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CO-OPERATIVE LEARNING IN COGNITIVE SYSTEMS

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Contemporary approaches to the formation of co-operative systems ignore a consideration of capability/compatibility factors of their agents. In fact, capabilities/compatibilities define the organisation and performance of co-operative systems. We consider a co-operative system as a cognitive system, which consists of a number of knowledge-interrelated cognitive agents. Interrelation is defined by the agents' available knowledge/skill capabilities with respect to the required capabilities for the learning/performance of tasks. We define co-operative learning as learning from series interactions with the other agents in the cognitive system. Each cognitive agent has to be not only capable of learning its task(s) but also to be compatible with the other agents in the system in order to ensure co-operative learning/performance. We consider knowledge/skill factors as critical variables in co-operative learning. We address problems in the formation of a cognitive system that is capable of co-operative learning. We also identify conditions for co-operative learning in cognitive systems, define knowledge integration as a major task in formation of co-operative cognitive systems and present a formal approach to the engineering of cognitive structure in co-operative cognitive systems.

СОВМЕСТНОЕ ОБУЧЕНИЕ В СИСТЕМАХ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

В.Плеханова

1. Introduction

Co-operatives and the notion of co-operative learning/performance are not new or modem concepts in research and industrial communities. The conceptual role of co-operation was defined in various applications and fields such as management, economic, political and sociological sciences. From the earliest developments it is recognised that structural and functional relationship of agents (members) of co-operative systems are a focus of understanding co-operatives and co-operative organisations [1, 2].

Historically, in applications the phenomenon of co-operative systems/agents for information agent technology, the influence the system's capability/compatibility aspects do not take into account. Furthermore, contemporary approaches to the formation of co-operative systems ignore a consideration of capability/compatibility factors of their agents. Even though it is agreed that capabilities/compatibilities define organisation and performance of co-operative systems.

Co-operative agents (or information agents) and their modelling are generally considered from technical or technological viewpoints. However, co-operative agents need to have knowledge/skills to conduct high-level communication, to be capable of collaborating with each other to accomplish tasks, to co-ordinate and negotiate goals. In this paper we consider knowledge/skill factors as critical variables in co-operative learning and address problems in the formation of cognitive systems capable of co-operative learning. That is, we consider a co-operative system as a cognitive system that consists of interrelated cognitive agents.

We define a cognitive agent as an intelligent agent whose mental model is represented by knowledge and consider a cognitive agent who is capable of peer learning, integrating to another agents, and defining flexible cognitive structures with respect to practical need(s). Like human agents, the cognitive agents can be self-organised and can be integrated into the cognitive system that performs the tasks or solves the problems.

The content and formation of cognitive systems is dependent on **cognitive structures** and **cognitive processes**. We consider **cognitive structures** that represent the way in which knowledge is stored in the cognitive system. **Cognitive processes** describe manipulation of knowledge during the formation and utilisation of the cognitive system (or a mental model [4, 5]). A cognitive system consists of knowledge-interdependent multiple agents.

In fact, a cognitive agent has to have knowledge in order to be co-operative, autonomous, adaptive, reactive, etc. We define **knowledge** as the range of information, experience and understanding that someone must possess to perform a given task efficiently and effectively, and **skill** as the ability to perform a given task reliably and with facility (achieving expected outcome(s)) [6]. In order to oversee a task, an agent has to possess a number of key knowledge factors, the integration of which allows the completion of the task. *A formal analysis of the available knowledge of cognitive agents is required to ensure the performance of tasks at a desired performance/technology level while utilising the available knowledge capabilities effectively and efficiently* [6–8].

We define agents' **compatibility** as the capability of cognitive agents that are used together without adaptation, adjustment and modification [7]. We consider knowledge capabilities/compatibility factors and their impact on the formation of the cognitive system and its performance. We recognise that capabilities/compatibility factors influence the integration of knowledge in cognitive systems, since agent availability issues do not contribute much to the successful performance of a task. Furthermore, there is a risk of inappropriately selecting agents to do work because they are simply available and not because they have correct combinations of key knowledge factors. Moreover, agents can be both available and capable of overseeing cognitively-driven tasks, but factors such as knowledge and/or technological, may be *incompatible*. That is, co-operative agents also have to be compatible with each other in order to perform the tasks. Hence, an evaluation of agents' capabilities/compatibilities has to be an important task in the formation of co-operative cognitive systems.

A challenge for co-operative learning is to ensure required or desired levels of the performance/actions of cognitive system are maintained. We define cognitive system by knowledge capabilities of cognitive agents, cognitive structure and cognitive processes. We address problems of knowledge integration and analysis of knowledge capabilities of cognitive system in order to provide better opportunities for co-operative learning.

In this paper we consider conditions for co-operative learning in cognitive systems, define knowledge integration as a major task in formation of co-operative cognitive systems and present a formal approach to the engineering of cognitive structure in co-operative cognitive systems.

This paper has the following organisation. First we introduce basic definitions of knowledge profiles which are used for the description of a cognitive agent/system. Then we show how profiles and the integration of profiles may be used for modelling of cognitive system in conjunction with tasks/activities. Next we represent a formal approach to structure function definition and consider the impact of agents' knowledge properties on the formation of the cognitive system structure for co-operative learning/performance. Lastly, we conclude with discussions on the general applications of the proposed approach and present a summary of the paper.

2. Knowledge Profile: Basic Definitions

Knowledge factors are considered as basic factors in the modelling of cognitive agents/systems, since agents must have particular knowledge capabilities to perform and learn their tasks. In a description of the knowledge of cognitive agents we identify the importance/priority of the factor for performance of the task, the property (level, grade, degree) and existence or non-existence of the factor.

Knowledge of a cognitive agent is described by a set of knowledge factors, each factor is defined by multiple characteristics. A set of such factors forms a knowledge profile [8]. We represent a factor by qualitative and quantitative information. Quantitative description of the ith knowledge factor is defined by indicator characteristic, property, and weight. In particular, we define a **profile** b as a set of factors $b_1, b_2, ..., b_n$: $b = \{b_i, \; i = \overline{1,n}\}$, where the ith factor b_i is represented by a pair $b_i = (\iota_i, e_i)$ with

- n – a number of factors,
- ι_i – an identification of the ith factor, i.e. a name or label or type of the ith factor,

- e_i – the 3-tuple of the *i*th factor as the Cartesian product: $e_i \in \mathcal{E}_i \times V_i \times W_i$, $e_i =< \varepsilon_i, v_i, w_i >$

where

- ε_i – indicator characteristic, that indicates and expresses, by factor presence in the description of a cognitive agent, the existence of certain conditions. In particular,

– ε_i may be defined as a time characteristic of the *i*th factor $\varepsilon_i = \varepsilon_i(t)$:

$$\varepsilon_i : \mathcal{J} \to \mathcal{E}_i \quad \text{or} \quad \mathcal{J} \times \mathcal{E}_i = \{(t, \varepsilon_i),\ t \in \mathcal{J} \quad \text{and} \quad \varepsilon_i \in \mathcal{E}_i\}.$$

Domain constraints may define bounds, i.e. $\varepsilon_i^b \le \varepsilon \le \varepsilon_i^u$, where $\varepsilon_i^b \ge 0$, $\varepsilon_i^u \ge 0$ represent bottom (lower) and top (upper) values of the *i*th factor time range, respectively. Time characteristic can represent duration (or length) of experience or factor utilisation.

– ε_i may also represent a number of times of factor utilisation

– ε_i may represent a binary case. For instance, factor existence ε_i=1 or non-existence ε_i=0; Boolean variable: ε_i=1 if factor is true or ε_i=0 if factor is false.

- v_i – property of the *i*th factor: $v_i \ge 0$. Since property may be changed with time, v_i can be defined as a function of time $v_i = v_i(t)$:

$$v_i : \mathcal{J} \to V_i \quad \text{or} \quad \mathcal{J} \times V_i = \{(t, v_i),\ t \in \mathcal{J} \quad \text{and} \quad v_i \in V_i\}.$$

Domain constraints may define bounds, i.e. $v_i^b \le v_i \le v_i^u$, where $v_i^b \ge 0$, $v_i^u \ge 0$ represent bottom (lower) and top (upper) values of the *i*th factor property range, respectively.

- w_i – weight of a factor which defines either the factor importance or the factor priority: $w_i \ge 0$. Factor weights can vary, and therefore, w_i can be also considered as a function of time $w_i = w_i(t)$:

$$w_i : \mathcal{J} \to W_i \quad \text{or} \quad \mathcal{J} \times W_i = \{(t, w_i),\ t \in \mathcal{J} \quad \text{and} \quad w_i \in W_i\}.$$

Domain constraints may define bounds, i.e. $w_i^b \le w_i \le w_i^u$, where $w_i^b \ge 0$, $w_i^u \ge 0$ represent bottom (lower) and top (upper) values of the *i*th factor weight range, respectively.

Weight can be defined by deterministic and stochastic approaches. In particular, in the deterministic approach weight is defined as a function: $w_i = w_i(t)$. In the stochastic case, weight can be defined as a **probability measure**. That is, profile factors are represented by their associated probabilities of occurrence or importance. So, the *i*th factor occurs with the probability w_i. It is meant to convey the probability that profile has the *i*th factor. Weights of the factor can be determined in the context of practical applications.

Example: Let us consider the *i*th knowledge factor: $b_i = (\iota_i, e_i)$, where $e_i < \varepsilon_i, v_i, w_i >$. Assume that the factor characteristics have the following values:

- i =5, i.e. the number of the *i*th factor,
- ι_5 = Monte Carlo, i.e. knowledge of Monte Carlo Method has the identification or name Monte Carlo,
- $\varepsilon_5 = 1$, i.e. existence of knowledge of Monte Carlo Method,
- v_5 =2, i.e. we suppose that 2 is an intermediate level of knowledge complexity,
- w_5 =0.3, i.e. we suppose that the priority weight is equal to 0.3,

or the 5[nd] knowledge factor b_5 may be defined as follows: b_5 = (Monte Carlo, <1,2, 0.3 >).

3. Profile Superposition

A factor itself may have multiple properties that may be presented by a profile. In this case, we define **profile superposition** as a set of profiles (called factor profiles):

$$Ps = \{b^{(1)}, b^{(2)}, ..., b^{(N)}\} \text{ or } Ps = \{(u(b^{(j)}), < \varepsilon(b^{(j)}, b^{(j)}, w(b^{(j)}) >), \ j = \overline{1, N}\}$$

where

- $u(b^{(j)})$ -name or identification of the *j*th factor profile,
- $\varepsilon(b^{(j)})$ – profile-factor existence $\varepsilon(b^{(j)}) = 1$ or non existence $\varepsilon(b^{(j)}) = 0$ (i.e. time characteristic of the *j*th factor profile),
- $b^{(j)}$ – the *j*th factor profile,
- N – number of factor profiles.

We define by $Ps^{(0)}$ a required profile superposition.

Example: 1) *Knowledge profile* of cognitive agents may be defined as a set of knowledge profiles of individual agents presented by a profile superposition $Ps = \{b^{(1)}, b^{(2)}, ..., b^{(N)}\}$, where $b^{(j)} = \{b_j^{(j)}, i = \overline{1, n_j}\}$, $j = \overline{1, N}$ is a knowledge profile of the *j*th cognitive agent with n_j number of knowledge factors.

4. Available and Required Profiles

In order to ensure successful performance of the cognitive system, we need to analyse knowledge capabilities of cognitive agents. We consider the knowledge of a cognitive agent from two viewpoints: availability and requirements. We define **required** knowledge/skills as a requisite set of knowledge and skill-related factors that are required for performance of given task with expected outcome(s). Alternatively, **available** knowledge/skills are a set of knowledge and skill-related factors that are available to perform a given task [6, 7].

Thus, we consider **required** $b^{(0)}$ (as a set of required factors $b_1^{(0)}$, $b_2^{(0)}$,..., $b_n^{(0)}$) and an **available** b (as a set of available factors b_1, b_2,..., b_n) profiles. That is, we define:

- **required factor** $b_i^{(0)}$ as a predetermined factor reference or a theoretical expectation,
- **required profile** $b^{(0)}$ as a set of the required profile factors and/or the predetermined profile references: $b^{(0)} = \{b_i^{(0)}, i = \overline{1, n}\}$,
- **available profile** b as a set of a-priori estimated and/or known values of the profile factors that we call the **available factors** b_i : $b = \{b_i, i = \overline{1, n}\}$.

Depending on data availability, the presentations of required and available capabilities profiles can be introduced on qualitative and/or quantitative levels.

5. Classification of Knowledge/Skills in Cognitive Systems

In fact, co-operation of cognitive agents is possible when a cognitive agent/system has required knowledge capabilities to oversee the particular tasks. When we allocate cognitive agent(s) to the performance of a cognitively driven task, we need to compare available knowledge with required knowledge [6–8]. That is we define some relations between these knowledge profiles. When we analyse these profiles we clearly define criteria (or criterion) for their comparison.

Available agent's capabilities may be classified with respect to required knowledge/skills. We consider knowledge/skills that satisfy the required ones, and knowledge/skills that are in reserve, critical and missing knowledge/skills [6].

Knowledge/skills in reserve are represented by the complement of required knowledge/skills relative to available knowledge/skills. That is, knowledge/skills in reserve are available factors, but are not used for the given task.

Let us consider required knowledge profile $b^{(0)} = \{b_i^{(0)}, i = \overline{1, n}\}$ and available knowledge $b = \{b_i, i = \overline{1, m}\}$, where n – a number of required knowledge factors and m – a number of available knowledge factors. If $l = (n - m)$ and $l < 0$, then the available knowledge profile has knowledge in reserve.

Missing knowledge/skills with respect to the available knowledge/skills are defined by the complement of available knowledge/skills relative to required knowledge/skills. Missing knowledge/skills are knowledge/skills, which are *essential* for the task, but are absent from the required set of knowledge/skills for the given task.

That is, if $l=(n-m)$ and $l>0$, then the available knowledge profile has missing knowledge.

Critical knowledge/skills with respect to the required knowledge/skills are represented by knowledge/skills where the properties (e.g. levels) do not satisfy the properties of required knowledge/skills.

That is, if we consider the 3-tuple of the *i*th required factor $e_i^{(0)} =< \varepsilon_i^{(0)}, \nu_i^{(0)}, w_i^{(0)} >$ and the 3-tuple of the *i*th available knowledge factor $e_i =< \varepsilon_i, \nu_i, w_i >$ and $\nu_i^{(0)} > \nu_i$ then the *i*th available factor b_i is a critical knowledge.

6. Knowledge Integration in Co-operative Cognitive System: A Formal Approach

Let us consider two cognitive agents the knowledge of which is represented by the homogeneous profiles [8]:

$$b^{(1)} = \{b_1^{(1)}, b_2^{(1)}, ..., b_n^{(1)}\} \text{ and } b^{(2)} = \{b_1^{(2)}, b_2^{(2)}, ..., b_n^{(2)}\}.$$

Denoting by:

- $\mathcal{J}=\mathcal{J}(b)$ - a set of all names or identifications of the profile $b: \mathcal{J}(b) = \{ \iota_i : \iota_i \; \iota(b_i),\ i=\overline{1,n} \}$,
- ι_i – name or identification of the *i*th factor,
- ι – a subset of identifications of the factors: $\iota = \{ \iota_i : \iota_i = \iota(b_i),\ i \in \{1,2,...,n\} \},\ \iota \subset \mathcal{J}(b)$

we define knowledge integration via union of knowledge profiles.

The **union** U_p **of two knowledge profiles** $b^{(1)}$ and $b^{(2)}$ we define as the set of all pairs $(\iota_i, e_i(b^{(1)} \cup b^{(2)}))$, the factor identifications of which belong to $b^{(1)}$ or to $b^{(2)}$ or to both

$$\iota_i \in \mathcal{J}(b^{(1)}) \cup \mathcal{J}(b^{(2)}) = \{ \iota \mid \iota \subset \mathcal{J}(b^{(1)}) \text{ or } \iota \subset \mathcal{J}(b^{(2)}) \}$$

and the 3-tuple for the *i*th knowledge factor is defined as

$$e_i(b^{(1)} \cup b^{(2)}) = \begin{cases} < \varepsilon_i, \max[\nu_i^{(1)}, \nu_i^{(2)}],\ w_i >, & \text{if } \nu_i^{(1)} \neq \nu_i^{(2)} \\ < \max[\varepsilon_i^{(1)}, \varepsilon_i^{(2)}], \nu_i, w_i >, & \text{if } \nu_i^{(1)} = \nu_i^{(2)} \end{cases}$$

where ε_i takes the value from a profile with $\max[\nu_i^{(1)}, \nu_i^{(2)}]$, if $\nu_i^{(1)} \neq \nu_i^{(2)}$; and ν_i from a profile with $\max[\varepsilon_i^{(1)}, \varepsilon_i^{(2)}]$, if $\nu_i^{(1)} = \nu_i^{(2)}$; $w_i = \max[w_i^{(1)}, w_i^{(2)}]$..

Then, the union of two knowledge profiles is

$$U_p = b^{(1)} \cup b^{(2)} = \{(\iota_i, e_i(b^{(1)} \cup b^{(2)})) \mid \iota_i \in \mathcal{J}(b^{(1)}) \cup \mathcal{J}(b^{(2)}) \}.$$

That is, the set U_p represents an *integration of available knowledge profiles* $b^{(1)}$ and $b^{(2)}$.

Example:

Cognitive agent 1: Qualitative and quantitative description of knowledge

$b^{(1)}$= {Java,<3, 2, ¼ >;Windows,<4,3,¼ >;HTML,<3,2,¼ >;e-commerce, <4,3, ¼ >}

Qualitative description of knowledge: $\mathcal{J}(b^{(1)})$ = {Java, Windows, HTML, e-commerce }

Cognitive agent 2: Qualitative and quantitative description of knowledge

$b^{(2)}$ = {JavaScript, <3, 2, ¼ >; Windows,<5,3,¼ >;HTML,<4, 3, ¼>; e-commerce, <4, 3, ¼>}

Qualitative description of knowledge: $\mathcal{J}(b^{(2)})=$ {JavaScript, Windows, HTML, e-commerce }.

Qualitative and quantitative description of integrated knowledge

The **union** U_p of two knowledge profiles $b^{(1)}$ and $b^{(2)}$ is then

U_p={Java,<3,2,¼>;JavaScript,<3,2,¼>;Windows,<5,3,¼>;HTML,<4, 3,¼>;e-commerce,<4,3,¼>}.

Qualitative description of integrated knowledge

The **union** $\mathcal{J}(b^{(1)}) \cup \mathcal{J}(b^{(2)})$ of two knowledge profiles $b^{(1)}$ and $b^{(2)}$ is:

$$\mathcal{J}(b^{(1)}) \cup \mathcal{J}(b^{(2)}) = \{ \iota \mid \iota \subset \mathcal{J}(b^{(1)}) \text{ or } \iota \subset \mathcal{J}(b^{(2)}) \} = \{\text{Java, JavaScript, Windows, HTML, e-commerce}\}$$

7. Cognitive System: A Formal Model Representation

We describe a number of cognitive agents by a **cognitive system**, which is defined as a complex system B, in which the elements are interrelated knowledge profiles. That is, a cognitive agent is represented by knowledge profile and a cognitive system by a set of N interrelated *available* knowledge profiles. Profile's relationships define the cognitive structure of the cognitive system which can be described by the relational structure function $\beta=\beta(h(B))$ of order N [3]. Thus, a cognitive system is represented by a profile superposition (a set of available knowledge profiles) and their cognitive structure: $B=\{(b^{(1)}, b^{(2)}, \ldots, b^{(N)}), \beta\}$.

We associate with each available knowledge profile a variable $h^{(j)}=h(b^{(j)})$, $j=\overline{1,N}$ (as a state) such that:

$$h^{(j)} = \begin{cases} 1, & \text{if } b^{(j)} \text{ knowledge profile exists in a cognitive system B,} \\ s, & \text{if } b^{(j)} \text{ knowledge profile has critical knowldge factors,} \\ 0, & \text{if } b^{(j)} \text{ knowledge profile does not exist in a cognitive system B.} \end{cases}$$

The N-tuple $h(B)=(h^{(1)}, h^{(2)}, \ldots, h^{(N)})$ will be called an **indicating set** whose elements show if certain profiles in a cognitive system exist or not (i.e. if there is missing or critical knowledge in the cognitive system).

Notice that the same sets of profiles can form alternative relationships (structures). In this case, we can describe a cognitive system as follows: $(B, \beta_k(h(B)); k=\overline{1,K})$ where $\beta_k(h(B))$ is the kth structure function; K is a number of alternative cognitive structures generated by B.

A task can be associated with:

- the set of M_i available knowledge profiles

$$B_i = \{b^{(j)}, j=\overline{1,M_i}\}, \quad B_i \subset B, \; M_i \le N$$

or

- K number of alternative sets of the available knowledge profiles: $\Xi = \{B_i, i=\overline{1,K}\}$. That is the required knowledge profile for a task may correspond to a number of different combinations with different available knowledge profiles. These combinations define the alternative cognitive systems.

In order to select all combinations of the available knowledge profiles we should define how they satisfy the required knowledge profile (or performance profile) for a task.

8. Capability-Compatibility Metric for Cognitive System Analysis

We use capability measurements to compare and analyse the available knowledge profiles with respect to each other and/or to the required knowledge profile. The values of the ith knowledge factor capability can be determined by the following formula [7]:

$$V(b_i) = \pi w_i \left(\frac{\varepsilon_i}{\varepsilon_i^{(0)}} \right) \left(\frac{v_i}{v_i^{(0)}} \right)^2$$

where v_i, ε_i are available level and time/existence, respectively; $v_i^{(0)}$, $\varepsilon_i^{(0)}$ – are required level and time/existence.

Assume that we need to determine the distance between available and required knowledge profiles. A "deviation" of available knowledge profile $b \in B$ from a required knowledge profile $b^{(0)}$ can be measured by any L_p metric, which can be used as a distance between profiles. That is, the distance between an available knowledge profile and a required knowledge profile is defined as:

$$\left\| b - b^{(0)} \right\|_p = \left[\sum_{i=1}^{n} \left| V_i - V_i^{(0)} \right|^p \right]^{1/p}, \quad p \in \{1,2,3,\ldots\} \cup \{\infty\}$$

where n is a number of required knowledge factors for a task; $b \cap b^{(0)} \neq \varnothing$.

We define the **distance** from the knowledge profile $b^{(i)}$ to the knowledge profile $b^{(j)}$ as:

$$d_p(b^{(i)}, b^{(j)}) = \left\| b^{(i)} - b^{(j)} \right\|_p .$$

It can be easily shown that such a defined distance on B satisfies the metric definition. This distance we call a **capability-compatibility metric**. Thus, B can be defined as a metric space (B,d) with the metric $d_p(b^{(i)}, b^{(j)})$.

A given or required distance we call a **radius** $r=r(b)$. An available knowledge profile b **covers** the required knowledge profile $b^{(0)}$ if the distance is less or equal to the given radius: $d_p(b, b^{(0)}) \leq r(b)$.

9. Co-operative Performance/Learning of the Cognitive System: Knowledge Integration Model and Series Cognitive Structure

A knowledge structure (or cognitive structure) is an essential element in the modelling, design, development and management of cognitive systems. The internal properties of knowledge factors change with time and effect both the cognitive system structure and the performance of the cognitive system. In turn, cognitive structure defines the type (or strategy) of learning. Therefore, the possibility of modelling the cognitive structure provides an opportunity for the selection and management of learning processes, their continuous improvement and engineering.

Presently, heuristic/intuitive approaches are used for structure formation of complex systems. As a rule, heuristic approaches to engineering the system structure address only the performance characteristics (e.g. *error rate, accuracy, productivity, cost, reliability*) *without correlation to corresponding internal properties of the elements of the complex system.* However, the same performance characteristics of a cognitive system may be obtained by different knowledge that can be integrated into a cognitive system and which may form different structures. Since different knowledge may have different variable internal property constraints (e.g. capabilities and compatibilities), they will also possess different performance constraints.

The possibility of formal modelling the cognitive system structure provides an opportunity for the management or modification of the cognitive system structure towards the desired direction and/or within given boundaries. In turn, this influences the formation of cognitive systems. Therefore there is a need to develop formal approaches to structure function definition and to consider the impact of the knowledge properties (knowledge capabilities and compatibilities) of cognitive agents on the formation of the cognitive system structure.

In order to ensure co-operative learning/performance of the cognitive system we address the problem of agents' knowledge integration. We determine a knowledge integration model that encompasses *integration criteria* (e.g. with respect to capability/compatibility and/or performance factors), *priorities/importance of the knowledge profiles* and *knowledge integration goal(s).* In co-operative learning it is important to ensure the available knowledge profile of a cognitive agent satisfies the knowledge profiles required for the successful co-operative learning/performance processes. That is, a cognitive system should consist of available knowledge that satisfies the required knowledge capabilities to ensure better co-operative performance and/or problem resolution. Results of knowledge integration can be represented by profile superposition. *We may identify different requirements (e.g. integration criteria, priorities) for not only models of knowledge representation but also for knowledge integration models and, therefore, define a set of integration models.*

In the following section we introduce the knowledge integration criteria for the formation of the co-operative cognitive system. The goal of knowledge integration is to match the satisfaction of available knowledge of the cognitive system to the required knowledge for the co-operative learning or co-operative performance of the task.

10. Cognitive Structure for Co-operative Learning

We consider co-operative learning as learning from a series of interactions between cognitive agents. Cognitive agents should send (accurate) information to other agents in order to provide the best opportunity/chance of using this information. One co-operative agent receives initial information (i.e. a condition) from the other agents and needs to be capable of independent actions in open and uncertain environments. That is, co-operative agents are dependent from initial constraints defined by the other agents.

Therefore to ensure independent learning/performance of the task(s) co-operative agents need to understand and be capable of accepting results/constraints defined and reported by other agents in the cognitive system. In fact, co-operative agents learn their tasks in ordered manner with respect to each other, and therefore, their knowledge/skill capabilities should be complemented for co-operative learning in cognitive systems. Cognitive structure should be defined by predetermined order of agents' knowledge profiles.

In particular, we define the available knowledge profiles $b^{(1)},b^{(2)},\dots,b^{(M)}$ as **mutually complementary** *with respect to* **factor identifications** if the factor identifications of a union of the available knowledge profiles belong to a set of *required* knowledge factor identifications.

The available knowledge profiles are defined as **mutually complementary** *with respect to the* **available** knowledge **factors** if a union of M available knowledge profiles satisfies the given metric d (the integration criterion):

$$d\left(\bigcup_{j=1}^{M} b^{(j)}, b^{(0)}\right) \le r.$$

That is, a union of available knowledge factors represents the required knowledge factors for the performance/learning of a given task, i.e. the required knowledge profile is covered by a union of available knowledge profiles and this union is a non-empty set: $\bigcup_{j=1}^{M} b^{(j)} \neq \varnothing$.

Then, we represent a relational structure defined by the function $\beta=\beta(h(B))$, whose components are M mutually complementary profiles **distributed in series**, in the following way: $\beta(h(B)) = \prod_{j=1}^{M} h^{(j)}$..

This relational structure function corresponds to a cognitive system that is represented by all required knowledge factors for a given task:

$$(\forall j:\ h^{(j)} = 1) \Rightarrow (\beta = 1);\ \ (\exists j: h^{(j)} = 0) \Rightarrow (\beta = 0);\ \ (\exists j: h^{(j)} = s) \Rightarrow (\beta = \tilde{s}: \tilde{s} \neq 0, \tilde{s} \neq 1).$$

If $\beta = \tilde{s}$ ($\tilde{s} \neq 0$ and $\tilde{s} \neq 1$), then the cognitive system has critical knowledge and improvement of available knowledge of cognitive agents/system is required for the learning/performance of the task. If $\beta=0$, then the cognitive system has missing knowledge and new/novel knowledge of cognitive agents/system is needed for the learning/performance of the task.

The co-operative cognitive system is obtained by placing in series the available knowledge profiles that are mutually complementary with respect to the available knowledge for a given task. Each knowledge profile of the cognitive agent is used for the performance of the task and knowledge profile takes its turn in the chain of tasks. That is, co-operative learning/performance of the cognitive system involves the learning of the particular task(s) by each agent in the cognitive system. Since when one agent reports the result of its performance to the other agent(s), this agent may not learn the other tasks in the chain of tasks. Thus, each co-operative agent may be responsible only for the particular task due to the particular combination of available knowledge/skills. In fact, while the last agent in the chain of co-operative learners has a fixed goal, agents in a chain of co-operative learning/performance may not have a well-defined goal.

11. Applications

The proposed conceptual and/or formal approach can be used for the modelling/formation of any cognitive systems where (knowledge/skill) capabilities/compatibilities factors are critical variables. Most interesting applications of the proposed scenario can be defined in Internet Systems, Interface Agents, Neurosystems/Brain modelling, i.e. where system analysis and knowledge integration are the key steps in the formation and modelling of cognitive systems.

12. Summary

In this paper we introduced a knowledge/skill-capability approach to the formation of co-operative cognitive systems. The concepts of knowledge integration, knowledge capability and compatibility factors are the key features of the proposed approach to co-operative learning/performance. We state that initial analysis of knowledge/skill capabilities and compatibilities of co-operative agents/systems ensures continuous performance of the series of tasks and successful co-operative learning. This is due mainly to the fact that incapable and incompatible agents cannot learn or perform their tasks which will lead to the failure.

This approach provides for the consideration and analysis of the impact of knowledge factors and their properties, on the formation/performance of the co-operative cognitive systems. That is, we consider the engineering of the cognitive systems via engineering of cognitive structure and knowledge integration. In fact, by knowledge integration for co-operative learning we can generate new/novel cognitive systems that can be used as a tool for (cognitive) solutions of (new) problems/tasks.

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