Generating Test Cases for Collaborating Uncrewed Aerial Vehicles from Analysis of Emergent Behavior

Master's Thesis

Supervisor: Prof. Dr. Alexander Pretschner
Advisor: David Marson, Nicola Kolb
Email: `david.marson@tum.de, nicola.kolb@tum.de`
Phone: `+49 (89) 289 - 17311`
Starting date: immediately

Informatics 4 – Chair of Software and Systems Engineering
Prof. Dr. Alexander Pretschner

TUM School of Computation, Information and Technology
Technical University of Munich

Boltzmannstr. 3 (5611)/I
85748 Garching b. München

`https://www.cs.cit.tum.de/en/sse/`

Context

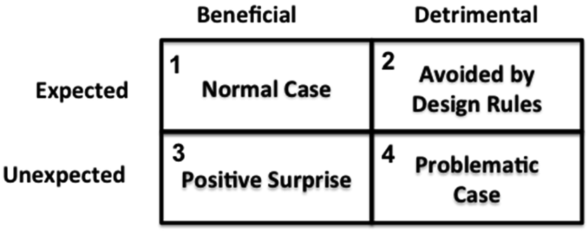
Autonomous cyber-physical systems (CPSs) such as uncrewed aerial vehicles (UAVs) must be tested to ensure correct behavior prior to operating in the real world. The usage of UAVs is projected to increase [1], [2], and some of these systems include autonomous capabilities such as commercially-developed or open-source autopilots. To expand existing UAV capabilities, current research efforts are investigating how multiple UAVs may autonomously collaborate to perform tasks; for example, to execute collision-free group flight as a swarm [3] or to transport a large payload [4]. As usage of autonomous UAVs increases, the need to ensure correct behavior also increases.

Existing literature on testing collaborating UAVs for unexpected behaviors, including failures, is limited. We can consider a group of UAVs as a single system, and each individual UAV as an agent of the system. In existing cases, testing is usually conducted using models of the system under test (SUT) and simulations of a relevant operational scenario. These test cases are used to demonstrate a design concept or explore the sensitivity of a design to parameter changes; examples can be seen in [5]–[9]. While these tests may address functional requirements - "what" the system must do - they do not address quality attributes - "how" the system performs. In other words, systematic methodologies to test quality attributes of collaborating UAVs are understudied, despite their increasing importance.

Quality attributes can include safety, effectiveness, efficiency, or others. Analyzing the safety of a UAV has been explored in [10] and includes the concept of a safety distance - i.e., between the UAV and obstacles in the operating environment - to test for safe behavior. Effectiveness and efficiency can be more dependent on the application: for a payload transportation example, effectiveness may be measured by cumulative mass of payload transported in a time span. Efficiency may be measured by the energy consumed by the system to transport the payload to the delivery location.

Additionally, when a system consists of multiple interacting agents, the system may exhibit emergent behaviors: generally defined as behaviors that can be observed at the level of the overall system, but that cannot be derived or predicted from observing any individual agent [11]–[13]. For example, when considering the previously-mentioned drone swarm as a system: all agents in the system move in the required direction without separating too far away from each other and also without colliding with each other. This formation cohesion is the system's emergent behavior, and it results from simple rules defined at the agent level: a reference distance that each agent tries to maintain from its immediate neighbors, and a common goal direction that is given to all agents [3]. Observing a single agent in the group will reveal the agent's exact motion but will not reveal the exact motion of agents elsewhere in the group. Another example is a system composed of a group of agents with imperfect sensors: an individual agent is able to detect but unable to "confirm" a target, so the agent broadcasts a signal to attract other agents until the target is detected by enough agents to be considered "confirmed" [14]. The system's ability to confirm the target is the system's emergent behavior, and it also results from simple rules defined at the agent level: maneuvering to search for the target, broadcasting a signal, and maneuvering towards a signal if one is detected.

Emergent behaviors can be classified based on their effects on the system's operations and on the expectations of the system's user, as shown in Figure 1. When considering a quality attribute such as safety, emergent behaviors classified as "problematic cases" would lead to collisions and harm - and by definition, are not known to the system user prior to their occurrence. Therefore, a strategic goal could be to use testing to maximize what is known about a system's emergent behaviors in order to minimize occurrences of problematic cases when the system is operating in the real world.



	Beneficial	Detrimental
Expected	1 Normal Case	2 Avoided by Design Rules
Unexpected	3 Positive Surprise	4 Problematic Case

Figure 1: Classification of emergent behavior [12]

Goal

The goal of this thesis is to identify a methodology that detects or tests for emergent behaviors in collaborating CPSs. Existing methodologies from other research areas, such as multi-agent systems (MASs) may need to be consulted and then adjusted for application to CPS testing. Ideally, the methodology would detect or test for "unexpected detrimental" emergent behaviors, classified as "problematic cases" in [12]. The specific SUT of interest is a group of collaborating UAVs modeled by the "SwarmLab" UAV swarm simulation developed by the authors of [15]. At least two quality attributes should be tested for with appropriately referenced definitions. For example, if testing for safety, the methodology should produce test cases that try to cause a group of collaborating UAVs to behave in an unsafe way, such as causing a collision. The methodology's ability to generate relevant test cases for the quality attributes of interest should be compared.

Working Plan

1. Become familiar with collaborating CPSs and current research in emergent behaviors in CPSs (note that a variety of terminology is used to refer to this type of system)
2. Become familiar with the SwarmLab simulation tool
3. Identify at least two quality attributes to test for and define them with appropriate references
4. Conduct a literature search of methodologies that detect or test for emergent behaviors of systems
5. Write the exposé
6. From the literature search results, identify a methodology that could be applied to testing CPSs (directly or with some conversion)
7. Implement the methodology such that it generates test cases for the previously identified quality attributes for the collaborating UAVs modeled by SwarmLab
8. Evaluate the methodology's ability to generate relevant test cases; for example, for cost effectiveness in test case generation or severity of system behavior elicited by the tests
9. Write the report and presentation

Deliverables

- Exposé describing the results of the literature review
- Source code of implementation using MIT License incl. documentation
- Final thesis report written in English and in conformance with TUM guidelines, comprehensively describing the findings, methodologies, and implementation
- Presentation of the work at the Chair

References

[1] "Unmanned aircraft system traffic management - concept of operations v2.0," US Department of Transportation - Federal Aviation Administration, Mar. 2, 2020. [Online]. Available: `https://www.faa.gov/researchdevelopment/trafficmanagement/utm-concept-operations-version-20-utm-conops-v20` (visited on 11/03/2022).

[2] "U-space ConOps (edition 3.10)," EUROCONTROL, D4.1, Jul. 13, 2022. [Online]. Available: `https://corus-xuam.eu/new-u-space-conops/` (visited on 11/08/2022).

[3] E. Soria, F. Schiano, and D. Floreano, “Distributed predictive drone swarms in cluttered environments,” *IEEE Robotics and Automation Letters*, vol. 7, no. 1, pp. 73–80, Jan. 2022, Conference Name: IEEE Robotics and Automation Letters, ISSN: 2377-3766. DOI: `10.1109/LRA.2021.3118091`. [Online]. Available: `https://ieeexplore.ieee.org/abstract/document/9562281`.

[4] J. Wehbeh, S. Rahman, and I. Sharf, “Distributed model predictive control for UAVs collaborative payload transport,” in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, ISSN: 2153-0866, Oct. 2020, pp. 11 666–11 672. DOI: `10.1109/IROS45743.2020.9341541`.

[5] M. Kovacina, D. Palmer, G. Yang, and R. Vaidyanathan, “Multi-agent control algorithms for chemical cloud detection and mapping using unmanned air vehicles,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, Sep. 2002, 2782–2788 vol.3. DOI: `10.1109/IRDS.2002.1041691`.

[6] R. Liu, F. Jia, W. Luo, *et al.*, “Trust-aware behavior reflection for robot swarm self-healing,” in *Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems*, ser. AAMAS ’19, Richland, SC: International Foundation for Autonomous Agents and Multiagent Systems, May 8, 2019, pp. 122–130, ISBN: 978-1-4503-6309-9. (visited on 03/07/2023).

[7] A. Kopeikin, A. Clare, O. Toupet, J. How, and M. Cummings, “Flight testing a heterogeneous multi-UAV system with human supervision,” in *AIAA Guidance, Navigation, and Control Conference*, ser. Guidance, Navigation, and Control and Co-located Conferences, American Institute of Aeronautics and Astronautics, Aug. 13, 2012. DOI: `10.2514/6.2012-4825`. [Online]. Available: `https://arc.aiaa.org/doi/10.2514/6.2012-4825` (visited on 03/07/2023).

[8] L. Marsh, G. Calbert, J. Tu, D. Gossink, and H. Kwok, “Multi-agent UAV path planning,” in *MODSIM05 - International Congress on Modelling and Simulation: Advances and Applications for Management and Decision Making, Proceedings*, Type: Conference paper, 2005, pp. 2188–2194, ISBN: 0-9758400-0-2 978-0-9758400-0-9. [Online]. Available: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-80053125893&partnerID=40&md5=b94757ee59286fefe4d8ce0d8523d97d`.

[9] S. Huang, R. S. H. Teo, J. L. P. Kwan, W. Liu, and S. M. Dymkou, “Distributed UAV loss detection and auto-replacement protocol with guaranteed properties,” *Journal of Intelligent & Robotic Systems*, vol. 93, no. 1, pp. 303–316, Feb. 1, 2019, ISSN: 1573-0409. DOI: `10.1007/s10846-018-0818-4`. [Online]. Available: `https://doi.org/10.1007/s10846-018-0818-4` (visited on 03/06/2023).

[10] T. Schmidt, F. Hauer, and A. Pretschner, “Understanding safety for unmanned aerial vehicles in urban environments,” in *2021 IEEE Intelligent Vehicles Symposium (IV)*, Nagoya, Japan: IEEE, Jul. 11, 2021, pp. 638–643, ISBN: 978-1-72815-394-0. DOI: `10.1109/IV48863.2021.9575755`. [Online]. Available: `https://ieeexplore.ieee.org/document/9575755/` (visited on 10/13/2022).

[11] H. Jun, Z. Liu, G. M. Reed, and J. W. Sanders, “Ensemble engineering and emergence,” in *Software-Intensive Systems and New Computing Paradigms: Challenges and Visions*, ser. Lecture Notes in Computer Science, M. Wirsing, J.-P. Banâtre, M. Hölzl, and A. Rauschmayer, Eds., Berlin, Heidelberg: Springer, 2008, pp. 162–178, ISBN: 978-3-540-89437-7. DOI: `10.1007/978-3-540-89437-7_11`. [Online]. Available: `https://doi.org/10.1007/978-3-540-89437-7_11` (visited on 03/17/2023).

[12] H. Kopetz, A. Bondavalli, F. Brancati, B. Frömel, O. Höftberger, and S. Iacob, “Emergence in cyber-physical systems-of-systems (CPSoSs),” in *Cyber-Physical Systems of Systems: Foundations – A Conceptual Model and Some Derivations: The AMADEOS Legacy*, ser. Lecture Notes in Computer Science, A. Bondavalli, S. Bouchenak, and H. Kopetz, Eds., Cham: Springer International Publishing, 2016, pp. 73–96, ISBN: 978-3-319-47590-5. DOI: `10.1007/978-3-319-47590-5_3`. [Online]. Available: `https://doi.org/10.1007/978-3-319-47590-5_3` (visited on 03/17/2023).

[13] S. Tyszberowicz and D. Faitelson, “Emergence in cyber-physical systems: Potential and risk,” *Frontiers of Information Technology & Electronic Engineering*, vol. 21, no. 11, pp. 1554–1566, Nov. 1, 2020, ISSN: 2095-9230. DOI: `10.1631/FITEE.2000279`. [Online]. Available: `https://doi.org/10.1631/FITEE.2000279` (visited on 03/08/2023).

[14] A. L. Alfeo, M. G. C. A. Cimino, N. De Francesco, A. Lazzeri, M. Lega, and G. Vaglini, “Swarm coordination of mini-UAVs for target search using imperfect sensors,” *Intelligent Decision Technologies*, vol. 12, no. 2, pp. 149–162, Mar. 7, 2018, Publisher: IOS Press, ISSN: 18724981, 18758843. DOI: `10.3233/IDT-170317`. [Online]. Available: `https://doi.org/10.3233/IDT-170317`.

[15] E. Soria, F. Schiano, and D. Floreano, “SwarmLab: A matlab drone swarm simulator,” in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, ISSN: 2153-0866, Oct. 2020, pp. 8005–8011. DOI: `10.1109/IROS45743.2020.9340854`.

Informatics 4 – Chair of Software and Systems Engineering
Prof. Dr. Alexander Pretschner

TUM School of Computation, Information and Technology
Technical University of Munich

Boltzmannstr. 3 (5611)/I
85748 Garching b. München

`https://www.cs.cit.tum.de/en/sse/`

Generating Test Cases for Collaborating Uncrewed Aerial Vehicles from Analysis of Emergent Behavior – Master's Thesis