Final Technical Report

GRANT # : **N62909-18-1-2176**
PRINCIPAL INVESTIGATOR : Pascal Bouvry
INSTITUTION : University of Luxembourg, SnT
TECHNICAL OFFICER: Ayodeji O Coker
GRANT TITLE : HUNTED
AWARD PERIOD : 15 August 2018 - 14 August 2021

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
12/10/2021	Final	08/15/2018-08/14/2021

4. TITLE AND SUBTITLE
NICOP - HUNTED - Heterogeneous multi-swarms of UNmanned auTonomous systEms for mission Deployment

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N62909-18-1-2176

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bouvry, Pascal; Danoy, Grégoire; Stolfi, Daniel, H.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITE DU LUXEMBOURG ETABL. PUB
2 avenue de l'université
L-4365 Esch-Sur-Alzette
LUXEMBOURG

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research Global
86 Blenheim Crescent
Ruislip MX HA4 7HB
United Kingdom

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The HUNTED project aims at designing a novel generation of mobility models for heterogeneous multi-swarms of Unmanned Autonomous Systems (UAS) for surveillance and tracking of imminent threats. Such swarms are composed of several vehicles moving in an autonomous and coordinated manner in the air, on the ground, and in the sea. Each of them can embed different sensors (e.g., video, infrared, radar) ensuring complementarity and resilience. This document summarizes the technical achievements during the 3-year HUNTED project.

15. SUBJECT TERMS
swarm intelligence, Unmanned Autonomous Systems, bio-inspired approaches, chaotic dynamics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Bouvry Pascal
					19b. TELEPHONE NUMBER *(Include area code)*
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OBJECTIVE :

The HUNTED project (Heterogeneous multi-swarms of UNmanned auTonomous systEms for mission Deployment) aims at designing a **novel generation of mobility models for heterogeneous multi-swarms of Unmanned Autonomous Systems (UAS)** for surveillance and tracking of imminent threats.

Such swarms are composed of several vehicles moving in an autonomous and coordinated manner in the air, on the ground, and in the sea. Each of them can embed different sensors (e.g., video, infrared, radar) ensuring **complementarity** and **resilience**. While the UAS are conducting their mission in a fully autonomous manner, connectivity to one or multiple base stations is optimized which will ensure an efficient and reliable collection of data for further post processing and decision making by the ground forces.

Such systems are still poorly developed because of the intrinsic difficulty to obtain an efficient global behaviour while relying on local decisions from distributed and heterogeneous entities.

APPROACH:

The HUNTED project is the first of its kind to exploit the determinism of chaotic dynamics and adaptive clustering to create a unique cooperation approach where entities communicate across pheromone maps to build a **synergetic alliance** between heterogeneous swarms. Extending this scheme to UAS missions using various swarm behaviours borrowed from nature can unleash an **immense potential** for innovative and efficient solutions.
HUNTED introduces a classification of heterogeneous swarms of UAS as a network composed of homogeneous swarms evolving in the air, on the sea and land. Our **disruptive mobility models** are divided in three primary classes: *Inter-swarm level models*, *Intra-swarm level models*, and the related *Networking and Communication models* which also correspond to three core work packages of the project, WP2, WP3 and WP4

Each level will be addressed with innovative methods specifically designed for each class:

- WP2 - *Inter-swarm level models:* **Bio-inspired approaches** will be designed for the inter-swarm level where independent swarms share a virtual resource, i.e. pheromones map. The main objective is to allow the UAS to develop collective behaviors in order to solve a common problem.

- WP3 - *Intra-swarm level models:* **Chaotic dynamics** will be used to define mobility models to coordinate UAS in each swarm. The objective is to have an **autonomous and fully distributed algorithm** that permits to obtain unpredictable yet efficient **UAS trajectories** for different missions. By using different kinds of swarm formations relying on chaotic dynamics, UAS will develop different exploration abilities which is required considering the potential context evolution.

- WP4 - _Networking and Communication:_ **Adaptive clustering** methods will be designed to provide an optimized **communication and networking** layer for the intra- and inter-swarm level. Swarms can divide themselves into several smaller swarms increasing the system's **adaptive capabilities** and thus increasing the mission success rate.

ACCOMPLISHMENTS:

(This ACCOMPLISHMENTS section should describe concisely the accomplishments of the entire granting period)

WP2: _Inter-swarm level models_

- **Attractor Based Inter-Swarm collaborationS (ABISS) mobility model** [1]: ABISS has been designed for improving the surveillance of restricted areas performed by several homogeneous swarms of unmanned autonomous vehicles, e.g. Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV). The ABISS model parameters, including the collaboration willingness, have been first studied using a state-of-the-art sensitivity analysis method (i.e., Morris) and then optimized using a dedicated evolutionary algorithm (EA). The obtained configurations permitted to improve the coverage of the surveillance area, while also promoting collaboration between swarms.
- **Multi-swarm chaotic mobility model** [3]: The surveillance system has been extended to a multi-swarm one where UAVs, UGVs and UMVs collaborate to achieve early detection of escapers from a restricted area. A new chaotic mobility model called CROMM-MS (Chaotic Rössler Mobility Model for Multi-Swarms) was introduced. A new Competitive Coevolutionary Genetic Algorithm (CompCGA) was designed to optimise the vehicles' trajectories as well as the escapers' evasion ability using a predator-prey approach.

WP3: _Intra-swarm level models_

- **Bayesian optimization to select Rossler system parameters used in the Chaotic Ant Colony optimisation for Coverage (CACOC) mobility model** [2]: Evaluating a single parameter configuration of CACOC is computationally very demanding. We have thus investigated the usage of a surrogate-based optimization method relying on Bayesian optimization to efficiently explore the parameter space of the Rossler system for CACOC, in order to improve the resulting area coverage performance of the swarm. The Bayesian optimization permitted to obtain CACOC parameterizations that improve the speed of coverage of the UAV swarm compared to the previously existing configuration based on expert knowledge.
- **Enhanced Intra-level coordination using cooperative evolutionary techniques** [9] : a set of parameters, namely pheromone amount, pheromone radius, and pheromone scan depth, has been defined to increase area coverage when the UAVs are performing

surveillance tasks. Each UAV parameter has been optimized independently using a specifically designed Cooperative Coevolutionary Genetic Algorithm (CCGA).

- **Collaborative/Competitive Coevolutionary Optimization of a Predator-Prey model** : building up on the optimized parameters, we have proposed a Predator-Prey model to test our surveillance system in a more realistic scenario where not only the area coverage matters but also the ability of the swarm to detect intruders. To this end, we have defined an intelligent intruder (prey) model to avoid UAVs (predators). The UAVs' configuration has been optimised using a specifically designed cooperative coevolutionary genetic algorithm (CCGA) [7]. The next step of the study additionally optimised the intruders model by performing competitive tournaments for training and testing our specimens [8]. Finally, we have improved the competitive approach by developing the Competitive Coevolutionary Genetic Algorithm (CompCGA) [5].
- **CONcentric Swarm mObiLity modEl (CONSOLE)** [4]: this new swarm-based surveillance system arranges UAVs in concentric security rings and uses solutions of chaotic systems as well as virtual pheromones to improve early intruder detection. An Evolutionary Algorithm (EA) was specially designed and tuned for optimising CONSOLE's parameters and its better performance than five state-of-the-art mobility models, namely MAMM, MAMM2, CROMM, CACOC, and CACOC+.
- **Game-theoretical swarm mobility model** [6]: the SuSy-EnGaD model is a surveillance system enhanced by games of drones. It is based on cooperative UAVs that explore the area of interest arranged in concentric rings (i.e., relying on the CONSOLE model). It features a compromise between maximum flying time (most UAVs in the innermost ring) and maximum area coverage (a smart strategy to fly by different rings according to each UAV's battery state). Three different approaches have been introduced and their parameters optimised using multi-objective genetic algorithms in order to obtain the best strategy.

WP4: *Networking and Communication*

- A genetic algorithm (GA) was proposed to **optimize the exchange of pheromone maps** used in a novel parameterized version of the CACOC (Chaotic Ant Colony Optimisation for Coverage) mobility model named CACOC+ . Experiments have been conducted using realistic simulations, which also permitted to assess the impact of packet loss ratios on the system's reliability and area coverage performance. Initial results have been published as a short paper in [11] and the final experiments as a full paper in [12].

WP5: *Validation*

- **High-level simulations**: a simulation model called Hunted-Sim and its visualization environment have been developed specifically for the project. Initially based on Python and then ported to C++, it permits to implement different mobility models using also different types of vehicles. Pheromones, attractors, as well as intruders and collision avoidance algorithms are also included. Hunted SIM has also been extended to multi-swarm systems. An article on the Hunted SIM and the different UAS swarming mobility models it includes has been accepted and presented in [10].

- **Realistic simulations**: Realistic simulations have been conducted using the multi-physics robot simulator ARGoS which permits to accurately simulate the UAS physics but also the data transmission model. Examples of HUNTED simulations are made available on the project website (https://hunted.gforge.uni.lu/results.html).

CONCLUSIONS *:*

The HUNTED project has resulted in the design and validation of several novel mobility management algorithms for both intra and inter swarm mobility management for UAS. These models rely on different unique combinations of nature inspired (pheromone-based), chaotic dynamics and game theory. Empirical evidence of their better performance than the state-of-the-art approaches has been provided on surveillance and detection/tracking use cases using high-level and/or realistic simulations.

SIGNIFICANCE : The HUNTED project has demonstrated that it is possible to design efficient distributed behaviors for (multi-)swarms of UAS for surveillance and tracking missions through a first of its kind integration of state-of-the-art solutions: bio-inspired approaches, chaotic dynamics and game theory.

PATENT INFORMATION : No patent has been filed.

AWARD INFORMATION :

- Promoted to the **University Rectorate** (Rector, Vice-rector for Research and Dean of the Faculty) and broader audience. This included a visit of Dr. Ayodeji Coker, Dr. Predrag Milojkovic and Lt. Col. Shad Reed at the University on October 16, 2018. The visit was followed by a news article on the University website: https://wwwfr.uni.lu/fstm/actualites/prestigious_award_from_us_navy
- Promoted at the **Interdisciplinary Center (SnT) level** and broader audience via a news on the SnT website: https://wwwfr.uni.lu/snt/news_events/snt_drone_team_wins_prestigious_us_navy_award
- A **HUNTED project website** has been created and updated during the project. It provides information on the project goals, members, results, publications and presentations : https://hunted.gforge.uni.lu
- All 11 publications and conference/team presentations referring to the HUNTED project acknowledge the received award.

PUBLICATIONS and ABSTRACTS (for total period of grant) :

Total of **five accepted journal articles and six international conference articles** while one journal article and three conference articles were initially targeted. One additional journal is under review.

Journals:

1. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. Emerging inter-swarm collaboration for surveillance using pheromones and evolutionary techniques. Sensors, 20(9):2566, 2020.
2. M. Rosalie, E. Kieffer, M. R. Brust, G. Danoy, and P. Bouvry. Bayesian optimisation to select Rössler system parameters used in chaotic ant colony optimisation for coverage. Journal of Computational Science, 41:101047, 2020.
3. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. UAV-UGV-UMV multi-swarms for cooperative surveillance. Frontiers in Robotics and AI, 8:5, 2021.
4. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. CONSOLE: intruder detection using a UAV swarm and security rings. Swarm Intelligence, 2021.
5. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. A competitive predator–prey approach to enhance surveillance by UAV swarms. Applied Soft Computing, 111:107701, 2021.
6. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. SuSy-EnGaD: Surveillance System Enhanced by Games of Drones, IEEE Transactions on Aerospace and Electronic Systems (Submitted)

Conferences:

7. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. Optimizing the performance of an unpredictable UAV swarm for intruder detection., In Proceedings of the Third International Conference on Optimization and Learning (OLA), volume 1173 of Communications in Computer and Information Science, pages 37–48. Springer, 2020.
8. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. Competitive evolution of a UAV swarm for improving intruder detection rates. In 2020 IEEE International Parallel and Distributed Processing Symposium Workshops, IPDPSW 2020, New Orleans, LA, USA, May 18-22, 2020, pages 528–535. IEEE, 2020.
9. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. A cooperative coevolutionary approach to maximise surveillance coverage of UAV swarms. In 17th Annual Consumer Communications & Networking Conference (CCNC). IEEE, 2020.
10. D. H. Stolfi, G. Danoy, and P. Bouvry, Simulation-based UAS swarm mobility optimisation, in Proceedings of the 18th International Conference on High Performance Computing & Simulation (HPCS 2020)
11. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. Optimising pheromone communication in a UAV swarm. In Proceedings of the Genetic and Evolutionary Computation Conference Companion, GECCO ’21, pages 323–324, New York, NY, USA, 2021. Association for Computing Machinery.

12. D. H. Stolfi, M. R. Brust, G. Danoy, and P. Bouvry. Improving pheromone communication for UAV swarm mobility management. In Computational Collective Intelligence (ICCCI), pages 228–240, Cham, 2021. Springer International Publishing.

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LUXEMBOURG

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research Global
86 Blenheim Crescent
Ruislip MX HA4 7HB
United Kingdom

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