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# Consensus Algorithms within the C4ISR Architecture

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## Abstract

Ubiquitous computational devices, usually referred as agents, sense their environment, collect data and disseminate them with various degrees of precision and trust. The state where every agent has the average knowledge of all agents in the area is called average consensus. This is a typical distributed objective in these systems with numerous industrial and military applications.

This paper reviews the recent theoretical developments in the area of distributed consensus with applications to unmanned vehicles navigation and discusses their integration into the C4ISR architecture. Simulation results are presented and evaluated. Future applications are considered with the adoption of more enhanced control methods.

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## 1 Introduction

Distributed systems analysis and design is an active area of research with both commercial and military applications. C4ISR architecture is a framework issued by the Department of Defense (DoD) to provide a standard approach to deal within the complex virtual and real digital environment with emphasis to military distributed applications ([1] and [2]).

The distributed multiagent coordination of mobile agents (nodes) has received much attention by the researchers. The main problem was the problem of coordinate motion and cooperative control of multiple autonomous agents, usually simple agents with limited computing power and sensing capability, in order to design a local action such that collectively a desired pattern or behavior can emerge. Every node or agent in this environment collects this information and tries to achieve the knowledge of all the other despite the noise, malicious interference etc. The communication is based on message passing to neighbor nodes with or without infrastructure. The most common approaches ([3] and [4]) propose control algorithms to accelerate and tune the overall performance.

The applications are numerous in transportation systems ([4]), mobile robots ([5]), military applications ([6-7]), etc.

Artificial intelligent algorithms derived from biology like fuzzy methods and artificial neural networks have been used ([5]) in distributed models.

The nodes may use this common knowledge to define the center of gravity for a formation, to move as group defining a flock. Flocking or schooling behavior of living beings have many advantages such as avoiding predators, saving energy, increasing the chance of finding food. Flocking is a form of collective behavior of large number of interacting agents with a common group objective. For many decades, scientists from many diverse scientific areas such as animal behavior, physics and biophysics, social Sciences, computer science etc have been attracted by the emergence of flocking in groups of Agents through local interactions.

## 2 C4ISR revisited

The Department of Defense Architectural Framework (DoDaF) provides the theoretical and practical framework for analysis, design, implementation and evaluation of all systems, systems of systems (SoS) in combat and non-combat environments ([1]). This framework has succeeded the C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance) architectural architecture framework, which was developed in the 1990s. In August, 2010 the newest version 2.02 of DoDAF was released.

The DoDaF defines concepts and model to the distributed area of modern military operations. The models are grouped in viewports, namely capability, data and information, operational, project, services, standard and systems.

In data and information viewport the problem of common knowledge is discussed.

The messages are considered to flow within the Operational Resource Flow Matrix ([1]).

## 3 Background

The network is described as an indexed set of nodes and links that connects them. If all nodes are connected to all other nodes, the networked is called fully connected mesh network. In most cases the nodes are connected to a small portion of neighboring nodes due to physical obstacles and the limited range of the antenna. In this context, connection is considered as bilateral.

The Laplacian or admittance or Kirchhoff matrix describes the network in a compact form

$$L_{i,j} = \begin{cases} 0 \; if \; nodes \; i \; and \; j \; are \; not \; connected \\ -1 \; f \; nodes \; i \; and \; j \; are \; connected \\ \sum_{j=1, i \neq j}^{N} L_{i,j} \;\; if \; i = j \end{cases} \qquad (1)$$

This $N \times N$ matrix, where $N$ is the number of the nodes is a key notion to the next analysis.

Each node has a piece of information presented as a vector $x_i$. Each node updates the local information as follows

$$x_i(k+1) = f(x_1, x_2, ..., x_N) + g(k) \qquad (2)$$

where the $k$ is the local time index, $f(\cdot)$ is a feedback function of the received information and $g(\cdot)$ an independent control input.

The nodes are modeled as system state description using suitable communication deployment transition matrices. Conventional or evolutionary control methods can be used to design the feedback and control input functions $f(\cdot)$ and $g(\cdot)$ as well as time or energy constraints. The problem derives to an optimization

A theoretical background of the consensus problem in distributed systems is formally defined in both continuous and discrete time systems. The lack of a global clock is mentioned and is managed using the notion of “happened-before” concept of Lamport logical clock ([8]).

In [9] the stability properties in a system of multiple mobile agents have been investigated. A stable flocking motion of a group of mobile agents have been generated by the use of a coordination control scheme which gave rise to smooth control laws for the mobile agents. It was ensured cohesion and collision avoidances for the group of agents and also an aggregate motion on a common heading direction through these control laws which are a combination of attractive and repulsive alignment forces. The interconnections between the agents were represented by a graph. The stability analysis of the system was performed based on LaSalle's invariant principle, which they numerically verified through simulations of ten mobile agents with identical second order dynamics.

## 4 Objectives

Consensus is the agreement of all participating nodes of a group to a common knowledge. The knowledge may be a vector of numbers or in the simplest case an average, usually called average consensus.

In this context the nodes have a direct connection with its neighbors. It also possesses an initial knowledge about its identification, state and any arbitrary command. Messages can be exchanged using their direct communicating links. The nodes update their internal values by a suitable aggregation algorithm.

The overall performance of the system is tested under various algorithms, and the most reliable results are shown.

## 5 Methodology

Consensus can be studied using experimental and simulation methods. A mathematical model is used in the simulation and compared to experimental data. Furthermore, evolutionary algorithms are used to compensate the noisy environments and the random messaging errors.

The feedback function in (2) was chosen as a static implementation of the Laplacian matrix.

More sophisticated approaches were tested, as in [5] but in this case a simpler implementation was preferred.

The simulation tool is the GNU Octave which is a high-level interpreted language, primarily intended for numerical computations. It is a portable solution and can be used for computational modeling.

Two time models exist, namely synchronous and asynchronous. The first model defines that each node in the networks has a clock that ticks at the times of a rate of a Poisson process. The second model in the contrary assumes that the time is slotted evenly across all the nodes in the network. In each time slot the nodes contact one of its neighbor nodes in an independent and random manner. In this time model all nodes are communication simultaneously in contrast to the asynchronous model where only one node can communicate at a given time. However, in both models each of the nodes can contact only one other node at a time.

# 6 Simulation studies

To further study of the proposed methodology.

## 6.1 Case 1. Static nodes

A typical network of five nodes or agents is presented in Figure 1. The links are represented as straight lines and initial information vectors are assigned to each node.

The network is connected and no islands are created. If the agents are still, the Laplacian matrix of the system is static and if they move a new arrangement the matrix is dynamic and may result to possible delays or isolations.

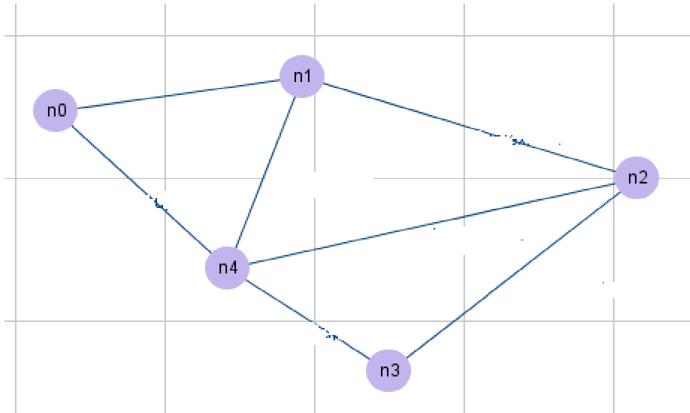


Figure 1: Typical network with 5 agents with permanent links

The initial vector knowledge is defined as

$$x = [\,2 \quad 3 \quad 4 \quad 5 \quad 6]^T$$

and the expected average value is $\bar{x} = 4$. The response of the system is shown in Figure 2.

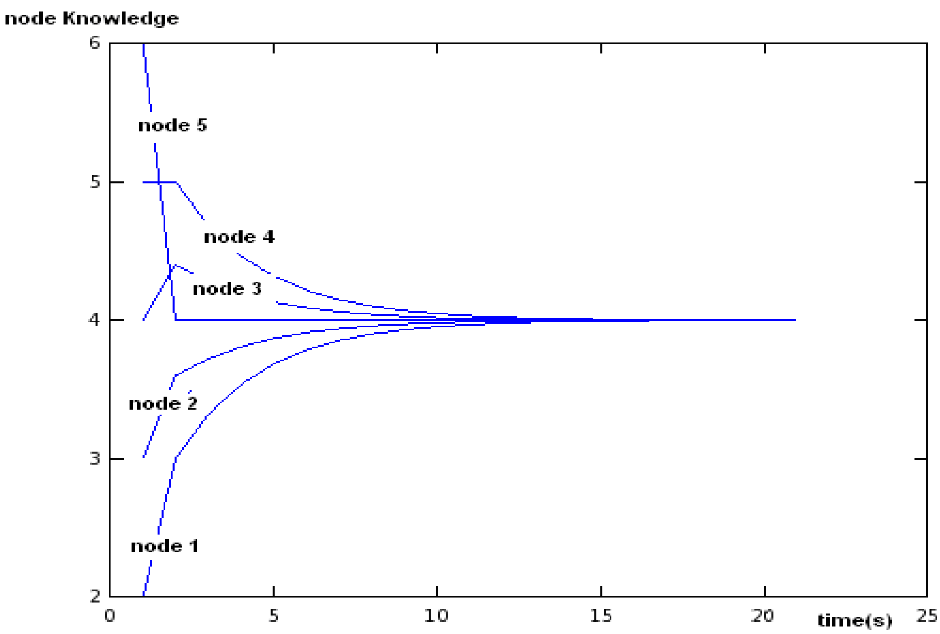


Figure 2: Response to consensus

The essence of consensus is the common knowledge about a strategic decision.

## 6.2 Case 2. Mobile nodes

Mobile nodes are presented in Figure 3.

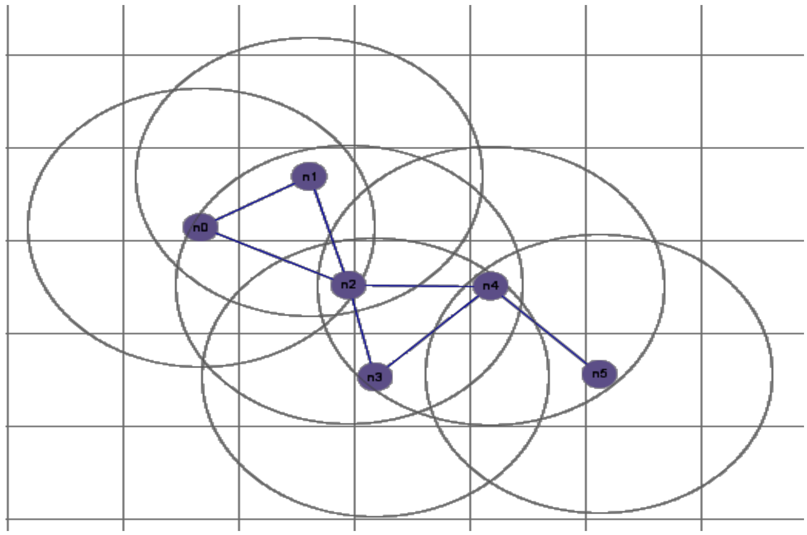


Figure 3: Mobile and wireless network with 6 agents with omnidirectional antennas

Initially the nodes are assigned a unique identification and begin a handshaking process. They locate their own position according to a global coordinate system. They exchange messages to their neighbors to derive the consensus, which in this case is the center of gravity of this group. In the same time they move in a circular formation around this proposed center. They take position at a specified angle according to their identification number that was assigned to them.

The initial positions of the nodes are

$$x = [236 \quad 324 \quad 355 \quad 475 \quad 366 \quad 538]^T$$

$$y = [563 \quad 634 \quad 514 \quad 528 \quad 426 \quad 444]^T$$

whereas the expected average is

$$\bar{x} = 381 \text{ and } \bar{y} = 518.$$

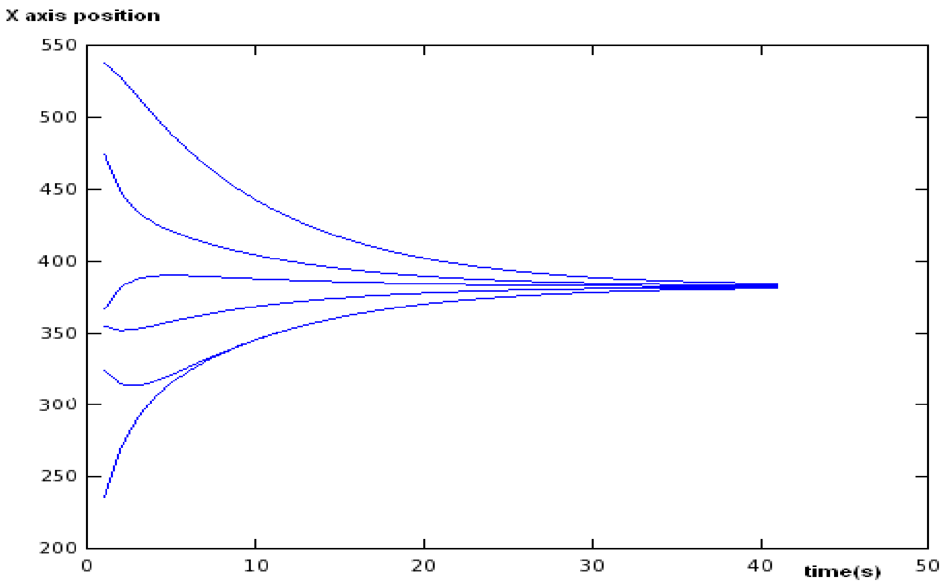


Figure 4a: Response of consensus convergence for x  axis center of gravity

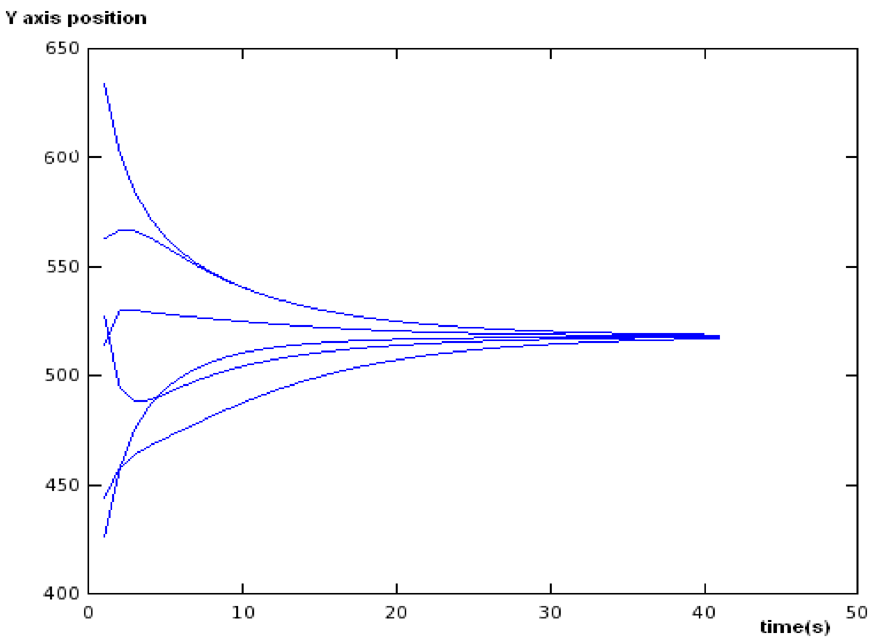


Figure 4b: Response of consensus convergence for y axis center of gravity

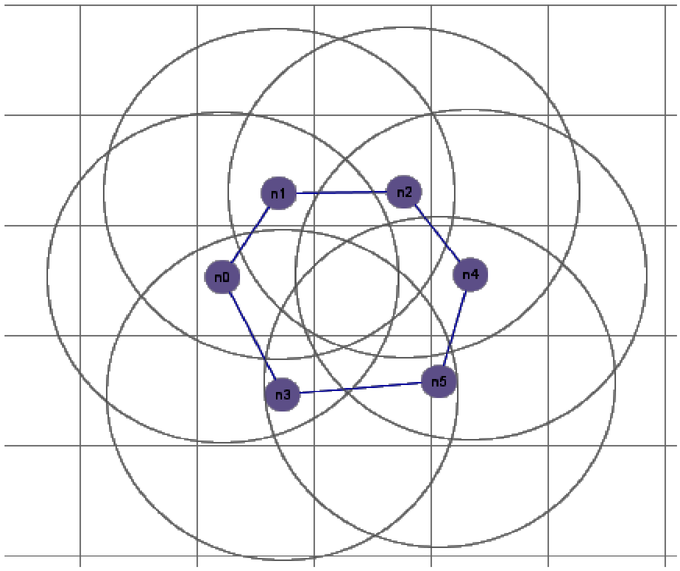


Figure 5: Final formal of mobile network after successful consensus

The network is described in the C4ISR architectural with equivalent principles using UML elements in the three views, namely operational, system and technical. The representation of the system response is interpreted accordingly to every architectural view.

## 7 Evaluation and conclusion

The presented schema was based on recent advances consensus algorithms. The cooperative spectrum sensing is modeled as a multi agent coordination problem. There is no need for a common centralized receiver in order to do data fusion for reaching the final decision. Only local information exchange is need in order for secondary users, which cooperatively sense the spectrum, to detect the presence of primary users.

Simulations were also performed in order to compare the performance of the proposed scheme with that of an existing or-rule cooperative sensing scheme. The simulations results were presented in order to illustrate the effectiveness of the proposed scheme. It was shown that missing detection probability and false alarm probability can be significantly reduced in the proposed scheme compared to those in an existing scheme.

The consensus algorithms are placed in the C4ISR architecture. The simulation results are compared in a variety of control methods and considered satisfactory. Finally, guidelines to their application and interpretation in military environments are discussed.

## References

[1] A.H. Levis and L.W. Wagenhals, C4ISR architectures: I. Developing a process for C4ISR architecture design, *Systems Engineering*, John Wiley & Sons, Inc., **3**(4), (2000), 225-247.

[2] B.P. Zeigler and S Mittal, Enhancing DoDAF with a DEVS-based system lifecycle development process, *IEEE Trans on Systems*, Man and Cybernetics, 2005.

[3] P. Yang, R.A. Freeman and K.M. Lynch, Multi-Agent Coordination by Decentralized Estimation and Control, *IEEE Trans on Automatic Control*, **53**(11), (2008), 2480-2496.

[4] S. Kraus, et al., A Study on Gossiping in Transportation Networks, *IEEE Trans. on Vehicular Technology*, **57**, (2008), 2602-2607.

[5] A.N. Tsapanoglou and D.P. Iracleous, Fuzzy Tuned Gossip Algorithms in Mobile Ad Hoc Networks, *17th Mediterranean Conference on Control and Automation*, Makedonia Palace, Thessaloniki, Greece, June 24-26, 2009.

[6] N. Doukas, A. Drigas and N.G. Bardis, Design of an Interactive Game for Teaching War Ethics, Technology Enhanced Learning, *Quality of Teaching*

*and Educational Reform Communications in Computer and Information Science*, Springer-Verlag Berlin Heidelberg, **73**, (2010), 558-564.

[7] N. Bardis, A. Drigas, N. Doukas, and N. Karadimas, Optimised Information System Reliability Techniques for Knowledge Society Acceptance, *Int. J. Knowledge and Learning*, **5**(3/4), (2009), 207-221.

[8] B. Sundararaman, U. Buy and A.D. Kshemkalyani, Clock synchronization for wireless sensor networks: a survey, *Ad Hoc Networks*, **3**(3), (2005), 281-323.

[9] H.G. Tanner, A. Jadbabaie and G.J. Pappas, Flocking in Fixed and Switching Networks, *Trans. on Autom. Control*, **52**(5), (2007), 863-868.