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EXPLORATION OF NATURAL IMMUNE SYSTEM FOR MULTI-AGENT COALITION FORMATION

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ABSTRACT

Coalition formation is used for cooperation of intelligent agents in the multi-agent systems. Coalition is composed of homogeneous or heterogeneous agents able to effectively solve complex problems requiring decomposition of the task into the subtasks. Various approaches can be used for multi-agent coalition formation, e.g. game theory, dynamic programming, graph theory or genetic algorithms. Natural immune system is complex system containing compartments where processes similar to the coalition formation appear. The paper identifies actual problems in multi-agent coalition formation and investigates properties and mechanisms of natural immune system as the source of inspiration for solving some of these problems. The paper establishes next steps in the research of multi-agent coalition formation with the aid of metaphors based on the behaviour of the natural immune system and principles of artificial immune systems.

Keywords: coalition formation, multi-agent system, natural immune system, immune algorithm.

INTRODUCTION

Coalition formation (CF) is one of the most studied research subareas of multi-agent systems (MAS). It is widely used form of cooperation between autonomous agents of MAS. The coalition is a goal-oriented and short-lived group of agents that solves predefined specific problem. Cooperation with agents from different coalitions is not supposed, but can be realized if an output of one coalition depends on an output of another coalition (Horling and lesser, 2005). Coalition can be composed of cooperative (pro-social) agents which try to maximize the benefit of the group. The own benefit is not so important for them in contrast to self-interested agents which are competitive and interested in maximizing own benefit. Reasons of forming coalitions can be various. One agent need not be able to complete a task because of its abilities, knowledge or damage. One agent can be able to complete a task, but others agents are able to do it better. Agents can receive higher benefit if they join and solve a problem together. We can speak about coalition formation of robotic agents or software agents. Robotic agents should be able to organize themselves in efficient manner, e. g. in case of extensive ecological disasters, humanitarian or rescue operations. Searching semantically relevant information or knowledge sources by software web agents is different example. Web agents dispose of different knowledge bases thus cover wider search space with web documents.

Investigated problems of multi-agent coalition formation are related to (Sandholm, *et al*., 1999), (Rahwan, 2007):

- distributed coalition value calculation,
- finding optimal coalition structure,
- maintenance of a coalition in stable state,
- efficient dynamic organization of agents.

The coalition value measures the usefulness of a coalition and thus decides on the forming of multi-agent coalition. Coalition value calculation is time-consuming for each coalition composed of many agents. Distributive solution can be more effective.

The coalition structure is a group of different coalition combinations which can solve specific problem. The question is how to find the coalition structure containing agents able to use their sources optimally. Number of coalition structures increases exponentially with the number of agents. The goal is to find efficient algorithms which are able to search the space of solutions with minimal spending on time and computational sources. Dynamic programming, genetic algorithms or greedy algorithms are used for this purpose (Rahwan, *et al*., 2009).

Coalition stability is connected with the administration of rewards for agents. The reward is the motivational mean for ensuring stability of coalition. Game-theoretic concepts are used for solution of this problem most often (Klusch and Gerber, 2002).

Agents should be able to operate autonomously in dynamic and unpredictable environment. The question is how to ensure coalition restructuring in real time and what type of cooperative architecture is suitable for it.

The paper is mainly focused on the second and third problem, i.e. on finding optimal coalition structure and maintenance of a coalition in stable state. Properties and mechanisms of natural immune system (NIS) of human are investigated for these two problems in the paper. Survey of the past and actual research in multi-agent coalition formation showed that the immune processes and properties do not play common role in multi-agent coalition formation. It is necessary to investigate various aspects of behaviour of natural immune system with the goal to find useful metaphors for solving

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above mentioned problems in multi-agent coalition formation.

The paper is structured as follows. Chapter 2 introduces basic properties and processes of natural immune system of human. Chapter 3 explains possible connections between multi-agent coalition formation and behaviour of the natural immune system. Concrete examples of immune processes are mentioned where formation of groups of different immune cells (coalitions) appears. These processes can became metaphors for development of the new immunity-based algorithms used for multi-agent coalition formation. Chapter 4 presents key algorithms of artificial immune systems and their applications. Chapter 5 introduces problems solved with the usage of immunity-based algorithms, but these one are only similar to multi-agent coalition formation. Chapter 6 mentiones actual and future research in multi-agent coalition formation. Chapter 7 concludes the paper.

NATURAL IMMUNE SYSTEM

Natural immune system (NIS) is a complex system essential for survival every living organism. It is able to recognize dangerous objects able to damage the organism. Antigens (Ag) are objects that can invoke the immune response. Ag can be a part of the organism and risky for it (self-Ag) or come from the outer environment, e. g. viruses, bacteria or fungi (non-self-Ag). Healthy NIS maintains homeostasis of the organism and efficiently reacts to the danger. NIS is often perceived as the layered system with innate and adaptive immunity (Abbas, Lichtman and Pillai, 2011). Innate immunity is the first line of defense. It guards the organism with the aid of mechanic barriers (skin, rheum, saliva, tears) and different types of immune cells. Adaptive immunity is targeted to already identified objects. B-lymphocytes (B-ly) and T-lymphocytes (T-ly) are main representatives of this layer. B-lymphocytes are producers of antibodies (Ab) and can play a role of memory cells. T-ly eliminate dangerous Ag or regulate functions of others immune cells (Murphy, 2014).

MULTI-AGENT COALITION FORMATION IN THE VIEW OF NATURAL IMMUNE SYSTEM

We can find similarities between formation of immune cells into groups and group behavior that is often necessary in solving complex problems of artificial intelligent agents. The following paragraph firstly mentions necessary properties of artificial intelligent agents for coalition formation and the next paragraph characterizes NIS as the inspiration for dynamic and distributive coalition formation.

Essential properties of agents for coalition formation

Coalition formation should provide reliable, fast and efficient completion of certain task. The most important features can be divided into the following sections:

- Distributiveness: If the agent fails to filling the task, the task should be completed. Coalition formation should not be directed by one central agent of MAS.
- Dynamics and adaptation: Coalition of agents should behave flexibly in case of changing environment.
- Robustness: Agents should monitor their states and state of the coalition. If something is wrong, agent should signalize it to others agents.
- Stability: Agents should be motivated to stay in the coalition during the mission fulfillment.
- Learning and memory: Agent should be able to learn and use learned in the future. Agent´s memory helps to adequately react to stimuli.
- Self-organization: Only relevant agents should fulfill the task. It is necessary to optimally distribute agents according to their roles for realizing tasks.
- Communication: The communication can be direct (e. g. protocols) or indirect (stigmergy). It helps in receiving information from the environment, e. g. agents or others coalitions.

Properties of the immunity as the inspiration for multi-agent dynamic and distributed coalition formation

Above mentioned properties of agents are in healthy NIS, too. The following attributes can be the inspiration for dynamic and distributed coalition formation:

- Distributiveness: NIS is distributed system. This attribute occurs e. g. in case of production of lymphocytes by bone marrow in different places of the organism. It implies that positive and negative selection is distributed process. B-ly are activated on different places, too. It implies that clonal selection has also distributed nature. Immune network forming the immune memory is not centralized, too.
- Learning and memory: Immune cells are able to learn with the aid of feedbacks received from the environment and to remember already once identified Ag. These properties ensure faster reaction of immune cells in the future. Memory is formed with the aid of immune network, gene libraries or memory cells.
- Self-organization: It is the natural process of NIS used for homeostasis maintenance. Self-organization occurs e. g. in gene library evolution (Kim and Bentley, 2002). Fragments of DNA molecules are gradually diversified. These fragments are used for lymphocytes generation. Clonal selection is a self-organization process, too. It produces off-springs of the B-ly that recognized Ag. Others are eliminated. Immune network is self-organization system. It contains B-ly that are stimulated on the basis of recognizing objects of the environment. Suppressed B-ly are not a part of the immune network.
- Communication: Immune cells communicate directly or indirectly with the environment. Direct

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communication is executed mainly with the aid of adhesive molecules. Indirect communication can be realized e. g. by communication molecules cytokines (products of activites of immune cells) (Stites and Terr, 1994).

Dynamics, adaptation, robustness and stability are expressed in cooperation of different immune cells and organs. These processes lead in the emergent property of NIS.

Mechanisms of the immunity as the inspiration for multi-agent dynamic and distributed coalition formation

Some mechanisms of NIS are very similar to the coalition formation. Some of them can be the inspiration for dynamic and distributed coalition formation.

The osmotic lysis (OL) is the final process of activation of a complement system (CS). The CS is a group of proteins which circulate in non-active form in a blood stream. On the base of specific stimuli they became active and influence different immune processes. One of them is the formation of specific proteins into the shape which is able to sieve the membrane of the Ag (OL). Invasion of the structure of the antigenic membrane causes the catharsis of this membrane. The death of the Ag is the result of the OL (Delves, 2008). There is a similarity with the coalition formation in MAS. One protein (artificial intelligent agent) of CS is not able to disturb membrane enough for elimination of the Ag. More competent proteins (C5b, C6, C7, C8, C9) are able to do it, see Figure-1 (amended according to the (Väkevä, 1995)).

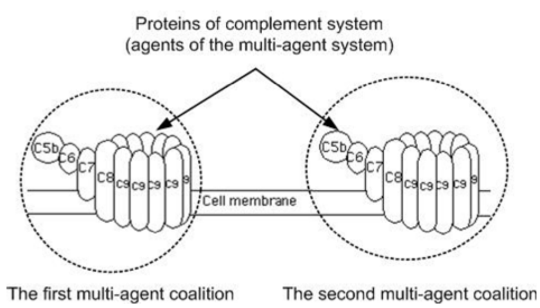

Figure-1. Osmotic lysis as a process of coalition formation.

Phagocytosis is focused on the elimination of dangerous Ag with the aid of immune cells - phagocytes (Abbas, Lichtman and Pillai, 2011). This process is divided into several steps. In the view of coalition formation, the similar process is phagocytic microbicide. Lysosomes migrate in the direction to the phagosome after the ingestion of Ag by phagocyte (e. g. macrophage). The phagosome contains the antigenic material that is dissected and eliminated by digestive enzymes of lysosomes. Lysosomes can be apprehended as artificial intelligent agents waiting for the danger objects. Development of the phagosome is the signal for lysosomes to create the coalition which eliminates the danger object. More lysosomes are able to eliminate danger object faster and efficiently than only one of them, see Figure-2.

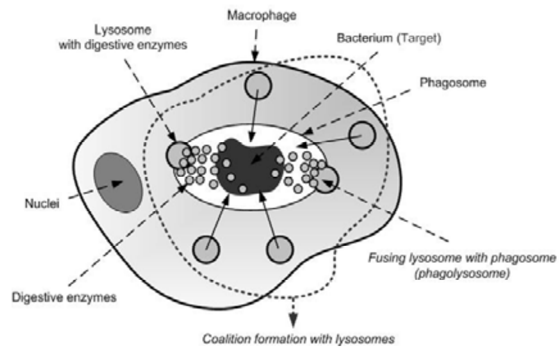

Figure-2. Phagocytic microbicide as a process of coalition formation.

Cytokines are significant regulators of NIS. They are produced by immune cells influencing their development or activation (interleukins), provoke their chemotaxis in the direct of the side of the infection (chemokines) or have the antiviral effect (interferons) (Stites and Terr, 1994). In the multi-agent coalition formation point of view, cytokines can be apprehended as information signals invoking forming of the coalition of agents. Role of interferons in the immune response on the presence of viruses is explained in the Figure-3. Infected cell produces interferons as a reaction to the viral attack. Interferons stimulate uninfected cells that set the antiviral protection. Antiviral proteins of uninfected cells block the replication of viruses in the cells (Figure-3A). The second effect of interferons is connected more with the coalition formation. Interferons are able to coordinate e. g. NK cells. They activate them and provoke them for eliminating of infected cells (Figure-3B). NK cells will be concentrated in the sides of virus presence.

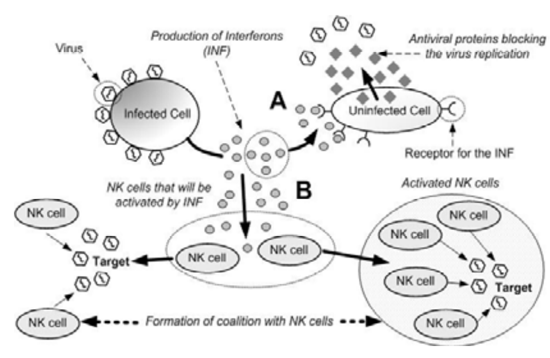

Figure-3. Coalition formation with the aid of interferons.

Other example is demonstrated in Figure-4. Chemokines are peptide-based information molecules able

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to invoke migration of leukocytes in the direction of a side of infection (Murphy, 2014). Damaged tissue signals the presence of a danger by releasing of chemokines. Immune cells with chemokine receptors are able to react to this signal and move across from the vessels and eliminate the danger. More immune cells are more effective in danger elimination that only one of them.

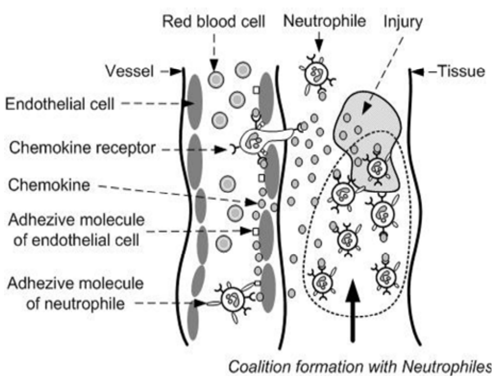

Figure-4. Chemokine as the impulse for coalition formation.

ARTIFICIAL IMMUNE SYSTEMS AND ALGORITHMS

Artificial immune systems (AIS) are inspired by properties and mechanisms of NIS. Research in AIS is focused on (Castro and Timmis, 2002), (Hart and Timmis, 2005), (Castro, 2006):

- discovering others properties of human NIS that can be useful in solving particular problems,
- discovering mechanisms of immune systems different from human NIS (e. g. NIS of plants),
- investigation of new domains in which algorithms of AIS can also be used,
- specification or extending frameworks for AIS development,
- improvement of current AIS.

There are four groups of artificial immune system algorithms (AISA), see Figure-5. The first one stems from the diversity generation of immune cells with the aid of gene libraries (Castro and Timmis, 2002). These libraries contain gene fragments that are combined for creation different immune cells. There are artificial gene libraries (AGL) in AIS. These AGL are used for generation of potential solutions that are changed with the mutation process towards the approximation to the optimal solution. The second one is the group of selection algorithms - algorithm of positive selection (APS), algorithm of negative selection (ANS), algorithm of clonal selection (ACS) and their modifications (Castro and Timmis, 2002), (Castro, 2006) and (Dasgupta and Nino, 2008). The APS is inspired by immune process called the positive selection (PS) which eliminates own immune cells with functionless immune receptors. The ANS is inspired by the negative selection (NS) preventing the organism from spreading autoimmune cells. The ANS is used more often in comparison to the APS. It is applied mainly for classification and recognition problems. Computer security or fault detection is typical application of ANS. ACS is inspired by the principle of clonal selection (CS) explaining the process of antibody generation. If a B-ly recognizes the Ag, clones of the same specificity as the B-ly are created (clonal expansion). Mutation occurs during the cloning. It can improve the affinity (tightness of bond) between Ag and B-ly in the future reunion (affinity maturation). The immune memory evolves in this way. ACS is used especially for optimization or classification problems (Castro and Zuben, 2000), (Brownlee, 2007).

The third group of AISA is inspired by the immune network theory by N. K. Jerne (Jerne, 1974). This theory apprehends the NIS as a network of interconnected stimulated B-lymphocytes interacting with each other. AIS use two groups of artificial immune networks (AIN) (Castro and Timmis, 2002), (Castro and Timmis, 2003), (Castro, 2006), (Dasgupta and Nino, 2008): continuous AIN (CAIN) and discrete AIN (DAIN). CAIN are used mainly for modeling and simulation of NIS with the aid of differential or difference equations. In most cases, DAIN are based on differential equations or iterative procedures (Castro and Timmis, 2002). They are used mainly for pattern recognition, data analysis, machine learning or optimization problems.

The last group of AISA is inspired by functions of dendritic cells influencing differentiation of lymphocytes and can play a role of antigen-presenting cells or phagocytes. The dendritic cell algorithm (DCA) has already been used for anomalies detection in a computer network as a classifier for scanning computer ports (Greensmith, Whitbrook and Aickelin, 2010).

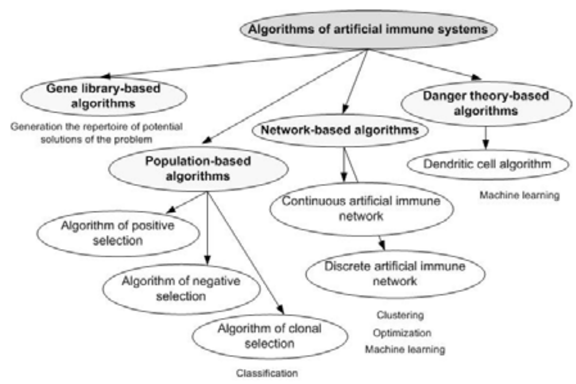

Figure-5. Algorithms of artificial immune systems

ARTIFICIAL IMMUNE SYSTEMS FOR MULTI-AGENT COALITION FORMATION

NIS is characterized by attributes which are necessary for ensuring decentralized and dynamic coalition formation of agents in MAS. In present, multi-agent coalition formation is insufficiently solved by NIS metaphors and algorithms of AIS. On the other hand, we can find some few similar domains or projects of AIS research area that are closed to the coalition formation.

Similar problems solved with artificial immune systems

The project Symbrion (Symbiotic Evolutionary Robot Organisms) is focused on the development of autonomous intelligent system (swarm intelligent robots) able to self-configure, self-protect, self-optimize and self-repare (Kernbach, 2008). Architecture of autonomous robotic agent is inspired by the lymphatic system. Each swarm robotic agent represents a lymph node that is able to autonomously and collectively receive the source of energy with others robotic agents. If the robotic agent is not able to surpass the barrier alone, other suitable robotic agents join with it. One bigger robotic agent is built up and able to bridge the barrier.

Job Shop Scheduling Problem (JSSP) is another example. This NP-hard problem tries to find optimal schedule for each machine (source) that fulfills some task (job). The goal is to find a schedule containing jobs that are finished in minimum time. This problem can be solved with the AIS approach (Coello, Rivera and Cortés, 2003). The artificial gene library approach and the algorithm based on the clonal selection principle (CLONALG) are used for this problem.

The problem of finding mines in the environment is solved with the aid of artificial immune network (Yeom and Park, 2006). This network is composed of B-ly (altruistic and deliberative self-(robotic) agents) that are able to communicate and cooperate each other. Self-(robotic) agents inform (stimulate) other self-(robotic) agents about the position and count of mines.

CURRENT RESEARCH AND FUTURE DIRECTIONS

Some of the existend clonal selection-based immune-algorithms have been investigated for multi-agent coalition formation. They are used for efficient elimination of oil spills (Husáková, 2011), (Husáková, 2012), (Husáková, 2013). Clonalg-opt and BCA algoritm is applied for this purpose. The Opt-IA algorithm is mainly used for optimization problems (Castro and Zuben, 1999), (Castro and Zuben, 2000). It is the next immunity-based algorithm which is going to be tested for the multi-agent coalition formation. Opt-aiNet and Dopt-aiNet (Dasgupta and Nino, 2008) are algorithms of discrete immune networks. They stem from the data clustering algorithm aiNet (Castro and Zuben, 2001) and are partly inspired by the idiotypic immune network theory by N. K. Jerne (Jerne, 1974). They are also used mainly for optimization purposes and they are going to be used for optimal coalition structure calculation.

The most interesting part of the future research is focused on finding interesting processes occurring in the natural immune system of human for their usage in the multi-agent coalition formation. Some of the most promising processes are identified in the paper. These processes are going to became the inspiration for development of novel immune-algorithms used for solving problems in multi-agent coalition formation.

CONCLUSIONS

The paper deals with the coalition formation of artificial intelligent agents of MAS in the context of the NIS. The paper finds similarities between formation of coalitions of artificial intelligent agents and particular properties and mechanisms of NIS. These processes can be the inspiration for solving coalition formation problems, especially dynamic and distributed formation of coalitions. The novel immune algorithms are going to be developed on the basis of these metaphors and already existed immunity-based algorithms are going to be used for the multi-agent coalition formation in the elimination of oil spills. The paper mentions algorithms which are going to be tested with regards to the finding of optimal coalition structure.

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