Fuzzy Consensus Algorithms for Mobile Ad Hoc Networks Flocking

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Abstract: - The field of mobile ad hoc networks, MANETs, and the application of flocking rules for node mobility are investigated. MANETs are modelled as agents forming communities without fixed infrastructure for a certain time period often presenting cooperative behaviour. Fuzzy logic is used as an effective way to achieve consensus and apply flocking behaviour on the movement of the mobile agents. The method which is a biological inspired algorithm is an approach of using knowledge in similar way to the human brain. A formal analysis of the dynamics of flocking behaviour is derived and a formal analysis of network representation is given. The fuzzy algorithm is illustrated and simulation results depict the performance of the fuzzy tuned algorithm.

Key-Words: - MANETs, multi-agent systems, consensus, flocking, coordination, fuzzy logic, biologically inspired algorithms.

1 Introduction
Coordination and control of MANETs, especially collaborative target localization is an emerging research area [1-6]. There is several application scenarios in which the nodes of a MANET need to be navigated to a desired location in the mission space for a closer investigation of the environment. Navigation of a group of nodes to a desired target location is another requirement.

In [7] the authors investigated the UAV placement and navigation strategies with the goal of improving network connectivity. They proposed a technique based on flocking behaviours of birds in order to effectively connect a large fraction of mobile ground nodes. They used the three flocking principles which Reynolds proposed for controlling the flight patterns of the UAVs. They posed some constrains on the UAVs flight. The UAVs could not remain stationary at any point of time and they had an orientation at any time instance as they are not point objects. The motion between two way points depended on the initial orientation of the UAV and on the maximum allowed turn angle. They performed simulations of the presented flocking rules of their flocking algorithm and made comparisons with a stationary grid based placement scheme. The flocking proved to work as well as static greed placement in a fixed constraint environment while it outperformed the latter when there was an overall motion of the nodes towards a particular direction. Flocking adapted effectively to the group mobility of the nodes and as proved by the simulations the flocking UAVs provided good coverage connectivity and load-balance to the underlying ground nodes.

In [8] two novel structures for optimal navigation of swarm mobile sensors were presented to achieve global and local tasks such as radioactive detection, landmine detections and fire fighting. The proposed structures were based on collective intelligence which was implemented two techniques. The first one was based on the particle swarm optimization algorithm or PSO and the second one on a swarm of fuzzy logic controllers. The authors presented a three tier hierarchical architecture. They have implemented a swarm of fuzzy logic controllers for
the navigation of the mobile nodes using conventional fuzzy logic where the membership functions and the rule base were developed based on heuristics and with the use of optimal FLCs.

Another work based on fuzzy logic for the control of mobile nodes is presented in [9]. The authors proposed fuzzy logic control approach to achieve average consensus. Each robot is considering each other robot in the network as information storage. The ad hoc network is used to collect each robot’s information which was used as an input on the FLC controller in order generate a crisp output as sending message.

In [10] the flocking of multiple agents of significant inertias was considered which evolve on a balanced information graph. It was shown that the agent’s inertial effect can cause unstable group behaviour. Passive decomposition was used to decompose the closed loop group dynamics in two different decoupled systems, one shape system for representing the internal group information and a locked system for describing the motion of the centre of the mass. The proposal was a novel provably stable flocking framework which ensures that the internal group formation of the mobile agents is exponentially stabilized to a desired shape while the velocities of all agents converge to the, time invariant, centroid velocity.

In a recent research [11] the authors considered the problem of trust establishment and consensus in a distributed network. The used directed graphs in order to represent the information exchange between the nodes. They proposed both a continue time and a discrete time bilinear trust update scheme for trust consensus. They described, in terms of the steady state and the convergence bound the convergence characteristics of these schemes. The provided an application of these update schemes in team behaviours including flocking and formations. The trusts were considered to be in the \([0, 1]\) range.

Olfati-Saber, R. in [3] addressed distributed target tracking for mobile sensor networks with the use of the extension of a distributed Kalman filtering algorithm which was introduced in a previous research of the author. Distributed tracking for mobile sensor networks was addressed with a flocking based mobility model using a cooperative network of micro Kalman filters. A metric for information value of sensor measurements was also introduced. The author demonstrated that a flocking based mobility model that is using the previously introduced distributed algorithm is an information driven motion control algorithm for cooperative tracking.

In [12] the authors considered the challenge of the development of robust distributed motion algorithms that can always achieve network connectivity in applications such as consensus seeking and flocking by embedding the requirement for connectivity of the underlying communication network in the controller specifications.

In another research [13] the authors considered the case of multiple mobile agents moving in the space with point mass dynamics. They have introduced a set of coordination control laws which can enable the group of the mobile agents to generate a desired stable flocking motion.

Biologically inspired methods have been used in consensus and flocking [14, 15]. In this paper a further investigation on these methods is tested and evaluated.

## 2 Problem Formulation

A network can be described as a set of nodes and edges and a matrix is defined in every time instance in order to identify all the possible interconnections between the nodes. This matrix, which is a Laplacian matrix, in the case of MANETs is defined as:

\[
L_{ij} = \begin{cases} 
-d_{ij}, & i \neq j \\
\sum_{i=1}^{n} d_{ij}, & i = j 
\end{cases} 
\]  

where \(i, j \in [1 \ldots n]\), \(d_{ij}\) is the metric between the nodes \(i\) and \(j\) which in MANETs is 1 if the nodes communicate and 0 otherwise. The above equation states that the diagonal elements of the Laplacian matrix are equal to the sum of all row elements.

At every time instant \(k\) where \(k \in [1, 2, \ldots, \infty]\) the state of the \(i^{th}\) node is represented by \(x_i(k)\) where \(i \in [1, 2, \ldots, n]\) and represents the amount that needs to be coordinated between the agents.

The average initial state of the network at time \(k = 0\) is given by:

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i(0) 
\]  

A discrete time consensus protocol can be summarized by:

\[
x_i[k + 1] = \sum_{j \in \mathcal{N}[i]} \beta_{ij}[k]x_j[k] 
\]
According equation (3.7) the next state of an agent is updated as the weighted average of the agents’ current state and the current states of its neighbours. The discrete time linear consensus can be written as:

\[ x_i[k + 1] = D[k]x[k] \]  

(4)

where \( D[k] \) is a stochastic matrix with positive diagonal elements. It can be said that consensus is achieved for a group of agents if:

\[ \|x_i - x_j\| \to 0 \text{ as } t \to \infty, \forall i \neq j \]  

(5)

### 2.1 Formal definition of boids model

In sequence the formal analysis of the boids model based on Reynolds’s original paper[1]. The entire flock of boids is made up of the set \( B \) of \( n \) Boids \( b_i \).

\[ B = \{b_i, \quad i = 0, 1, \ldots, n - 1\} \]  

(6)

Each boid has a set of attributes namely position \( p_i \), velocity \( u_i \), and the three steering forces (separation, cohesion and alignment). The formal definitions of the three steering forces follow.

#### 2.1.1 Separation

The tendency of every boid to avoid collisions with its neighbours is called separation or collision avoidance. In order to define this steering force, vectors defined by the position of the boid \( b_i \) and each visible boid \( b_j \) are summed and the separation steer defined by

\[ \vec{s} = \sum_{b_j \in V_i} (p_i - p_j) \]  

(7)

#### 2.1.2 Cohesion

The steering force that causes the movement of a boid toward the centre of the visible flock and that acts as a complement to the separation steering force is called Cohesion or flock centring. It is calculated by the equation

\[ \vec{c}_i = \sum_{b_j \in V_i} \frac{p_j}{m} \]  

(8)

Secondly the tendency of the boid \( b_i \) to navigate toward the centre of density of the visible flock \( V_i \) is calculated as

\[ \vec{k}_i = \vec{c}_i - p_i \]  

(9)

#### 2.1.3 Alignment

Finally, the alignment or velocity matching steering force is important in order for the boids to follow an impetus. This steer force is denoted by \( \vec{m}_i \) and it is calculated as the average velocity of the visible flockmates by

\[ \vec{m}_i = \sum_{b_j \in V_i} \frac{u_j}{m} \]  

(10)

### 3 Problem Solution

#### 3.1 Fuzzy consensus

Three steps are used in the fuzzy control. In order to propose an effective approach and an easy model to define the flocking algorithm fuzzy reasoning will be implemented using fuzzy toolbox in MATLAB.

Fig. 1: MATLAB implementation of the proposed fuzzy controller.

Three linguistic variables will be used: node vicinity, node speed and artificial coordination force. These three linguistic variables describe the rules that are applied in order to coordinate the movement of agents according to the flocking rules originally defined in Reynolds work [1]. They define how each node moves in relation to the neighbouring nodes according to their speed and position in order to keep the desired moving pattern. Node vicinity, node speed and artificial coordination force are described by fuzzy sets as shown in Fig. 2-3-4.

#### 3.1.1 Fuzzification

There are nine types of linguistic variables that are used as inputs to the fuzzy controller. The node speed is expressed by the linguistic variables Slow, Average and Fast. The node vicinity, which is related with the local node and the position of its neighbours, is presented by Near, Intermediate Distance or Far. The interaction force is expressed as Repulsive, Negligible and Attractive.
3.1.2 Fuzzy rules
The fuzzy rules use an expert’s experience, in our case are based on the flocking rules originally defined in the boids model of Reynolds, and control knowledge and are shown in Fig. 5.

3.1.3 Defuzzification
This step the inferred fuzzy values of the linguistic output variables are being transformed into single crisp numeric values. The Centre of Area (COA) method was used, as defined by the following equation

\[
c_v = \frac{\sum_{i=1}^{r} \mu_{R_i}(a_1, ..., a_n) L_{R_i}}{\sum_{i=1}^{r} \mu_{R_i}(a_1, ..., a_n)}
\]  

(11)

3.2 Agent flocking
Agents measure and identify their positions. This information is exchanged by messages to neighbour agents and average consensus is achieved of their centre.
Each agent is tracked to a previously specified location about the centre of all using standard Newtonian dynamics.

4 Simulation Studies
4.1 Six node example
4.1.1 Initial network topology
The test-bed for the simulation of the proposed algorithm is shown in Fig. 6. It consists of a MANET of six wireless mobile nodes. It is a two dimensional approach for simplicity but it can easily adapted to three dimensional.

Each node has an initial guessing of the position of the centre of all nodes. They exchange messages to achieve consensus and they move to form a circle around this centre.

4.1.2 Consensus of the centre of the formation
The nodes gradually learn the coordinates of the centre of their group. In Fig. 7 the time evolution of this process is depicted for the coordinates x and y. Each node is represented with a different colour.
4.1.3 Final formation of the MANET
The nodes align to the proposed circle around the centre. Fig. 8 represents their motion trajectories, as well as Fig. 9 their final position.

4.2 A larger example
A larger example of 11 nodes is briefly presented.

The nodes are organised in a circle after message exchanging as in the previous example. Fig. 11 present the resulting graphs produced again in MATLAB.

5 Further work
Other biologically inspired algorithms such as immune systems, genetic algorithms and artificial neural network systems can be used and evaluated in order to examine their effectiveness on the proposed theory. Detailed investigation of all the available mobility models for the mobile agents in MANETs and comparison of each one of them with the proposed flocking model in order to compare the effectiveness is another idea.

The simulations performed in this paper assume an ideal network space without any obstacles. So an
extension of the proposed approach would be the assuming of a network space with obstacle presence and evaluation of the effectiveness of the algorithm.

6 Conclusion
Fuzzy consensus has been used successfully in previous works. Here an important extension was made to integrate consensus with flocking. Nodes move accordingly to the group centre as ring in equal angle. This formation was chosen arbitrarily and any other is acceptable as well.

A main issue of the proposed approach is its locality. When an isolation of the nodes happen, it is probable not to be able to connect again. Then, two or more isolated islands occur.

The convergence can be accelerated with finer selection of the fuzzy variables and rules. Nevertheless, the rough selection of parameters gave a very good behaviour.

References: