Design of Trace-based NS-3 Simulations for UAS Video Analytics with Geospatial Mobility

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ABSTRACT

The continuous evolution of commercial Unmanned Aerial Systems (UAS) is fuelling a rapid advancement in the fields of network edge-communication applications for smart agriculture, smart traffic management, and border security. A common problem in UAS (a.k.a. drone systems) research and development is the cost related to deploying and running realistic testbeds. Due to the constraints in safe operation, handling limited energy resources, and government regulation restrictions, UAS testbed building is time-consuming and not easily configurable for high-scale experiments. In addition, experimenters have a hard time creating repeatable and reproducible experiments to test major hypotheses. In this paper, we present a design for performing trace-based NS-3 simulations that can be helpful for realistic UAS simulation experiments. We run experiments with real-world UAS traces including various mobility models, geospatial link information and video analytics measurements. Our experiments assume a hierarchical UAS platform with low-cost/high-cost drones co-operating using a geo-location service in order to provide a 'common operating picture' for decision makers. We implement a synergized drone and network simulator that features three main modules: (i) learning-based optimal scheme selection module, (ii) application environment monitoring module, and (iii) trace-based simulation and visualization module. Simulations generated from our implementation have the ability to integrate different drone configurations, wireless communication links (air-to-air; air-to-ground), as well as mobility routing protocols. Our approach is beneficial to evaluate network-edge orchestration algorithms pertaining to e.g., management of energy consumption, video analytics performance, and networking protocols configuration.

Keywords: Trace-based Simulations, Unmanned Aerial Systems, Edge Network Testbeds, Drone Video Analytics, NS-3 Simulations

1. INTRODUCTION

The rapid proliferation of Unmanned Ariel Systems (UAS) is benefiting many application areas such as smart agriculture, disaster management, and military applications.[1,2] Geospatial video analytics with UAS in these applications is popular, and involves a workflow of data processing pipelines to extract environmental situational awareness using videos gathered from multiple perspectives. Currently, deploying realistic UAS testbeds with suitable network edge-communication protocols is time-consuming and expensive due to the constraints in: safe operation, handling limited energy resources, and government regulation restrictions. Moreover, UAS testbed building for high-scale experiments is difficult, especially when there is a need for experimenters to create repeatable and reproducible experiments to test major hypotheses.

Traces from UAS (a.k.a. drone) video analytics simulations can allow for real-time experimentation with edge-cloud configurations, diverse drone mobility models, and control connection status between devices and infrastructure. They also can allow for adaptation/policy experiments in video analytics based on network performance measurements.[3] In addition, network simulations relating to UAS-based geospatial video analytics algorithms can involve setup of multi-UAV configurations with custom wireless communication and network links (air-to-air; air-to-ground), as well as mobility routing protocols. However, based on our literature survey[4],[5] simulations of drones and networks are not typically jointly designed, which presents limitations in simulations of UAS configurations testing. There are effective drone simulations for measuring flight movements, battery

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life, application performance, etc., however they lack integration with relevant network simulators. On the other hand, powerful network simulators exist, however they lack the necessary features to verify UAS-specific issues realistically and at high-scale. Synergizing drone and network simulations can provide benefits to experimenters such as the ability to e.g., (a) test various system configurations such as network security protocols,[6] and (b) implement different flight algorithms (e.g., swarms) before they are deployed on the field.

In this paper, we investigate state-of-the-art approaches on advanced UAV simulators involving trace generation for: (a) network communication between multi-drone edge-server architectures, and (b) computation in drone video analytics covering multiple application scenarios. Based on the knowledge gaps from the literature survey, we propose a trace-based simulation design that uses NS-3[7] integrated multi-drone simulations among a hierarchical UAS configuration (involving wide-area search and intelligence gathering drones) to serve applications with geo-spatial environmental situational awareness. The hierarchical UAS platform we consider involves low-cost/high-cost drones co-operating using a geo-location service in order to provide a 'common operating picture' for decision makers. Our novel approach synergizes network and drone simulators in a manner that shows apparent benefits when running trace-based simulations involving realistic drone video analytics pipelines. We implement a synergized drone and network simulator that features three main modules: (i) learning-based optimal scheme selection module, (ii) application environment monitoring module, and (iii) trace-based simulation and visualization module. Simulations generated from our implementation have the ability to integrate different drone configurations, wireless communication links (air-to-air; air-to-ground), as well as mobility routing protocols. Using our simulator implementation, we run experiments with real-world UAS traces including various mobility models, geospatial link information and video analytics measurements.

The remainder of this paper is organized as follows: In Section 2, we present related works and our investigation into current network and drone simulators. In Section 3, we describe our synergized drone and network simulator design approach. Section 4 details the performance evaluation experiments of our approach. Section 5 concludes the paper.

2. RELATED WORKS

The popularity of UAS networks, as subsets of MANETs (Mobile Ad-Hoc Networks),[8] has steadily increased over the recent years, especially in next-generation civil applications such as: consumer product delivery, autonomous and mobile environmental monitoring, search, rescue, and disaster management. In our previous works,[9–11] we proposed a framework that aids in improving computation offloading and control networking for drone video analytics for applications as shown in Figure 1. Our framework for drone video analytics leverages edge and cloud computing resources to optimize video-processing pipelines involving multiple drones co-operating at the network-edge. It features a learning-based dynamic computation offloading scheme, and a control networking scheme to manage various application requirements, and to intelligently schedule tasks to enhance video analytics performance, and intermittent transmission failures.

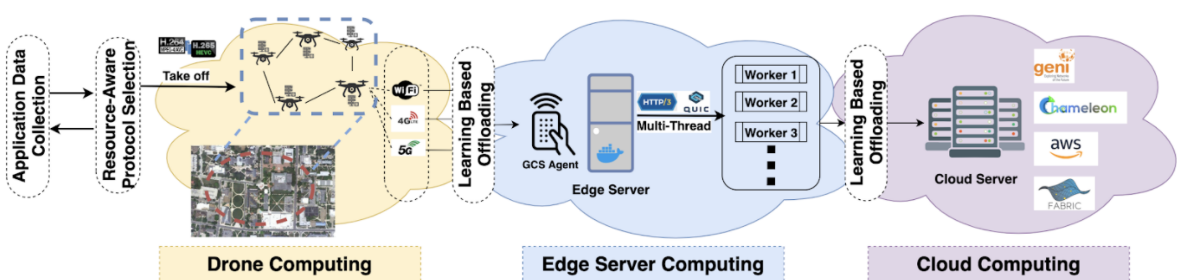

Figure 1. Illustration of the integration of data collection and processing through a learning-based computation offloading and network protocol selection scheme.

2.1 Prior Work on Network Simulators

There are many challenges for simulations involving the management of dynamics e.g., high-mobility in UAS networks to handle application user requirements for drone video analytics.[12] Specifically, simulators need to support experimentation such as e.g., optimal policy-based network protocol selection (amongst QUIC, UDP, TCP) and video codec configuration (e.g., H.264, H.265). Authors in "A Trace-based ns-3 Simulation Approach for Perpetuating Real-World Experiments"[13] propose a method of using NS-3 with real-world network traces focused on improving the 'propagation loss model' within NS-3 in order to make simulated experiments more closely resemble their real-world testbed counterparts. Their new 'trace-based propagation loss model' provides less error than the standard propagation loss model supported by NS-3, especially for cases of increasing real Signal-to-Noise Ratio (SNR) sampling rate. Further, authors in[14] improve upon the aforementioned trace-based model and expand it for simulation of multiple access wireless scenarios. This improvement allows for the trace-based model to be used in a wider array of simulations, most importantly UAS simulations. They do so, while still providing simulated results that are reproducible as well as accurate. It provides closer-to-real evaluation conditions and allows for access of offline, faster than real-time, experiments to a broader audience. An extensive evaluation of the trace-based simulation is presented by using the Fed4Fire+ w-iLab.2 testbed. Experiment results show that their approach outperforms pure simulation by more than 50% in terms of accuracy.

2.2 Prior Work on Drone Simulators

Network protocol simulations merit the need for using relevant trace datasets which allow for machine learning models to predict optimal decisions for a wide variety of application user requirements. For instance, UAV communication trace datasets need to take into account application-specific system configurations, real-time network environment measurements of devices and infrastructure, and geo-spatial location data. Amongst existing drone simulators, we found that UB-ANC[15] (focused mainly on UAV simulations) and FlyNetSim[16] (focused mainly on Ground Control Station capabilities) are exemplar in providing easy-to-use interfaces for users to simulate network events, as well as drone movements. In the UB-ANC implementation,[15] authors propose an extensible platform for multi-drone experiments spanning simulation to real-world experimentation using the same software that is also executed on real drone hardware. UB-ANC also features NS-3 integration for use in the back-end with respect to controlling the networking aspect of the experiments. UB-ANC has a graphical user interface based on the open-source ArduPilot[17] software that is popular for use in real-world maps and mission planning. Similarly, FlyNetSim implementation[16] connects pure-UAV simulators with pure-network simulators in order to achieve the ability to run realistic UAS testbed simulations. Users can not only run simulation experiments relating to the high-level aspects of systems, but also they can accurately model the lower-level details involved with both UAV and other Internet of Thing (IoT) devices. FlyNetSim allows for many-to-many communication between nodes and is also implemented using NS-3 and ArduPilot.

3. SYNERGIZED DRONE AND NETWORK SIMULATOR DESIGN

To synergize drone and network simulator components and generate comprehensive experimental traces, we consider trace generation for: (a) network communication between multi-drone-edge-server architectures, and (b) computation in drone video analytics covering multiple application scenarios. In this section, we first present our system design that synergizes drone and network simulations. Following this, we present our implementation of the software components through a user-friendly interface to run synergized drone and network simulations.

3.1 System Design

Our proposed design is focused on NS-3 simulator integrated for multi-drone simulations featuring a hierarchical UAS setup involving wide-area search and intelligence gathering drones as shown in Figure 2. In the hierarchical setup, we consider co-ordination of a number of search drones that have peer-interactions while surveying a wide-area in order to inform a more highly-capable sensor-equipped drone to perform strategic intelligence collection. The application requirements we consider for simulations pertain to drone video analytics that is aimed towards creating a 'common operating picture'. Trace-based NS-3 simulations leverage our drone video analytics related algorithms[9–11] for realizing a function-centric paradigm for policy management involving: drone mobility models, computation protocol analysis and video processing pipelines.

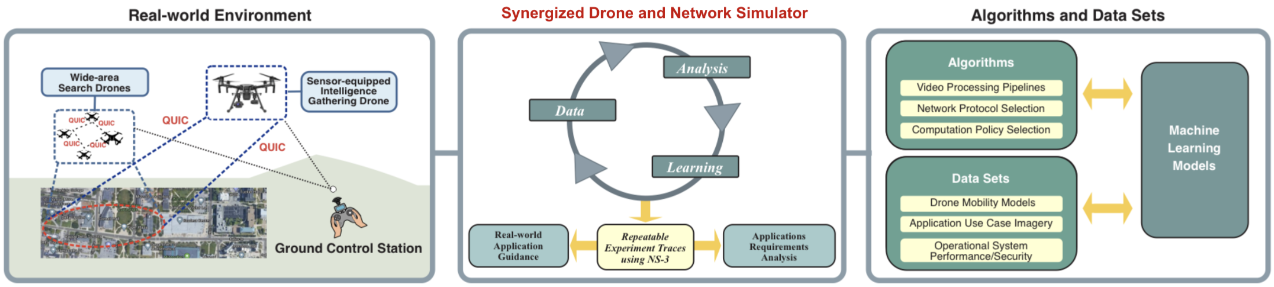

Figure 2. Hierarchical trace-based UAS+network simulation design for experiments on geo-spatial drone video analytics using edge computing and machine learning algorithms.

3.2 Software Components for Systematic Trace-based UAS/network Simulations

The three main software modules in our implementation are: (i) learning-based optimal scheme selection module (*Learning*), (ii) application environment monitoring module (*Data*), and (iii) trace-based simulation and visualization module (*Analysis*). Our implementation also uses a number of machine learning models to predict and generate traces from real-world trace datasets. To assist in the visualization of experiments that involve various algorithms and datasets, we also developed a web-based user interface (UI) for showing simulation outputs, details of traces and as well as the video analytics results. Figure 3 shows our implemented software components that are designed to decouple the trace generation and visualization features in order to make our simulator more flexible and extensible. Our UI provides users (i.e., scientists, researchers and hobbyists) a visualization tool that helps with animation and intuitive simulation configurations. For instance, users can configure multi-drone flight animations based on traces generated by either real-world experiments or trace-based simulation. Further, users can use the multi-drone visualization animation along with network information and track accuracy over various time periods.

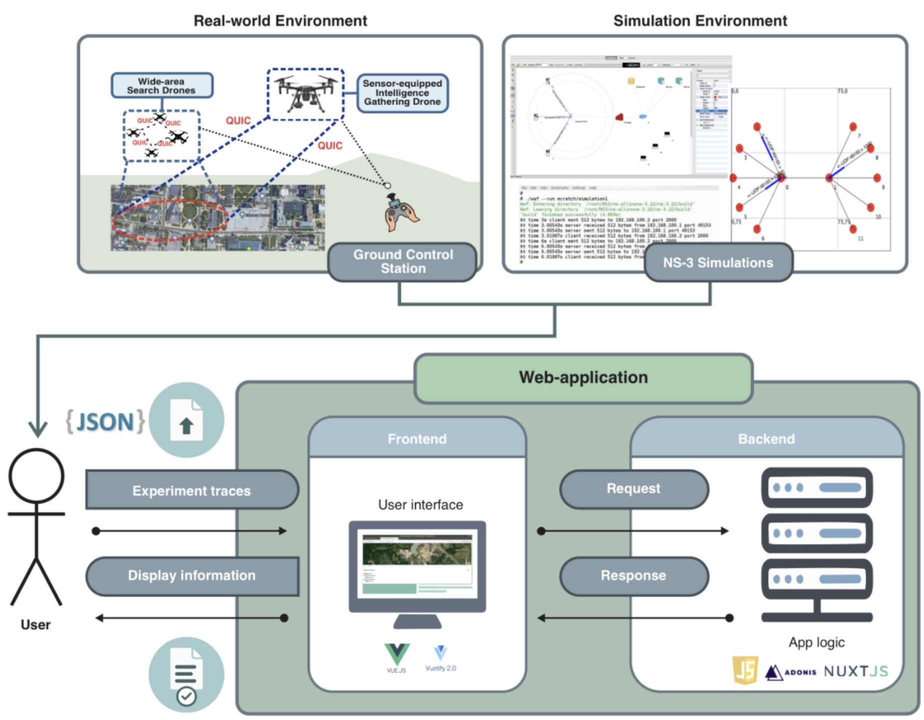

Figure 3. Software components in the web-application to synergize drone and network simulations with real-world traces.

We adopt best practices for the front-end and back-end design and development of the web-based application. The interactions between the front-end and the back-end are executed in a matter of seconds in order to provide an interactive user experience. Importantly, the web-based UI is built on top of open-source frameworks, including JavaScript as the main component that provides reliability of the data displayed. For the front-end, we leverage the simplicity of Vuetifyjs, which is built on top of Vuejs and that provides clean, semantic and reusable components to help maintain the source code improvements in a sustainable manner. Lastly, the back-end of our web-based UI runs on top of Node.js. Node.js is a JavaScript runtime and an open-source server environment that runs on various platforms including Windows, Linux, Mac OS and others. It uses JavaScript on the server and can generate dynamic page content. In addition, the back-end relies on AdonisJS, which is a Node.js Model View Controller framework that provides flexible coding structures.

4. EXPERIMENTAL EVALUATION AND DEMONSTRATION

In this section, we first introduce the experimental setup and data sets gathered from a real-world drone-based application scenario. Next, we discuss a drone analytics application demonstration featuring a multi-drone edge-server simulation.

Figure 4. Real-world experimental traces from the Visdrone dataset with multi-drone scenarios.

4.1 Traces Generation for Simulation Experiments

We collect traces from real-world drone experiments in order to analyze and perform machine learning to learn features from those traces. Based on the learning, we generate scripts that help with repeatable drone and network simulation experiments. For the trace collection, we use drone video feeds with different ground surveillance video resolutions (480p, 720p, 1080p and 2K), video codecs (H.263 and H.264), corresponding to real-world multi-drone scenarios. Figure 4 shows exemplar real-world experimental video captures with multi-drone scenarios from the open-source Visdrone dataset[18] and a related normalized dataset.[19]

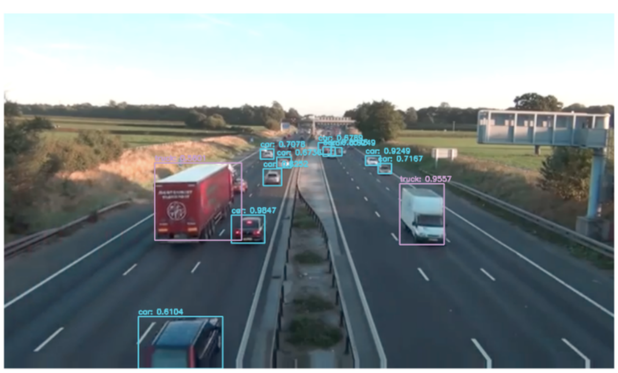

Figure 5. Example of a moving object classification on ground surveillance video from a drone.

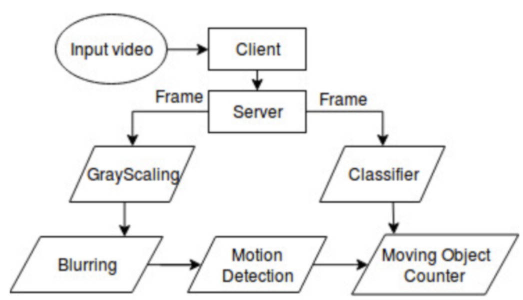

Figure 6. Image processing pipeline to investigate computation offloading.

4.2 Drone Video Analytics Demonstration

Herein, we demonstrate the benefits of synergizing drone and network simulations. We use a function-centric pipeline for drone video analytics application that involves implementation of motion detection and object tracking (as shown in Figure 5) from a drone video feed of ground surveillance. We decomposed our application pipeline into microservices based on the pipeline decomposition shown in Figure 6. The microservices are deployed as Docker containers that communicate via RESTful API calls and execute computation offloading decisions on e.g., where a certain function should be placed/computed. Our implementation runs on the Python Flask package and uses OpenCV and TensorFlow functions for application processing to complete tasks execution.

Figure 7 shows how users guided by the user interface can understand in an intuitive and visualized manner all the information they gathered from simulations of real-world scenarios. An interactive map provides realistic visualization, including drones tracking contextual markers of changing co-ordinates (from drone simulator), and network information relating to network health and control networking protocols (from network simulator). Specifically, users can access each drones' information such as latitude, longitude, energy consumption in a simulation experiment. Similarly, the network health information users can access corresponds to e.g., drone-to-drone links status, and drone-to-GCS links status. Simulation outputs such as tracking accuracy over time can be accessed by users via interactive and animated plots. Thus, our web-based simulation platform can be useful in several scenarios involving synergistic drone and network simulations, where users can study the impact of decisions such as e.g., edge/cloud selection for application-related drone video processing over time.

Figure 7. Simulation demonstration with an interactive map interface providing realistic multi-UAV traces and real-time network status along with drone video analytics results.

5. CONCLUSION

In this paper, we studied synergies between network and drone simulators to experiment control networking schemes in drone video analytics relating to applications such as: smart agriculture, smart traffic management, and border security. Our studies are motivated by the need for realism and high-scale experimentation, which are desirable attributes to meet drone video analytics requirements of applications. We used traces generated from real-world application configurations featuring multi-drone scenarios in a simulation demonstration to show the synergies of combining network and drone simulations. We considered traces that helped analyze various mobility models, geo-spatial link information and real-time network status. Lastly, we showed how machine learning can be used in trace-based simulations to perform predictions that help in resource management decisions of drone video analytics. Through a web-based implementation, we showed that our approach is beneficial and extendable to evaluate network-edge orchestration algorithms pertaining to e.g., management of energy consumption, video analytics performance, and networking protocols configuration.

Our future work scope includes extending our approach to perform bold simulations at high-scale considering advanced network protocol settings, and different wireless networking environments with emerging layer 1 techniques such as e.g., 5G and WiFi-6.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Award Number: CNS-1647182 and the Army Research Lab under Award Numbers: W911NF1820285 and W911NF1910181. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the Army Research Lab.

REFERENCES

[1] Gillis, J., Calyam, P., Bartels, A., Popescu, M., Barnes, S., Doty, J., Higbee, D., and Ahmad, S., "Panacea's glass: Mobile cloud framework for communication in mass casualty disaster triage," in [*2015 3rd IEEE International Conference on Mobile Cloud Computing, Services, and Engineering*], 128–134 (2015).

[2] Vassell, M., Apperson, O., Calyam, P., Gillis, J., and Ahmad, S., "Intelligent dashboard for augmented reality based incident command response co-ordination," in [*2016 13th IEEE Annual Consumer Communications Networking Conference (CCNC)*], 976–979 (2016).

[3] Calyam, P., Haffner, M., Ekici, E., and C.G.Lee, "Measuring interaction qoe in internet videoconferencing," in [*Real-Time Mobile Multimedia Services*], Krishnaswamy, D., Pfeifer, T., and Raz, D., eds., 14–25, Springer Berlin Heidelberg, Berlin, Heidelberg (2007).

[4] da Cruz, E. P. F., "A comprehensive survey in towards to future fanets," *IEEE Latin America Transactions* **16**(3), 876–884 (2018).

[5] Mairaj, A., Baba, A. I., and Javaid, A. Y., "Application specific drone simulators: Recent advances and challenges," *Simulation Modelling Practice and Theory* **94**, 100 – 117 (2019).

[6] Mukherjee, B., Neupane, R. L., and Calyam, P., "End-to-end iot security middleware for cloud-fog communication," in [*2017 IEEE 4th International Conference on Cyber Security and Cloud Computing (CSCloud)*], 151–156 (2017).

[7] Riley, G. and Henderson, T., [*The ns-3 Network Simulator*], 15–34, Springer Berlin Heidelberg, Berlin, Heidelberg (2010).

[8] Chriki, A., Touati, H., Snoussi, H., and Kamoun, F., "Fanet: Communication, mobility models and security issues," *Computer Networks* **163**, 106877 (2019).

[9] Chemodanov, D., Qu, C., Opeoluwa, O., Wang, S., and Calyam, P., "Policy-based function-centric computation offloading for real-time drone video analytics," in [*2019 IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN)*], 1–6 (2019).

[10] Qu, C., Wang, S., and Calyam, P., "Dycoco: A dynamic computation offloading and control framework for drone video analytics," in [*IEEE 27th Intl. Conference on Network Protocols (ICNP)*], 1–2 (2019).

[11] Ramisetty, R. R., Qu, C., Aktar, R., Wang, S., Calyam, P., and Palaniappan, K., "Dynamic computation off-loading and control based on occlusion detection in drone video analytics," in [*Proceedings of the 21st International Conference on Distributed Computing and Networking*], *ICDCN 2020*, Association for Computing Machinery, New York, NY, USA (2020).

[12] Fotouhi, A., Qiang, H., Ding, M., Hassan, M., Giordano, L. G., Garcia-Rodriguez, A., and Yuan, J., "Survey on uav cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," *IEEE Communications Surveys Tutorials* **21**(4), 3417–3442 (2019).

[13] Fontes, H., Campos, R., and Ricardo, M., "A trace-based ns-3 simulation approach for perpetuating real-world experiments," in [*Proceedings of the Workshop on Ns-3*], *WNS3 '17*, 118–124, Association for Computing Machinery, New York, NY, USA (2017).

[14] Fontes, H., Campos, R., and Ricardo, M., "Improving the ns-3 tracebasedpropagationlossmodel to support multiple access wireless scenarios," in [*Proceedings of the 10th Workshop on Ns-3*], *WNS3 '18*, 77–83, Association for Computing Machinery, New York, NY, USA (2018).

[15] Modares, J., Mastronarde, N., and Dantu, K., "Ub-anc emulator: An emulation framework for multi-agent drone networks," in [*2016 IEEE International Conference on Simulation, Modeling, and Programming for Autonomous Robots (SIMPAR)*], 252–258, GitHub repository, Last accessed 04 April 2020 - https://github.com/jmodares/UB-ANC-Emulator (Dec 2016).

[16] Baidya, S., Shaikh, Z., and Levorato, M., "Flynetsim: An open source synchronized UAV network simulator based on ns-3 and ardupilot," *CoRR* **abs/1808.04967**, GitHub repository, Last accessed 04 April 2020 - https://github.com/saburhb/FlyNetSim (2018).

[17] Ardupilot, "Full-featured and reliable open source autopilot software," (2020). Last accessed 01 March 2020.

[18] VisDrone, "Visdrone-dataset." https://github.com/VisDrone/VisDrone-Dataset (Last accessed 04 April 2020).

[19] Qu, C. and Yu, J., "Normalized drone video dataset based on visdrone." https://github.com/CaesarQu/Normalized_VisDrone (Last accessed 01 April 2020).