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# Cooperative intelligent agents for speeding up the Replication of Complement-Based Self-Replicated, Self-Assembled Systems (CBSRSAS)

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## Abstract

Self-replication of CBSRSAS may occur as a result of completing the complementary parts of the system or self-assembly of the whole system. Self-replication process is a time-consuming process that depends on the dynamics of the system components and environmental factors that describe how system components are distributed across the media and how viscous is the media when the viscosity of the media means how the media supports or burdens the movements of system components. Therefore, we will suggest different models for Multi-agent systems that can speed up the replication process of CBSRSAS systems; we will describe how agents can help in the replication process either at the initiation of replication or through the replication process by bringing system components to their system complementary parts. We will measure how far the degree of cooperation between agents and their intelligence level affect the process of replication.

## 1. Introduction

CBSRSAS, The complement-based self-replicated and self-assembled system, was introduced as a general model for self-assembled and self-replicated systems inspired from bio-molecular system by (Ellabaan (A), 2007). It differs from cellular automata model that used by Jan Van Neumann to represent his model for self-replication systems (Neumann, 1966). CBSRSAS systems bases on system components that have the capabilities of interaction with each other and dynamical behavior that brings them to interact, while cellular automata model bases on specific number of cells, each cell state can be changed to one state of the states pool defined in advance. CBSRSAS systems are more related to biological systems while cellular automata related in general to chemical and physical systems and in specific to particle systems (Neumann, 1956). CBSRSAS systems give the ability to produce in a very simple manner robust self-assembled and self-replicated systems.

CBSRSAS systems replication may be difficult in some circumstances. This difficulty emerges from the barriers within the environment surrounding CBSRSAS systems. These difficulties can be summarized in how system components are capable to move freely in the environments. In some environments, the viscosity is too high, which burdens the movement of the CBSRSAS system components making their accessibility to CBSRSAS complementary divided parts difficult, and consequently making CBSRSAS self-replication more difficult. So, the need for external agents that have greater dealing with the environment is beneficial.

Aiming at making self-replication process more natural, robust and efficient, it is suggested to utilize the concept of agents. In bimolecular system such as DNA and RNA, their replication processes occur as a process of interaction between DNA systems with some agents or enzymes that initiate the process of replication and bring system components or nucleotides to the appropriate interaction sections. Hence, utilizing agents is a natural case. Moreover, utilizing agents that varies of their capabilities can lead to the specialization which leads to a quick production of the replication process as the agents will be experts in their areas of specialization. Moreover, specialization requires agents to know less and do more work. The process of replication would be more powerful if it is done in a cooperative manner between intelligent agents. Solving the problem by utilizing multi-agents system has many advantages than any other approaches. An agent can represent computer program, human, and robots, so it is a general approach as CBSRSAS systems is. CBSRSAS can be applied for biological systems, nano-scale machines, games and robotics. Moreover, there are a lot of research has been dedicated to Multi-agents system that leads to making the concepts of multi-agents system more obvious and much easier to be understood, and we can utilize this work to build advanced models of multi-agent system that can be utilized in the replication process of CBSRSAS.

In this chapter, we introduce three models for multi-agent systems that can be used to support replication process of CBSRSAS systems. In the first model, we utilize homogeneous stigmergy multi-agent system that can utilize the concept of stigmergy (i.e. to put sign) (Theraulaz, 1999) to communicate between agents. Having homogeneous Multi-agent system requires its agent to have a quite big database of rules to deal with environments. Finding appropriate rules may take times leading to slowing the replication process down little bit. In addition, having such a lot of rules may sometimes lead to choose a wrong one which, consequently, may lead to inappropriate replication or mutation of the replica. Moreover, to learn a lot of rules may also require a lot of time, so at the initial stage of agents life the replication process is noticeably slow.

In the second model, we suggested another multi-agent system, the heterogeneous stigmergy-based multi-agent system, which also utilizes the stigma as an approach for communication among agents in the multi-agent system. This approach has proven its success especially when agents are specialized and distributed in a comparable manner with the distribution of system components in CBSRSAS. Balanced workload among agents is supported by this approach. Moreover, this model has approved that simple rules with clear objectives and a simple cooperation scheme can achieve superiority over very complicated systems with a huge database of rules as the case in the previous model.

In heterogeneous Multi-agent system, we introduced a simple model of diversity between agents with a limited level of cooperation powered by stigma. So in the third model, we introduced another model with a higher level of diversity and communication called *Robosoccer Team-based Multi-agents system*. This model was inspired from soccer robots player (Nebel, 2001) where robots have to work in teams, have to be able to localize both itself and the

ball, and planning their path and motion in a cooperative manner. Based on these lessons, we introduce the third model, but this model has a different feature. This feature refers to that the teams are not working against each other, and they also work in cooperative manner to arrange the path planning between agents belonging to different teams.
This chapter consists of four sections, the first one gives an overview about CBSRSAS systems in terms of their basic concepts and their potential applications. The second section provides a detailed introduction about multi-agent systems in terms of what is the agent? What are the main types of agent-based systems and multi-agent systems? In addition, it involves a detailed explanation of two famous models of multi-agent systems: stigmergy-based or Ant colony inspired multi-agent system and Soccer-inspired multi-agent system. In the third section, we provide three models of the multi-agents that can be used to speed up the replication process of CBSRSAS. Two of these models utilize stigmergy-based model, but they differ according the difference between agents. They can be also classified into: homogeneous stigmergy-based multi-agent system where agents have same structure and capabilities, and heterogeneous stigmergy-based multi-agent system where agents vary in their capabilities and structures. The final model is *the Robosoccer team-based multi-agent system* where agents vary in their capabilities and structures but they work in a cooperative manner and compete with other teams. In the fifth section, we give a detailed discussion and future work of the application of multi-agent systems in CBSRSAS.

## 2. Complement Based Self-Replicated, Self-assembled System (CBSRSAS): An overview

CBSRSAS, the complement-based self-replicated and self-assembled system, bases on the generalization of the concepts of assembly and replication of bio-molecular systems such as DNA and RNA. CBSRSAS systems base on two rule sets: the assembling rule set and the complementary based replication rule set. These rule sets control the interaction between self-assembling sections of the CBSRSAS and self-replication sections of CBSRSAS. The CBSRSAS consists of a group of items called system components. Each system component consists of two types of sections controlling its interactions with other system components such as self-assembling section types and complement-interaction section types. Thus, system components can interact with each other once they are close enough. For autonomous interaction, system components should be given a behavioral model that controls how these components move or behave. This model is represented by a dynamical or kinematical model that will be explained later in this section. These concepts are the main concepts required for building systems of the CBSRSAS type. So how can CBSRSAS self-replicate into more other systems? For the replication phase of the CBSRSAS systems, as biologically inspired CBSRSAS systems, to replicate, the replication process should be initiated. This case is modeled in CBSRSAS systems as the replication initiation rule set which determines in which condition the CBSRSAS system will start to self-replicate. The replication process itself can be done by two ways: the first refers to the autonomous version of self-replication where system components dynamical behavior and interactions through complementary-interaction sections build the new CBSRSAS sibling systems guided by the complementary parts of the parent CBSRSAS; the second approach bases on supporting of agents spread over the nearby environment; this approach called the agent-based replication machinery which will be explained in details throughout the chapter. CBSRSAS may be considered as a blue print for systems that can exhibit the living organisms' features of self-assembly and self-replication. In this section, we will give an overview of the basic concepts of CBSRSAS systems and their potential application

## 2.1 Basic Concepts of CBSRSAS

In this section, we will explain the main components and rules suggested for generating complement-based self-replicated and self-assembled systems. We will explain what the basic system components and what the characteristics of these main components are, and how these characteristics may lead to autonomous replication and assembling of the systems (Ellabaan (A), 2007).

Firstly, defining *System component* is one of the most important steps in defining CBSRSAS systems. It is considered as the basic building blocks of the CBSRSAS. Defining system components should be driven from the application area. In CBSRSAS systems, system components are composed of two types of sections: self-assembly section type, and complement interaction section.

The first section type or self-assembly section type defines the section that its interactions are controlled by self-assembly rule set that will be described later in this section. A system component may have more than one interaction section. In bio-molecular systems such as DNA or RNA, system components or nucleotides in case of DNA or RNA have two self-assembly sections (See Figure 1)

The second section type, the complement interaction section type, defines sections at which interaction between complementary system components occurs. This part plays an important role in self-replication process and in generating replicates. A system component may have more than one complement interaction section. The more the complement interaction sections a system component has, the more replicas can be generated by CBSRSAS system through the self-replication process.

Secondly, all types of system components are represented by *system component set*. If CBSRSAS systems composed of N system component X, then X should be included in *system Component set*

$$Y \text{ is CBSRSAS system and } Y = \begin{pmatrix} x_1 & x_2 & .. & x_i & .. & x_n \end{pmatrix} \text{ where } x_i \text{ is a system component}$$
$$and\ x_i \in \rho \text{ and } \rho \text{ is system component set}$$

CBSRSAS system is considered as spatial order of basic system components chosen from the system components set. CBSRSAS length may be larger than system component set.

Thirdly, each item in $\rho$ (*the system component set*) may have one or more complements. Each pair of items (item and its complement) is called a *complement-based replication rule*. *Complement-based replication rule set*, which is donated by ξ, includes all system complement-based replication rules. There are three types of complement-based replication rule set:

1. Complement-based replication rule set for many to many relationships between system components. This kind of system has a very high mutation level during self-replication process due to the many complementary relationships that a system component has. So it is recommended for high variability or evolvable systems.

$$\xi = \{(A, A), (A, B), (A, C), (B, D), (C, C), (D, F)\}$$

2. Complement-based replication rule set bases on one-to-one relationships between system components. Each system component has one and only one relationship with

either itself or with another system component. The mutation level is expected to be very small if existed.

$$\xi = \{(A, B), (C, C), (D, F)\}$$

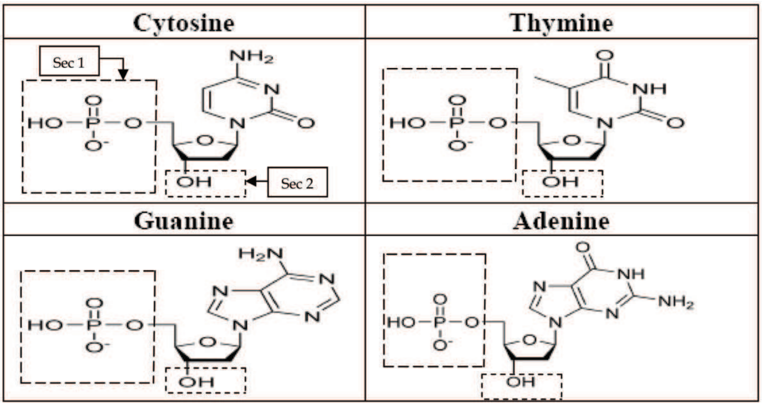


Figure 1. Show that DNA has two self-assembly parts surrounding by dashed rectangles

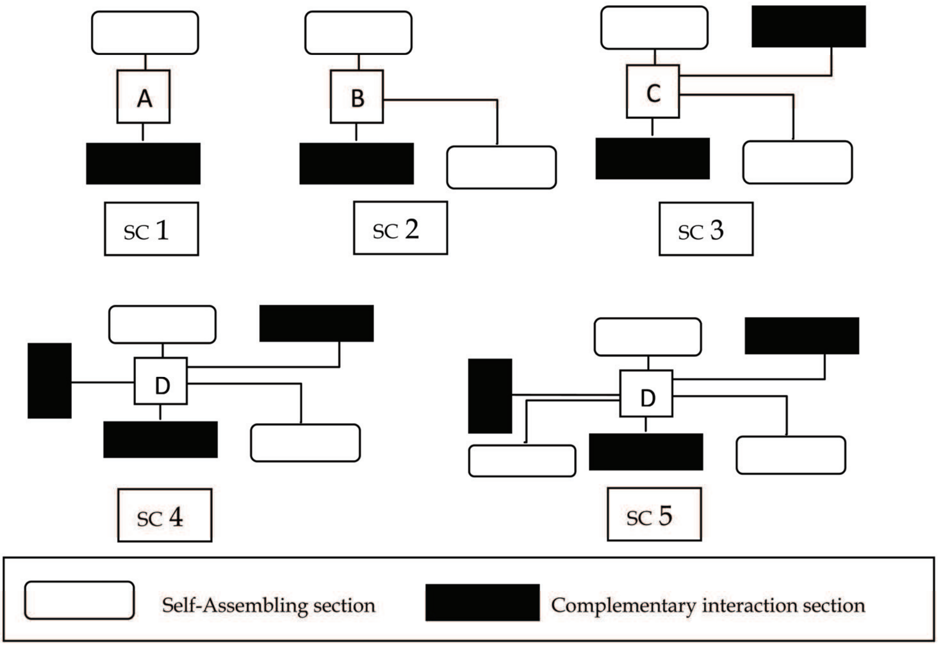


Figure 2. Shows different examples of system components where SC1 is a system component composed of a complement interaction and a self-assembly interaction section, SC2 is composed of two self-assembly sections and one complement interaction section, and SC5 is composed of three self-assembly interaction sections and three complement interaction sections (Ellabaan (A), 2007)

3. Incomplete complement-based replication rule set refers to the complement-based replication rule set that has one or more system components that do not involved in a complementary relationship with either itself or other system components. So the mutation at this point will be very high either at self-replication process or at normal life of CBSRSAS systems.

$$\xi = \{(A, B), (D, F)\}$$

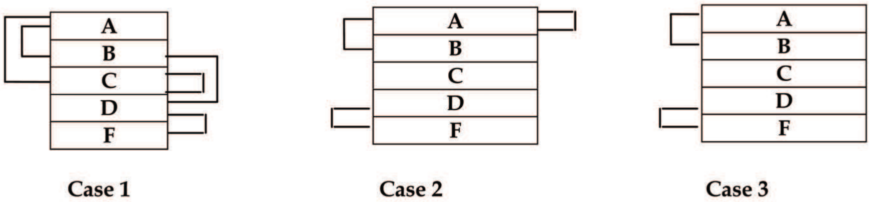


Figure 3. (Case 1) Replication rule set with a many to many relationship; (Case 2) Replication rule set with a one to one relationship; (Case 3) refers to incomplete replication rule set where one or more items have no complementary replication rule with itself or with its

Fourthly, *the assembling rule set* determines how system components interact with each other in case of collision between self-assembling sections of system components. This idea is driven from Wang tile or Wang dominoes proposed by (Wang, 1961). His main purpose was to use a given finite set of geometrical tiles to determine whether they could be arranged using each tile as many times as necessary to cover the entire plan without gap (Ellabaan and Brailsford, 2006). In the assembling rule set, the interactions between colors (distinctive options for self-assembly section) are stored in a symmetric matrix called the interaction matrix (Ellabaan (B), 2007). To illustrate, assume we have two system components. Each one has one self-assembling section with color A for the first system component and color B for the second one. If the interaction between color A and B in the case of collision satisfies a specific rule, they either stay together if they satisfy the stability condition defined in the rule or continue moving according their previous states.

Fifthly, *kinematics model* represents the basic behavior of the basic system component. Each system component should have capabilities to move freely and autonomously. This movement should not burden the capabilities of objects to interact with each other from the side of either self-assembly or self replication section. The kinematics model is not only dedicated to the kinematics model of the system components, but it may also include a kinematics model of the complement interaction sections and self-assembly interaction sections.

Sixthly, *replication-initiation rule sets* are the main signals that may be required to initiate the replication process. By these signals, the complementary relations of the system are broken leading to break the system into its complementary parts. The number of complementary parts depends on the number of the complement interaction sections in the system components. If the system component has N complement interaction sections, then the process of breaking system component will lead to N complementary parts. Each complementary part can generate the system again. Although the advantages of having more than one complement interaction sections, generating many replicates requires a difficult procedure for setting replication-initiation rule sets.

Seventhly, *replication Machinery* refers to the approach utilized for *CBSRSAS'* replication. To illustrate, let us drive an example. To replicate *CBSRSAS* systems, it is required to break the system into its complementary parts and bring the system components for each of these parts. There are two machinery types for handling this type of replication. The first type of machinery depends totally on system components and its kinematics model which is called the *autonomous replication machinery*. The second machinery depends on the interaction between the system and other systems or *agents*. This machinery is called the *agent-based replication machinery*. The agent-based replication machinery is the most famous in biological or natural systems, and will be extensively studied in this chapter.

In this section, we have described the seven basic principles that outline the CBSRSAS systems by which it is easy to generate robust self-replicated and self-assembling machines. In the following subsection we will discuss some of the potential application areas for CBSRSAS systems.

### 2.2 Applications

CBSRSAS systems has a good potential as a general framework for self-replicated and self-assembled system inspired from the most robust self-assembled and self-replicated bio-molecular systems. This generality and robustness inherited from the most robust biological system makes CBSRSAS system a good model to be applied for wide areas of research that have recently attracted a lot of scientists' interests such as artificial life, robotics, multi-agents systems and systems biology.

Firstly, building artificial system that can behave like biological system is one of the main objectives of artificial life. CBSRSAS system can generate itself (i.e. to self-replicate) and can aggregate from simple subsystems or system components (i.e. self-assemble), so artificial life can be seen as one of the application area of the CBSRSAS systems. Secondly, applying CBSRSAS to robotics may be an interesting future investigation. CBSRSAS can help building self-assembled and self-replicated robots. If robots are built with CBSRSAS characteristics, defining self-assembly interaction sections and complement interaction sections and defining self-assembling rule set as well as self replication rule set, It may generate a powerful robots with interesting behavior and capabilities of generating themselves either through self assembly or self-replication. Thirdly, Investigating the possibility of generating CBSRSAS at atomic or molecular details in Chemistry may lead to discovering other systems with higher assembling and replication rate than the existed ones such as DNA and RNA and, consequently, creating a new type of living systems (Ellabaan (A), 2007).

## 3. Multi-Agent system: an Introduction

Multi-agent systems refer to the systems composed of multiple interacting intelligent agents, which can be utilized to solve the problem with high complexity that makes it too difficult to be solved by a single agent system or monolithic systems. The main characteristics that distinguish the multi-agent systems form the other kinds of systems can be summarized in the following three properties: The first is the *autonomy* which refers to the agent should be at least partially autonomous. The second is *local view* which means that agent can only recognize the local area where it lies. In other words, it cannot have a global view of the system and environments as the system may be too complex to be understood even if the global view is available to the agent. The third feature is the *decentralization* which means that there is no agent having a full control over the system (Wooldridge, 2002). By these features, the multi-agent systems are not only able to provide distributed parallelism, but they also gives the flexibility to add new agents to the system as the complexity of the problem, which the multi-agent system tries to solve, increases. There are many examples for problems solved utilizing the concept of multi-agent system such as online trading (Rogers, 2007), disaster response (Schurr, 2005), and modeling social structure(Sun, 2004).

Multi-agent systems have been applied to lots of applications in real word. For example, they have been used in computer games, film production and in analyzing massive scientific data. Relative to military wise, scientists are trying to build multi-agent system for coordinated defense system (Gagne, 1993) (Beautement, 2005). They have been also applied to transportation, logistic and graphics. Moreover, they have been utilized in network and mobile technology to achieve automatic and dynamic load balance, high scalability, and self-healing networks. Nowadays, scientists try to utilize Multi-agent system as a frame work for studying complex systems as explained in (Boccara, 2004).

In this section, we will explain the basic concepts of multi-gent systems. What is the agent? And what are the basic components of the agents? These questions will be explained in agent definition subsection. In addition, the different categorization of the agent-based systems will be explained as well as the Multi-agent classification. By the end of this section, we will explain in details some important multi-gent system models widely used as multi-agent system models for solving problems.

### 3.1 Agent Definition

The main concept that should be clarified in the multi-agent system is the concept of the agent. An agent is an entity with the power to act (Flores-Mendez, 1999). The agent may be represented as an animated character in animation or computer graphics, a robot, or a software component. In this chapter, we consider agents nature as same as the nature of CBSRSAS systems. In other words, if CBSRSAS systems are modeled or represented as animated systems on computer graphics then the agents will be represented as animated characters. If CBSRSAS systems are modeled in a robotic-wise, then the agents will be also modeled in a robotic-wise.

Agent designing is an important process in designing multi-agent systems. The gent designer should consider four important aspects of agents. The first aspect relates to where the agent will be; the second aspect how the agent will sense or perceive the surrounding environment; in response to either internal or external stimulus, how the agent will behave in response to these stimulus, and finally, how the agent will move in its surrounding environment (see figure 4). All these questions are considered in the following four models that the designer should consider in agent design process as proposed by (Millar et al, 1999):

1. ***Environmental model***: refers to the environment where the agent lies. This model determines the basic characteristics of the environment such as viscosity and obstacles.
2. ***Perception model*** refers to how an agent perceives its environment. There are many approaches that can enable an agent perceiving its environments: the first approach is the zonal approach by which the agent is equipped with ability to sense specific regions or perception regions. The agent will be able to perceive any object if it lies in these regions. The smaller the zonal region, the weaker collision avoidance and path planning capabilities will be. The larger the zonal region, the more computationally expensive it will be. The second approach refers to *the sensory approach* which involves placing

synthetic sensors on the character such as sensors for smelling, hearing, and seeing. Agent designer should be careful about the orientation and location of each sensor to enable alertness and high quality perception. *Synthetic vision approach* is the third method that can be used by an agent as a perception model. This approach can utilize the advancement in human vision to give the agent a vision of its surrounding world. This approach is only useful for vision; no other stimuli will be detected.

3. ***Behavioral model*** refers to how the agent responds to internal or external stimulus perceived by perception model. There are many approaches for handling behavioral aspect of the agent. For example, the rule-based approach can be utilized to handle the behavioral aspect of the agent by giving the agent a set of rules defining his behavioral aspects relative to different situations. In addition, designers also can utilize network approaches, cognitive approaches, and mathematical approaches for deal with behavioral aspect of the agents. Cognitive or AI approaches are preferred because it can utilize the advanced models for intelligent behavior suggest in AI.
4. ***Motor model*** handles the movement of the agents only, while path planning is handled by the behavioral model or components. This model is responsible only for achieving a movements request from its behavioral components and execute the request by using specific motor movement approach.

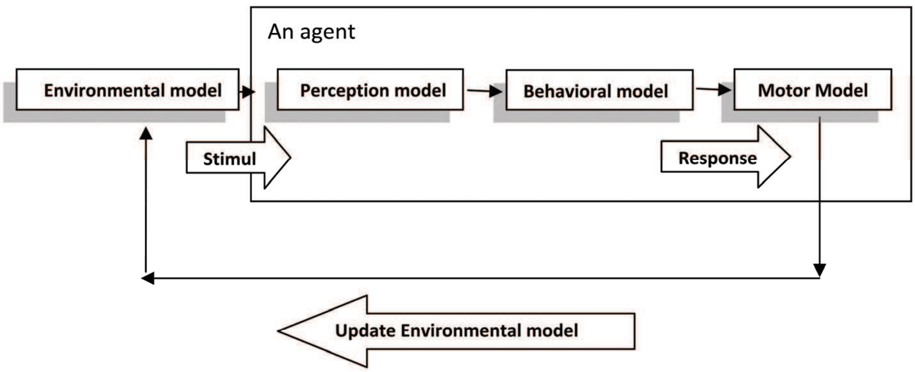


Figure 4. Shows the interaction between the agent and the surrounding environment

### 3.2 Types of Agent-based systems:

Here, we will explain two important types: Centralized agent system and General multi-agent system.

- Centralized agent System – Single Agent system

Single agent systems refer to agent systems that have a single agent making all the decision, while the others act as remote slaves. Single agent system might have multiple entities for example several actuators or even several robots provided that each entity sends its perceptions to and receives its action from a single and central process. In other word, all agents work as a single agent (Stone & Veloso, 2000).

- Distributed or General Multi-agent systems

Unlike the centralized agent system, Distributed or general multi-agent system is composed of multiple autonomous, interacting and intelligent agents. Each agent in such model concerns about its own interest, does its work in autonomous manner, and shares its sensory information if the sharing will not be against its own interest. Moreover, the global view is not available. Decision making process is done in distributed manner. In other words, each agent takes decision by itself and according to the profit that will be gained which can be described by the local view of the system. To conclude, these features of the agents determine the essential three properties -(autonomy, local view, and decentralization)- of multi-agent system.

### 3.3 Multi-agent system Classification

There are many approaches for classifying multi-agent systems. Multi-agent systems can be classified, for example, according to the management prospective into centralized and decentralized multi-agent systems, and according to the similarity of the agents into homogenous multi-agent system and heterogeneous multi-agent system. In this section, we will explain in details of the similarity-based multi-agent classification. This classification divides multi-agent system into two groups according to the similarity between agents in the multi-agent system. The first type is the homogeneous multi-agent systems in which agent are very similar in, for example, their capabilities and domain knowledge. The second type refers to the heterogeneous multi-agent system in which agents varies in their capabilities, goals and/or domain knowledge.

#### 3.3.1 Multi-agent system classification based on the similarity among agents:

We will study here how we can classify multi-agent system based on the similarities and/ or differences between the agents involved in the multi-agent system.

##### 3.3.1.1 Homogenous Multi-agent systems

A Homogenous Multi-agent system refers to the Multi-agent system with several agents having identical structure (domain knowledge, decision functions, and sensors and effectors). These agents situated differently in the environments as they have different sensor inputs and effectors outputs. They make their own decision regarding which action to take. Multi-agent system requires different effectors output, otherwise it will not be considered as multi-agent systems. Consequently, homogeneous multi-agent system must have different sensor input, otherwise they will act identically leading to violating the necessity conditions of multi-agent systems previously mentioned. This scenario of systems assumes that the agents cannot communicate directly (see figure 5).

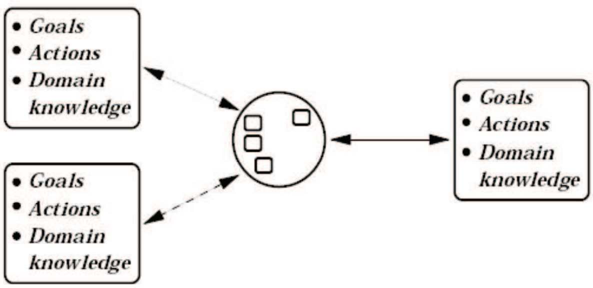


Figure 5. MAS with homogeneous agents. Only the sensor input and effectors output of agents differ, as represented by the different arrow styles. The agents' goals, actions, and/or domain knowledge are all identical as indicated by the identical fonts (Stone & Veloso, 2000)

### 3.3.2 Heterogeneous Multi-agent Systems

Heterogeneous multi-agent systems refer to multi-agent systems with significantly different agents having different domain knowledge, goals and/ or actions which refer to heterogeneity conditions. In this scenario, agents are situated in the environment differently, causing them to have different sensory inputs and necessitating different actions. This kind of scenario provides system designers a great deal of power over system. There are two different scenarios for these types of system: *Heterogeneous non-communicating multi-agent systems* and *Heterogeneous communicating multi-agent systems*.

*Heterogeneous non-communicating multi-agent systems* refer to multi-agent systems having different agents that do not sharing their knowledge, goals and their sensory inputs. They just interact together indirectly See figure 6.

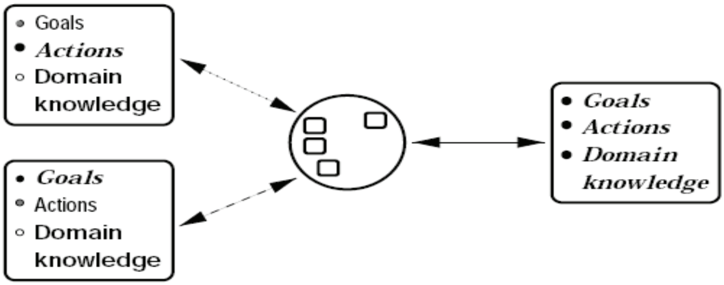


Figure 6. The general heterogeneous MAS scenario. Now agents' goals, actions, and/or domain knowledge may differ as indicated by the different fonts. The assumption of no direct interaction remains (Stone and Veloso, 2000)

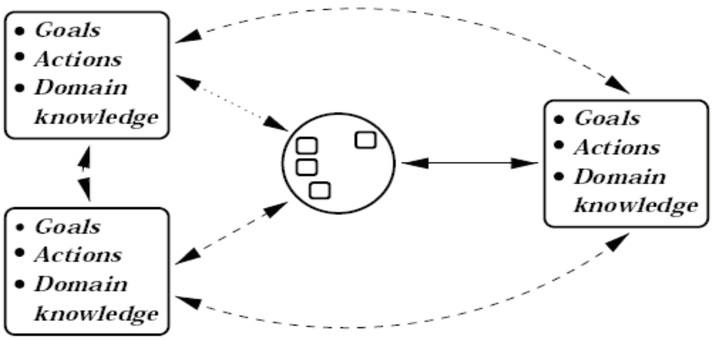


Figure 7. The general communicating MAS scenario. Agents can be heterogeneous to any degree. Information can be transmitted directly among agents as indicated by the arrows between agents. Communication can either be broadcast or transmitted point-to-point (Stone and Veloso, 2000)

In heterogeneous communicating multi-agent systems (see figure 7), agents have capabilities to communicate with each others. Having agents with different sensory data, goal, actions and domain knowledge and empowered with communication capabilities can provide a very complex and powerful multi-agent systems. Adding the concept of communication can turn multi-agent systems into single-agent system or centralized agents systems if there is an agent capable to send its sensory inputs and commands to other agents who in turn just achieve the commands. Therefore, the heterogeneous multi-agent system scenario can span the full range of the complexity in agent systems.

### 3.4 Important Multi-agent System Models:

Here, we will explain two famous examples of multi-agent system models that are widely used as models for different multi-agent systems such as (Valckenaers, et al, 2001), (Nebel, 2001), and (Theraulaz, 1999). These models either inspired from biological system as the stigmergy-based multi-agent systems or inspired from the soccer game as the robosoccer multi-agent system model (Theraulaz, 1999). Literature has a lot of work that have been done to investigate the possibility enabling robots to play games like human beings (Nebel, 2001), and (Gutmann, 2000). Soccer game is a very famous game, representing the complex cooperative behavior of team players. It is a good area to investigate the cooperative team-work where agents cooperatively work together to achieve their teams' goal as it will be explained in robosoccer multi-agent systems model.

#### 3.4.1 Stigmergy-based Multi-agents systems

This model is inspired from ant-colony where ants put signs or stigmas (i.e. pheromone) to influence other ants' behavior. Like ants in ant-colony, agents in stigmergy multi-agent system model utilizes stigma or signs to communicate or affect the performance of each others. With stigmergy, agents observed sign in their environments and act upon them without the need to synchronize with other agents. Stigmergy can be classified as indirect interactions between agents (Valckenaers, et al, 2001). This model enables agents to utilize locally available signs to learn about the global properties of the system. In this model, agents work in the same manner as the ant foraging for food or search for food where food foraging ants execute a simple procedure in which their behavior is guided by permanently changing environment. Ants forage for food works as explained in Figure 8. As ants start their work by random search, the agents will start searching for their targets or CBSRSAS systems, put signs at the CBSRSAS system components. When other agents find it, they start searching for the complementary system components to the one at which they find the stigma. In section four, we will explain in details different stigmergy-based multi-agent system models and how each one of these models work.

**Ant Foraging for food**

1. *In absence of any signs in the environment (consisting of by scents from chemical substance called a pheromone), ants perform a randomized search for food.*
2. *When an ant discovers a food source, it drops a chemical smelling substance – i.e. pheromone – on its way back to the nest while carrying some of the food. Thus it creates a pheromone trail between nest and food source.*
3. *When an ant sense sings in form of a pheromone trail it will b e urged by its instinct to follow this trail to the food source.*

Figure 8. Pseudo code for Ants Food foraging (Valckenaers, et al, 2001)

The main advantages of stigmergy-based multi-agent system model can be summarized as follow: firstly, utilizing a simple model of communication reduces the complexity in agent

design; secondly, this model considers the environment as a part of the solution; thirdly, global information is locally made available. On its way through the system this information is transformed in appropriate manners, to enable the agents to make local decisions based on locally available information while being aimed at global goals.
But this model also suffers from many drawbacks. For example, stigmergy-based multi-agent system model utilizes a simple communication approach which based on stigmas which fails to support high level of cooperation between agents. Thus, it is difficult to find team-working in such model. In addition, Task achievement in this model is randomly done due to the absence of cooperative planning. Conflict is unavoidable in such models, and its possibility is higher due to the limited communication, and consequently limited cooperation. To sum up, the simplicity of communication inherited from stigmergy method is behind the limited or absence of cooperation, and, consequently, behind high level of conflict expected from stigmergy-based multi-agent system.

### 3.4.2 Robosoccer Multi-agent system model

Unlike the stigmergy-based multi-agent system model, Robosoccer multi-agent system model have a higher level of cooperation between agents belonging to the same team as this model is built based on the existence of high level of communication between agents. This system works in similar way as robot players. As the agents start their work searching for the ball, once finding it, they pass it to each other, until achieving their goal. There are many lessons to be learned from robosoccer team such as cooperative sensing and cooperative path and motion planning. We will discuss three main lessons of the robosoccer team in the following subsections.

#### 3.4.2.1 Cooperative-Sensing:

Cooperative-sensing refers to observations sharing process among a group of agents. The main advantage of this approach is the compensation of sensor limitation that may restrict the region in which an object can be sensed. Moreover, it is providing agent with combined estimates that the agent can utilize to narrow down their hypotheses to correct their estimates. In Soccer Robot wise, it can be beneficial in two aspects. Firstly, in *cooperative self-localization*, an agent is able to utilize the sharing of observations with other agents to determine its current position. Secondly, in *cooperative object localization*, agents utilize sharing of observation to localize the object or ball in case of soccer robot. Cooperative sensing has proven its powerful as more accurate and reliable tool for localization (Nebel, 2001).

#### 3.4.2.2 Cooperative Path and motion planning:

Basic motion planning problem (Latombe, 1991) is the problem of moving single object in an Euclidian space which called work space from an initial position (and orientation) to a target position. Robots are responsible for planning their own trajectory from the initial state to the goal state avoiding obstacles in non-cooperative motion planning. In cooperative path and motion planning, a group of robots is sharing their views to plan the motion trajectories for them. Cooperative sensing leads to more accurate and reliable tools for localization (Nebel, 2001). Therefore, the initial and goal are reliably and accurately determined. This approach facilities the process of path and motion planning. Although cooperative sensing is computationally reasonable, the computation cost of cooperative path planning is much more difficult and expensive.

There are two types of cooperative path and motion planning:

- Cooperative path planning with global communication:

This schema of cooperative path planning assumes that all agents can communicate with each other. There are two approaches utilizing this schema. The first one in which the multi-robot path planning problem can be solved centrally which so-called *centralized approach*. This approach does not guarantee optimality and completeness. Moreover it is not efficient enough for even only a moderate number of robots (Nebel, 2001).

In *decoupling approach*, the second one, (Latombe, 1991) one robot or agent plans independent path trajectories for all robots and then combine them, resolving conflicts when they happen. It is a good method in reducing complexity, but it does not also assure completeness and optimality. In literature, there are two methods basis in decoupling approach. The first one is path coordination methods in which robots planning their paths independently and afterword coordinate their movements without leaving their plans. Coordination methods usually utilize a collision-free schedule and coordination diagram to solve the problem of path planning. The second one is the prioritized planning approach. In this approach, multi-robot path planning problem solved as a sequence of path planning problems (Erdmann & Lozano-Perez, 1987). This approach may lead to *deadlock* (Nebel, 2001).

- Cooperative path planning with only local communication:

In cooperative path planning with local communication, agents or robots planning their path independently, and utilize local coordination to solve conflicts (Nebel, 2001).

#### 3.4.2.3 Role Assignment in dynamic environment

How to assign roles for a member of groups is one of the main issues to be considered in teamwork-based multi-agent system design. The problem of role assignment in dynamic environment can be solved by associating a set of behavioral pattern with agents in order to support coordination between the agents (Nebel, 2001).There are two methods suggested to handle this problem. The first one is CS Freibrug team done in 1998 (Gutmann et al, 2000). This approach based on using fixed assignments. The second approach is CMUnited's SPAR method (stone et al, 1999) which is more advanced than the previous one. This approach is able to handle the problem of role assignments in dynamic environments to account for the current positioning and to support team reconfiguration after break down or removal of individual team members, and having flexibly positioning that takes into account the entire situation on the field (Nebel, 2001).

## 4. Multi-agent Systems for speeding up the Replication of Complement-Based Self-Replicated, Self-Assembled Systems (CBSRSAS)

In this section, we will explain three multi-agent systems. Two of these systems are inspired form biological system or ants' colony. In these systems, agents act as ants search for food, once finding it, they leave pheromones or stigmas as signs for other ants to be able to discover food as soon as they become near to it. Relative to the other multi-agent system, it was inspired from the robosoccer teams where agents work as they search for the ball and pass it to each other until achieving the goal. This system bases on high level of cooperation among the agents. To achieve this high cooperation level, Agents utilize a higher level of communication than level of communication of the previously mentioned stigmergy-based multi-agent systems. The details will be explained in the following subsections.

### 4.1 Stigmergy-based Multi-agent system for speeding up the replication process of CBSRSAS systems:

Stigmergy refers to the process by which agents put signs or stigmas as in Greek to influence each other's behavior. Stigmergy which was introduced in (Grasse, 1959) is a good approach for small-grained interactions compared to coordination methods that require an explicit rendezvous among agents. When agents observe signs in their environments, they act upon them without need to synchronize with other agents. The stigmergy-based multi-agent systems are the multi-agent systems that utilize the concept of stigmergy or putting signs or stigma as a communication approach between agents. This system works in the same manner as the ants foraging for food as explained in figure 8 (Valchenaers et al, 2001).

Here, we suggested two models based on stigmergy: the first one is the *heterogeneous stigmergy-based multi-agent system*. In this model, agents specialized in specific task. Some of the agents are specialized in discovering and putting signs at CBSRSAS's system components, called discoverer agents and others which are specialized in searching and carrying system components to their complementary system components in CBSRSAS systems, called carrier agents. For carrier agents, we classified them into two kinds of carriers: specialized carriers referring to the agents that able to discovery and carry only specific type of system components (see figure 9) and general carrier referring to the agents with abilities to discover and carry any system components. The same classification also works for the discoverers agents. The second model is *homologous stigmergy-based multi-agent* in which all agents are of the same type and with same capabilities. These models will be explained in details in following subsections.

#### 4.1.1The heterogeneous stigmergy-based multi-agent system

This system consists of at least two types of agents. Each type is specialized in a specific task. These types are categorized into: discoverer agents, and carrier agents. Discoverer agents are responsible for discovering the existence of CBSRSAS system and put sign, stigma, at the system components. There are two options for implementing discoverer agents. The first option is to generate a general discoverer agent that can discover any system components belongs to the CBSRSAS systems, and generate different kinds of stigma that differ according to system components. The second option is to generate a specialized discoverer agent that can deal with a specific type of system components. A discoverer agents start its mission by random search for CBSRSAS as Ants search for its food, once recognizing the nearest system component, it assign a specific sign (stigma) to the system component. After that it continues another search for another specific system component in case of specialized discoverer agent or the next system component in the case of the general discoverers.

Relative to carrier agents, it should be able to have the capabilities for recognizing free system components in the media, to be able to carry them, and to be able to recognize stigma of the carried system components. Carrier agents start random search for a specific free system components if it is *a specialized carrier agent* or any free system component if it is *a general carrier agent*, once carried it, the carrier agent starts searching for the nearest stigma to target its movement toward the stigma and searching for the shortest path.

The intelligent behavior of the suggest system depends on rule-based modeling of intelligent behavior. Agents having many rules makes decision little bit slower; as the agents require traversing their database of rules to determine the appropriate decision to take. Moreover, having a lot of rules may lead to contradictions which may lead to the failure of the replication process, so specialized agents make their decision faster and more reliable than general or multi-tasking agents. Therefore, it is recommended to utilize specialized agents with larger systems. Sometimes, it is recommended to utilize some of the generalized agents to assure the load balance among agents especially if the specialized agents are not equally distributed compared to the distribution of CBSRSAS's system components types.

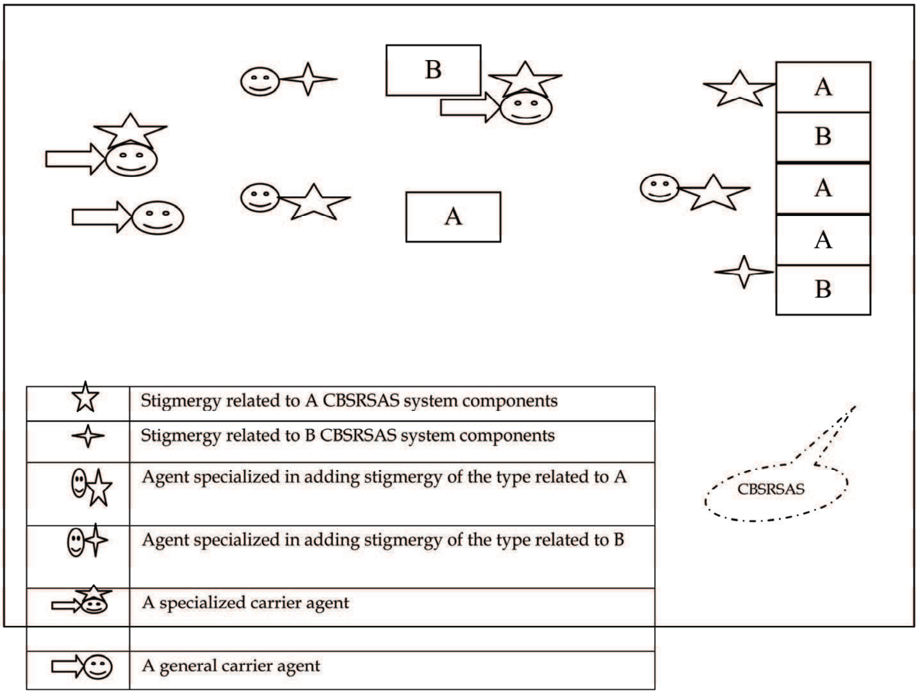


Figure 9. show a simple representation of heterogeneous Multi-agent System and how it can support the replication process of CBSRSAS systems

The behaviour of the heterogeneous multi-agent system can be represented:

$$F_{Total} = \sum_{i}^{M}\sum_{k}^{n} x_{i,j}^{\rightarrow CBSRSAS} + x_{i,j}^{\rightarrow SC} \quad (1)$$

M refers to the number of agents. N refers to the number of system components in the CBSRSAS system that their complementary parts have been carried by carrier agent $i$. $x_{i,j}^{\rightarrow CBSRSAS}$ refers to the effort that the carrier agent $i$ exerts to bring system components to their complementary ones in CBSRSAS. $x_{i,j}^{\rightarrow SC}$ refers to effort that the carrier agent $i$ exerts to find the appropriate system components. The main goal is to minimize this function considering balanced work load among the agents. This function can also represent the total required time to achieve replication process of CBSRSAS systems.

$x_{i,j}^{\rightarrow SC} = (\xi_{i,j}^{\rightarrow SC} + d_{i,j}^{\rightarrow SC})$ $\xi$ is utilized to describe time required by the carrier agent to recognize required system component SC. $x_{i,j}^{\rightarrow CBSRSAS} = (\rho_{i,j}^{\rightarrow CBSRSAS} + d_{i,j}^{\rightarrow CBSRSAS})$ $\rho$ is utilized to describe time required by the agent to recognize the stigma associated with the system component j.

$$F_{Total} = \sum_{i}^{M}\sum_{k}^{n}(\rho_{i,j}{}^{\rightarrow CBSRSAS} + d_{i,j}{}^{\rightarrow CBSRSAS}) + (\xi_{i,j}{}^{\rightarrow SC} + d_{i,j}{}^{\rightarrow SC}) \quad (2)$$

This new model (Equation[2]) consider how the level of agent intelligence affect the agent-based replication process of CBSRSAS system represented in recognition factor that vary from agent to another and from interaction to another.

For heterogeneous systems, $\xi$ , the intelligent factor, for specialized carrier agent is slightly lower than $\xi$ for general carrier agents, as specialized agent has small size of rules, it can arrive a decision quicker than the general one. Moreover the experience the agents in a specific field can improve his recognition level. Consequently, it is recommended to design this kind of multi-agent system with specialized carrier agents and to make the distribution among these agents comparable to the distribution of different system components in CBSRSAS systems.

Added to the recognition factor, there is another factors which is $\rho_{i,j}{}^{\rightarrow CBSRSAS}$ that measures the recognition level of carrier agent *i* to the stigma at j$^{th}$ system component in CBSRSAS systems. Consequently, $\rho_{i,j}{}^{\rightarrow CBSRSAS}$ value depends on the recognition of the agent which associates to his level of intelligence and the ability of discoverer agents to put signs or stigma. To illustrate, if the carrier agent *i* was successful detecting the system component *k* and discoverer agent was not able at that time to recognize the complement system, this action will result in delaying the delivery of system component *k* to its complementary system component in CBSRSAS system. Consequently, the general behavior of the system will be affected by the behaviour of less intelligent agents.

Task sharing for the heterogeneous stigmergy-based multi-agent system is at least assured even if there are only general carriers and general discovers. Task sharing here is achieved autonomously without pre-intention. As one of the general agent will be required to assign stigma, while the other will be required to search for free system components to bring.

Relative to conflict, as inherited form the stigmergy approach, agents can not directly communicate with each other. This prevents agents with same goal - for example two agents targeting the same stigma- from discovering that they are targeting the same goal. Therefore, the possibility of conflict is high in such model.

**Relative Speed Up of Replication process**

Relative speed up of the replication process can be measured as the ratio between a single agent system and a multi-agent system of M agents. This model includes the intelligent factor as factor the speeding up the replication process equation [3].

$$\text{Relative Speed up} = \frac{M\left(\sum_{j}^{L}(\rho_{1,j}{}^{\rightarrow CBSRSAS} + d_{1,j}{}^{\rightarrow CBSRSAS}) + (\xi_{1,j}{}^{\rightarrow SC} + d_{1,j}{}^{\rightarrow SC})\right)}{\left(\sum_{i}^{M}\sum_{j}^{N}(\rho_{i,j}{}^{\rightarrow CBSRSAS} + d_{i,j}{}^{\rightarrow CBSRSAS}) + (\xi_{i,j}{}^{\rightarrow SC} + d_{i,j}{}^{\rightarrow SC})\right)} \quad (3)$$

### 4.1.2 The homogenous stigmergy-based multi-agent system

In this system, all agents have similar capabilities (perception model, behavioral model and motor model). An agent can discover CBSRSAS systems, assign stigma to system components and carry system components to their complementary parts in CBSRSAS system. Designers of the homogenous stigmergy-based multi-agent system should consider a complex behavioral model as the agent should be trained for different functions.

In the homogenous stigmergy-based multi-agent system model, an agent starts working by doing a random search for either CBSRSAS systems or system components. In case of finding CBSRSAS systems, the agent puts a sign or stigma at the nearest system component of the CBSRSAS system, afterword agents start searching for the complementary system component of the discovered CBSRSAS system components. If the agent finds a system component earlier than CBSRSAS systems, the agent carries it and determines the position of the nearest stigma and start path and motion planning toward it.

Conflicts may occur in this model with a higher probability than the previous one because of the lack of specialization and the limitation of communication inherited from the stigmergy-based communication model. For instance, path and motion planning is done by each individual. There is no sharing of path planning details which may lead to conflict between agents when they collide together. Moreover agents also conflict when they are targeting the same stigma. Targeting the same stigma is frequent case in this model. To resolve this type of conflicts, the agents have to re-planning their path to the target for the first type conflict, and to retarget another stigma for the second type of conflict.

Task sharing is difficult to be arranged in this model as limited specialization and communication, so the conflict and unbalanced work load is expect with high probability in the homogeneous stigmergy-based multi-agent systems.

The behavior of this the homogenous multi-agent system can be represent as in Equation (4):

$F_{Total}$ = cost of assigning stigma to CBSRSAS + cost of bringing system components to their complementary parts at CBSRSAS systems

$$F_{Total} = \sum_{i}^{M} x_{i,j} + \sum_{i}^{M+K} \Upsilon_{i,j} \tag{4}$$

M refers to the number of system components belonging to CBSRSAS systems, K refers to the number trails that agents tried to bring system components to the stigma and find that it is already achieved by another agent. $x_{i,j}$ represents the effort that the agent *j* has done to assign stigma at the $i^{th}$ system component of system components in CBSRSAS systems. $\Upsilon_{i,j}$ refers to the effort that the $j^{th}$ agent does to bring the system component to its complementary system component in CBSRSAS systems. $\sum_{i}^{M+K} \Upsilon_{i,j}$ can be divided into $\sum_{i}^{M+K} \Upsilon_{i,j} + \sum_{i}^{K} \Upsilon_{i,j}$ . $\sum_{i}^{K} \Upsilon_{i,j}$ represents the effort wasted as result of conflict between agents. To illustrate, two agents bring two system components to the same complementary system component in CBSRSAS systems. The complementary part might accept only one. So the effort done by one of the agents is wasted. The main goal of this behavioral model is to minimize the energy or efforts.

**Relative Speed Up of this model:**

Assume we have a system of only one agent, then the time required to brings all system components to their complementary components in CBSRSAS system can be expressed

$$F_{Total}(t) = \sum_{i}^{M} x_i(t) + \sum_{i}^{M} \Upsilon_i(t) \tag{5}$$

Where $x_i(t)$ refers to the time required by the agent to put stigma at the $i^{th}$ system components in CBSRSAS systems. $\Upsilon_i(t)$ is the time that the agent requires to bring the complementary system components to the $i^{th}$ system components in CBSRSAS systems. $F_{Total}(t)$ refers to the total time required to achieve the replication process by single agent.

$$F_{Total,N}(t) = \frac{\sum_{i}^{M} x_{i,j}(t) + \sum_{i}^{M} \Upsilon_{i,j}(t)}{N} \quad \text{where } 1 \le \text{j} \le N \tag{6}$$

This model refers that the total time required by N agents to achieve replication of CBSRSAS systems. This model assumes that there is no any conflict between multi-agents systems, so the maximum speed up for the replication process that can be achieved by the homogenous multi-agent system can be computed as:

$$SpeedUp(N) = \frac{N\left(\sum_{i}^{M} x_i(t) + \sum_{i}^{M} \Upsilon_i(t)\right)}{\left(\sum_{i}^{M} x_{i,j}(t) + \sum_{i}^{M} \Upsilon_{i,j}(t)\right)} \tag{6}$$

But this representation of speed up does not include the intelligent behavior, so the following model considers the time required by decision making processes which differ from an agent to another, from a system component to another and from function to another. Many factors are involved, but we summarized the measure of intelligent behavior into factor $\xi_{i,j}(t)$ which describe the time required by the $j^{th}$ agent to take a decision about the $i^{th}$ system component and make the appropriate stigma that fit with the $i^{th}$ system component and factor $\gamma_{i,j}(t)$ which describes the time required to take decision about whether the agent found the system component or not which system components to carry the following equation explain the speed up.

$$SpeedUp(N) = \frac{N\left(\sum_{i}^{M}\left(x_i(t) + \xi_{i,1}(t)\right) + \sum_{i}^{M}\left(\Upsilon_i(t) + \gamma_{i,1}(t)\right)\right)}{\left(\sum_{i}^{M}\left(x_{i,j}(t) + +\xi_{i,j}(t)\right) + \sum_{i}^{M}\left(\Upsilon_{i,j}(t) + \gamma_{i,j}(t)\right)\right)} \tag{7}$$

### 4.2 A Robosoccer Team-Based Multi-agent System for speeding up the replication process of CBSRSAS systems:

In this system, agents have different capabilities (perception model, behavioral model and motor model), but they have the same capabilities to communicate. A group of agents agrees to work together forming a team work. Working as a team provides agents with cooperative sensing which means the limited sensing capabilities of an agent can be overcome by support from other agents (Nebel, 2001) this gives the group capabilities to localize the objects which, in our case, are system components in CBSRSAS systems and their complementary system components. Moreover, cooperative sensing provides agents with capabilities to localize themselves by either indentifying their position using (Rekleitis et al, 1997) schema which depends on well known immobile agents or identify their relative position using multiple-hypothesis approach (Fox et al, 2000). The first approach for localization is best for avoiding odometry error and the second is good for dealing with well know environments (Rekleitis et al, 1997).

In this model, agents start their work by building teams or coalitions. They negotiate together till forming the teams (Dignum et al, 1999). Once formed, each agent in the team start searching for a goal to the team. The goal can be determined by either finding free system components in the environments or finding the CBSRSAS systems. For the first case, the goal is to find CBSRSAS systems that can utilize these system components in the replication process. For the second case, the goal is to find system components that help in CBSRSAS system replication. Once, the goal is determined, the team agents start cooperatively planning their motion and path using local communication between team agents to avoid conflict among team agents and global communication among teams to avoid conflict between teams' agents. Moreover, agents communicate together to help each other in dynamic environments. Once an agent find system component, the agent broadcast its findings to other team agents that, in turn, plan faster achievement of the task by defining sequence of passing system components to each other till providing system components to their complementary system components in CBSRSAS systems.

The advantages of this model of multi-agent systems are enormous. Firstly, this model follows the main theme of nature which is the *diversity* (Loreau et al, 2006), as the model provides different agents with different capabilities. Secondly, since agents vary according their capabilities, *delegation of responsibilities* of this model is an important issue handled by this model as it is team-based multi-agent system (Norman and Reed, 2000). To illustrate, if an agent x in team y has higher capabilities to deal very well with current situation, and an agent z carries a system component, the agent z will broadcast its findings and environmental conditions, and the best free agent will handle it. Thirdly, *cooperation between agents* in this model of multi-agent system is much better than the previously mentioned stigmergy-based multi-agent systems. Fifthly, *load balance among agents* is assured. For example, if agent x did a lot of work and feel tired, it will not respond to the broadcast from the agents holding system components. Sixthly, *passing of objects* is the main powerful characteristic inherited from soccer playing model, as the agent will pass the system components to another agents, afterwards it will be free to participate in another job, saving extra time. Seventhly, this model provides different way for optimizing the behavior of all system. For example, number of teams and average number of agents a team can be used to optimize behavior. Moreover, policies utilized through agent-to-agent and team-to-team interactions can be optimized. Consequently, there are many parameters used to improve the total behavior of entire multi-agent system. To conclude, soccer inspired team-based multi-agent system is a powerful multi-agent system with enormous advantages.

**Total cost & relative speed up**

To measure the total effort or cost exerted by this type of multi-agent system, we propose the following function. The main goal we seek is to minimize this objective function as much as we can. This function consists of three terms. The first, $\gamma_{i,j}(t)$, refers to the effort $i^{\text{th}}$ team exerts to find out the system component *j*. The second, $\psi_{i,j}(t)$, expresses the effort team *i* exerts to find the CBSRSAS's system component that its complementary is the one that the team has. $\Im_{i,j}(t)$, the third, is utilized to express the total effort done by the team agents to bring the system component *j* to its complementary at CBSRSAS systems.

$$F_{Total} = \sum_{i}^{Tms} \sum_{j}^{I_{Sc}} \left( \gamma_{i,j}(t) + \psi_{i,j}(t) + \Im_{i,j}(t) \right) \tag{9}$$

$Tms$ refers to the number of teams participate in replication process of the CBSRSAS systems, and $I_{Sc}$ refers to the number of system components that the i[th] team brings to their complementary system components in CBSRSAS system.
Relative to speed up, to compute the relative speed up that N teams of agents can achieve, we propose the following equation [10]. The relative speed up of a multi-agent system is the ratio between the period of time required by a team of one agent to get all the system components to their complementary system components in CBSRSAS systems to the period of time required by the n teams to achieve the same objective.

$$SpeedUp(N) \leq \frac{N\left( \sum_{j}^{M} \left( \gamma_{1,j}(t) + \psi_{1,j}(t) + \Im_{1,j}(t) \right) \right)}{\left( \sum_{i}^{N} \sum_{j}^{I_{Sc}} \left( \gamma_{i,j}(t) + \psi_{i,j}(t) + \Im_{i,j}(t) \right) \right)} \tag{10}$$

## 5. Discussion and future work

Replication is not only an important process of CBSRSAS, but It is also important process for all living creatures by which they maintain their existence. Industrially, it has a lot of advantages, but the main advantage of this process is the massive production of the product. The Autonomous replication of CBSRSAS system is a time consuming process as it depends not only on the kinematic capabilities of the system components, but also on the viscosity environments.
So, in this chapter, we have proposed three multi-agent system models to be used in speeding up this process. These models vary in their way of organizations, communication, and cooperation. In the first and second models: the heterogeneous stigmergy-based multi-agent systems, and the homogeneous stigmergy-based multi-agent systems, we have utilized the concept of stigmergy or putting signs which is inspired from ant-colony as an approach for communication between agents. By stigmergy, on one hand, we succeeded to make the global goal which is to bring free system components to their complementary in CBSRSAS systems locally available to the agents.
But, on the other hand, we expect that the conflict between agents in stigmergy-based approaches is high because of the limited cooperation and communication capabilities of agents. These limitations prevent agents from collective behavior where many agents are involved. To illustrate, carrier agents may collide or conflict together, which may lead to system components carried by these agents either to self-assemble into bigger complex which may be difficult to be carried by one of them or to be lost leading them to restart searching for free system components. Moreover, conflict may happen when two agents target the system stigma, leading to lose efforts that have done by one of them and subsequently to *ineffectiveness* in achieving tasks.
The third model, the robosoccer team-based multi-agent system, utilizes high level of communication and cooperation between agents. Agents belonging to one team have many

advantages. For example, they utilize the cooperative sensing where the limitation of the agent sensing capabilities has been overcommed. In addition, they can arrange their work in a cooperative manner through utilizing the cooperative path and motion planning and dynamic role assignments to deal with different conditions and circumstances. To explain, agents with higher capabilities to deal with complicated environment where a lot of burdens exist arrange themselves to help other agents through such kind of environments.

Relative to the task sharing among agents, the stigmergy-based multi-agent system does not assure sharing of tasks among agents in general. The heterogeneous type is better than homogenous one from the tasking sharing wise, but this task sharing is evolved not as matter of cooperation but as the result of heterogeneity among agents that lead subsequently specialization among agents. This specialization assures that the agents do only a specific piece of the task. In the robosoccer team-based multi-agent systems, the task sharing among agents is a dynamic process and varies according the environmental conditions. Thus, task sharing is an added advantage of the robosoccer multi-agent systems.

In this chapter, we theoretically derive some mathematical models that represent how these models can relatively speed up the replication process of the CBSRSAS systems. These mathematical models take in consideration how the cooperation among agents and their intelligence level affect the replication process of CBSRSAS systems. The models can be considered by multi-agent systems designers to balance between the cost of the multi-agent system and the objectives.

$$\text{Absolute speed up} = \frac{F_{total}^{\text{Autonomous Replication CBSRSAS}}}{F_{total}^{\text{Multi-agent -based replication of CBSRSAS}}} \tag{11}$$

To measure the absolute speed up of the multi-agent system, we have to compare the replication of CBSRSAS utilizing the multi-agent system against the autonomous replication of CBSRSAS system (see Equation [11].). The absolute measure of the speed up is not only a good evidence of how the multi-agent system is supportive to the replication of CBSRSAS systems compared to the autonomous replication of CBSRSAS systems, but it is also a good measure of which multi-agent system performs better relative to common criteria or the execution time required by the autonomous replication of CBSRSAS systems. Unlike the absolute speed up, the relative speed up measures how the number of agents affects the speed up of the replication process. Thus, the relative speed up is a good approach for determining the best number of agents to be utilized, while the absolute speed up is a good approach for determining which multi-agent system model is better for the current situation or circumstances for replication of CBSRSAS.

Relative to future investigation, we are looking for integrating these multi-agent system models with multi-agent modeling tools such as MASON (Luke et al, 2004), and JADE. In addition, we are looking for utilizing advanced cooperation methodologies that clearly explained in literature such as the market model (Smith, 1988), and scientific community metaphors such as (Kornfieldeld, 1979), and (Lenat, 1975) to fully utilize the agents' capabilities.

The multi-agent system models suggested in this chapter assume that the CBSRSAS system replication rule set is of the 2nd category (see section 1) where each system components have one and only complementary system components and one and only complement interaction section, leading to a very simple model of CBSRSAS systems. Thus, one of the major directions for future investigation is to build a general multi-agent system capable of handling the potential complexity of CBSRSAS systems. To handle such complexity in the future, the agents should be integrated with a powerful learning strategy and an AI induction or reasoning approach as well as a good cooperation approach.

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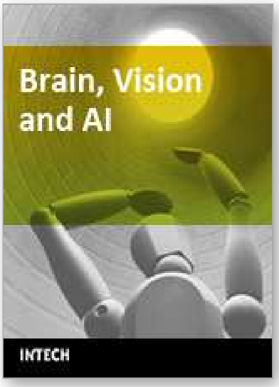


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The aim of this book is to provide new ideas, original results and practical experiences regarding service robotics. This book provides only a small example of this research activity, but it covers a great deal of what has been done in the field recently. Furthermore, it works as a valuable resource for researchers interested in this field.



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