Self-Organization as a Supporting Paradigm for Military UAV Relay Networks

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Abstract—The modern battlefield scenario presents a number of challenges that highlight the importance of data gathering and information flow as crucial to the success of a military operation. In this context, network-centric warfare systems play an important role to bridge the gap between data and information sources and consumers. These systems are generally composed of different types of networks both deployed on the field and on back-end facilities. A paramount problem faced when conceiving the interconnection between the networked devices is how to provide robust and dependable connections to the devices on the field. This work tackles this issue proposing the use of the self-organizing paradigm to design efficient UAV relay networks to support military operations. As a proof of concept, realistic simulation experiments are performed providing clear indications of the claimed benefits of the self-organizing paradigm applied to these military systems.

Index Terms—Network Connectivity, Self-Organization, Network-Centric Military Systems, UAV Relay Network.

I. INTRODUCTION

The complex battlefield scenarios of today require timely and precise decision support systems. Command and Control (C2) systems have evolved considerably in the last years, providing situation awareness (SA) to support informed decision making [1]. However, C2 systems do not operate by themselves; in fact they are part of a large network-centric military system. The entire system is very complex and is composed of several diverse elements, which themselves may be composed of other minor networks, such as Wireless Sensor Networks (WSNs) or networks of Unmanned Aerial Vehicles (UAVs). The latter can be referred to as the “last mile” system or the Tactical Edge Devices and Networks (TEDs and TENs) [2].

Despite the usefulness of the above mentioned military information system, an important problem that has to be addressed is the maintenance of interconnection links to TENs. In order to understand why this problem is so severe, it is necessary to analyze the conditions under which military operations take place. Military operations usually occur in hostile environments in which all sorts of difficulties and “traps” may be found. Particularly related to data communication, a number of disturbing phenomena may happen such as interference and jamming. These phenomena may be permanent or intermittent, which makes it very challenging to provide solutions based on conventional network protocols or design approaches.

Current network centric military systems presented in the literature predominantly use a centralized network control paradigm which is not robust enough to adequately deal with network disruptions [2], [3]. In contrast, the paradigm of self-organizing (SO) systems [4] exhibits autonomic and decentralized behavior with a high degree of robustness and at the same time being governed by a small set of very simple rules and actions. Moreover, such systems depend only on locally available information. These properties enable systems to adapt to dynamically changing environments and unforeseen situations while at the same time maintaining and delivering the desired services. This paradigm has been successfully applied in many areas [5]. Thus, this letter has the following contributions: (i) further promotion of the application of the SO paradigm to solve challenges in military network-centric systems, particularly those involving teams of UAVs, (ii) a show-case how a multi-goal mission (reconnaissance together with forming of a UAV relay network) can be designed in a relatively simple way by applying the SO paradigm instead of complex mathematical modeling and reasoning.

II. MILITARY APPLICATIONS OF SELF-ORGANIZATION

It seems fair to state that all network-centric military systems exhibit some cooperative aspects to some degree. However, in order to better illustrate the benefits and usefulness of the SO paradigm in this domain, a class of applications using cooperative teams of UAVs is presented.

The employment of UAVs in military operations became an important asset in the modern battlefield reality. Remotely piloted individual UAVs already proved their value in the recent past years. Despite their usefulness, the possibility of using autonomous UAVs performing missions in cooperative teams would bring them to a higher level of importance to the military, for which the following application examples can be highlighted: Target Tracking; Area Surveillance and Patrolling; and Relay Network to Support connectivity of TEDs, TENs and troops-carried devices [1], [2].

All the above mentioned applications have a crucial dependency on the communication among the UAV-team members. This dependency refers to different communication layers, e.g. establishing and maintaining link connectivity at the physical layer, routing messages in the network, and load balancing of the military application. Moreover, they need to be reliable, robust and adaptable to continuous changes, which are in fact quite common in military operational scenarios. As a consequence, the supporting network has to deliver reliable services, which have to be robust to overcome adverse situations. Moreover, communication requirements change depending on the...
current mission. For instance, target tracking needs different QoS than area surveillance.

There are also essential military properties that have to be addressed: secrecy and unpredictability. Ongoing mission(s) should not be disclosed to the enemy, i.e. UAVs should be hard to spot or detect. In the case they are detected, it should not be trivial to predict their trajectories in order to minimize the chance of shutdown or disclose the purpose of the mission. This can be solved by (i) embedding randomness into the UAVs behavior, (ii) minimizing the number of UAVs needed for a mission, as well as (iii) minimizing the total number of conducted missions by combining them into a single multi-goal mission.

A concrete example of a networked UAVs application with multiple goals is combining patrolling or surveillance missions together with a mission to form a relay network for sparse sensor networks in hostile and remote areas, such as the Amazon forest and the Artic area. These sparse networks may form islands of isolated nodes which are unable to reach a sink (or a base station). A UAV relay network would then provide connectivity to the back-end C2 network. This scenario is shown in Figure 1 together with the main parts of the system. This multi-goal mission has three conflicting objectives: (i) maximize the physical connectivity among UAVs to form a relay network, (ii) maximize the area coverage (distance among UAVs), and (iii) minimize the number of deployed UAVs. It is understandable that one objective cannot be fully satisfied on account of the others, thus the mission has to provide a certain balance among them. Additionally, a movement pattern with some randomness has to be used in order to ensure secrecy and unpredictability [6].

Reflecting on these requirements typically involve intricate mathematical models and computationally intensive algorithms for optimization of UAV behaviors with several conflicting goals [2], [3]. An alternative and promising approach to complex mathematical models and optimization is to apply the SO paradigm which is based only on a local interaction of a small set of simple activities.

III. APPLYING THE SELF-ORGANIZING PARADIGM IN A MILITARY UAV RELAY NETWORK

SO can be explained as a dynamic process in which a system acquires its structure or organization by itself without any external help or control [4]. For instance, the acquired structure can be new routing rules or a topology of networked UAVs. This process can be either centralized or decentralized. In case of a centralized process (CSO), there is an entity in the system that coordinates all activities. However, the dependence on a central coordination entity, a single point of failure, is a major disadvantage. This can be overcome with another type of SO which is decentralized where each entity in the system is making its own decisions and interacts only locally, i.e. based on nearby information and with its direct neighborhood. Examples of local activities are “join new communication group of UAVs”, “turn left”, “forward data to the nearest UAV”, etc. This type of behavior in which local interaction gives rise to a global phenomenon is called Emergent Self-Organization (ESO).

In general, SO systems can autonomously adapt to various (unplanned) changes while still trying to maintain their main goals. Nevertheless, ESO systems are more robust to various failures than systems with “centralized SO”. This is due to the fact that decision making of each entity (UAV) is based only on locally acquired information. An entity then tries to make a locally optimal decision what should be the next action. This also means that “balancing” between various conflicting goals (as those described in Section II) is done on-the-fly in each entity and without a need to have a global knowledge. This also minimizes the need for communication as no global coordination is required. Therefore, ESO is more suitable for the given military application of UAVs.

A. Design

Emergent SO is a kind of heuristics in which locally optimal decisions may lead to a system-wide optimal solution. However, a certain level of “trade off” in decision making must be introduced to avoid undesirable global behavior (e.g. too excessive fulfilling of one goal at the expense of others). Therefore, the concept of negative and positive feedbacks is applied in the design of SO systems to “regulate” local decisions allowing the balance between conflicting goals. The positive feedback is responsible for an amplification of (small) changes or disturbances in order to increase the output the system. To limit the output of the system the negative feedback is applied.

In the multi-goal mission of the UAV-team targeted in this work, the two conflicting goals are the reconnaissance and the provision of a relay network. The goal of the reconnaissance is to cover as largest area as possible, ideally the whole region. This can be achieved by letting the UAVs fly more apart from each other. This is modeled as the positive feedback. On the other hand, if UAVs get too much apart, the connectivity among UAVs (at physical and link layers) will drop and the relay network will eventually break. This is avoided by applying the negative feedback which will force some UAVs to “turn back” to restore the connectivity.
The proposed solution is shown in Figure 2a. A main principle of this solution is that each UAV performs a small and very simple set of activities (move forward, turn right or left x degrees). The decision of which activity will be selected is driven by the positive (pure random-walk) or the negative feedback (turn into the direction where there is a chance to recover the connectivity). The process of selection is relatively trivial, does not require any complex mathematical modeling, and is done with the use of only locally available information (reception of the beacon packet from the neighboring UAVs).

Design of the positive feedback is straightforward: All UAVs move accordingly to a selected mobility model which should be a variation of random-walk to ensure secrecy and unpredictability as required in military applications (Section II). In this model, each UAV repeatedly decides in which random direction to proceed, i.e. it randomly selects one of these activities: move forward, turn right or left.

To trigger the negative feedback there is a need for a mechanism to detect that the UAVs are getting too far apart. For this reason, the designed scheme states that the base station will periodically broadcast the so called beacon packet which contains only two fields: a sequence number selected by the base, and a hop counter (initially set to zero). Figure 2b shows how beacon packets are processed in each UAV. To avoid flooding of the network, only packets with a new sequence number are forwarded until the maximum number of hops is reached. If a UAV has not received any beacon packet within a certain period (which is greater than the estimated maximum time to forward the packet via all UAVs aligned in a chain) it means loss of connectivity. This will trigger the negative feedback which forces the UAV to turn in the direction where there is a chance to recover the connectivity. For example, return to the direction of the most powerful reception from the last beacon sequence.

The experiments were conducted using a modified Simbeeotic [7] simulator, which provides a realistic physical model of small sized UAVs. To achieve better accuracy of results, the simulator was extended with communication models based on existing IEEE wireless protocols standards. The proposed SO algorithm does not depend on any communication protocol. However, for the experiments with communication among UAVs the IEEE 802.15.4 with extended range to allow medium range communication (300+ meters) was used. This protocol was chosen due to the fact that it is widely used in WSNs and as one of the possible discussed applications considers the UAV-relay network supporting connectivity to isolated WSNs, this represents a reasonable choice. The simulation model assumes that each UAV has collision avoidance capabilities so that in case of potential collision, the UAV starts turning 45 degrees right until collision is avoided. The remaining important parameters are listed in Table I.

### Results

The first objective of the multi-goal mission (Section II) was to maintain the connectivity at the physical and link layers among UAVs so they can effectively form a relay network. The successful accomplishment of this objective is presented in Figure 3. It can be clearly observed that during regular reconnaissance missions using random walk only, the connectivity continuously drops until the whole relay network is disconnected. However, when the proposed SO algorithm is enabled, the connectivity converges into a relatively high value which is later maintained during the whole mission. In case of the Figure 3 the connectivity of 7 UAVs converges to 5.8, i.e. at any moment of time, there is on average 5.8 UAVs connected and forming a relay network. The proposed SO algorithm also relatively quickly converges as shown in Figure 3 at approximately 250 seconds after start of the mission. In Figure 4 it is possible to observe that the average connectivity of the SO algorithm is always higher for any reasonable number of deployed UAVs.

#### B. Experiments setup

Due to the limited length of this article, partial results only are presented showing the correctness of the proposed solution and the feasibility of applying the SO paradigm to design multi-goal military missions with requirements to communication such as the one described above. Results are shown with a constant beacon rate set at one second and from numerous options for the negative feedback type applying only the return to the direction of the most powerful reception from the last beacon sequence.

The following table lists the simulation parameters used for the experiments:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mission duration</td>
<td>3600 seconds</td>
</tr>
<tr>
<td>surveillance area</td>
<td>square of 10x10 km</td>
</tr>
<tr>
<td>maximal speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td>flying altitude</td>
<td>250 m</td>
</tr>
<tr>
<td>802.15.4 tx power</td>
<td>25 dBm</td>
</tr>
<tr>
<td>rx SNR margin</td>
<td>10 dBm</td>
</tr>
<tr>
<td>rx sensitivity</td>
<td>-10 dBm</td>
</tr>
<tr>
<td>propagation model</td>
<td>free space optical</td>
</tr>
<tr>
<td>mobility model</td>
<td>random walk</td>
</tr>
</tbody>
</table>

![Table I](image-url)
Another mission objective (Section II) was to maximize the area coverage, i.e. ideally to cover the whole area under the surveillance. In Figure 5 it is shown how the average area coverage of the mission depends on the number of deployed UAVs. It is understandable that the coverage with the algorithm to form a relay network will be smaller than a pure reconnaissance mission because UAVs are not allowed to fly too far apart in order not to break the connectivity.

In general, both the average connectivity and the coverage can be improved by deploying additional UAVs as shown in Figure 4 and Figure 5. It can be argued that by adding more UAVs there is no need for the proposed SO algorithm. The same can be said reasoning in another way, i.e. it is possible to offset worse coverage of the SO algorithm by adding more UAVs. However, adding more UAVs can compromise the secrecy of the mission which is one of the stated objectives described in Section II. Another parameter that could also advocate for the use of a lower number of UAVs is the total cost of the mission. However, this paper will not further explore this particular aspect. It is up to a mission commander to decide what is the current priority and how many UAVs will be needed in a particular multi-goal mission.

IV. CONCLUSION

This letter aims to promote the use of self-organization, more precisely its decentralized flavor (referred as ESO), as a promising paradigm to design efficiently network-centric military systems such as UAV-relay networks. Examples in which particular areas of military communication can benefit from this paradigm are highlighted. The main advantages of this paradigm are autonomy, robustness, simplicity of actions, and use of only locally available information. The design of a SO relay network of autonomous UAVs is presented and its operation is simulated. The experimental results from this simulation demonstrate the claimed usefulness of the SO paradigm to address the complexity and the desired features of military network-centric systems.

REFERENCES


Fig. 3. Evolution of the average connectivity to the base station (directly or indirectly) during one-hour mission with 7 UAVs (aggregated every 10 seconds). Without the proposed solution (green line) the connectivity continuously drops as UAVs perform random walk. When the proposed self-organizing solution is used (violet line), the average connectivity reaches 5.8 and remains maintained. Initial high connectivity is due to UAVs launch positions. Data from 50 simulation runs are shown.

Fig. 4. Average connectivity (1.0 means all UAVs are connected) of the relay network when proposed self-organizing relay algorithm is enabled or disabled (i.e. only pure random walk) as a function of the number of deployed UAVs. Average values of 50 simulation runs per point are shown.

Fig. 5. Area coverage (1.0 means full coverage) when proposed self-organizing algorithm is enabled or disabled (pure random walk) as a function of the number of deployed UAVs. Average values of 50 simulation runs per point are shown.