achieved applying cases. It is approximately 30% of all goals. During achievement of the last 20 goals average planning time reached 8 seconds for one plan, while the case retrieval time is 0.005 seconds. It affirms the statement that case based reasoning can remarkably reduce the time necessary for plan generation.

The complementary data shows that 64 situation descriptions have been generated. It is a very small number if compared with the maximum 390,625.00 descriptions that may be encoded using 8 distance sensors with 5 possible states (values) for each sensor. This remarkable reduction is achieved by applying associative reasoning. It is also supported by rather small knowledge base if we take into account the fact that each rule is more or less bound to a certain situation. This ascertains the essential necessity to use associative reasoning in autonomous intelligent systems.

2.7 Conclusions and application analysis

Theoretical results of the thesis

The research allowed achieving the following theoretical results:

- The term "complex environment" is defined and appropriate characteristics of the sophisticated environment are given as well as their impact on the autonomous intelligent system's functionality is analyzed. The properties are defined on the basis of the properties of complex systems. The most important of them are: difficult predictability, uniqueness and the preservation of the main processes resisting outer influence.
- On the basis of the analyzed properties the necessary functionality of the autonomous intelligent system is defined. The functionality involves: the ability to sense environment, to act, to make sequential decisions, to learn, to reason associatively, to apply knowledge in unexpected situations, to sense a sequence of events and to be goal driven.
- On the basis of the defined functionality the most widely used symbolic and subsymbolic techniques are analyzed. Although the results of the analysis prove the conclusion that none of them can support all of the necessary functions, a certain combination of methods can provide all required functions. Therefore it is concluded that a general method of combination is required.
- In order to supply the defined functionality, hybrid structures as well as their correspondence with the functionality are analyzed. On the ground of the analysis results a conclusion is made that the so-called intercommunicating (or integrating) structure can support all of the functions.
- The most important theoretical result is the developed structure of autonomous intelligent systems that for the first time combine inductive, deductive, case based and associative reasoning methods in a single system. The combination of the above mentioned methods supports all of the defined functions and provides high flexibility and adaptability in conditions of a complex environment. The thesis analyzes the structure's properties, advantages and disadvantages obtained.

Practical results of the thesis

The research allowed toe achieve of the following practical results:

- The developed structure is able to operate and adapt using several widely applied techniques in a single system. It has the ability to learn and adapt in environments with stochastic events or the so-called hardly predictable environments.
- The developed hybrid structure can operate and adapt if at the start the knowledge base is empty, i.e. it realizes the so-called bottom-up learning. This ability is essential when the system faces unknown situations.
- There is developed a knowledge representation schema that binds rules, cases, situation descriptions, actions, frames queue and goal description in one structure. The experiments reveal that the developed structure is flexible and effective enough to support all of the involved techniques. The used symbolic representations are easy for the researcher or user to use. It should be stressed that the structure is known from the start but the knowledge units and appropriate relationships are defined by the system on the ground of the acquired experience.
- The experiments revealed the importance of the associative and case based reasoning techniques thanks to a remarkable knowledge amount reduction and planning time decrease.
- As it was pointed out above, the developed structure does not limit the use of algorithms for particular implementation. Thus it may be adjusted for use in particular domains as well as it may be complemented with additional modules, namely a map, cinematic model, speech recognition module or any other task-specific mechanism. This widens the potential sphere of application of the developed structure.
- The developed structure operates with discrete states and appropriate state transitions. If there is a necessity to reason about continuous processes then it is possible only via splitting the process into discrete states. This feature potentially limits the structure's application.
- The experiments revealed that the goal is defined in terms that are directly observable by the implemented system, i.e. a particular state is defined as the appropriate state of the system's sensors. It means that the system is not able to identify abstract goals (that have no direct sensor maps).

Directions of future research

After the research and experiment series, the author sees several advancement possibilities of the developed structure that allow to define the following directions of future research:

- Investigation of possibilities to restructure the frames queue mechanism in order to allow to reason about longer periods of time. Under perfect conditions the restructured queue should provide a mechanism to reason about different time intervals with ease similarly to humans reasoning about them and processes that last during those periods.
- Research of the possibilities to use different algorithms for implementation of appropriate modules in order to determine their practical value in particular implementations.
- Investigation of possible extension of the developed structure by including specific modules, for example, maps that allow to reason about things, which cannot be directly observed.
- Investigation of the possibilities to use complex sensors, for example, stereo vision systems, Global Positioning System (GPS) and others in order to study the ability to process much larger amount of knowledge. In this context it should be recommended to determine the possibilities to implement the developed structure using parallel computing techniques thus allowing to increase the efficiency of the developed structure.

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