Situation Awareness and Routing Challenges in Unmanned HAPS/UAV based Communications Networks

Ogbonnaya Anicho, Philip B Charlesworth, Gurvinder S Baicher and Atulya Nagar
School of Mathematics, Computer Science and Engineering
Liverpool Hope University
Email: anichoo@hope.ac.uk

Abstract—This paper examines Situation Awareness (SA) as a factor in addressing routing challenges in HAPS/UAV based networks especially in multi-HAPS/UAV implementations. Routing in UAV-based networks is a critical element for successful transmission of data from source to destination node. However, in UAV based networks the concept of routing assumes a more challenging dimension mainly due to the mobility of the vehicles or platforms. This paper highlights how situation awareness can impact routing decisions and consequently improve network throughput. It is suggested that SA should be considered a factor in mitigating routing challenges in UAV based networks.

I. Introduction

The application of Unmanned Aerial Vehicle (UAV) communications networks as either infrastructure based or ad-hoc networks is a promising area of research. UAVs however, operate in a uniquely challenging environment compared to terrestrial based networks. For instance, unmanned High Altitude Platform Stations (HAPS), which are essentially UAVs operating at stratospheric altitudes between 20 to 50km [1] must remain aloft in order to fulfil any service. These challenges assume higher dimensions when the UAVs operate as a network of vehicles or platforms providing communications services like area coverage; figure 1 shows a conceptual multiple HAPS network. In this work, unmanned HAPS will be used interchangeably with UAV, since HAPS is a type of UAV operating in high altitude (stratosphere). In the literature UAV based networks are variously described as Flying ad-hoc networks (FANETs) [2], [3], UAV Ad-hoc Network(UANET) or Unmanned Aeronautical Ad-hoc Network (UAANET) [2], [4]. Regardless, these types of UAV based networks are plagued by challenges of high mobility and frequent topology changes. These challenges ultimately make designing an appropriate routing protocol a very difficult task [5], [6].

Over the years different routing protocols have been proposed for UAV based networks though with caveats on fitness for purpose. Routing in this context refers to sending information (payload) or control data through inter-UAV links and not UAV navigation waypoints or path planning. Some of the routing protocols generally discussed in the literature are; destination sequence distance vector routing (DSDV), ad-hoc on-demand distance vector (AODV) [7], optimised link-state routing (OLSR) & predictive-OLSR (P-OLSR) [3] and geographic greedy forwarding (GGF) [8]. Others include, adaptive hybrid reinforcement learning, self-learning routing protocol (RLSRP) [9], fuzzy system approach with QoE/QoS guarantee [10], geographic routing protocol for aircraft ad hoc network (GRAA), aeronautical routing protocol (AeroRP) [11] and so many others [7], [11]. UAV based routing protocols can be more generally classified into three main groups; Topology-based, Position-based and Clusteredbased protocols [7], [11]. However, no single routing protocol has been considered adequate for UAV based networks, as the high mobility and dynamic topology makes routing complex unlike in MANETS or VANETS. A careful review of the mentioned routing techniques show that these schemes are influenced by the architecture of classical routing protocols. A different design paradigm or approach may be needed to address routing challenges peculiar to UAV networks; merely modifying traditional or MANET specific protocols may not solve the problem. For instance, in an earlier paper [6], the authors proposed integrating routing and UAV autonomy algorithms to mitigate link availability challenges for improved routing performance. In order to address routing challenges, innovative and proactive approaches are needed, even if it leads to adjusting design architectures.

The concept of Situation Awareness (SA) is also discussed as a factor in mitigating routing challenges in UAV based networks. In this context UAV SA can be seen as artificial situation awareness as described in [12]. The application of SA to routing may be a departure from current approaches which generally limits its scope to addressing layer 3 elements (a purely organic approach). The approach considered in this paper assumes a more external approach by including the UAV autonomy algorithm (SA resides here) in the UAV decision making framework as proposed by Anicho et al [6]. This design approach ensures that at the conceptual level UAV autonomy and the routing algorithm is addressed simultaneously.

This paper contributes to the UAV based network routing problems by investigating how SA may enhance decision making if integral to the autonomous capability of the UAV; and could be designed and engineered to mitigate routing based challenges in UAV networks. In this paper, section I gives an overview of UAV based networks and proposed routing schemes and challenges. Section II introduces the concept of Situation Awareness and its connection with UAV autonomy and routing; while section III

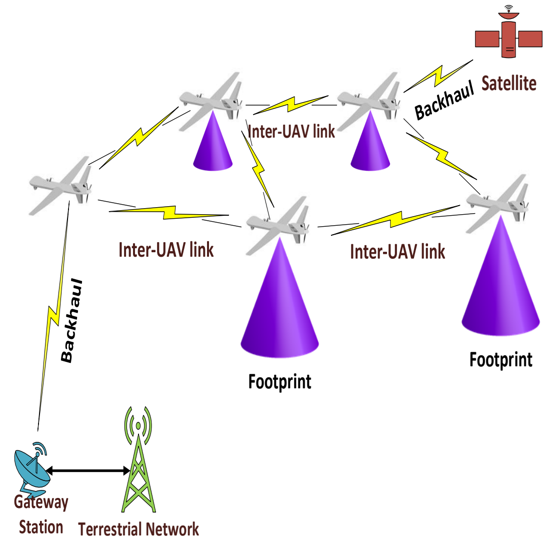

Fig. 1. Conceptual Multiple HAPS Network

describes the problem scenario and solution proposed. Section IV, describes the modelling and simulation methodology applied in this work. In section V, simulation results and analysis are presented. Finally, section VI draws conclusions on the work and considers future work.

II. Situation Awareness (SA) and UAV Autonomy Capabilities

SA by definition covers three specific levels of awareness [13]–[16];

1) Perception of elements in the environment.
2) Comprehension of the perceived elements.
3) Projection of the elements' status into the near future.

It can be deduced from the analysis above, that higher dimensions of UAV SA may significantly improve the UAV's decision making capabilities. Which implies that if UAVs can perceive elements within their environment, comprehend and analyse these elements and project with some statistical accuracy their future status then the UAVs will have some level of SA capability for better decisions. As a theoretical concept this capability can be synthesised but practically very complex to achieve. However, it is important to examine the intersection of UAV SA and UAV autonomy algorithms, and its likely impact on routing. Autonomous capabilities are highly desirable in UAVs and current research efforts all tend towards designing more autonomous vehicles. However, autonomy is not an absolute state, but calibrated in levels and often defined within the context of decision making or self governance in unmanned systems [5]. Autonomy can be viewed as a spectrum of capabilities ranging from zero autonomy to full autonomy e.g. the Pilot Authority and Control of Tasks (PACT) assigns levels of authority, from level 0 (full human pilot authority) to level 5 (full UAV autonomy) [17]. Fully autonomous UAVs are still theoretical constructs and may not be necessary in all use cases, however, understanding the level of autonomy suitable for any specific use case is relevant. Moreover from regulatory and ethical standpoints, autonomy levels may be subject to restrictions for variety of reasons. Nonetheless, from a conceptual and design based consideration it is important to understand how UAV SA ties in with autonomy algorithms/capabilities. It is expected that as UAV autonomy increases the SA distribution between the UAV and any human-in-the-loop will vary across the autonomy spectrum [13]. In this paper the level of autonomy assumed is restricted to the aspect of the UAV autonomy algorithm that controls the relocation and repositioning decisons.

Niklasson et al [18] proposed a unified SA model (SAM) which integrates human (manual) and automated SA in order to improve the overall capacity for decision making. Drury et al [15] also considered the need to decompose UAV-related SA in order to characterise the SA of the human operators with a view to developing a model specifying SA needs in such operational environments. Similarly, Cuevas and Aguiar [16] focused on ways to develop behavioral measure for assessing SA in UAS operators and how each operator's characteristics impacted mission success. Nguyen et al [14] notes that in beyond visual line of sight (BVLOS) scenarios, SA responsibility has to be shared between the UAS operator and 'increasingly autonomous' UAV. The use of mental models to predict future states of the environment was considered by [12] as a critical requirement for UAV SA capability.

However, none of the above papers or authors have considered UAV SA in the context of aiding network routing decisions. Majority of proposals have approached UAV SA in the context of UAV operator SA improvement for enhanced mission success. While this is a relevant issue, this paper approaches UAV SA as a component of UAV autonomy and should be a consideration in designing autonomous UAV systems. In this work the UAV SA is examined as a capability that could address the limitation of current routing protocols by contributing to the decision making loop that controls routing decisions.

III. Problem Scenario and Solution Approach

Another important consideration in addressing the routing problem in the UAV-based network is to clearly understand the use case or problem scenario. The effectiveness of the routing protocol adopted will largely depend on the problem scenario or use case under consideration. For instance, the requirements for routing in a search and rescue operation using a purely UAV ad hoc network will vary significantly to a partly fixed, partly ad hoc UAV based network for area coverage. The topology changes and link availability will vary between the two scenarios. In this work the problem scenario under consideration is the use of a UAV based network to provide area coverage to a community of mobile and fixed users. Some of the key characteristics of this problem scenario are summarised below;

- The UAVs are homogeneous (in form and capability).
- The UAVs are cooperative and exchange information.
- The UAVs can relocate or reposition to cover more users/improve links.
- The UAV mobility is unpredictable contingent on user density.

- The UAVs are restricted to a defined area of interest.
- The UAVs provide area coverage to fixed and mobile users.
- The UAV network is both infrastructure and ad hoc based.
- The UAV network has a mesh topology.

A. Solution Approach

The solution adopted in this work considers improving UAV situation awareness as a factor in mitigating routing challenges in UAV based networks. As mentioned earlier, majority of proposals reviewed merely modified existing routing protocols or proposed new ones with considerations to layer 3 elements. These methods made no attempt to consider other possible higher decision making elements in the UAV architecture. In reality these protocols are limited to the applied routing metrics and the unpredictable nature of the network. For instance, topology-based routing protocols exploit IP addresses in the network; position-based protocols exploit geographical positions in addition to computing traffic density parameters while cluster-based protocols rely on clustering or swarming metrics [7], [11]. This observation is further reflected in some of the documented challenges of the approaches e.g. link failures, packet losses, high routing overhead and low convergence rates in networks [7], [11].

In order to address some of these challenges especially the link failure problem the authors proposed an approach (see figure 2), where the UAV autonomy algorithm through better SA can improve routing decisions. This is achieved by enhancing the UAV decision making capabilities by adding UAV SA to the decision loop for routing. By placing the UAV autonomy algorithm which processes UAV SA parameters above the routing logic, improved decision making outputs can improve inter-UAV link availability.

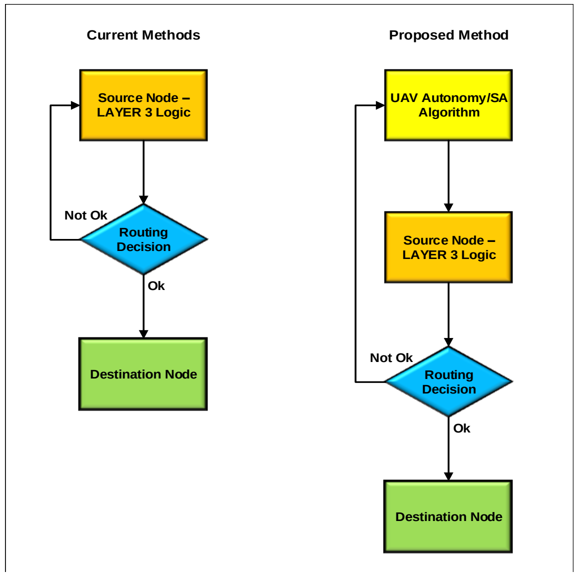

Fig. 2. High Level Overview of Current and Proposed Decision Loops.

IV. Modelling and Simulation Background

The simulation implemented software models of multiple solar-powered fixed-wing unmanned HAPS providing area coverage over a specified geographical region. The UAVs are designed to have positional situation awareness as they are able to acquire and comprehend positional vector of each UAV in the network. All the UAVs in the network form a mesh topology, interconnecting each other through inter-UAV links. However, the inter-UAV links must maintain a specific range to be considered a valid link for communication (200km is specified for this simulation, a valid range for optical links). In other to meet this criteria, each UAV must maintain positional SA ensuring it perceives where each UAV is positioned in relation to itself. To compute the positional vector of each UAV at every instant is computationally burdensome and involves significant overhead. This challenge is mitigated by designing the UAV autonomy algorithm to request and compute this vector at specified intervals or events e.g. at the point of relocation and change in attitude. In the problem scenario under consideration, this is a valid assumption as the UAVs maintain a holding pattern unless required to relocate to cover more users. The UAVs operate as a swarm and cooperatively engage to ensure maximal user coverage; the swarm intelligence based algorithm (see algorithm 1) described below is designed to aid swarming and improve positional SA in the UAV network;

Algorithm 1 Swarming and SA algorithm

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Input: Number of HAPS (N)
HAPS maintains holding pattern over area of interest
Broadcasts Position Vector and User density to other HAPS.
Updates and Processes Broadcast data from other HAPS at intervals.
Evaluates current Position Vector and local user coverage in relation to other HAPS
if Current Position <= 200km or User Coverage is above threshold then ▷ Hard-coded threshold values
    HAPS remains in current location.
else if Current Position > 200km or User coverage is below threshold then
    HAPS evaluates Utility of adjusting position or relocation to cover more users. ▷ Utility measures cost of adjustment vs non adjustment as a function of link availability and user coverage
    HAPS estimates position vector of other HAPS during and after adjustment or relocation using speed and bearing data.
    if Readjustment or Relocation Decision = Positive then
        HAPS adjusts Position to improve link availability.
    else if Readjustment or Relocation Decision = Negative then
        HAPS maintains current Position and recomputes vectors at intervals until decision is positive.
    end if
end if
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The awareness of each UAV of the position of other UAVs in the network and how that relates to link quality and availability provides a higher level decision loop that impacts positively on routing. This approach is most suitable for networks where the UAVs maintain regular holding pattern and swarm together to cover users. Essentially it means that position adjustment or relocation by UAVs occur as a result of cooperative efforts to achieve global network goals. This approach ensures that by improving positional situation awareness each UAV ensures optimal positioning to maintain quality link availability. The idea is to proactively ensure that the UAV network has links within acceptable range for transmitting information thereby avoiding dropped packets or other link associated challenges.

In the next section the simulation results of this concept is further analysed; table I, describes the communications and link budget parameters used in the simulation to cover an area populated by fixed and mobile users. The mobility pattern of the users caused the UAVs to relocate in order cover more users and consequently introducing link fluctuations and topology changes. However, the UAVs are constrained to the area of interest thereby ensuring no UAV strays away.

V. Results and Analysis

The simulation was run with four (4) HAPS covering an area of interest providing communications coverage to mobile and fixed users. The initial positions (latitude and longitude) of the HAPS for each run of the experiment are; HAPS1:[51.4738, 0.0106], HAPS2:[52.9181, -1.1319], HAPS3:[51.8825, -3.1500], HAPS4:[53.3761, -2.7798], with initial altitude of 20km. In one scenario of the simulation called the benchmark scenario the UAV network was implemented without a swarming and SA algorithm. In essence the simulation was run with the UAV making random relocation decisions with no positional situation awareness or any form of cooperation between the UAVs. During the simulation the link range measurement or profile of the mesh network was captured essentially describing the link quality

TABLE I
HAPS System Communications and Link Budget Parameters

s/n	Item	Specification	Justification
1	Half Power Beam Width (HPBW)	145 degrees	Specific to Model
2	Normalised Signal to Noise Ratio (Eb/No)	10 dB	Assumed for Link
3	EIRP	Depends on Slant Range	Power to support 1 subscriber at edge of cover
4	Data Rate	10 Kbit/s	Desired Link Data Rate
5	HAPS Transmitter Antenna Efficiency	0.75	Assumed for Model
6	Ground Receiver Antenna Gain	1	Assumed for Model
7	Signal Frequency	7 GHz	Assumed for Model
8	System Noise Temperature	350K	Standard

as a function of distance between the UAVs in the network. Conversely in the second scenario, algorithm 1 was implemented, with swarming and positional SA in use and link profile of the UAVs captured as well. Both results were compared to see what impact the swarming and positional SA had on the link profile. One basic requirement for routing to be successful in a UAV network is for UAVs to have available links to route information through. If at the point of information exchange there is no available hop (UAV node) or the link degrades or is broken then routing will fail. The unmanned HAPS are modelled as solar-powered, consequently the simulation was carried out during the day to mitigate the impact of solar energy fluctuations at night.

A. Benchmark Scenario

The link profile of the benchmark scenario after the simulation is captured in figure 3, and provides an overview of how the links decayed over time. In the figure, each UAV's link is measured with respect to itself and others in the mesh i.e. each UAV is treated as a reference (its distance against itself is zero, as shown in the figure). It can be seen from the result that the inter-UAV link could not maintain the targeted link threshold target. The links were consistently fluctuating and in some instances almost doubling the 200km threshold set for the optical system. Another way of interpreting this result is that the inter-UAV links will be unpredictable for any type of routing protocol applied. The fundamental issue from the results shown is that the network or more specifically the UAVs have no sense or awareness to aid the routing decisions. From a link availability perspective this type of network will suffer considerable link failures.

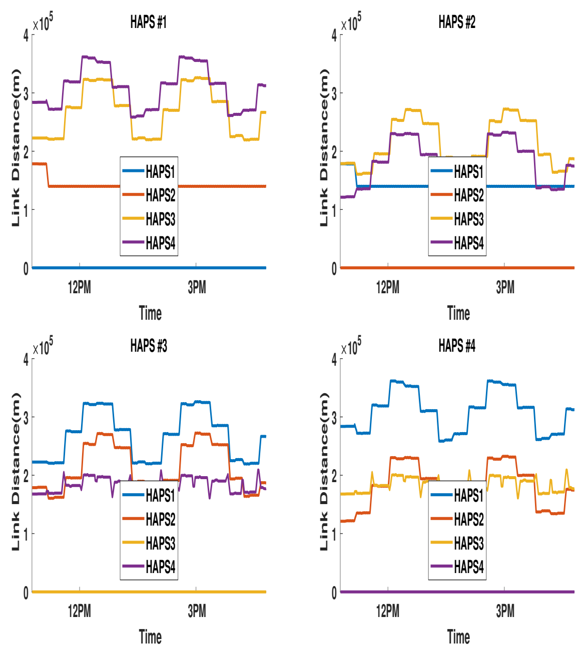

Fig. 3. Inter-HAPS link status without Swarming/SA Algorithm (Benchmark).

B. Swarming/SA Enabled Scenario

In this scenario, the swarming and positional SA algorithm was enabled and the link status captured and analysed as required. In figure 4, the HAPS through the swarming algorithm initiated a clustering manoeuvre to improve user coverage and link availability for the mesh network. At the start of the simulation the average link distance was clearly above 200km; reaching almost 300km in some cases. However the HAPS were able to use both the swarm intelligence based algorithm and the positional SA advantage to achieve a network wide link stability. All through the simulation the link distance was maintained at the specified threshold (a form of convergence), thereby guaranteeing better link availability and minimal topology changes. This clearly demonstrates routing challenges can be mitigated by integrating other higher level decision parameters traditionally overlooked in the routing framework. The approach can be described as proactive; the network in this case hedges the risk of link failure by using the higher decision elements of the UAVs to conform or constrain the UAV formation to a routing friendly posture. This minimises the emphasis on the routing protocol itself but adopts a more integrated approach. The stability of the links is a desirable condition for improved routing regardless of the specific routing protocol adopted.

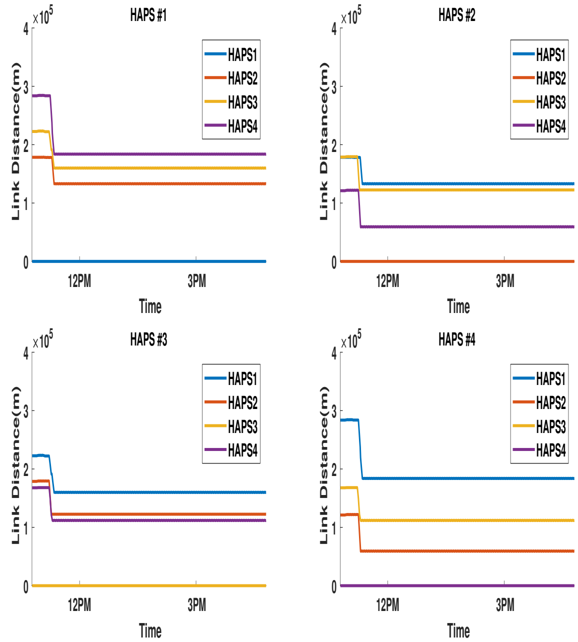

Fig. 4. Inter-HAPS link status with Swarming/SA Algorithm.

VI. Conclusions and Future Work

This paper examines Situation Awareness (SA) and its impact on routing in UAV based networks. Different routing techniques have been proposed for UAV based networks especially FANETS, where high UAV mobility and topography changes impact routing. The general approach to this problem has been to modify traditional routing schemes or propose new ones based on the architecture of classical routing protocols. However, this work highlights the importance of looking beyond classical routing architectures to higher levels in the UAV decision making hierarchy. One of such approach is to integrate the UAV autonomy algorithms and the routing algorithms. This work specifically examines how UAV SA can impact routing positively. By considering SA as part of the UAV autonomy framework, it is possible to design UAV autonomy algorithms that will mitigate routing challenges. This work provides a framework to harness such capability by demonstrating that in the area coverage problem scenario, improved UAV SA can alleviate the intermittent link degradation and topology changes common in UAV based networks.

Future work will explore how to enhance current SA algorithms to further improve routing. For instance, elevating the autonomy level of the UAVs by adding more SA parameters beyond just positional elements. It is also important to address the challenge of obscuration by the body of the UAV. The UAV body obscuration and how the autonomy algorithm manages the UAV attitude SA to reduce the impact of obscuration on link stability will be quite interesting.

Another area of interest is extending SA to Delay Tolerant Networks (DTN); SA about node locations could be used as a basis for forwarding packets opportunistically in the direction of the destination node, even if no end-to end (E2E) path is available.

References

[1] International Telecommunications Union (ITU). Terms and definitions. Radio Regulations Articles, 2016.

[2] Jinfang Jiang and Guangjie Han. Routing Protocols for Unmanned Aerial Vehicles. IEEE Communications Magazine, 2018.

[3] S. Rosati, K. Krużelecki, G. Heitz, D. Floreano, and B. Rimoldi. Dynamic Routing for Flying Ad Hoc Networks. IEEE Transactions on Vehicular Technology, 65(3):1690–1700, March 2016.

[4] Jean-Aime Maxa, Mohamed Mahmoud, and Nicolas Larrieu. Secure Routing Protocol Design for UAV Ad Hoc Networks. IEEE, 2015.

[5] Ogbonnaya Anicho, Philip B Charlesworth, Gurvinder S Baicher, and Atulya Nagar. Integrating Routing Schemes and Platform Autonomy Algorithms for UAV Ad-hoc & Infrastructure Based Networks. In 28th International Telecommunication Networks and Applications Conference (ITNAC). 28th International Telecommunication Networks and Applications Conference (ITNAC), IEEE, November 2018.

[6] O. Anicho, P. B. Charlesworth, G. S. Baicher, A. Nagar, and N. Buckley. Comparative study for coordinating multiple unmanned haps for communications area coverage. In 2019 International Conference on Unmanned Aircraft Systems (ICUAS), pages 467–474, June 2019.

[7] Muhammad Yeasir Arafat and Sangman Moh. Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey. IEEE Access, 7:99694–99720, 2019.

[8] J. D. M. M. Biomo, T. Kunz, and M. St-Hilaire. Routing in Unmanned Aerial ad hoc Networks: A Recovery Strategy for Greedy Geographic Forwarding Failure. In 2014 IEEE Wireless Communications and Networking Conference (WCNC), pages 2236–2241, April 2014.

[9] Zhigao Zheng, Arun K. Sangaiah, and Tao Wang. Adaptive Communication Protocols in Flying Ad Hoc Network. IEEE Communications Magazine, 2018.

[10] Jorge Souza, José Jailton, Tássio Carvalho, Jasmine Araújo, and Renato Francês. A Proposal for Routing Protocol for FANET: A Fuzzy System Approach with QoE/QoS Guarantee. Wireless Communications and Mobile Computing, 2019, 2019.

[11] Omar Sami Oubbati, Abderrahmane Lakas, Fen Zhou, Mesut Güneş, and Mohamed Bachir Yagoubia. A Survey on Position-based Routing Protocols for Flying Ad hoc Networks (FANETs). Vehicular Communications, 10:29–56, 2017.

[12] Owen McAree, Jonathan M. Aitken, and Sandor M. Veres. Towards Artificial Situation Awareness by Autonomous Vehicles. International Federation of Automatic Control (IFAC), Elsevier, 2017.

[13] Julie A. Adams. Unmanned Vehicle Situation Awareness. volume 19. Proceedings of HSIS 2007, ASNE Human Systems Integration Symposium, 2007.

[14] Thanh Nguyen, Chee Peng Lim, Ngoc Duy Nguyen, Lee Gordon-Brown, and Saeid Nahavandi. A Review of Situation Awareness Assessment Approaches in Aviation Environments. IEEE SYSTEMS JOURNAL, 2019.

[15] Jill L. Drury, Laurel D. Riek, and Nathan Rackliffe. A Decomposition of UAV-related Situation Awareness. ACM SIGCHI/SIGART, pages 88–94, 2006.

[16] Haydee M. Cuevas and Marisa Aguiar. Assessing Situation Awareness in Unmanned Aircraft Systems Operations. International Journal of Aviation, Aeronautics, and Aerospace., 4(4), 2017.

[17] Philip B. Charlesworth. A Game Theoretic Approach to Coordinating Unmanned Aerial Vehicles with Communications Payloads. PhD thesis, Cardiff University, 2015.

[18] Lars Niklasson, Maria Riveiro, Fredrik Johansson, Anders Dahlbom, Göran Falkman, Tom Ziemke, Christoffer Brax, Thomas Kronhamn, Martin Smedberg, Håkan Warston, and Per M. Gustavsson. A Unified Situation Analysis Model for Human and Machine Situation Awareness. the 3rd German Workshop on Sensor Data Fusion: Trends, Solutions, Applications (SDF 2007) Bremen, Germany., September 2007.