Flying Ad-Hoc Networks

Michael Müller – {michael-4.mueller@uni-ulm.de}

***Abstract*—The research presented here aims on releasing a swarm of Micro-Air-Vehicles from a base station. The swarm organizes itself to search for a user in a large area. Once the user is found a communication link must be established and maintained from the base station to the user.**

The two concepts presented here aim on building a swarm that only relies on local communication with neighbors. No global positioning is available. Analogous to real swarms the sensors only provide data about the immediate environment of an individual.

I. Introduction

Swarming Micro Air Vehicles (SMAVs) can be used to provide a large area with a communication network. The research presented in this article aims on releasing a swarm of autonomous MAVs who organize themselves to establish a wireless communication network. We specifically address the issue of establishing a link from a base station to a user startion. The MAVs hereby are explicitly not equipped with any Global Positioning Systems (GPS), cameras, laser range finders or radars. Sensors which are dependent on the environment have the disadvantage that they are expensive in terms of energy, size, cost and weight. Additionally GPS is unreliable or not necessarily possible in disastrous areas. For positioning the GPS receiver must read four satellites simultaneously. To get the most exact localization, a line-of-sight with the necessary satellites is ideal. In confined spaces like a city with tall towers or a closed hall this is not necessarily possible. Since it can't be ensured that GPS always is exact, this effectively limits the deployability of the system [1].

Instead the researchers aim for minimal platforms which are cheap, safe, light-weight and easily deployable. The MAVs hereby are equipped with sensors that enable them to sense their immediate environment. Those sensors provide heading, altitude, speed and possibly communication with their direct neighbors.

Examples for scenarios where a communication link spanned by a flying swarm is needed include disaster areas where the topology of the compound does not allow to install base stations in a short amount of time. Other examples are disasters where floods prevent a stable power supply.

The typical scenario addressed in the research presented in the following sections, is a group of rescuers who arrive at a disaster scenario and rapidly have to set up a base station and a communication network. MAVs are then launched from the base, one after the other, and must organize themselves to find rescuers or victims. Once found a communication link has to be established and maintained until no longer needed.

Flying robots are especially fitted for such scenarios because of their easy deployability and their ability to spread out over difficult terrains like flooded areas or debris.

A connection between rescuer and base station is helpful for exchanging rescue-related informations, positions of victims or photography.

The fundamental role that modern information and communication technologies (ICT) play in rescue operations, such as environmental and humanitarian relief operations, has been recognized in the last few years. In the following article we address the field of preservation of nature and human lives through utilization of modern technologies. Modern technologies can be used by search-and-rescue teams to gather a more precise knowledge base, resulting in an increased efficiency of operations [2].

II. Swarm behavior

The research presented in this article aims on establishing a communication link from a base station to a user station, which is placed somewhere in the search area. To solve this task many Micro-Air-Vehicles (MAVs) are released into the air. Each of the MAVs has a wireless network link integrated. This way MAVs can communicate with each other and send packets. Through using Ad-Hoc routing protocols and each MAV as a node, a communication network can be established. This way a base station is able to communicate with the user station through the network.

Together the MAVs form a flying swarm with each individual acting on his own. Since each MAV only senses its immediate environment and has no knowledge of any global state, a swarm behavior has to be established. Meaning altogether the swarm works towards one common goal, though the individuals act on their own. This is called emergent behavior. Craig. W. Reynolds proposed several rules for enabling bird-like flocking within a swarm in 1986 [3]. The rules were derived from real bird-flocks and can be briefly summarized as: move with the same speed and direction as neighbors, avoid colliding with them and stay close.

Before a communication link to a user station can be established the swarm first has to search the area for the user station. Since the MAVs can only communicate with their direct neighbors the swarm forms a tight chain. Most of the experiments assume a rough knowledge of the direction of the user station. After the user station is found a communication link has to be established and maintained. Ideally the MAVs should arrange themselves in the best way to maintain the network. This way the packet delivery rate of the network gets optimized the longer the communication link is established. We will now present two basic approaches for finding and connecting to a user station.

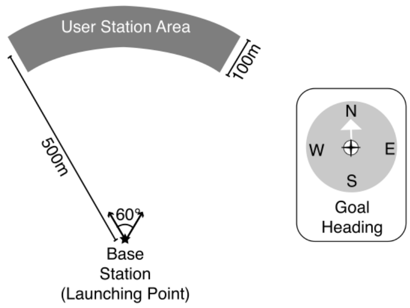

Fig. 1: In this scenario environment a swarm should be able to find user stations placed within the User Station Area. The image is taken from [4].

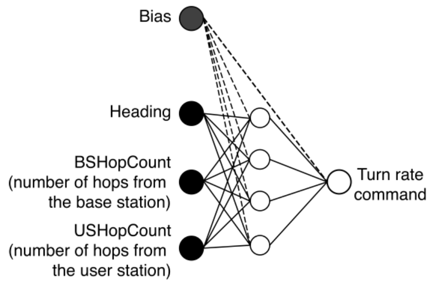

Fig. 2: This neural network is used as a controller for the MAVs. The best fitting weights of the neural network are gathered using artificial evolution and extensive testing. The image is taken from [4].

The first approach uses genetic programming as a mean to generate controllers for the MAVs. Later the generated program is reverse-engineered and adapted to the specific situation.

The second approach we present, aims on modeling the swarm behavior on patterns observed and studied in nature. These bio-inspired techniques are used to build a model for the controllers.

III. Artificial evolution

There is currently no proven methodology to deterministically design software with emergent behavior for a swarm which is directed towards a common goal. It is hard to use traditional programming techniques therefore, because problems of interest are not linear, stochastic or deeply enough understood. As an alternative approach the researchers within the SMAVNET project [4] [5] use artificial evolution to generate neural controllers for fixed-wing MAVs. An advantage of evolutionary approaches is the discovery of creative swarm strategies, which otherwise would not have necessarily been thought of.

A. The MAV model

The researchers use a 2D simulation in which MAVs are launched every 15 ± 7.5 seconds within 50 m surrounding the base station. In a real life scenario the MAVs would get launched one after another.

The user station is placed in the area 500 ± 50 m away, in an angle of ± 30° from the base station. This means an approximate knowledge of the user station location is assumed to be known (see Fig. 1).

The MAVs in this model constantly fly at a speed of 14 m/s. One assumption of the communication model is that two agents are able to perfectly communicate if they are less than 90 m apart. Communication gets noisy from 90 m to 100 m. The probability of dropping a message increases linearly. If they are 100 m or more apart, communication is assumed to be entirely lost.

The agents can send two types of messages. Control messages have the purpose of coordinating the swarm and are broadcasted by each node every 50 ms. Data messages are used for the application of the communication (e.g. video, voice or data transportation). They are sent between the base station to the user station.

B. The neural controller

For the artificial evolution a weighted artificial neural network (see Fig. 2) is used. Artificial neural networks can be used to model complex relationships between an input and an output. They can be described as a mathematical function $f : X \rightarrow Y$ or a distribution over X and Y. The neural network for the MAV controller consists of several inputs:

1) Heading: A magnetic compass is used to determine the heading of the MAV.

2) BSHopCount: The minimum number of network hops from the MAV to the base station.

3) USHopCount: The minimum number of network hops from the user station to the base station.

The inputs were scaled to fit the range $[-1, +1]$ and as a neural function a hyperbolic tanget (tanh) was used. Synaptic weights were chosen in the range $[-4, +4]$ and coded on 8 bits. Additionally there are 4 hidden neurons in the neural networks. This was found to yield neural controllers with the highest fitness for the swarm controllers. It is noticeable that all inputs are exclusively derived from the immediate environment of the MAV (situated communication, [6]).

The neural network outputs a turn rate, which is adopted by the MAV. The speed of the MAV is not taken into consideration for the neural network, since it is assumed to stay constant.

15 independent evolutions were executed using a genetic algorithm [7]. For the first generation the genomes were initialized randomly. Selection was used to favor inter-agent cooperation. From the generated neural controllers a swarm of 100 individuals was formed. Each individual in the swarm was equipped with the same neural controller (a homogenous swarm). In real-life applications this would be an advantage since it enables interchangeable agents and allows for scalable systems. The fitness of each swarm was then evaluated for 10 user stations randomly placed within the user station area.

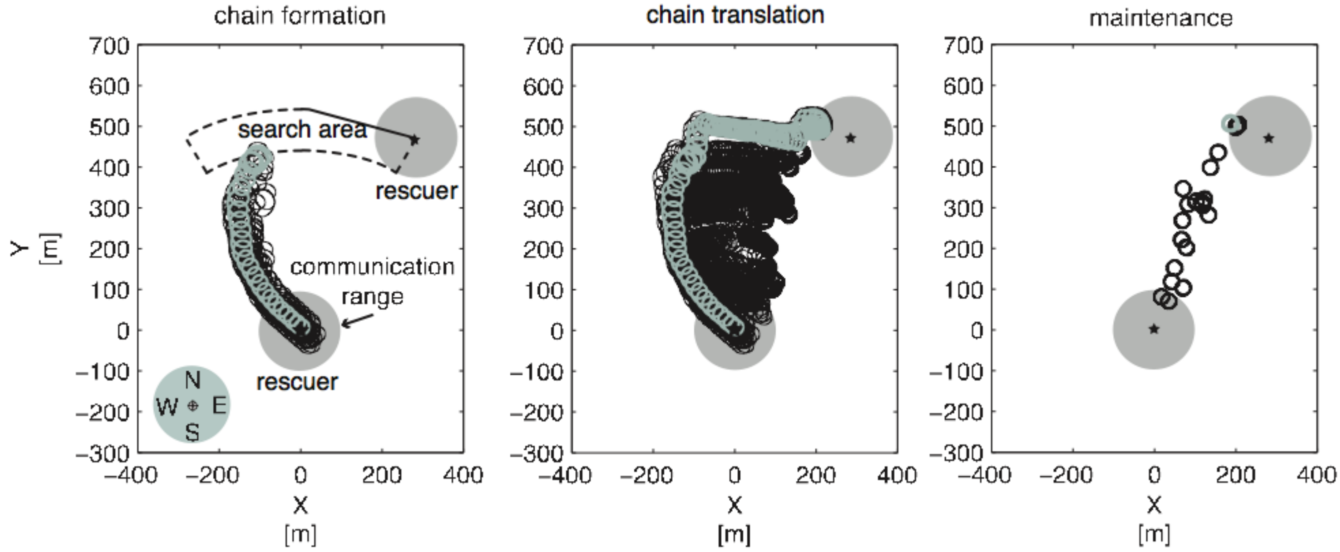

Fig. 3: The first two images show the sweeping behavior of the swarm. The image on the right shows how the MAVs maintain a communication link to the base station. The light gray line shows the trajectory of the first launched MAV. The image is taken from [5].

The top 10 performing controllers were then copied to a new population (elitism). The remaining population for this new swarm was generated by randomly pairing individuals within the first 30 ranks. The researchers favored controllers which were able to rapidly establish a connection and maintain it through the entire duration of the trial (30 minutes).

To achieve selection which favors the maintenance of a connection, the fitness F of each swarm is measured by the mean connectivity between base and user station throughout the duration T of the trial.

$$F = \frac{1}{T} \sum_{t=0}^{T} c(t)$$

Furthermore the connectivity of the network was regarded by introducing $c(t)$, the number of disjoint paths between base and user station. $c(t)$ also expresses the minimum number of MAVs that need to be removed for the communication link to break. As an additional action agents who lost contact to the base station for more then 30 s were assigned a fitness of 0.

After this phase, the best controller was tested with randomly placed user stations in the search area for 1000 trials. The connectivity of the best evolved controller can be seen in Fig. 4. The connectivity during the first couple minutes is 0 because the swarm has not spread far enough yet. But once a connection is established it is maintained throughout the remaining duration of the trial.

C. Analysis of the swarm behavior

It is important to understand the evolved controllers. Only through a deep understanding it is possible to modify the controllers and rapidly adapt them to new scenarios. This way controllers need not to be re-evolved for each scenario. These principles can possibly be used in further research to hand design swarm strategies for MAVs. For this purpose the swarm behavior was analyzed to find the underlying principles responsible for the emergent behavior.

Several simple patterns were found to be responsible for the performance of the swarm. The MAVs do not fly straight. They rather fly in circular trajectories and periodically modify their turn rate. Though they fly in circles, this can be characterized as a flight in a global direction, since they adapt the turn rate. The trajectory results in shapes like Fig. 3. The maximum turn rate is limited to 100°/s. Agents are unable to make turns sharper than 18 m in radius. By modifying their turn rate the MAVs influence their direction and the speed in which they move towards one direction. Though our MAV model assumes a constant speed of 14 m/s the circular trajectories result in a small overall speed. This way MAVs who are already deployed and fly are able to wait for newly launched MAVs. MAVs who are further away from the base station adopt a negative heading angle. This results in a slightly curved swarm chain as seen in Fig. 3.

The swarm forms a tight chain that coherently moves from one side of the search area to the other. This results in the

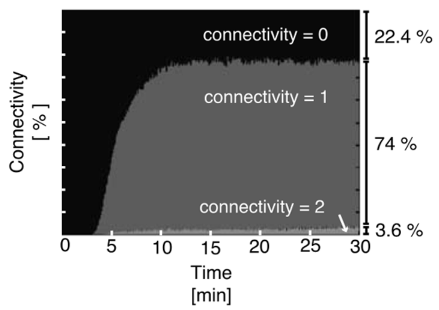

Fig. 4: The connectivity of the best evolved controller over 1000 trials. Image taken from [4].

whole swarm scanning the area. Once a user station is found and a connection is established, the swarm reorganizes to maintain the connection. For this purpose the MAVs basically adopt a hovering behavior. Since the MAVs constantly move, they adopt the smallest, for their fixed-wing architecture, possible trajectory.

It was found that after MAVs disconnect from the base they adjust their turn rate to get back to a connected state, by tracking back. This behavior is further used to synchronize the swarm. After all MAVs are launched the whole swarm will eventually disconnect from the base station. At this point all MAVs perform a backtracking operation. This results in the whole swarm synchronizing on the heading. This way all MAVs display the same heading at at given time. This results in the swarm being able to move coherently from West to East. The connection and disconnection phases are used to align all MAVs.

This issue of synchronizing a swarm via broadcasted signals has also been addressed in one article on this seminar last year [8].

D. Results

Through simulations the performance has been extensively tested and as a result the swarm was able to find more than 97% of the user stations placed within the search area. The swarm was able to maintain the communication network active throughout the remaining trial. All by just gathering informations via immediate sensors or through direct communication with neighbors. No global positioning was used. The researchers aim on being able to adapt the controllers to a variety of different scenarios in the future. The key concepts found within the artificially generated neural controllers can possibly be used to manually create controllers for a specific task.

IV. Army Ants

In this section we present another approach for the same problem discussed before: finding, establishing and maintaining a communication link to a user station placed within a search area.

The approach presented here aims on using techniques observed in nature to build bio-inspired swarm controllers for MAVs. Extensive research [9] [10] found that different army ants species have evolved different raid patterns for different food distributions. The results indicate that the observed patterns maximize the amount of food brought back to the nest. The ants use this structure as an optimized mechanism for exploring and exploiting food resources [11] .

A. The Ant Model

In the model discovered ants leave the nest at a constant rate. They navigate through a grid of Y-branches while constantly emitting pheromone. On each branch the ant chooses to turn either left or right. This decision depends on the amount of pheromone laying on the branch. The pheromone is also used as an indicator for the amount of ants who already chose to

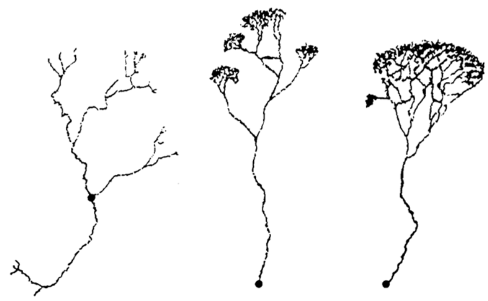

Fig. 5: Foraging patterns of different army ant species, adapted to different distibutions of food sources. Each covering some 50 m x 20 m. The image is taken from [9].

walk on a certain branch. This way the pheromone can be used to limit the number of ants deciding for a certain branch. The initial choices are made randomly, which explains the big difference in movement speed. The ants on the trails move very rapidly, they choose which branch to take very fast. Ants at the front on the other hand move much slower, with more hesitation. An explanation for this is that the explored trail is very well marked whereas the front is unmarked.

Once an ant finds a point which contains food it takes an item and returns to the nest. On the way back it lays a greater amount of pheromone on the path. This way a yielding path is signalled. Eventually the pheromone laid on a path evaporates over time.

Fig. 5 shows different army ant species, each species hunts for different food resources. For example the *Eciton hamatum*, shown on the left, hunts for widespread, scarce food resources whereas the *Eciton burchelli* shown on the right largely feeds on a single, very large food resource.

B. Searching the area

The idea of using pheromone trails for coordinating the actions of many MAVs in a swarm is described in [12]. The authors have designed a behavior for the MAVs that enables them so search the area. The problem of depositing pheromone trails could be solved by either depositing physical objects or chemicals. But depositing substrate in the air is very unstable due to the rapidly modifying environment. Depositing the pheromone on a virtual map is also not possible, since the MAVs only have local position awareness. The researchers used another approach instead: Virtual pheromone is deposited by separating the MAVs into two types: node-MAVs and ant-MAVs.

Node-MAVs form the environment in which virtual pheromone can be deposited. This is realized by the node-MAVs indicating the deposited pheromone for the left and right branch.

Ant-MAVs are then able to navigate through a grid of node-MAVs. Once they reach a node-MAV they select either the left

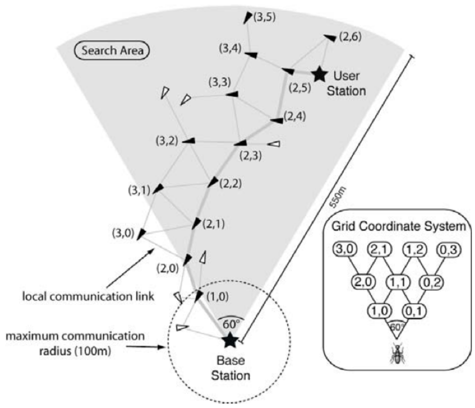

Fig. 6: A simulation of 20 MAVs establishing a link from a base station to a user station. Node-MAVs (black triangles) build a grid through which the ant-MAVs navigate using pheromone based rules. Ant-MAVs virtually deposit pheromone through local communication with the node-MAVs. The image is taken from [13].

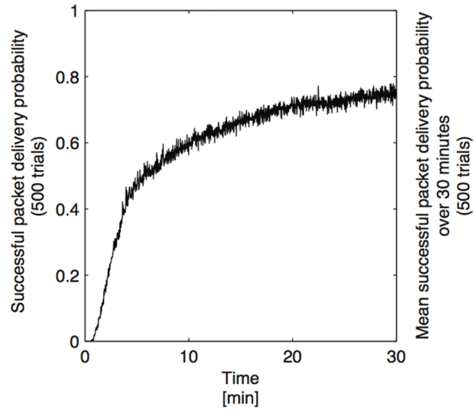

Fig. 7: The mean probability of succesfully delivering a packet increases till the end of the trial. This can be explained by the self optimizing mechanism of the MAVs: they are attracted to useful positions within the communication network. The image is taken from [12].

or right branch based on the pheromone information which the ant-MAV contains. Once they don't find any node-MAV on the other side of the path or once they lose contact with the last node-MAV they dynamically change their type and become a node-MAV.

The pheromone saved within a node-MAV gets increment once ant-MAVs walk by, but it also evaporates over a time and is limited by a maximum number. Once the pheromone is entirely evaporated the state of the MAV changes to ant-MAV. The MAV then returns back to the base node. From there it is redeployed again, meaning it selects a destination node based on the pheromone information in the base node. Then it navigates through the grid to the destination node, checks the pheromone information and selects a new destination node. While navigating towards the destination node the communication link with the last reference node will eventually break. The ant-MAV then waits for contact with the destination node. If there is no contact with the destination node after a certain time the ant-MAV will assume that is doesn't exist and change its type from ant-MAV to node-MAV. The coordinates of the new node-MAV are corresponding to the aimed destination node. The new node-MAV will also have an initial amount of pheromone.

The branch which an ant-MAV chooses to fly on is probabilistically chosen. The equations for the probability were determined on base of the natural model described in [9]. Following the model ant-MAVs favor branches with a higher pheromone amount, but there is also a parameter ensuring that unexplored directions are favored. Initially the choices are made randomly.

Through taking care of unexplored directions it is ensured, that the MAVs will eventually search the whole area. The goal of the grid navigation is not to occupy the whole search area with a grid of MAVs. The goal rather is to dynamically establish a grid in one direction and then slowly adapt it to other directions.

The problem of the swarm splitting up was taken care of by constraining the type-change of ant-MAVs to node-MAVs. Their neighbor node has to be a direct neighbor.

C. Establishing a connection

Once a user station is found the MAVs have to build and maintain a communication link from a base station to the user station. A pheromone trail is used to signal the path from the base station to the user station.

Once a rescuer is found and a link is established the network structure is optimized and stabilized. MAVs are attracted to useful positions in the network using the virtually deposited pheromone trails. This is realized by the node-MAVs being able to detect if they are on a communication path which requires the fewest packet hops from the base station to the user station, the least-hop-route. If they are positioned along such a route they will increase the pheromone on their node. The pheromone in node-MAVs which are not on a route to the user station or further away from the user station will eventually evaporate. They will then navigate back to the base node and redeploy to a new destination node. This ensures that all MAVs will eventually be aligned on a path towards the user station. This way they also form redundant pathways from the base station to the user station. This results in a self-optimizing network as can be seen in Fig. 7. The probability of a successful packet delivery steadily rises.

As shown in Fig. 6 an ideal grid would consist of node-MAVs who position themselves in a grid of Y-branches. The distance between two nodes on a branch should be approximately equal to the communication range between the two MAVs ($\approx$ 100 m) and the junction angle is approximately 60°. This angle was chosen because it maximizes the area coverage of the grid while at the same time generating redundant communication pathways.

MAVs are able to position this way because they are each assigned coordinates (i, j) in the grid. Here i and j are the number of branches the MAV needs to follow to reach a certain position. This is possible because the MAVs contain a magnetic compass and are launched from a fixed point, the base station, the root-node of the grid. Each node can be addressed by labeling them this way.

The problem of colliding MAVs has been taken care of by implementing altitude differing. The MAVs adapt their altitude due to surrounding MAVs.

D. Performance

The qualitative behavior of the swarm was evaluated using a 3D simulation. In 500 trials the swarm was able to find a randomly positioned user station in 91% of the cases. It was found that the performance of an established connection increases until the end of the trial. This can be seen in Fig. 7.

Only 2.6% of the 7.500 deployed MAVs collided with another MAV.

Through the trials the robustness of the network has been extensively tested. It has been found that even swarms with only 5 MAVs are able to find nearly 50% of the users over 500 trials and maintain a connection with them. Even with up to 98% packet delivery success. The performance of the SMAVNET however increases once more MAVs are deployed, which is due to the fact that an area can be searched faster. Also small swarms have difficulties reaching user stations positioned far away.

An animation of the simulation can be seen in the video material [14].

V. Further Research

A. Reality

The project in [15] aims on building swarm robots to validate the research previously described. Those are currently developed only in simulation and must be tested in real-life scenarios. The fixed-wing MAVs are built out of Expanded Polypropylene (EPP). They are light-weight (420 g) and have an 80 cm wingspan. They are equipped with a motor on the back and two control surfaces for controlling height and left/right movements. The MAVs are equipped with a micro-controller which gets input from 3 sensors: a gyroscope and two pressure sensors. The communication-based controllers are realized through an ARM based one chip computer running GNU/Linux. Communication with other MAVs is done using an USB WiFi dongle. The dongles were configured to use the 802.11n standard and to transmit in the 5 GHz band. This frequency was chosen because of less estimated interference with other devices, opposed to 2.4 GHz. The dongles were set in ad-hoc mode and have a communication range of about 500 m.

The flight patterns for the MAVs are derived from theses inputs, the controllers output a desired speed, turn rate or altitude which is adapted by the MAV. Under trials in real-life conditions it was found, that abrupt relative displacements between the MAV and a rescuer are a problem. Both approaches presented had the implicit assumption that the MAVs move constantly and freely. Windy conditions however might translate the MAV or even the whole swarm to a completely different location. Since the MAVs don't have any knowledge on a global state this will get quite a challenge to solve. One proposed solution is to frequently replace the MAVs by launching new ones which take the same position. The simulation results indicate that this largely reduces the drift of a swarm.

In the scenario described a rescuer would use the same WiFi dongle and software as used with the MAVs in order to communicate with them. Other research [12] proposes to use the 802.11b specification because it fits best for the technology most ground users use.

B. Other applications

There is other research on flying ad-hoc networks in a completely different context: Several projects work on using the idea of flying ad-hoc networks in a commercial context. They aim on establishing a broadband communication link into airplanes. The so called aeronautical ad-hoc networks use airplanes as hops to route packets. There is specific research done in the field of establishing a network over flight corridors like the north-atlantic [16].

Another broad research field are aerial swarm systems, organized through a global positioning system. The research aims on achieving tasks such as environmental monitoring (fire detection, toxic plume tracking), area surveillance or tracking and destroying objects.

There are also commercial applications using a swarm of flying robots equipped with cameras to build a high-resolution photographic map of an area.

VI. Conclusion

Flying swarms of robots are especially suited for applications in disastrous areas because of their flexibility and easy deployability. Since the swarm is homogenous this allows to easily remove, replace or add individuals. This makes a scalable swarm.

We have shown how different researchers aim on building swarms of MAVs without any knowledge of global positioning. To reach this goal a swarm with emergent behavior has to be created. For this purpose two approaches have been presented. They both assume a scenario where MAVs are started from a base station and search for a user station. Once found a communication link has to be established and maintained.

The first approach presented aims at artificially generating neural network controllers for the MAVs. The second approach presented aims on implementing a static set of rules, originally found in foraging patters of army ants, into controllers for MAVs.

There has not been done any direct qualitative comparison between the two approaches. The simulations conducted can not be directly related since they have slightly different conditions. The search area is chosen slightly different and the simulation was conducted in different dimensions. The ant inspired network was simulated using a 3D simulation whereas the artificial evolution approach was done in 2D space. However, both approaches are able to find more than 90% of the user stations and are able to successfully build and maintain a communication link to them. In the army ant inspired approach the network connectivity is steadily optimized due to the self optimizing nature of the network. This might be a possible indication for a better solution.

Both approaches have been tested through extensive simulation and there is current work done on translating the results into reality. This way algorithms could be validated in reality.

Through the recent Arab Spring revolutions it has become clear how repressive governments use the internet as a way to find and eliminate dissidents. A non-constrained, secure internet access is essential for the security of activists and protestors. One could imagine that the approaches described in this article could also be used to supply an area with an non-constraining, secure uplink to the internet. The approach of a small, light-weight MAV swarm is ideally suited for this scenario since the whole swarm can be operated by a single person who launches them manually by hand.

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