BULGARIAN ACADEMY OF SCIENCES

CYBERNETICS AND INFORMATION TECHNOLOGIES • Volume **7**, No 1

Sofia • 2007

HVAC Control via Hybrid Intelligent Systems

Mincho Hadjiski[1,2], *Vassil Sgurev*[1] , *Venelina Boishina*[2]

[1]*Institute of Information Technologies,1113 Sofia*
[2]*University of Chemical Technology and Metallurgy, 1756 Sofia*

Abstract: *A new hybrid intelligent system is proposed for Heating, Ventilation and Air Conditioning (HVAC) control by integration of Multiagent System (MAS), Dynamic Ontology (DO) and Ant Colony Optimization (ACO). The relevant combination between data driven and knowledge driven methods results in significant improvement of all behavioral indexes of HVAC control system – speed, stability, internal communication rate, robust according uncertainty and disturbances. Hybrid MAS/DO system is realized by developing Java-based software according FIPA specifications. Simulation results for simplified HVAC system are reported in order to demonstrate quantitatively the effect of hybridization.*

Keywords: *Ant colony optimization, dynamic ontology, HVAC control, multiagent system.*

1. Introduction

In the last years the energy efficiency strongly attracts the public attention as one of the most realistic shift levers to decrease the climate warming. The buildings use up 20-30% of the total country energy production and the systems for Heating, Ventilation and Air Conditioning (HVAC) could account a considerable part of this energy [11]. According certain assessments energy efficiency in HVAC system could be improved with 20-40% [16, 37]. This feasible improvement could be achieved via complex actions, including constructive rehabilitation and operational reengineering. The big variety of possible rehabilitation and reengineering degrees requires new approaches in both types of actions – constructive and operational. Two aspects are dominant here: (i) economic (investment and maintenance), (ii) requirements covering (thermal comfort, energy efficiency). Optimal balance among them must be achieved using nowadays technologies. Recently some new results have been reported directed to solve above problems based on hybrid intelligent systems, which include autonomous agents and ontologies [4, 7, 18, 19, 30, 37]. This kind of intelligent systems applied to

HVAC systems [2, 18, 19, 21, 30, 37] give promising results overcome some emergent problems:

- To develop new methods for a fast prototyping of HVAC control systems for big centralized industrial and administrative buildings. Agent / Ontology-based systems provide real possibilities to easy, fast and cost-reduced design of construction, control and optimization systems.
- To realize effective energy management of HVAC systems with heterogeneous energy sources – conventional heating and cooling, solar, thermal pumps, electrical heating, co-generation (gas turbine, diesels).
- To integrate subsystems with various functions: information processing, knowledge management, static and dynamic optimization, advanced control, decision making.

In the presented paper some problems of hybrid agent / ontology-based systems are considered in order to solve mainly operational tasks in HVAC of centralized buildings management.

2. HVAC control problems statement

In the last three decades HVAC system design and management of large administrative (business, societal, administrative) and industrial buildings mark significant changes in the next main directions:

- Satisfying the requirements of thermal comfort of habitants based on multicomponent index assessment [11, 22, 24, 25, 34]. Well established is PMV – index, proposed by Fanger [13, 25, 34] which is local nonlinear function of the next variables:
  - Air temperature Θ_a;
  - Radiant temperature Θ_r;
  - Air relative humidity RH;
  - Air velocity V_a;
  - Human activity level A_M;
  - Clothing insulation C_i.

Thermal control strategy takes into account human perception, not only data for air temperature and relative humidity as in the conventional approach.

- Energy efficiency attaining in order to meet ecological and economic requirements [24, 32]
  - Energy saving by constructive and operational measures;
  - Waste gases reduction (directly or indirectly);
  - Cost effective maintenance.
- Investment efficiency [1, 2]
  - Initial investments optimization taking into account all life cycle of HVAC;
  - Cost oriented maintenance.

The advanced HVAC management creation necessitates to overcome a variety of new arising problems:

• Processing of a wide range of *heterogeneous information*: basic sensors for the site parameters (Θ_a, Θ_r, RH, V_a) and system measurements (heat, cool), visual information or expert estimation for human activity level (A_M) and clothing insulation C_i, outdoor information, relative humidity, solar activity, wind (speed and direction).

• Complicated *modeling* at basic, regional and global level, models verification, validation and adaptation:

• Numerous problems with HVAC optimization:

▪ Multiobjective formulation (thermal comfort, energy efficiency, cost effectiveness),

▪ Mixed Integer / nonlinear optimization;

• Control problems:

▪ Nonsquarety of the controlled sub-plants due to the lack of corresponding number of manipulated variables [18, 21],

▪ Variety of time variant nonlinear models at basic, regional and global hierarchical levels,

▪ Stochastic time varying disturbances and operational conditions (technical conditions, available resources etc.),

▪ Changeable technological structure (functionality of sites, kind of energy sources (conventional, solar, thermo pumps, co-generation)).

To overcome above problems and difficulties a number of new methods and tools were developed recently:

• New sensors and methods for data processing and communication.

• New modeling tools for building energy simulation (MODELIKA, TRANSYS, SPARK, HVACS2M, EnergyPlus, BRIS etc.) [14, 37].

• New developments in multicriteria on- line optimization (multiparametric linear, non-linear, quadratic and mixed-integer linear programming) using available standard solvers for linear programming, quadratic programming and mixed-integer linear programming [3, 5], ant colony optimization [10].

• New approaches for advanced control of constrained linear and nonlinear plants [3, 5].

• Development of agent-based, ontology-based and hybrid control systems [15, 17, 18, 19, 30, 35, 36, 39].

In order to solve the outlined above sophisticated multicriteria problem a novel approach is proposed by using the latest achievements in intelligent Multiagent systems [39], Ontology-based systems [17] and Ant Colony Optimization [10]. The efficiency of the ontology-based systems in combination with MAS [36] is studied only for static ontologies. The interest torwards dynamic ontologies, which arises in last few years [6, 31] is directed mainly to Web-based systems, where the emphasis is on dynamic semantic matching with declarative presentation of concepts. For HVAC control systems with feedback, this approach is not applicable. In this paper a new type of dynamic ontology is considered where a part of concepts obtain a procedural presentation. In this way a relevant dynamic ontology-based approach is considered in order to overcome some drawbacks of conventional HVAC control systems.

3. HVAC intelligent control strategy

Intelligent control is only one of the sequential stages of HVAC advanced management, as shown in Fig. 1.

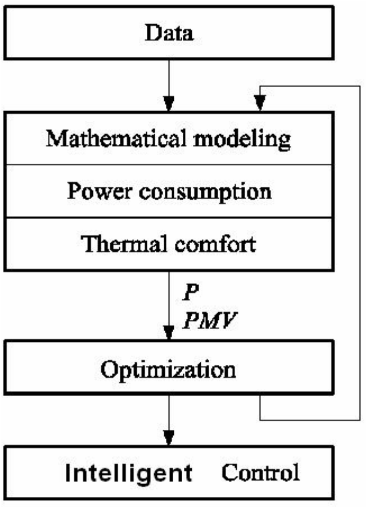

Fig. 1. HVAC Control Strategy

The optimization in Fig. 1 presents dual functions:

a) steady-state optimization of HVAC with:

(i) optimization of HVAC thermodynamic cycle,

(ii) reconfiguration (if necessary) of HVAC technological structure;

b) dynamic optimization of control system behavior after the steady-state optimization.

In this paper only the control system opti-mization is considered. Our previous results [2, 18, 19] show that Ant Colony Optimization (ACO) is suitable optimization approach to slope multiaspect problems as HVAC system optimization and control.

3. 1. Ant colony optimization

Ant colony optimization (ACO) is an engineering approach to the design and implementation of software systems for the solution of difficult optimization problems [9]. In the ACO a colony of artificial ants cooperate in order to find a good solutions of difficult discrete optimization problems. Cooperation is a basic component of ACO algorithms. In ACO the computational resources are allocate to a set of relatively simple agents (artificialants) that communicate indirectly by stigmergy.

Stigmergy depicts indirect communication and coordination within a dissipative field through asynchronous information exchange between agents. Such a coordination mechanism can be observed in social insect societies. The interaction of ants is based on pheromones only as ants do not communicate directly. Ants put down pheromones in their environment leaving signals to other ants and thus influencing their behavior. The main requirements are: sharing information on the costs and the degree of fulfillment of objectives for different alternatives; sharing information on preferable clustering of goods in order to allocate a shared resource. That can be fulfilled by a stigmertic information storage and updating [28].

Opportunities that environment offer have been demonstrated in the domain of behavior-based agents and situated multiagent systems. In behavior-based agent systems, interaction in the environment has been considered as an essential feature for intelligent behavior. The environment is a shared “space” for the agents, resources and services, which structure the whole system. Resources are objects with a specific state. Services are considered as reactive entities that encapsulate functionality. The agents as well as resources and services are dynamically interrelated to each other. The role of the environment is to define the rules which these relationships have to comply to. The system environment acts as a *structuring* entity for the multiagent system [38].

The concept of stigmergy is used to provide a good solution for HVAC control. In this paper we present a way to limit communications in ant colony by separating the environment and ants. The dynamic ontology is used for description of shared environment. The ants communicate indirectly thought system ontology.

3. 2. Intelligent control structures

In this contribution three control strategies are studied:

– Multiagent system (MAS)-based;
– Ontolgy-based;
– Hybrid Agent / Ontology-based.

MAS-based control. MAS-based control gives capabilities for concurrent control, monitoring and diagnostics of HVAC systems. The stigmergy mechanism uses interactions among artificial ants and environment for searching and spreading the knowledge in the system. The structure of MAS-based control system is presented in Fig. 2 and contains:

• *HVAC System*,

• *Sensor/Device Layer* – represent sensors and devices, which sends to multiagents system the measurement signals, and receives control signals from MAS,

• *Communication Layer*,

• *MAS* – the multiagents system is composed from: *Monitoring Agents*, *Diagnostics Agents*; *Control Agents* – computes the control signals using different control algorithms; *Optimization Agents* – searching for optimal control via Ant Colony Optimization (ACO); *Knowledge Agents* – contains the main system knowledge for proper HVAC Control; *Planning Agents* – defines the basic control and optimization structures; *Tasking Agents* – forms real-time optimization and control tasks.

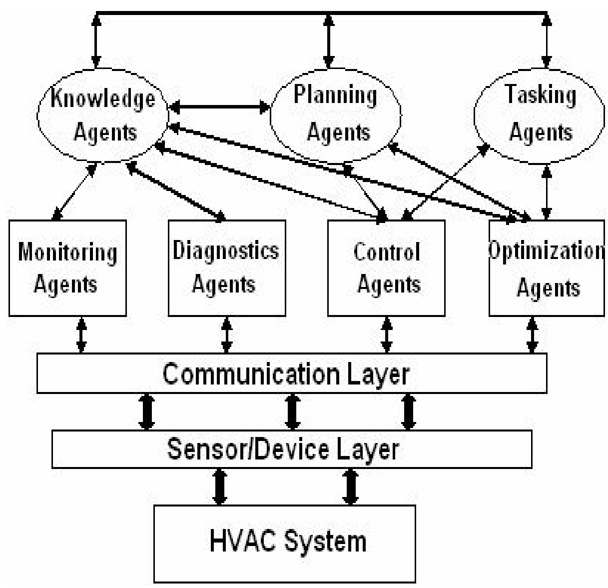

Fig. 2. MAS-based control

Ontology-based control. Some of the agent's functions could be taken from system ontology [20], which includes the knowledge about HVAC control, shared resources, optimization algorithms, planning and tasking. The main ontology-based control structure is presented in Fig. 3.

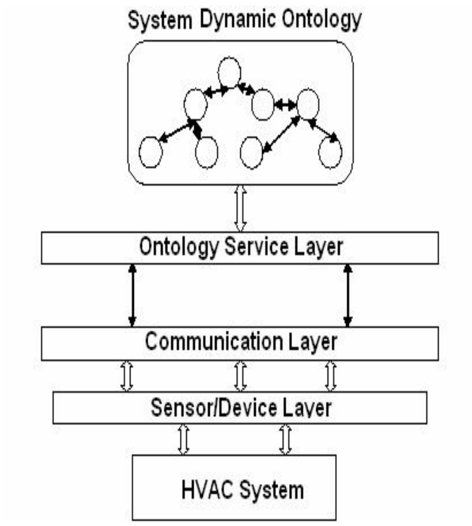

Fig. 3. Ontology-based control

Ontology-based HVAC control is composed of layers like in MAS-based control (*HVAC System, Sensor/Device Layer, Communication Layer*); additional layer is for *Ontology Service*, which accomplish functions for knowledge discovering, function redistribution, resource sharing and updating the ontology functions; *Dynamic Ontology (DO) Layer*-composed from different ontologies, including description of shared resources and agents system relationships. The DO model is given below.

Hybrid Agent Ontology-based control. The hybrid HVAC intelligent control uses Ant colony optimization (ACO) [10], for define an effective control. In this case the ant's environment and ant's functionality are separated. The environment is representing via system ontology. The architecture of HVAC hybrid system is presented in Fig. 4.

The hybrid system is composed of five layers:

- *HVAC System.*
- *Sensor/Device Layer.*
- *Communication Layer.*
- *Agents (ants) Layer* – composed from ant control system using stigmergy mechanism for searching an effective control.
- *Ontology Service Agents (OSA)* – agents for service the dynamic ontology, with the next functions: knowledge updating, knowledge discovering, connecting with different ontologies trough ontological servers.
- *Ontological Server Layer* – have functions for ontology supporting, knowledge commitment and connecting with different ontologies.

• *Dynamic Ontological Layer* – composed from different applying, domain and tasking ontologies, which are necessary to ant colony system for proper system work.

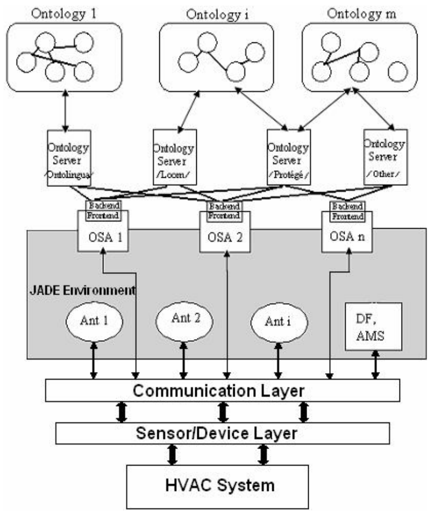

Fig. 4. HVAC hybrid intelligent control

4. Dynamic ontology model

4.1. Dynamic ontology model

According to the best known ontology definition given by [40] "An ontology in an explicit specification of a conceptualization". Within the ontology definition in this paper the formal ontology model (FOM) is accepted as an ordered triple

(1) $$O = < X, R, \Phi >,$$

where: X is a finite set of concepts (notations, terms), R stands for a set of relations over the concepts, Φ are interpretations in the form of axioms.

Therefore, the specification could be presented as an ordered pair $S = < X, R >$, and conceptualization as a pair, $C = < S, \Phi >$ to describe that S satisfies the axioms Φ derived from the domain model. Consequently, the FOM could be presented in the form

(2) $$O = < S, C >.$$

The formal ontology model (1) could present a number of particular cases when R or Φ could be empty sets [29]:

– When $R = 0$, $\Phi = 0$, ontology $O = V_s$ becomes a simple vocabulary V_s. This singular ontology could be useful only for specifications, for extending and maintaining domain dictionaries, but it has very limited implementation because it don't gives in explicite way the sance of the terms X.

– When $R = 0$, $\Phi \neq 0$, ontology $O = V_p$ becomes a passive vocabulary V_p; V_p is passive because all definitions of the terms are taken from an existing and fixed set X. This is not suitable in the case of Dynamic Ontology.

– When $R = \{\text{is\_}\mathbf{a}\}$ and $\Phi = 0$, ontology $O = T_s$ becomes a simple taxonomy $T_{s.}$ In this special class of ontologies the set of notions are hieratically connected with the relation is_**a** ("is element of the class **a**").

To present dynamic behavior of the domain, two relevant representations must be available:

– For the dynamic states, connected with a discrete time $t = kT_0$ (T_0 is a simple time) and defined over some time interval existence, given by special markers (e.g. k_b (beginning) and k_e (end)).

– For the discrete events, due to abrupt changes in structure, conditions, and parameters. The dynamic states are connected mainly with the concepts $X = X(k)$. Thus at least some of the concepts must have a finite procedural presentation, and the rest could have an usual (static) declarative one. Hence, concepts in dynamic ontology could be presented in the form

(3) $$X = X_1(k) \cup X_2 \qquad \forall k \in [k_b, k_e].$$

In this paper the discrete events are modeled by using multiontological approach [6, 31], where the dynamic changes could be both with relations R and interpretations Φ as well. Taking into account the necessity of explicitly specification of discrete events a model of ontological system is accepted in the form

(4) $$\Sigma = < O^{hl}, \{O^{d\&t}\}, \Theta > ,$$

where:

– O^{hl} is a meta ontology of the high level which defines discrete events (reconfiguration in the system, domain ontologies selection, interpretations, changes).

– $\{O^{d\&t}\}$is a set of domain ontologies and task ontologies, where some of them are dynamic ontologies

(5) $$O_i(k) = <S_i(k), C_i(k)> ;$$

Θ is the model of an inference machine, connected with the ontology system Σ.

4.2. MAS ontological structure

The main parts describing the domain ontology structure are Resource, Actions, Actors, Relationships and Events. Basic ant's knowledge about status, parameters and work of the HVAC system are represented in ontologies, which are hold of terms vocabularies, resources, concepts, system constraints etc. Each agent of the system have its own knowledge (about its plans, actions etc.) and extends the ontology with including extended vocabulary and ontology (Fig. 5).

Domain Ontology of MAS for HVAC Control according to (5) extends $S(k)$ (including system resources, relationships, and terms) and $C(k)$ ($S(k)$ with additional Actions, Actors and Events).

From Fig. 5 and equations (2) and (3), the vocabulary and ontology extension could be given by

(6) $$\text{ExtendedVocabulary} = <X_2(k+i), R_2(k+i)>,$$

(7) $$\text{ExtendedOntology} = < X_1(k+i), R_1(k+i), \Phi_1(k+i)> ,$$

where: k is the current moment; i – a future moment of ontology extensions ($i = 1,..., n$).

In the common case the extension of ontology caused from new events in agents system is presented as:

(8) $$O(k+i) = <S(k+i),C(k+i)> ,$$

where:

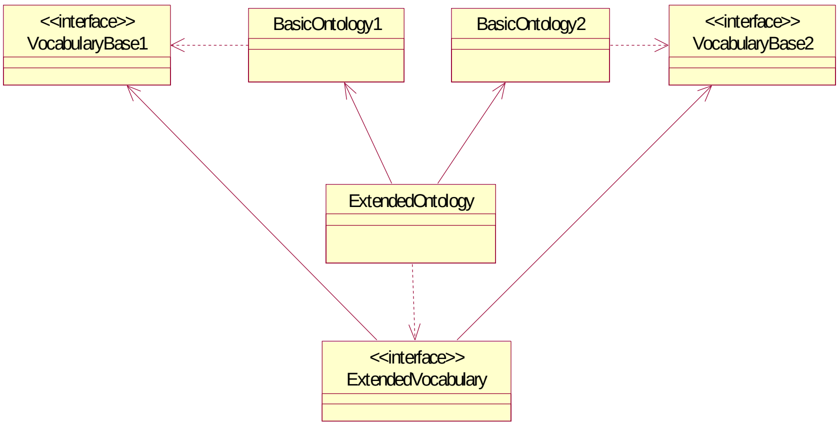

Fig. 5 Extension of ontology

(9) $$S(k+i)=<(X_1(k+i) \cup X_2(k+i)),(R_1(k+i) \cup R_2(k+i))>,$$

(10) $$C(k+i)=<S(k+i), (\Phi_1(k+i) \cup \Phi_2(k+ i))>.$$

The ontology units, which are in relation with the procedural knowledge change in the system $<X_1(k+i), R_1(k+i), \Phi_1(k+i)>$ compose the dynamic ontology component $O_1(k+i)$. The static (declarative) part of ontology is defined by $<X_2(k+i), R_2(k+i), \Phi_2(k+i)>$ and forms the static ontology component $O_2(k+i)$. The ontology extension in result of agents actions could be represented by the ontology state:

$$O_1(k) \neq O_1(k+i),$$

$$O_2(k+i)=O_2(k),$$

(11) $$O(k+i)=O_1(k+i) \cup O_2(k+i).$$

The future ontology extension is represent by $O_1(k+i)\neq O_1(k)$ and describes the dynamic ontology part. The $O_2(k)=O_2(k+i)$ forms the static ontology unit.

5. Knowledge update in HVAC system

5.1. Knowledge change in DO/MAS system

The agent's actions and system events bring to changes in dynamic ontology. Some of terms, relations, actors and concepts become invalid, changed or new appear. There are changes in system behavior, events and actions according the technological conditions and chosen algorithm of control.

The ACO mechanism is to chose an optimal control according to the probability for a good decision (12) or a bad decision (13) [9]:

(12) $$P_u(m) = \frac{(u_m + g)^b}{(u_m + g)^b + (l_m + g)^b},$$

(13) $$P_l(m) = 1 - P_u(m),$$

where: u_m is the number of ants that accepted the decision as good; l_m – the number of ants that accepted the decision as bad; $P_u(m)$ – the probability for the decision to be good; $P_l(m)$ – the probability for the decision to be bad; g and b – parameters; m – the number of all ants in the colony.

Some of the ants take actions by own beliefs, intentions and corresponding values of $P_u(m)$ and $P_l(m)$ accept or refuse the decisions of the other ants in system. A quantity of approved decisions $Q(k)$ [26] in a current moment could be presented as:

$$Q(k) = \frac{\mathrm{TP}(k)}{\mathrm{TP}(k)+\mathrm{FN}(k)}\frac{\mathrm{TN}(k)}{\mathrm{FP}(k)+\mathrm{TN}(k)}, \tag{14}$$

where: TP(k) is the number of ants that accepted $P_u(m)$ for positive; TN(k) – the number of ants accepted $P_u(m)$ for negative; FP(k) – the number of ants that accepted $P_l(m)$ for positive; TN(k) – the number of ants that accepted $P_l(m)$ for negative.

From equation (14) according [26] the change of quantity of pheromones (messages for the agents) $\tau_{ij}(k+1)$ is

$$\tau_{ij}(k+1) = \tau_{ij}(k) + \tau_{ij}(k)Q(k), \tag{15}$$

where $\tau_{ij} = \frac{1}{\sum_{i=1}^{a} b_i}$ is quality of dispatched pheromones; a – the number of all attributes participating in decision making; b – possible attributes values; $Q(k)$ is according to (5).

From equations (14) and (15), the knowledge change in HVAC system can be represented as

$$\mathrm{SK}(k+1) = \mathrm{SK}(k) + \mathrm{SK}(k)Q(k), \tag{16}$$

where: SK(k), SK(k+1) are the current and forgoing knowledge in the system.

The knowledge change in the next step (k+1) will be:

$$\Delta\mathrm{SK}(k+1) = \mathrm{SK}(k)Q(k), \tag{17}$$

where $\Delta\mathrm{SK}(k+1) = \mathrm{SK}(k+1) - \mathrm{SK}(k)$.

5.2. Ontology update mechanism

Continuously knowledge changes in system leads to necessity in changes in parts of ontology responding to proper system work. In absence of ontology update the positive information feedback in stigmergy is eliminated, which leads to unadaptation in environment. The ants lose their robustness and adaptation and takes bad decisions, and the HVAC system may becomes instable. Ontology Service Agents looks after knowledge changes (17) in agent's system in a order to eliminate a bad control. OSA checks for new knowledge and it classification. The OSA established a consistently knowledge and then update the static components of ontology. The current knowledge proceeds in dynamic part of ontological layer, which ensures positive information feedback and proper system work. The mechanism of knowledge update in ontology is shown in Fig. 6.

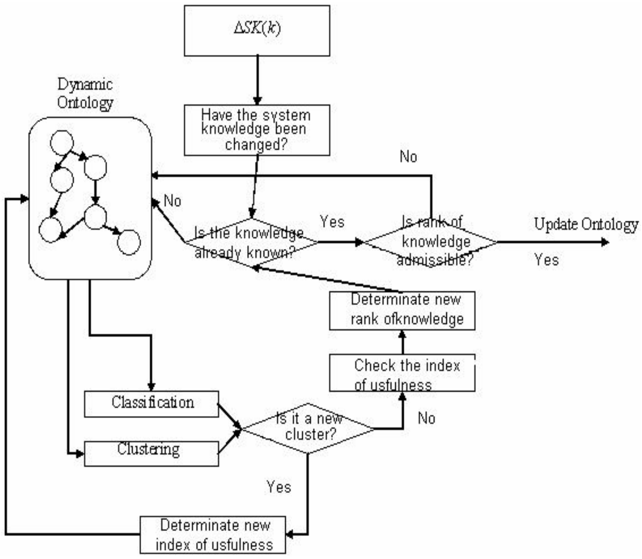

Fig. 6. Update Ontology

6. HVAC hybrid intelligent control

6.1. Control system

A HVAC control structure for isolated site with single manipulated variable is presented in Fig. 7. A simplified scheme of the plant in this case is shown in Fig. 8. It corresponds to single input two outputs (SITO) control of indoor temperature Θ_{air} and radiant temperature Θ_{rad} through the temperature Θ of the input air.

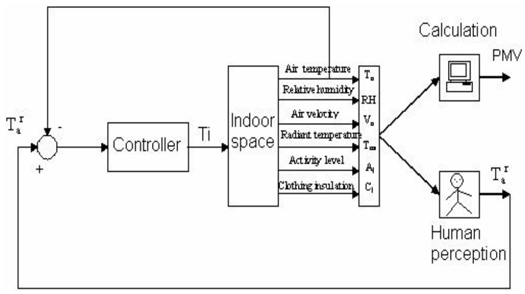

Fig. 7

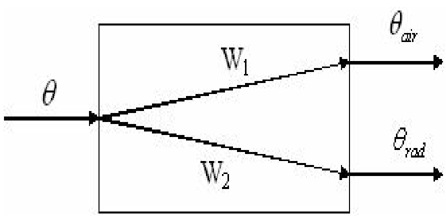

Fig. 8

The transfer functions are accepted in the form:

(18) $$W_1(s) = \frac{k}{Ts+1} e^{-\tau s},$$

(19) $$W_2(s) = \frac{k_1}{T_1 s+1} e^{-\tau_1 s},$$

where: k= 0.7, T = 10, τ = 4, k_1 = 1, T_1 = 20, τ_1= 8.

A number of control structures HVAC SITO control have been investigated. In Fig. 9 two of them (noted as A and B) are presented. The control task is to stabilize in an optimal way θ_{air} and θ_{rad} by relevant switching of manipulated variables u_{11} or u_{22} formed by R, R1, R2, R3 and Rm. Additional regulator R4 is included in schema B.

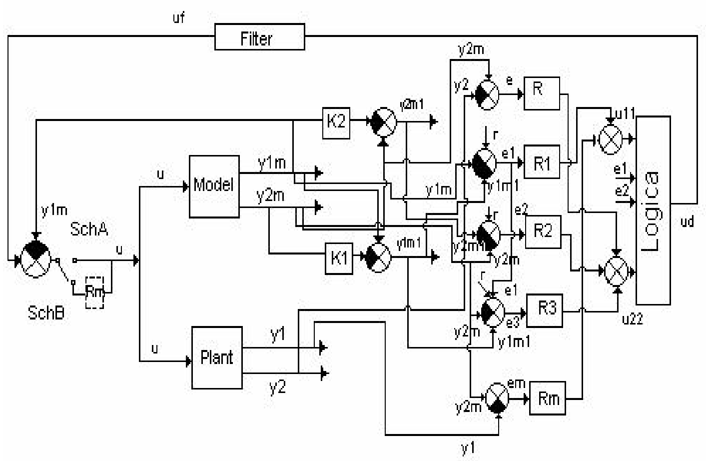

Fig. 9. Structure of schemes A and B

6.2. MAS/Dynamic Ontology (DO) software realization

A part of the UML ontology model of MAS for HAVC control is given in Fig. 10. There are shown some elements of the basic classes in the system, relations and dependence between them. The Predicate and the Concept are elements of the Basic Ontology [23]. Each class attribute is described in an ExtendedVocabulary (Fig. 5), which is a part of the system terminology. The classes and some schemes (PredicateSchema, ConceptSchema and ActionSchema), as well as some relations between them are included in the ExtendedOntology (Fig. 5). A parts of the abstract classes, classes, subclasses and relationships for some agents in ACO system are presented in Fig.10.

The ontology model is used in order to compose the system ontology with well established tool Protege [27]. The ontological code (Fig. 11) is accomplished in RDFS (Resource Description Frame Schema) which gives a possibility to connect with another ontologies through Ontological Servers (Fig. 4).

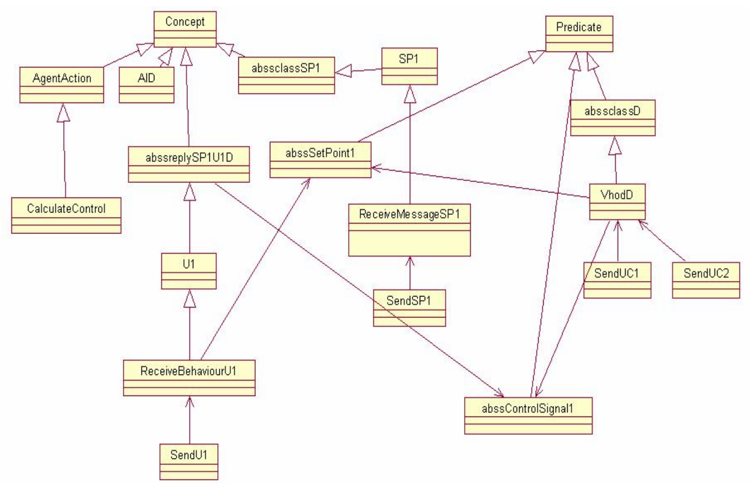

Fig. 10. UML ontology model

```
</rdfs:Class>
<rdfs:Class rdf:about="&rdf_;ReceiveBehaviourU1"
          rdfs:label="ReceiveBehaviourU1">
         <rdfs:subClassOf rdf:resource="&rdf_;U1"/>
</rdfs:Class>
<rdfs:Class rdf:about="&rdf_;ReceiveMessageSP1"
          rdfs:label="ReceiveMessageSP1">
         <rdfs:subClassOf rdf:resource="&rdf_;SP1"/>
```

Fig. 11. A part of DO source code in RDFS

6.3. MAS/Ontology functionality indices

A big volume of communications among agents in the control system exists due to interaction of ant colony and environment. The communication rate and control system speed are in straight dependence on the distribution functionality rank $MAS_{onto}(k)$ [20]:

(20) $$MAS_{onto}(k) = \frac{Onto_{functions}(k)}{Agent_{functions}(k) + Onto_{functions}(k)},$$

where $Onto_{functions}(k)$ – the number of ontological functions; $Agent_{functions}(k)$ – the number of agents functions. Generaly $MAS_{onto}(k)$ could be time variant.

Using moving average procedure the current value of $MAS(k+i)$ could be estimated as follows:

(21) $$MAS_{com}(k+1) = \frac{1}{(l+1)} \frac{\sum_{k+i-l}^{k+i} N_a(j) \sum_{k+i-l}^{k+i} Agent_{actions}(j)}{\sum_{k+i-l}^{k+i} S_{send\_messages}(k) + \sum_{k+i-l}^{k+i} R_{receive\_messages}(k)},$$

where: $N_{a(j)}$ are agents in MAS; $Agent_{actions}(j)$ –agent actions; $S_{send\_messages}(j)$– rate of the sanded messages; $R_{receive\_messages}(j)$ – rate of the received messages.

The control speed of system could be presented as:

$$MAS_{time} = \frac{\sum_{j=k}^{k+n} T(j)}{\frac{1}{(l+1)} \sum_{j=k+i-l}^{k+i} N_a(j) \sum_{j=k}^{k+n} Agent_{actions}(j)}, \tag{22}$$

where $T(j)$ is the computational time necessary for determination of optimal HVAC control action.

7. Simulation results

7.1. Multi Agent System (MAS) based HVAC control system

The concurrent work of ants and environment ensures a stable system control when the distribution rank is $MAS_{onto} \geq 0.35$. As it is shown in Fig. 12, the HVAC time settling behavior is big, because after the ants find out the optimal control action, they must change the ant system state by updating the environment [28]. The environment is ready to react, but it is waiting for be updated from the ants. Each agent waits to receive messages from the other agents and then takes decision. The messages could be received only after udaptation of environment [28].

7.2. Dynamic ontology-based HVAC control

In order to separate ants and environment the later is represented by dynamic ontology (DO). Using dynamic ontology directly for control action formation HVAC control system becomes instable (Fig. 13). This is caused by the lack of knowledge refreshing and no effective positive information feedback in stigmergy [28].

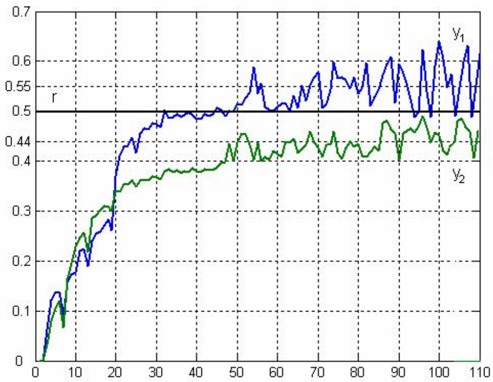

Fig. 12. HVAC control via MAS

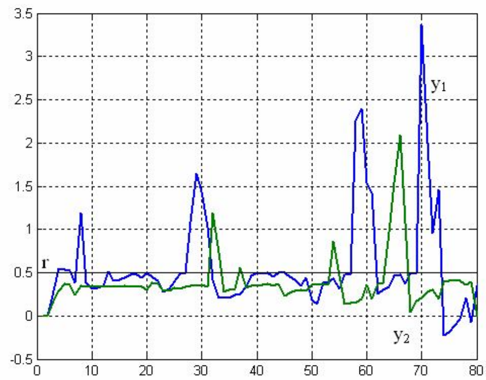

Fig.13. HVAC control via D

7.3. Hybrid intelligent MAS/DO – based HVAC control

The separation of ants and environment is a way to decrease the communication rate and increase the control system speed. For proper system control the Ontology Service Agents (OSA) are used. The OSA redistribute the ontology and agent functionality and update the dynamic ontology [21]. The optimal control when the ants and ontology are separated is presented in Fig.14.

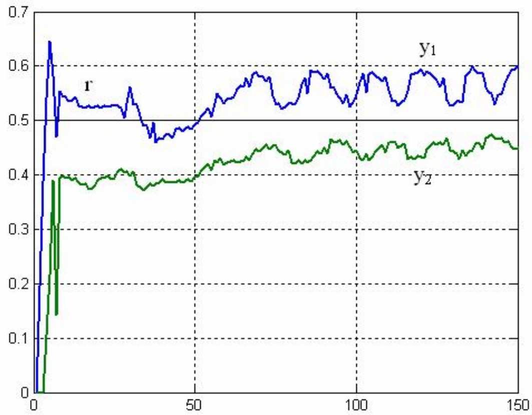

Fig. 14. Dependence between system accuracy and communication level

7.4. Communication problem

The knowledge and information exchange are necessary for coordination and decision making into the ant colony system, which leads to a considerable rate of communication. In Fig. 15 the communication rate are present for:

- multiagent control, where the communications are determinate according to [23] (pheromone broadcasting dispatch);
- ant multiagent-based system (MAS), were ants and environment work together;
- hybrid system (MAS/DO) with ants and environment separation;
- dynamic ontology DO-based control system.

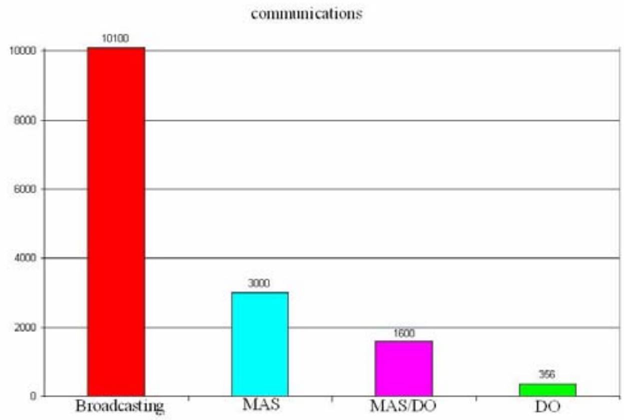

Fig. 15. System communications

The biggest communication rate is in case of agent-based systems, where each agent communicates with all other agents in the system. In case of ants-based system, where the ants and environment work together (MAS), the system communication rate is 3.36 times smaller. In hybrid control system with separation between ants and environment (MAS/DO), the communication rate is 6.7 times smaller than in agent's realization. When the system is controlled directly by dynamic ontology (DO), the communication rate is 30 times smaller than in agents - based control and 4 times smaller than in MAS/DO. Despite of this small communication rate the HVAC control system becomes instable (Fig. 13).

Accepting optimal rank of function distribution $\mathrm{MAS}_{\mathrm{onto}}(k)$ is 0.3-0.5, the communication rate vary among 2900 – 400 for each iteration (Fig. 16). The communication rate depends on current moment k, in which OSA decides to redistribute the functions in order to stabilize the system and to improve control accuracy.

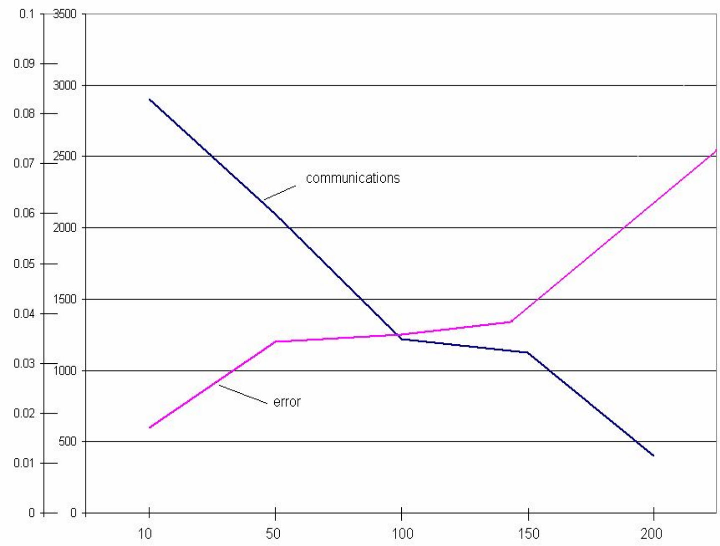

Fig. 16. Dependence between system accuracy and communication level

The future communication rate can be estimated by

$$r(k+i/k) = (k, \Delta e(k),\ \mathrm{MAS}_{\mathrm{onto}}(k),\ \Delta SK(k), O(k+i))\ . \quad (23)$$

The communication rate and control system speed depend on current time k, control system error $\Delta e(k)$, rank of function distribution $\mathrm{MAS}_{\mathrm{onto}}$, knowledge changes in HVAC system Δ SK(k) and future state of ontology $O(k+i)$.

8. Conclusions

Hybrid Multiagent (MAS)/Dynamic Ontology-based systems are promising approach for control of nonsquare, nonlinear plants with control structure reconfiguration via Ant Colony Optimization. The integration of data driven (MAS) and knowledge driven (DO) procedures with ACO show significant synergy effects on the all main performance indexes of the HVAC control system – speed of tracking, stability and communication rate. ACO is relevant optimizing method in conjunction with dynamic ontology, because changeable concepts could be presented explicitly in procedural form. This results in strong dynamic ontology volume reduction because the relationships between DO elements change from ant to ants towards ant to pheromones. Hybrid MAS/DO intelligent control system could be extended towards multidimensional centralized HVAC system using hierarchical coordination at the local, regional and global levels.

Acknowledgments. This work is supported by the project "Dynamic ontologies in multiagent information and control system" VU-TN 204/2006, granted by HSF-Bulgaria.

References

1. Anderasen, B. Energy Efficient HVAC Systems in Renovated Buildings. – In: Int. Conf. on Energy Efficiency, Plovdiv, 2000.
2. ASHRAE: Project TC4.11, Smart Sensor Systems for Reducing Bias Errors in the Measurement of Air Temperature and Flows in Air-Handling Units, 2002.
3. Bemporad, A., M. Moeari. Control of Systems Integrating Logiocs, Dynamics and Constraints. – Automatica, **35 (3)**, 1999.
4. Besana, P. Dynamic Ontology Mapping in MAS. **http://homepages.inf.ed.ac.uk/s0454959/ docs/ssptalks/ ssp01022005.pdf, 2005**
5. Borreli, F. Constrained Optimal; Control of Linear and Hybrid Systems. Springer, 2003.
6. Buitelaar, P., T. Eigner, T. Declerk. Onto Select: A Dynamic Ontology Library with Support for Ontology Selection. – In: Proc. of the Inter. Semantic Web, Japan, 2004. **http://iswc2004 .semanticweb.org/demos/16/ paper.pdf, 2004**
7. Carrilo, L., J. Marzo, P. Vila, C. Mantilla. MAantS-Hoc: A Multi-Agent Ant-Based System for Routing in Mobile Ad Hoc Networks, 2005.
8. Cartigny, J., D. Simplot, I. Stojmenovic. Localized Energy Efficient Broadcast for Wireless Networks with Directional Antennas. – In: LIFL 2002, July 17, 2002.
9. Dorigo, M., G. Caro. Ant Algorithms for Discrete Optimization, 2004.
10. Dorigo, M., M. Birattari, Thomas Stutzle. Ant Colony Optimization – Artificial Ants as a Computational Intelligence Technique. – IEEE Computational Intelligence Magazine, Vol. **1**, 2006, No 4, 28-39.
11. EIA, 2004. **http://www.eia.doe.gov**
12. Fahrig, T., M. Krafczyk, J. Tolke. Agent Based Measuring, Control and Regulation Techniques for HVAC – System Simulations.
13. Fanger, O. Thermal Comfort Analysis and Application in Environmental Engineering. McGrew Hill, 1972.
14. Felgner, F., S. Agustina, R. Bohigas, R. Merz, L. Litz. Simulation of Thermal Building Behavior in MODELIKA. – In: Proc. of the Second Modelica Conference, Oberpfaffenhofen, Germany, 2002.
15. Gavrailova, T., V. Horoshevski. Knowledge bases of Intelligent Systems. St. Petersburg, Piter, 2000.
16. Green Paper on Energy Efficiency. DG for Energy and Transport, EC, 2005.
17. Gómez-Perez, A., M. Fernandez-López, O. Corcho. Ontological Engineering. Springer, 2003.
18. Hadjiski, M., V. Sgurev, V. Boishina. Intelligent Agent Based Non-Square Plants Control. – In: Proc. of the 3rd IEEE Conference on Intelligent Systems IS'06, London, 2006.
19. Hadjiski, M., V. Sgurev, V. Boishina. Multi-Agent Intelligent Control of Centralized HVAC Systems. – In: IFAC Workshop on Energy Saving Control in Plants and Buildings, Bansko, Bulgaria, 2006.

20. H a d j i s k i, M., V. S g u r e v, V. B o i s h i n a. Function Distribution Optimization Between Agents and Ontologies in MAS-Based Combustion Control, Bulgaria, Bobov Dol, 2006.
21. H a d j i s k i, M., V. B o i s h i n a. Dynamic Ontology -based Approach for HVAC Control via Ant Colony optimization. – In: DECOM'2007, Izmir, Turkey, 2007.
22. Handout, ISO 7730: Moderate Thermal Environments. 5 Thermal Comfort – Metrics and Adaptive Comfort. 16387: Environmental Engineering Science 2, 2003.
23. JADE, 2007.
http://jade.tilab.com
24. M a r t i n, R., C. F e d e r s p i e l, D. A u s l a u n d e r. Supervisory Control for Energy Savings and Thermal Comfort in Commercial Building HVAC Systems.
25. N i c o l, F., M. A. H u m p h r e y s. Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings. – Energy and Buildings Journal, Vol. **34**, 2002, No 6.
26. P a r p i n e l l i, R., H. L o p e s, A. F r e i t a s. Data Mining with an Ant Colony Optimization Algorithm, 2002.
http://www.cs.kent.ac.uk/people/staff/aaf/pub_papers.dir/Ant-IEEE-TEC.pdf
27. Protege.
http://protege.stadford.edu, 2006
28. R e i t e r, B., T. J a g a l s k i, K. P e t e r s, B.-W e n n i n g, M. F r e i t a g, A. T i m m. Strategies of Social Insects and Other Bio-Inspired Algorithms for Logistics: State of the Art and New Perspectives, Applied Artificial Intelligence and Logistic. – In: Proc. of KI2004 Workshop, Germany, September 24, 2004.
29. S a m o y l o v, V., V. G o r o d e t s k y. Ontology Issue in Multi-agent distributed Learning. – In: Int. Workshop on Autonomous Intelligent Systems: Agents and Data mining, St. Petersburg, Russia, LNAI, 3505, V. Gorodetski, J. Lin, V. Skormin (Eds.), Springer, 2005.
30. S h a r p l e s, S., V. C a l l g h a n, G. C l a r k e. A Multi-Agent Architecture for Intelligent Building Sensing and Control. – International Sensor Review Journal, 1955, No 5.
31. S h v a i k o, P., F. G i u n c h i g l i a et a l. Dynamic Ontology Matching: A Survey, 2006.
http://eprints.biblio. unitn.it/archive/00001040/
32. T a y l o r, K., J. W a r d, V. G e r a s i m o v, G. J a m e s. Sensor /Actuator Network Supporting Agents for Distributed Energy Management, 2004.
http://mobile.act.cmis/TaylorEZAI
33. T h a n g, C., V. W u w o n g s e. An Ontology-based Approach to Information System Design, 2005.
http://fist2.mmu.edu.my/~m2usic/proceedings05/TS13/03-132
34. Thermal Comfort Models.
http://www.esru.strah.ac.uk/reference/ concepts/thermal_comfort.htm
35. V a n B r u s s e l, H., O. B a c h m a n, C. Z a m f i r e s c h. The Design of Multi-Agent Coordination and Control System Using Stigmergy, 2002.
http://www.mech.kuleuven.ac.be/ pma/pma.html
36. V a s s, K., K. N a k a t a. An Agent-Based Approach to Dynamic Ontology Construction.
http://www.etse.urv.es/recerca/rgai/toni/MAS/Publicacions/kes06IsernSanchez.pdf
37. W e t t e r, M. Simulation-Based Building Energy Optimization. PhD Thesis, Univ. of California at Berkely, 2004.
38. W e y n s, D., T. H o l v o e t. On the Role of Environments in Multiagent Systems. – Informatica **29**, 2005.
39. W o o l d r i g e, M. An Introduction to Multi-Agent Systems. John Wiley, 2002.
40. G r u b e r t, R. A Translation Approach to Portable Ontologies. – Knowledge Acquisition, 1993, No 5 **(2)**.