BioAIR: Bio-inspired Airborne Infrastructure Reconfiguration

Bo Ryu[1] Nadeesha Ranasinghe[1] Wei-Min Shen[1] Kurt Turck[2] Michael Muccio[2]

Abstract— **Maintaining constant communication between mobile entities distributed across a large geographical area is a crucial task for many commercial and military applications. For example when troops are deployed in hostile or sensor deprived environments, maintaining radio contact with a base station would increase the efficiency of coordinating the deployment, yet maintaining communications should not interfere with the primary tasks of these entities. The BioAIR system was developed to coordinate airborne communication nodes such as unmanned aerial vehicles (UAV) in order to autonomously form and maintain a dynamic communication network. This system draws upon inspirations from biological cell differentiation through hormone based communication to coordinate a swarm of airborne nodes in a distributed manner by mapping the radio signals into digital hormones.**

BioAIR offers three primary capabilities, namely collaborative communication, sensing and navigation. BioAIR performs collaborative communication by autonomously creating a mobile ad-hoc network. This network connects several designated nodes by strategically positioning other nodes based on the desired communication signal quality between them. BioAIR performs collaborative sensing by autonomously reinforcing critical locations based on network traffic, detecting any damage to the formed network, and self-repairing. Additionally, BioAIR can coordinate the sensing effort of possibly heterogeneous sensors distributed amongst all nodes in the network to form a distributed sensor network. BioAIR performs collaborative navigation by following the motion of designated nodes while maintaining the formed communication network, provided that the nodes can react fast enough.

Index Terms— **Ad hoc networks, Command and control systems, Communication networks, Decentralized control, Distributed algorithms, Intelligent Robots, Unmanned Aerial Vehicles, Wireless communication, Wireless sensor networks.**

I. INTRODUCTION

CONVENTIONALLY most autonomous mobile nodes, including unmanned aerial vehicles (UAVs), are operated remotely by human operators. As such, forming a mobile communication network to connect several airborne or ground-based nodes with multiple remotely controlled UAVs can be prohibitively costly and very inefficient because many operators are needed. Furthermore, the operators need to control the deployed UAVs, while coordinating with others and monitoring the performance of the deployed communication network. Hence, a feasible solution must support collaborative communication, sensing and navigation. BioAIR offers a solution to this problem by enabling multiple UAVs to autonomously control themselves based on network performance.

This technology can assist with a variety of commercial and military applications. For example, collaborative communication is required for applications such as communication in area-denial environments and high bandwidth internet in the sky. Similarly, collaborative sensing is required for applications such as communication in anti-access environments, remote sensing, geolocation, aerial surveillance, and border patrol. Collaborative navigation is required for applications such as target tracking, agricultural product care, mobile escorting and perimeter defense.

A successful solution to this problem must address several challenges. The first challenge is the limited range of wireless communications. To overcome this challenge, nodes must route their data traffic through their neighbors. However, in contrast to standard wireless networks, this is a mobile ad-hoc network with highly volatile connections due to environmental interference and frequent connects/disconnects. The BioAIR algorithm uses the strength of the wireless signals received by a node to determine its flying behavior, thereby allowing a node to control its connections/disconnections and minimize the chances of environmental interference intelligently.

The second challenge is coordinating the motion of nodes in a distributed manner and preventing the formation of suboptimal networks. BioAIR converts received wireless signal qualities from adjacent nodes into attractive and repulsive fields based on certain thresholds. By summing the strength and direction of these fields with virtual attraction fields from certain types of nodes that are out of range, BioAIR is able to control each node independently to accomplish the overall mission in a distributed manner.

The third challenge is flying heterogeneous airborne nodes from one point to another in a safe manner. Since most of UAVs have some limited autopilot capabilities based on GPS guidance, BioAIR commands the autopilot by monitoring the proximity sensors or the signal strengths from neighboring nodes to ensure both safety and success of the mission.

The fourth challenge is enabling one or more operators to monitor multiple nodes through a unified interface. BioAIR addresses this issue by using the formed ad-hoc network to relay control data back to centralized location and presenting a

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B. Ryu, N. Ranasinghe and W.M. Shen are with EpiSys Science Inc., Boulder View Dr. Poway, CA 92064 USA (e-mails: {boryu, nadeesha, wmshen}@episyscience.com). K. Turck and M. Muccio are with Air Force Research Laboratory (e-mails: {kurt.turck; michael.muccio}@us.af.mil).

graphical user-interface to interact with nodes when necessary.

The fifth challenge is seamlessly dealing with node failures. BioAIR utilizes any spare nodes to proactively reinforcement critical locations of the network to minimize the repair time in the event of failures.

The sixth challenge is maximizing the effectiveness of the radio network. BioAIR addresses this challenge by adjusting the position of nodes based on the criticality of data traffic.

In addition to these six main challenges there are several other factors which must be considered in a successful solution. For example the response time of the algorithm must be in a few seconds or less as the airborne nodes can fly several meters in that time. Similarly, the algorithm must minimize its communications overheads so as to reduce the network load. It must also minimize resource usage due to limitations on the amount of processing, memory and power onboard a node.

BioAIR assumes the availability of communication data and GPS location information (or a compass for direction), but no additional sensors are assumed. We also limit our scope to omni-directional radio antennas, although uni-directional antennas could be utilized with some additional overhead. The solution presented in this paper considers the latitude and longitude of each node, but largely ignores the altitude making it 2-Dimensional. However, this solution can be extended to 3-Dimensions with little effort.

The rest of this document is organized as follows. Section II summarizes the related work. Section III details the BioAIR system components and experimental setup. Section IV describes the BioAIR algorithm, with some experimental results in Section V. Section VI highlights potential future work and concludes the paper.

II. RELATED WORK

BioAIR offers a solution to coordinate the effort of mobile and stationary nodes autonomously in a distributed manner by enabling multiple unmanned nodes to control themselves using network connectivity and mission objectives. This robust solution stems from the Digital Hormone Algorithm (DHM) introduced by Shen et al in 2002 [1, 2]. The basic idea of the DHM is to form a network of nodes (aircraft, robots, ground stations etc.), propagate messages through its links without a global broadcast or uniquely identifiable nodes. BioAIR borrows the idea of digital hormone propagation to calculate both attractive and repulsive fields. In contrast to vector fields, the presence of two fields allows BioAIR nodes to influence each other and self-organize.

Some key innovations of BioAIR include the mapping of wireless signal strength (e.g. Wi-Fi strength from COTS hardware, or any similar sensor modality) to field strength, and the differentiation of fields based on two states, namely the global state of the system and the local state of the node. The global state of the BioAIR system is maintained and broadcasted to every node in the swarm periodically, while the local state is broadcasted to each node's immediate neighbors. Also, in contrast to the patented DHM algorithm, BioAIR nodes must have unique IDs or IP addresses for routing communications.

The bio-inspired BioAIR algorithm is designed and developed specifically for controlling a swarm of nodes. As such it must be compared against a few competitive swarm control algorithms such as EPFL's Swarming Micro Air Vehicle Network (SMAVNET) [3], Lakeside Labs' Self-organizing Intelligent Network of UAVs (SINUS) [4], John Hopkins University APL Co-Fields [5, 6], and UPENN's micro UAV swarm [7] etc. In contrast to these existing systems, BioAIR focuses on forming a wireless communication network between sites of interest, tracking node mobility, and self-repairing in the presence of damaged networks in a distributed manner. The SMAVNET developers have addressed some problems encountered in a partially connected ad-hoc network during search and rescue missions. They utilize an ant foraging algorithm to discover the best route to a target in a distributed manner, which admittedly takes very long to converge. In addition, such algorithms do not focus on rapid self-repair and smooth tracking. SINUS uses a centralized algorithm for sensor placement, with off-line planning.

The DHM predates Co-Fields, and it employs a natural diffusion-reaction model in contrast to the hand-crafted Co-Fields. This model has resulted in BioAIR having a repair capability that is not seen in Co-Fields. Ahmadzadeh's research focused on centralized planning which causes a single point of failure avoided by BioAIR. Focusing on BioAIR's ad-hoc network management capabilities warrants comparisons against [8], [9] and Zhan's research focuses on mathematical modelling and optimization of communications network, which in practical settings is less feasible due to interference. Gu provided a solution involving straight line node placement, but it does not factor multiple sites or repair.

III. EXPERIMENTAL SETUP

BioAIR was developed to support both fixed-wing and rotary-wing UAVs. However, the majority of testing was performed on a "hexarotor" rotary-wing platform provided by AFRL, shown in Figure 1. The payload attached to a hexarotor included an ODROID minicomputer developed by HardKernel, an Atheros Wi-Fi card connected to it, and a dedicated power pack developed by RavPower. The hexarotor's autopilot runs on a separate Raspberry PI minicomputer powered by a different supply. The ODROID and Raspberry PI communicate via an Ethernet connection through a software interface named "C3P0". C3P0 provides Global Position System (GPS) coordinates and altitude through an onboard GPS chip, and accepts target GPS waypoint coordinates.

Figure 1: Hexarotor UAV with ODROID payload

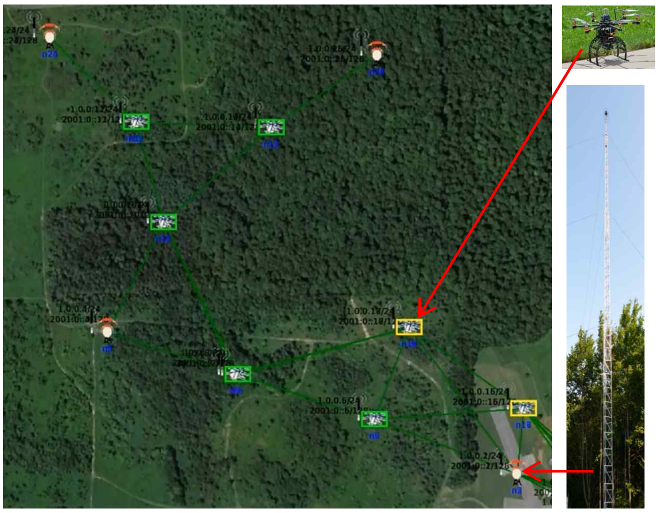


Figure 2: CORE Wi-Fi network emulator

In addition to hexarotors there were some ground-based destination and origin nodes. In this set of experiments such a node is represented by an ODROID or standard PC computer equipped with a GPS chip. Prior to performing live field tests BioAIR was thoroughly tested in simulation with hardware-in-the-loop using the Navy's Common Open Research Emulator (CORE) [10] network emulator as shown in Figure 2.

IV. BIOAIR ALGORITHM

The base case for forming a communications network is to establish the connectivity between two sites. An origin and a destination are networked together by forming a chain or a tentacle which is comprised of multiple airborne nodes. Nodes can be launched from anywhere at varying time intervals with some a priori knowledge about the location of an origin and a destination. Once connectivity is established between a set of nodes, the received signal quality is used to improve the overall performance of the network rather than the straight-line distance between them. It is important to note that typically the signal quality has exponential falloff with distance, which can change due to environmental conditions.

The idea behind this algorithm is to form tentacles from one or more origins to one or more destinations by growing them in a biological way through the accumulation of nodes as shown in Figure 3. In basic terms, initially all nodes will fly towards an origin. When a node encounters a tentacle or an origin it will fly towards the destination, and at the edge of its communication range to the existing tentacle or origin, it will hold position if it is rotary-wing or circular fashion if it is fixed-wing, thus extending the tentacle towards the destination as shown in Figure 4. When the tentacle reaches the destination, any extra nodes will construct new tentacles or reinforce existing nodes.

The BioAIR algorithm stops a node at the edge of its communications range to a neighbor by converting the received signal quality (SQ) into a field strength, which corresponds to being attracted or repelled by the nearest neighbor as shown in Figure 5.

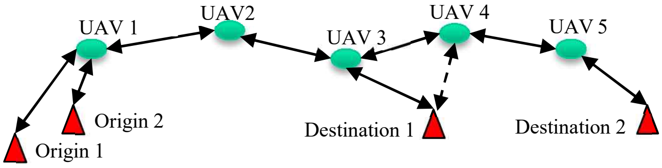


Figure 3: A tentacle connecting origins and destinations

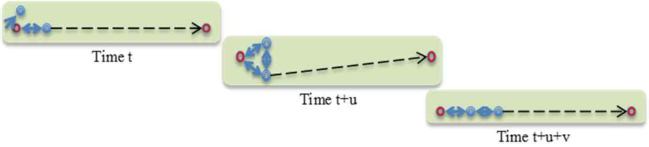


Figure 4: A tentacle growing towards a destination

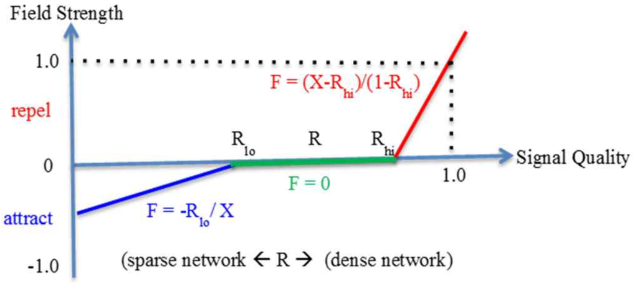


Figure 5: Profile of fields experienced by a node

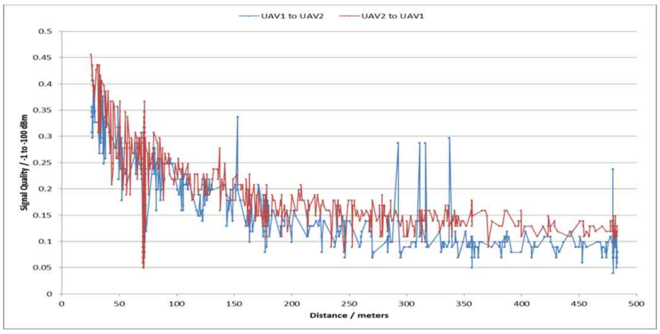


Figure 6: Actual signal quality measures between 2 airborne nodes

This field indicates that when the nodes are close to each other they repel to prevent collisions i.e. SQ > R_{hi}, when they are outside the acceptable range they attract i.e. SQ < R_{lo}, and when they are completely out of range there is no signal or field. At the onset, the destination's location is disclosed to each node to allow computation of a virtual attraction field even when it is out of range. The following equations constitute the field strength calculation and the resulting velocity components that are added to a node as a result of its neighbor's influence:

If ($X > R_{hi}$) Field = ($X-R_{hi}$) / ($1-R_{hi}$)
Else If ($X < R_{lo}$) Field = - R_{lo} / X
Else Field = 0
velocityX += Field * $(x_{self}-x_{other})/\mathrm{sqrt}((x_{self}-x_{other})^2 + (y_{self}-y_{other})^2)$
velocityY += Field * $(y_{self}-y_{other})/\mathrm{sqrt}((x_{self}-x_{other})^2 + (y_{self}-y_{other})^2)$

Figure 6 depicts real signal quality measures obtained between two airborne nodes during live field tests. Obtaining consistent signal quality measures is important to prevent the fields from changing drastically and causing erratic trajectories.

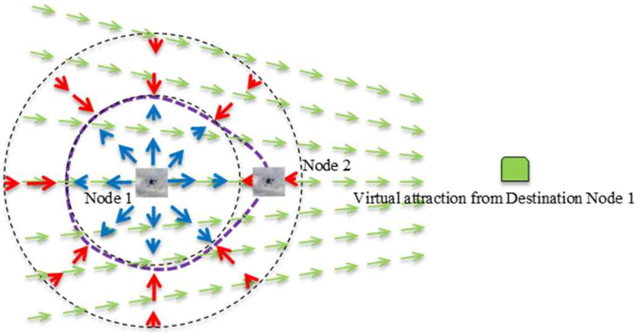


Figure 7: Fields guiding node 2 towards destination

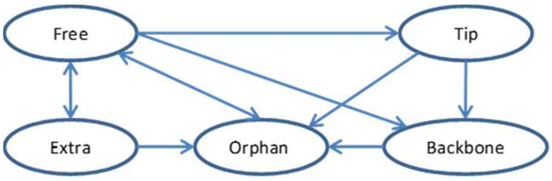


Figure 8: Valid role transitions for a node

Since there is significant variance between successive measures, the BioAIR algorithm achieves a smooth response by calculating an average value over a short interval (a sliding window). Figure 7 visualizes the fields interacting between two adjacent nodes and the destination's virtual attraction with a fixed magnitude of 1.0. The result of summing these fields is an elliptical trajectory marked in purple. This guides nodes to an equilibrium point that exists closer to the destination. Given noisy readings and the fact that a node may switch to flying in a circular pattern when it enters the equilibrium point, there is no possibility for a node to stop at the equilibrium point that exists further away from the destination.

In order to accomplish the construction and subsequent maintenance of tentacles, each node will take one of the following roles: "orphan", "free", "tip", "backbone" or "extra". The BioAIR algorithm dictates that when a node is disconnected from the tentacle or origin it is an orphan, and as such it will change its target to the nearest origin. When the origin or tentacle is detected the role will change to free. If no tentacle exists the node will reach its equilibrium point and become a tip, else it will move along the tentacle and become a new tip changing the previous tip to a backbone node. Once a tentacle reaches a destination if there are no further destinations, all free nodes become extra nodes, which are able to reinforce the existing tentacle. Figure 8 depicts the valid node role transitions.

A tentacle could be in one of the following states reflecting its progress towards connecting an origin to a destination: "forming", "complete", "next destination", "damaged" or "reinforcing". The state of the nearest tentacle is updated and communicated between all nodes within range containing the same tentacle identifier. Each node contains a list of destinations and an origin to build the tentacles from. Each tentacle is identified by a unique identifier belonging to the destination node. This tentacle identifier prevents adjacent but essentially different tentacles from interacting with each other, while allowing multiple tentacles with the same identifier to merge together in the event of concurrent construction or segmentation due to damage.

Figure 9: Valid state transitions for a tentacle

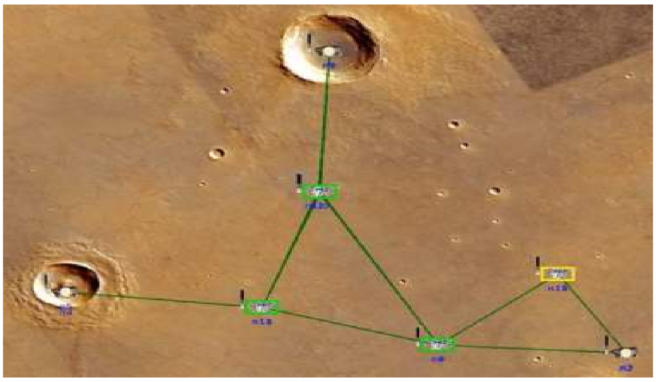


Figure 10: An extra node in yellow reinforcing an existing tentacle

Figure 9 depicts valid tentacle state transitions. In the forming state, a new tentacle is starting from an origin or a destination that has already been reached. Initially there will be no tips, but as soon as the first node reaches its equilibrium point it will become a tip. In this state the network can have some free nodes, backbone nodes, and one tip node. In the complete state, a tentacle must have at least one node between the origin and destination. When a free node reaches within communication range of a tip and the destination, it will complete the tentacle. When the tentacle is complete all nodes forming the tentacle will have the backbone role, and no tips will exist. If another destination exists, then the completed tentacle will proceed to the next destination state, which informs any free nodes to continue building in that direction rather than performing reinforcing.

In the reinforcing state as soon as a tentacle is complete, if no new destinations exist the free nodes will switch to the extra role and anchor to backbone nodes. Each backbone node will anchor one extra node such that it receives signals from two or more neighboring backbone nodes (see Figure 10).

This strategy ensures that a second tentacle is formed given sufficient nodes at a safe distance away from the first tentacle, meaning that if damage occurs the network will reroute its traffic with minimal interruption. A tentacle node must always be adjacent to two backbone nodes, a tip and a backbone node, or a backbone node and the origin or destination. If any backbone node does not meet these criteria, then the tentacle is in the damaged state. When damage is detected by a node its role changes to a tip, and any anchored extra nodes are released to perform the repair as shown in Figure 11.

Nodes can be launched from anywhere, but initially they must fly towards an origin to participate in forming tentacles. When multiple origins are available the operator must choose which one to assign for each node prior to launch, but BioAIR can reassign these dynamically based on the number of extra nodes and damage detected in the network.

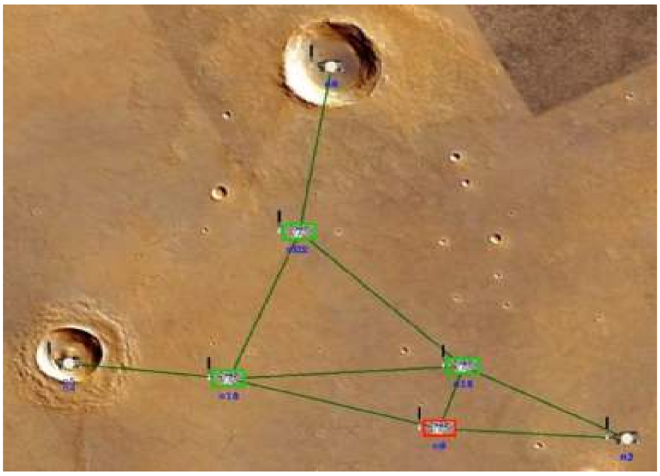


Figure 11: A damaged node in red replaced by an extra node

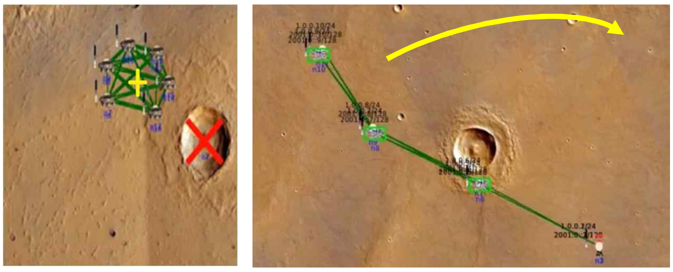
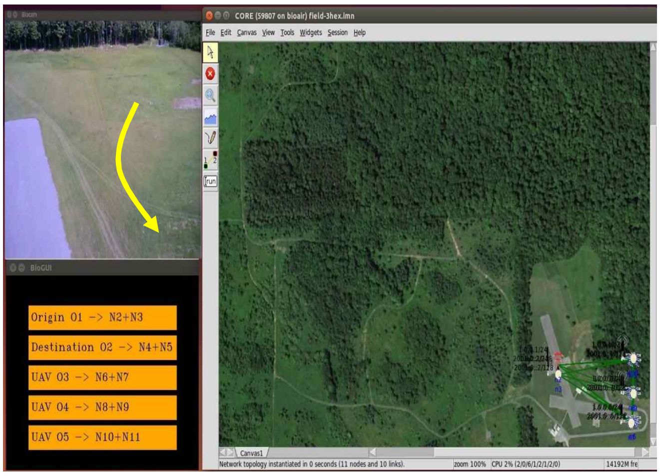


Figure 12: Swarm migration and tentacle sweep

In the presence of multiple destinations, BioAIR opts to complete a tentacle to the first destination, and then it builds another tentacle from that destination to the next, and so on. When two partially completed tentacles meet, a free node will encounter two tips resulting in BioAIR merging these tentacles into one. This process also helps repair damage at multiple locations simultaneously by forcing reinforcement nodes to arrive from the origin and the destination. All extra nodes will patrol and anchor to existing tentacles in the order the destinations where originally listed.

Another unique feature of BioAIR is the ability to alter the profiles of fields and assign virtual destination or origin locations for the purpose of changing the overall shape and/or response of communication network. For example in Figure 12 the network on the left is not tethered to an origin, instead all nodes are attracted to a virtual location. The nodes surround the virtual location, and moving it results in forming an efficient mobile escort. Also, additional fields from sensed obstacles could be added directly into the field strength calculation to ensure the safety of nodes as they move in the environment under communication constraints. Similarly, in Figure 12 the network on the right depicts a tentacle sweeping an area by moving a virtual destination defined along the perimeter of its maximum range permitted by the BioAIR configuration. This extends the applicability of BioAIR into a variety of real-world problems.



Network topology instantiated in 0 seconds (11 nodes and 10 links).

Figure 13: BioGUI with interfaces to launch, recover, localize and visualize node information

The ease of use of the user interface plays a pivotal role in enabling a single operator to monitor a swarm of airborne nodes. The objective of the graphical user interface (GUI) is to exchange information between the operator, BioAIR and the each underlying node's autopilot. This must be done in a concise, precise and timely manner. In BioAIR every node relays its data through the network to the origin or other centralized location for visualization and interaction. The initial prototype named BioGUI is shown in Figure 13. The GUI is comprised of windows to visualize sensor data such as geolocation and live camera feeds, and interactive buttons to launch or recover individual nodes. All of these features makes BioAIR a robust system for collaborative communication, sensing and navigation of mobile airborne nodes.

V. EXPERIMENTAL RESULTS

At present, there is no single well-defined performance metric which encompasses collaborative communication, sensing and navigation of multiple UAVs. Nor are there any comparable algorithms with publically available data to compare against. Therefore, in this experiment we compare the setup or formation time of a BioAIR network to what is theoretically achievable with multiple human operators manually controlling each UAV given that they stop at the same equilibrium point.

Several experiments were carried out in the real-world and in simulation by varying the distance between a tentacle's origin and destination, the number of nodes (launched simultaneously from the origin), and the direction of the tentacle. The maximum velocity of the UAVs were capped at 5 meters per second. Each simulated experiment was repeated at least 10 times to obtain averages, and cross-validated against data from about 5live field tests conducted using 2 hexarotors due to resource limitations.

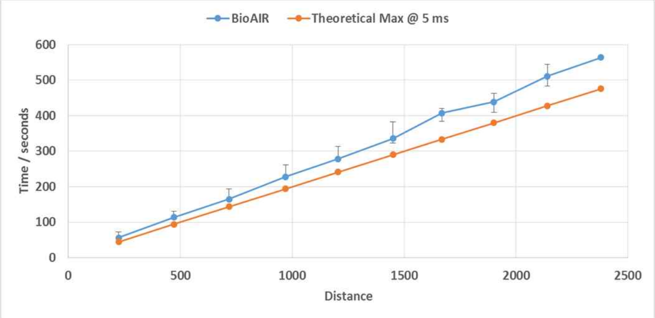


Figure 14: BioAIR tentacle formation times vs. manual operation

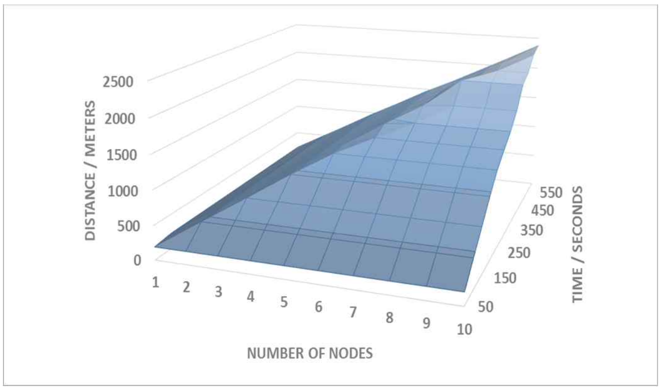


Figure 15:BioAIR scalability

The series labelled "BioAIR" in Figure 14 depicts the relationship between the distance covered by the UAVs measured in meters, and the time taken measured in seconds by BioAIR to connect the origin to the destination. The series labelled "Theoretical Max @ 5ms" in Figure 14 marks the theoretical human operator performance which was calculated purely on velocity and distance; as such it does not factor acceleration, deceleration, collision monitoring, network monitoring and fine-tuning involved in reaching the equilibrium points. The disparity in performance increases as the distance increases because greater distances require more nodes, which in turn spreads the swarm at the onset producing arced flight paths as opposed to straight lines which would result in collisions. Nevertheless, BioAIR autonomously converges to an efficient solution with desirable real-world safety and performance. Furthermore, Figure 15 depicts the relationship between the number of nodes, the distance between an origin and destination of a single tentacle, and the time taken to build it. Hence, any point below the contoured surface is a feasible solution for swarm UAV network deployment in the real-world.

VI. Conclusion & Future Work

This paper presents the BioAIR system for autonomous communication, command and control of a swarm of UAVs. The idea is to form a communication network comprised of one or more tentacles. Each tentacle grows from one or more origins to one or more destinations in a biological way through the accumulation of nodes. BioAIR enables applications which require collaborative communication, sensing and navigation of distributed airborne nodes, such as high bandwidth ad-hoc network deployment, remote sensing, geo-location/surveying, agricultural product care, border patrol, delivery of goods, and aerial tracking for law enforcement.

Presently, BioAIR is being improved by adding a centralized layer of intelligence to monitor the entire BioAIR network for anomalous behavior in the presence of external threats and catastrophic node failures. Also, the algorithm verifies bi-directional communication through simple 1-hop routing between adjacent homogenous nodes prior to making any control decisions, but the presence of heterogeneous nodes and/or other environmental conditions may require more robust network discovery and routing to be implemented. In future work, BioAIR must be extended and tested in 3-Dimensional scenarios.

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