Applicability of Swarm Intelligence to UAVs

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Abstract *— Unmanned Aerial Vehicles (UAVs) are a type of aircraft that can be controlled remotely or programmed to fly in an autonomous way. This project tested the applicability of strategies found in biological intelligence to UAVs. The UAV simulation code chosen was also discussed. Results show that some areas of the biological strategies translated were translated as they are exhibited on animals and plants. Other areas are translated differently since UAVs have either more capabilities than the different animals and plant in question or different capabilities. The applicability of biological strategies to UAVs is dependent on the capabilities of UAVs and the priority of the task that the swarm has to do. In applying these strategies of biological intelligence to UAVs, new possibilities can be introduced that will allow the UAVs to perform tasks in different ways and use different strategies that will improve UAV security.*

Key Terms *— Artificial intelligence, Biological intelligence, Swarm intelligence, Unmanned aerial vehicles*

INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are a type of aircraft that can be controlled remotely or programmed to fly in an autonomous way. They can be used for different types of applications as individual entities, both in military and civil tasks [1]. UAVs have been used for things like surveillance, search and rescue, agriculture, or forestry [2]. Swarm intelligence in UAV is categorized as an NP-hard problem that has been tackled by a number of different algorithms and models that deal with different areas of swarm intelligence. Some of these algorithms and models used have been inspired by different things that are seen in nature [3]. Some of these include Ant Colony Optimization (ACO), Bee Colony Optimization (BCO), Particle Swarm Optimization (PSO), Flower Pollination Algorithm (FPA), and Generic Algorithm (GA) [4] [5].

Jackson & Ratnieks [6] makes the argument that, from a biological perspective, the work to use mathematical and computational models to show how ants solve problems such as selecting the shorter of two paths between food and nest or selecting the better food source when presented with two of differing quality oversimplify how these biological processes occur. Because of this oversimplification, before this term, an extensive literature review was conducted to explore biological intelligence. The insights found before the start of this academic term are grouped into three categories: social structures, communication, and anti-predation. The goal of the project is to test the applicability of the insights gained from looking at biological intelligence in swarm UAVs using simulations. By incorporating the biological intelligence to swarm UAVs, we can not only improve the ways that UAVs complete tasks, but also make the UAV swarm able to handle different threats.

This work is based on the publication of the paper "Swarm Intelligence and UAV Security" on the The 23rd International Conference on Artificial Intelligence. An extensive literature review was conducted to investigate instances of swarm intelligence in biology. Intelligence of the following animals and plants were explored: ants, bees, fish, birds, wild guinea pigs, whales, dolphins, lizards, and wind-dispersed trees. The findings were organized into three categories: social structures, communication, and anti-predation.

METHODS

The different findings from the "Swarm Intelligence and UAV Security" paper were examined to assess their applicability to UAVs. After the analogy is completed, those areas that didn't have an applicability to Swarm UAVs were eliminated from the scope of this project. All other areas were examined to see which ones would be focused on in the simulation phase of the project.

The first area chosen to translate to UAVs was the strategy of wild guinea pigs to stop foraging, lift their heads up, and scan for intruders. The second area chosen to translate to UAVs is the wind-dispersed trees strategy of distributing empty seeds along with real seeds to deter predators from trying to find real seeds. The third area translated was the organizational structure of whales, dolphins, and fish: groups that assemble and disassemble throughout the day.

The fourth area translated was the separation of UAVs from an original swarm to form their own swarm, based on the ant strategy of budding, where a group of queens and workers separate from the original colony to form their own. The fifth area translated was the way that ants from monogyne colonies (colonies with one queen) respond to the queen dying. The sixth area translated from biological intelligence to UAVs was the communication strategy of the *Aenictus* ant where the pheromone communication has multiple components.

In the simulation that was chosen to base the implementations of the chosen strategies mentioned, there is a swarm of UAVs that has three intruders (identified in red) travels a search space. There is a leader UAV that is not visible and three squadron UAVs that are of different color to the rest of the swarm. The rest of the swarm follows that leader throughout the simulation. At a defined time frame, the squadron drops below the swarm to scan for intruders. Once that scan is complete, the squadron blasts the intruders out of the sky. After that defined time frame the squadron are below the swarm is over, the squadron joins the rest of the swarm until the end of the simulation.

RESULTS

In this section, the result of the translation of each instance of biological intelligence chosen to UAVs are presented. The way that these results are presented are structured as follows. A review of the strategy that the animals or plants use to survive, communicate, or organize themselves is first presented. Then, the changes made to simulation code chosen as the base for this project are presented, along with how the strategy implementation looked like in each simulation.

Strategy 1: Wild Guinea Pig Stop and Scan

The Wild Guinea Pig Stop and Scan Simulation is based on the wild guinea pig anti predation strategy of scanning their environment during their foraging bouts. The idea is that during their foraging bouts, the wild guinea pigs would stop foraging, pop their heads up, and scan their environment for predators.

The guinea pig anti predation strategy was translated to UAV by programming all the UAVs that are not intruders to stop moving after the squadron drops below the swarm. Then the UAVs scan their environment for anything that moves. Anything that moves is an intruder that needs to be blasted out of the sky.

All of the UAVs are following the leader UAV. In time 500, the squadron drops below the swarm. After the Squadron moves below the swarm, all of the UAVs that are not intruders stop moving (Figure 1). This would allow the squadron to identify the intruders by scanning their environment for anything that moves. Once those intruders are identified, the squadron takes down the intruders (Figure 2). Then the squadron rejoins the rest of the swarm. Any UAV that is about to hit one of the four corners of the mission space is bounced back.

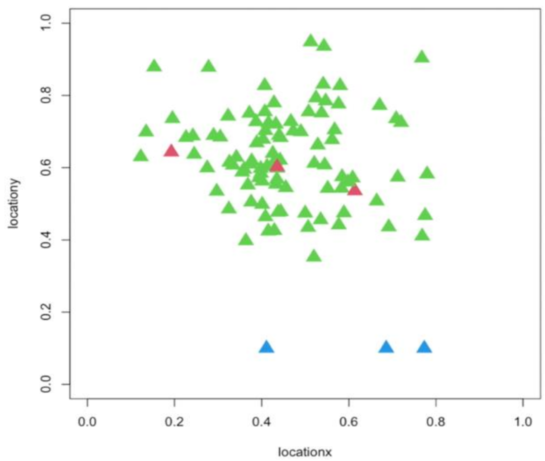

Figure 1
The Swarm freezes, while the Intruders keep moving

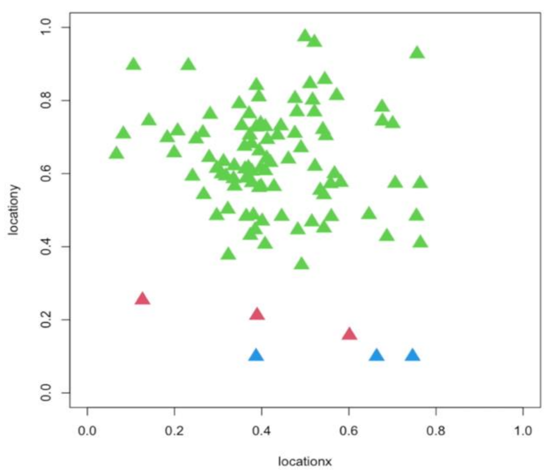

Figure 2
The Squadron taking down Intruders

Strategy 2: Empty Seed Simulation: UAVs Serving as Decoys

The Empty Seed Simulation is based on the anti-predation strategy of wind-dispersed trees. Wind-dispersed trees distribute empty seeds along with real seeds to deter predators from going after the real seeds. The principle translated to UAVs was the use of decoys to distract intruders from what the goal of the swarm is. The swarm UAVs used for the simulation were composed of a leader UAV, three intruders, three squadron, a decoy leader and twenty-five UAVs.

The decoys follow the decoy leader, but their movement is towards the outskirts of the rest of the UAVs, like the basketball players that are tasked with being as far out of where the play is taking place, so their defender becomes a non-factor. Shortly after the decoy swarm manifest themselves (Figure 3), the intruders start following them (Figure 4). The squadron drops below the swarm sometime after and takes the intruders down. As soon as the intruders are gone, the decoy swarm turns back to being green triangles and rejoins the rest of the swarm. The squadron also rejoins the rest of the swarm.

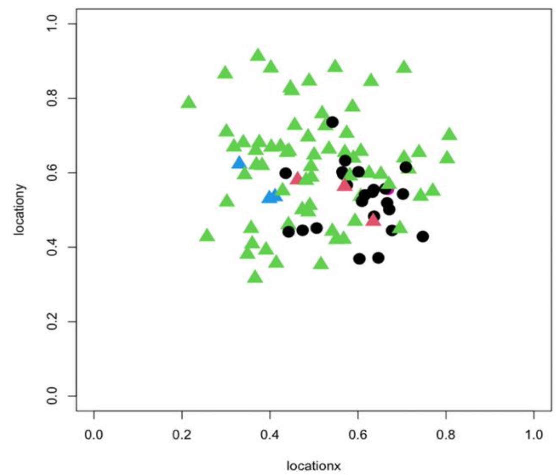

Figure 3
The Decoy Swarm reveals itself

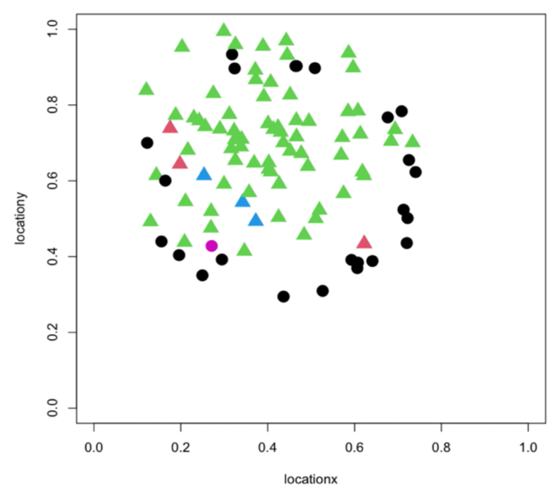

Figure 4
The Decoy Swarm and the Intruders go towards the outskirts of the rest of the Swarm

Strategy 3: Whale, Dolphin, and Fish High-Fission-Fusion Dynamics

This simulation is based on the whale and dolphin social structure of there being groups that would have members leave and join other groups throughout the day. Two versions of this simulation were created. The first is the group change with homogeneous UAVs, meaning that all UAVs are of the same type. The second is the group change happen with heterogeneous UAV. This means that there is more than one type of UAVs present in each swarm. This is consistent with the social structures of school fish and flock of birds that can be either of the same species or multi-species.

For this simulation, two swarms of fifty UAVs come together and have several UAVs from one group stop being members of that group and joined another. Forty-nine red UAVs started on the top of the space moving downwards and forty-nine blue UAVs started at the bottom of the space moving upwards. Then both swarms slightly passed together in the middle of the space, both swarms stop movement to allow the UAVs to change groups. The way that the swarms stopped movement is the same as the Wild Guinea Pig Stop and Scan simulation. In this case, ten members of the red group change from being a member of the red group to be a member of the blue group and follow the leader of the blue group. This change is shown by having the UAVs change to green before turning blue to highlight the UAVs that are changing (Figure 5 and 6 for the homogeneous swarm and Figure 7 and 8 for the heterogeneous swarm). Then, both groups would continue their way to complete other tasks.

Strategy 4: Budding Simulation

The budding simulation is based on the behavior of invasive species of ants where a group of queens and workers separate from the original colony to form a new colony. The budding simulation was implemented based on the whale and dolphin group change simulation. The translation of this strategy entails having a swarm of UAVs head from one task to another and at some point in the journey a group of UAVs would split from the original swarm, form their own mini swarm, and go in a different direction to the original swarm.

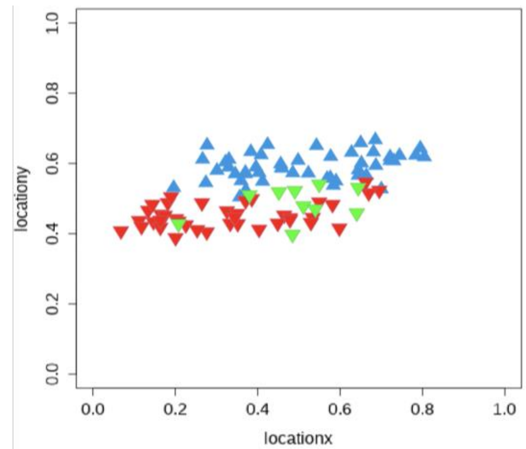

Figure 5
The Swarms crossing each other and beginning the Group change for the Homogeneous Swarm

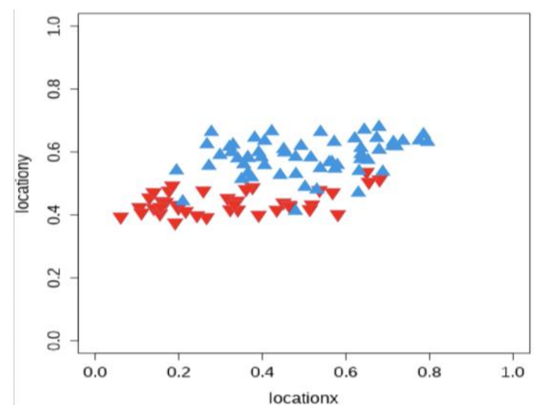

Figure 6
The Swarms finishing the Group change for the Homogeneous Swarm with the Blue Swarm having 60 UAVs and the Red Swarm having 40 UAVs

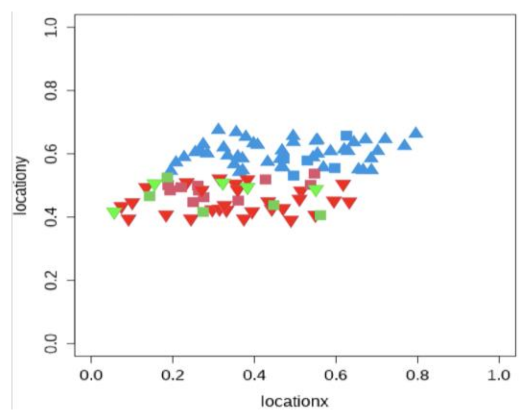

Figure 7
The Swarms crossing each other and beginning the Group change for the Heterogenous Swarm

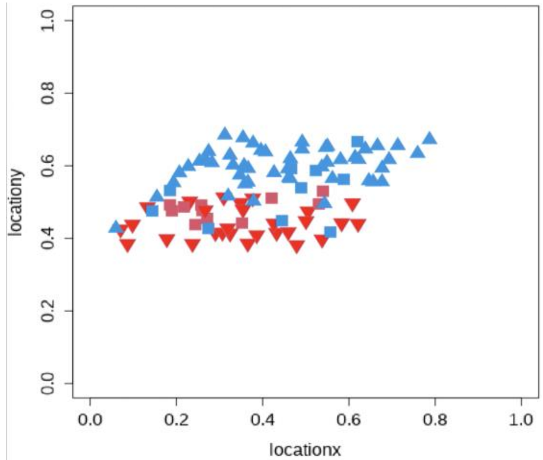

Figure 8
The Swarms finishing the Group change for the Heterogeneous Swarm with the Blue Swarm having 60 UAVs and the Red Swarm having 40 UAVs

For this simulation, the assignment of the groups part of the code was modified to initialize all UAVs as blue triangles that go from the bottom of the search space to the top of the search space at a 45-degree angle. The part of the code that execute the change in members of the red swarm to blue swarm in the group change code was modified so that the UAVs with id numbers 90 to 100 would separate from the original group. This was done by making the UAV with id number 90 the leader and changing the shape of all UAVs from regular filled triangles to triangle pointing down that were red (Figure 9). The color of the UAV with id num 90 was changed to have no color. The direction and degrees in which these UAVs travel changed from 45 degrees to 225 degrees (which make the change be from moving in an upward direction to moving in a downward direction).

Another modification made to the group change code for the implementation of the budding strategy is that the if loop that govern the movement of the UAVs before the mini swarm splits from the original swarm got modified so that all UAVs move in the same direction. Then, the if loop that govern the movement of the UAVs after the UAVs split from the rest of the swarm was modified to account for the change in which are the id numbers are used for the UAVs that splits from the original swarm.

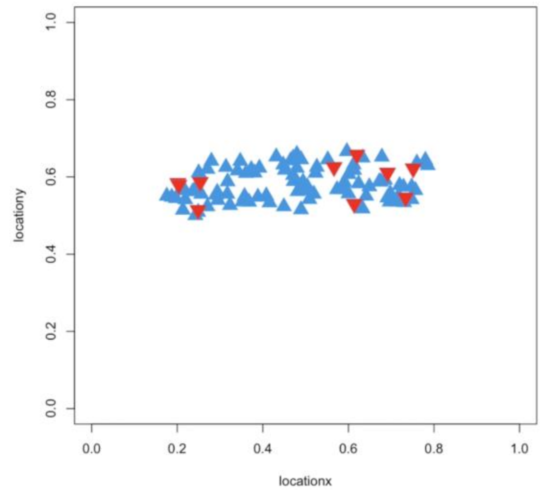

Figure 9
Ten UAVs splitting from the Original Swarm and going the Opposite Direction

Strategy 5: Response to when the Leader Goes Down

The “leader goes down” simulation is based on how ants from monogyne colonies respond to when the queen dies. When the queen dies, there is no longer a release of the queen pheromone. This means that at a certain point after the queen dies, the ants will no longer have the queen’s pheromones to go by. This is a moment where their social structure is threatened, since one of the fundamental components of that structure is compromised. The response of the colony when they sense that there is no longer a queen in the colony is for one of the female ants that have the queen genotype in a suppressed state goes through the process of transformation that entails having the gene activated and start emitting the queen pheromone. The worker ants start responding to the new queen’s pheromone and the social structure of the colony is restored.

One major difference between ants and UAVs is that the UAVs don’t necessarily have to wait for the leader’s virtual pheromones to decay until they sense that the lead UAV has been taken down. UAVs can use other mechanisms to determine whether the lead UAV has taken down. Not all

UAVs have to know that the leader has been compromised for the new leader to emerge. All it takes is for one UAV to realize that their organizational structure has been compromised to "decide" to spring into action.

The scenario that was simulated started off with a swarm of 100 UAVs. There was one lead UAV, 3 squadron, 3 intruders, and 93 other UAVs that don't have a defined role. They all start with movement that is independently from each other, following the lead UAV. For better visualization of the leader in this simulation, the leader UAV is shown as a purple triangle. At some point the lead UAV gets taken down, which is shown in the simulation by the UAV changing color to black and then going down past the plot space (Figure 10). When the location on the y axis of this leader is less than -3, the UAV chosen to be the leader emerges as a leader. For the sake of this simulation, that entails changing colors from green to purple and increasing in speed to match the color and the speed of the initial UAV leader (Figure 11). The other UAVs then stop following the initial leader and follow the new UAV leader. The squadron then goes below the swarm and takes out the intruders. Once the intruders are out of the picture, they rejoin the swarm.

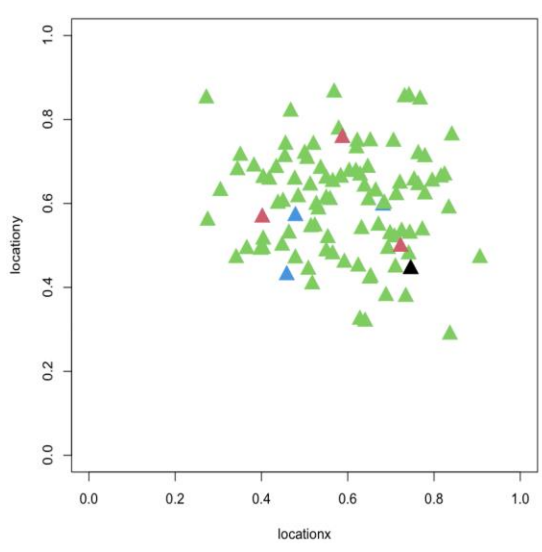

Figure 10
Leader gets take Down

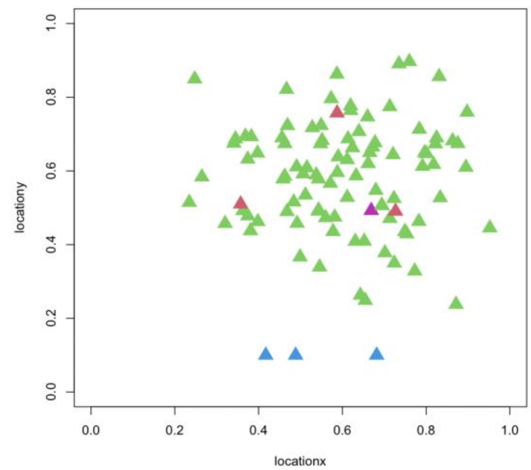

Figure 11
A UAV has detected that a leader is not present and steps up as a leader

Strategy 6: Communication with Messages having Multiple Components

The behavior translated in this simulation is the communication strategy that ants of the species *Aenictus* use to communicate. Pheromone communication in this genus of ant has multiple components. The first is a primer component and then there is a releaser component. For the ants to perceive the releaser component and, therefore, the totality of what is communicated, they must have perceived and responded to the primer component first. UAVs do not perceive chemical components like ants do, which makes the translation of this strategy look different for UAVs than it does for ants.

The start of this simulation is the same as the budding simulation, since this simulation was based on the budding simulation. All UAVs start on the bottom of the space moving upwards. Then, all of the UAVs in the swarm that are not intruders receive the first instruction, which is the equivalent to the primer component of the digital message. In this simulation, the first "digital message" is to "turn" the bool variable receive from FALSE to TRUE.

A bit after the first message gets executed, all UAVs receive the second set of instructions, which is the equivalent of the releaser component in ants. The second "digital message" is for the UAVs that have that variable receive set to "TRUE" to change direction from moving upwards to moving downwards, the shape from a triangle pointing upwards to a triangle pointing downwards, and the color.

The result of this change is that anyone that still has the original shape, the original color, and is still heading in the original direction is an intruder that the squadron should target. For the sake of this simulation, all UAVs are still following the leader, which means that the intruders have fallen behind the rest of the swarm (Figure 12). This allows for the squadron, which return to their original shape and color to take down the swarm, can do so in a more targeted way.

After the intruders are taken down, the rest of the swarm returns to the original shape, color, and direction.

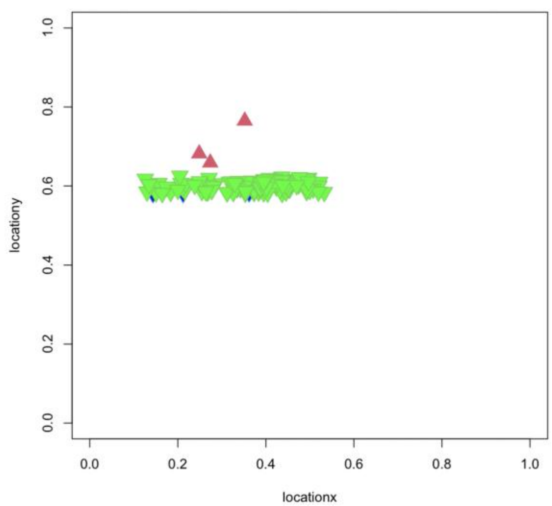

Figure 12

UAVs in the Swarm that are responding to the Second set of Instructions based on receive Value

DISCUSSION

This Master's Project investigated the applicability of instances of biological intelligence in swarm UAVs. The strategies chosen were the wild guinea pig stop and scan strategy; the wind-dispersed tree empty seed strategy; assembly and disassembly of groups in whales, dolphins, and fish; ant budding strategy; how to respond when the ant queen dies; the multiple component pheromone communication strategy in *Aenictus* ants; and the security of social structures based on ant monogyne and polygyne colonies.

The wild guinea pig "Stop and Scan" simulation is based on the guinea pig anti predation strategy of scanning their environment during their foraging bouts. Guinea pig stop and scan strategy is limited by the reality that they can either avoid or run away from predators. UAVs do not have that limitation. UAVs can either take a defensive or an offensive response strategy. UAVs can choose the strategy based on the intruder's action on the different capabilities of the swarm and the intruders.

Wind dispersed trees use the anti-predation strategy of spreading out empty seeds along with real seeds to increase the survivability of the real seeds, the predators can have up to fifty percent chance of finding empty seeds, which would deter them from persisting in the search for real seeds. In UAVs, there are two possibilities to carry out this strategy. The first is to have a part of the swarm be the decoy. This could have the intruders follow the decoy swarm instead of the original swarm, which can allow the original swarm to complete their mission. This strategy also has the implication of sending the decoy swarms on a suicide mission, but this is better than sending humans on a suicide mission just to have them serve as a decoy.

In the UAV group change simulation, the UAVs can determine what is needed to complete a task. Then two groups that do not have the requirements to complete any task can come together and have UAVs change groups to accommodate the current need. Then both groups can go on their way.

The budding strategy in ants entails a group of queens and workers separating from the original colony to form a new one a certain distance from the original swarm. UAVs can use this strategy to allow a swarm that has more UAVs than is needed to do a particular task to reduce their number of UAVs and be more efficient in operations. UAVs do not necessarily need to have the classification of certain roles to achieve this strategy.

The way that ants respond when the queen goes down depends on the decay of the queen's pheromones. UAVs do not necessarily have to wait for something after the UAV leader goes down before responding to the event because UAVs can use other sensory means to perceive that the UAV leader has been compromised or taken down quicker. This would make the strategy in UAVs activate quicker and that will improve on UAV security when this type of event occurs.

CONCLUSION

Six strategies were tested to determine the applicability of biological intelligence to UAVs. The results show that some areas of the biological strategies translated were translated as they are exhibited on animals and plants. Other areas are translated differently since UAVs have either more capabilities than the different animals and plant in question or different capabilities. The applicability of biological strategies to UAVs is dependent on the capabilities of UAVs and the priority of the task the swarm executes in a simulation. In applying these strategies of biological intelligence to UAVs, new possibilities can be introduced that will allow the UAVs to perform tasks in different ways and use different strategies that will improve UAV security.

REFERENCES

[1] G. Varela, P. Caamamo, F. Orjales, A. Deibe, F. Lopez-Pena, and R. J. Duro, "Swarm intelligence based approach for real time UAV team coordination in search operations," *2011 Third World Congress on Nature and Biologically Inspired Computing*, 2011.

[2] M. R. Brust and B. M. Strimbu, "A networked swarm model for UAV deployment in the assessment of Forest Environments," *2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, 2015.

[3] Q. V. Pham, D. C. Nguyen, S. Mirjalili, D. T. Hoang, D. N. Nguyen, P. N. Pathirana, & W. J. Hwang, "Swarm intelligence for next-generation wireless networks: Recent advances and applications," *arXiv preprint arXiv:2007.15221*. 2020.

[4] E. Chen, J. Chen, A. W. Mohamed, B. Wang, Z. Wang, and Y. Chen, "Swarm intelligence application to UAV aided IOT data acquisition deployment optimization", *IEEE Access*, vol. 8, pp. 175660–175668, 2020.

[5] H. B. Duan, S. Shao, B. W. Su, and L. Zhang, "New development thoughts on the bio-inspired intelligence based control for Unmanned Combat Aerial Vehicle," *Science China Technological Sciences*, vol. 53, no. 8, pp. 2025–2031, 2010.

[6] D. E. Jackson and F. L. W. Ratnieks, "Communication in ants," *Current Biology*, vol. 16, no. 15, 2006.