Revista Científica del Centro Universitario de la Guardia Civil
Revista Lógos Guardia Civil

Christine Dugoin-Clément
Associate researcher at the CREOGN and at the Artificial Intelligence Observatory and Chair "Risk" of Paris 1

LOYAL WINGMEN AND ARTIFICIAL INTELLIGENCE DEVELOPMENT: A STATE OF ART

LOYAL WINGMEN AND ARTIFICIAL INTELLIGENCE DEVELOPMENT: A STATE OF ART

Abstract: Drones are increasingly present in everyday life. Their use has also increased in the fields of security and defense, where they take on the 5D task (Dull, Dirty, Dangerous, Dear and Difficult) and help protect men in the performance of risky tasks, as well as enhance the visibility and surveillance of disturbed and/or extended areas. The evolution of drones means the rise of artificial intelligence, especially for the most sophisticated ones, such as Loyal Wingmen. With the Russian invasion of Ukraine, drones are the focus of particular interest, and the US Department of Defense (DoD) place an order for 1,000 collaborative fighter jets by Loyal Wingmen is in the spotlight. In this context, this article will present the main challenges that AI must meet to allow the development of this type of specific drones and will make a state of the art of the development of Loyal Wingmen. Finally, in the light of the issues identified, this paper will propose an industrial development path.

Resumen: Los drones están cada vez más presentes en la vida cotidiana. Su uso también ha aumentado en los campos de la seguridad y la defensa, donde asumen tareas 5D (Dull, Dirty, Dangerous, Dear and Difficult, es decir, aburridas, sucias, peligrosas, queridas y difíciles por sus siglas en inglés) y ayudan a proteger a los hombres en el desempeño de tareas arriesgadas, así como a mejorar la visibilidad y la vigilancia de áreas alteradas y/o amplias. La evolución de los drones significa el auge de la inteligencia artificial, especialmente para los más sofisticados, como los Loyal Wingmen. Con la invasión rusa de Ucrania, los drones son objeto de especial interés, y el pedido realizado por el Departamento de Defensa de los Estados Unidos (DoD) de 1000 aviones de combate colaborativos por parte de Loyal Wingmen está en el punto de mira. En este contexto, este artículo presentará los principales retos a los que debe enfrentarse la IA para permitir el desarrollo de este tipo de drones específicos y presentará un estado de la cuestión del desarrollo de los Loyal Wingmen. Por último, a la luz de los problemas identificados, este artículo propondrá una vía de desarrollo industrial.

Keywords: Drones, Loyal Wingmen, Artificial Intelligence (AI)

Palabras clave: Drones, Loyal Wingmen, Inteligencia Artificial (IA).

INTRODUCTION

Drones have become increasingly part of the defense and security system all around the world. Indeed, since more than one decade now, drones have played a key part/role in counterinsurgency and counterterrorism (Mahadevan, 2010) as well as for monitoring and surveillance missions, even if their use is limited by local national legislations (Tsiamis, Efthymiou & Tsagarakis, 2019).

Nevertheless, drones have been both used for military and police missions. We can refer to the use for border surveillance (Shishkov, Hristozov, Janssen, van den Hoven, 2017; Brumfield, 2017) for the fight against illegal immigration (Roma, 2017). In the European Union, they have been used by Frontex (Tikanmaki, 2011; Marin, Krajčíková, 2016). On the other side of the Atlantic Ocean, some US states' polices use drones for crime tracing and the monitoring of crime suspects as well as for crowd control (Stelmack, 2014), and in search and rescue operations (Villasenor, 2014).

On war theatres, drones have many different uses according to the type of device we deal with: they can be either Unmanned Ground Vehicles (UGV), Unmanned Maritime Vehicles (UMVs), or Unmanned Aerial Vehicles (UAV).

Recently the Russian invasion of Ukraine, which started in February 2022 emphasized the role UAV may assume especially with the efficient and agile drones used and sometimes made by Ukrainian Army and Ukrainian volunteer. Indeed, the Turkish Bayraktar TB2 (Witt, 2022) become well known and we also observe the Iranian Shaed-136 mobilized by the federation of Russia (Eslami, 2022) as well as, lately, the KUB-BLA, Lancet and Orlan (de Henning Michaëlis, 2023, Dugoin-Clément, 2023) and then of wasternes Switchblade et Phoenix Ghosts provided to Ukraine (Dugoin-Clément, 2023) invite many experts to question the drones role in future wars (Fuhrmann, & Horowitz, 2017 ;Al-Ghani, 2022 ; Kunertova, 2023 ; Calcara, Gilli, Gilli, Marchetti, Zaccagnini, 2022) as drones become a constant feature of modern conflicts.

Meanwhile Mykhailo Fedorov, Ukraine's Deputy Prime Minister for Innovation, Education, Science and Technology – Minister for Digital Transformation, announced on his Telegram channel that the first three UAV strike companies are ready for battle and are part of the Drone Army's state program supported by the UNITED24, the official fundraising platform of Ukraine[1]. That project includes pick-up trucks that will be used for raids behind enemy lines, delivery of goods and evacuation of the casualties, UAVs and attack copters. This announcement echoed the one concerning the first robotic strike unit launched by the Russian Federation in 2021, which was a further step in the use of AI to increase Russian combat capabilities (McDermott, 2021). Even if those drones had mixed results on the Syrian battlefield and had not been used in Ukraine, this communication had a tremendous effect on westerns countries back then.

This recent evolution invites some researchers to think about about an « unmanned revolution in military affairs » (Stulberg, 2007 ; Bryen, 2017 ; Altmann & Sauer, 2017) even if the Revolution in Military Affairs (RMA) born in the 70's to be developed in the 80's and applied in the 90's (Sloan, 2002 ; Davis, 1997) which wanted to benefit from Information System (IS) to gain a complete vision of the war theater, did not completely fulfill the expectations (Cansell & Desmoulin, 2017).

Talking especially of UAVs, their use in the coming years will tend to become widespread for all operational echelons, as they offer a wide range of services from reconnaissance to logistics, including saturation and targeted elimination strikes. As such many concept are studied by the military-industrial complex all around the world. If UAVs swarms are quite famous the Loyal Wingman is on the eve of becoming a cornerstone of air dominance and air doctrine of the future. Loyal Wingmen are a specific kind of drone that become paramount in aircraft strategies, especially since the U.S. Air Force, on March 8, 2023, announced its plan to acquire 200 fighters and no less than 1,000 CCA (Collaborative Combat Aircraft) drones as part of its NGAD (Next Generation Air Dominance) program. In practice, two drones would be allocated to each of the new 6th generation fighters as well as to nearly 300 F-35As, pending possible additional orders to equip the rest of the F-35 fleet. Nevertheless, US Air Force has not yet selected its CCA model(s), so it continues to develop technologies, tactics and employment doctrines based on the first generation of Loyal Wingmen, which is available in small numbers (Losing, 2023).

In other words, in the line of the RMA's hopes and expectations, in a near future, UAVs are expected to offer important capabilities for cooperation and integration with allied battlefield systems, well beyond their current use. Nevertheless, talking about drones swarms or about Loyal Wingmen implies to deal with the Artificial Intelligence (AI) that will sustain these systems.

Consequently, after presenting the Loyal Wingman concept, this paper will focus on a presentation of the main AI type dedicated to drones, and will end with a presentation of the actual design of Loyal Wingman-related AI.

1.- LOYAL WINGMAN CONCEPT

The Revolution in Military affairs (RMA), a new military doctrine was developed in the 1990s as a result of the Gulf War and the development of technology, particularly in the field of information technology (Jablonsky, 1994; Arquilla & Ronfeldt, 1997). The Military Technological Revolution (MTR), which was developed in the Soviet Union in the 1970s, can be credited of being at the origine of the RMA concept, which deals with using technology to turn the battlefield into a fighting space (Adamsky, 2008). The basic concept behind the MTR was that the West used advances in technology and science to neutralize the threat posed by the Soviet second echelon. The Gulf War is regarded as a turning point because it shows how the battlefield is changing. As such, Blackwell, Mazarr & Snider (1991) explained that «*the effects of technology-in precision guided weapons, in stealthy delivery systems, in advanced sensor and targeting systems, in battle management platforms-is transforming and in fact already has demonstrably transformed the way in which armed forces conduct their operations* » (p.21).

As a result, new research and development domains are being opened by the research and development (R&D) advancement of technology, particularly in the realm of information and communication technologies (ICTs). The Command and Control (C2C) system has undergone a thorough makeover, and much research has focused on replacing humans with robots or developing soldiers' inherent skills. Lethal autonomous weapons (LAWs), manned systems, and human enhancement technologies (HETs) all arose as a result. With regard to HETs, the objective is to create technologies and methods that will help people get over their current physical and cognitive constraints (Parens, 1998; Agar, 2004; Naam, 2004; Wilsdon and Miller, 2006; Garreau, 2005). A lot of research is being done on the LAWs and unmanned systems that are intended to either support or replace military personnel. Those replacement by drones is expected to be both « *morally preferable (not to mention strategically advantageous), as they can be used in place of human combatants* » (Etzioni, 2018, p. 1) and more efficient thanks to the speed allowed by calculation power when the system is supported by an Artificial Intelligence (AI).

The sixth wave of RMA emerged in the 2000s. This strategy emphasized various critical drivers. In particular, it emphasizes how China and Russia are stepping up their strategic confrontation with the US for supremacy on a variety of fronts, including political, economic, and military-technological growth.

As a result, another important factor is the emergence of military-technological innovation dynamics based on the fusion of science and technology, particularly through artificial intelligence, human-machine learning, cognitive manipulation, and between cyber and artificial intelligence (Raska, 2020). Because Raska (2020), the dissemination of dual-use technologies, notably autonomous and AI-enabled systems in the battlefield, is implied by the first two primary factors.

This special context is part of the answer explaining that « *the emergence of a new, unique AI-enabled RMA wave, i.e., the AI-RMA* » (p. 8).

With AI's developments, it is now possible to consider that some decisions made by UAVs may be automated with the use of decision-making procedures, freeing up human commanders to concentrate on more complex choices in current warfare scenarios, giving them a key tactical edge.

As a result, many nations are interested in creating unmanned aerial vehicle (UAV) projects to act as a devoted wingman for fighter pilots, or manned-unmanned teaming (MUM-T).

Generally speaking, unmanned Loyal Wingman, uninhabited Loyal Wingman, and Loyal Wingman are all words used to describe an uninhabited aerial vehicle that operates autonomously under the tactical command of a manned lead air vehicle (Humphrey, 2016). There is no remotely piloted aircraft in the unoccupied loyal wingman. Instances that allude to a man-operated vehicle will include the word "manned" in the description.

The devoted wingmen are meant to be able to fly on their own without assistance from humans. That is critical because having a person behind every devoted wingman would be too expensive (Nentwich & Horváth, 2018) and would negate the benefits of AI piloting. Yet, developing a UAV with AI that can be a reliable and effective wingman is quite expensive, both from a financial and environmental standpoint (UAV development). Indeed drones development may be costly especially in material including rare earth as many High technology products). But Loyal Wingmen must be affordable enough if we keep in mind that a devoted Wingman must be theoretically disposable.

This paper will present a quick literature review on the Loyal Wingman development's state-of-the-art, in order to clearly expose the design presented on the basis of the available data.

2.- LOYAL WINGMEN'S ACTUAL DESIGNS

According to a general agreement, jetfighters' lead pilot are already overloaded with duties (Houck, Whitaker & Kendall, 1992 ; Ree & Carretta, 1996 ; Mohanavelu, Poonguzhali, Adalarasu, Ravi, Chinnadurai, Vinutha & Jayaraman, 2020), and appreciate to delegate as many decisions as they can to their Wingmen. This entails as much autonomy in the unmanned system as is practical with regard to an uninhabited faithful Wingman. As a result, a command and control architecture that is compatible with contemporary manned operations is required, in which a manned lead gives precise instructions. The unoccupied faithful Wingman is required to carry out the following duties: automatically generate a mission plan based on lead communication. In the case of a changing threat environment or mission requirement, the mission should be replanned dynamically.

Consequently, connectors have to find technological ways to control UAVs, groups of UAVs and Loyal Wingman throughout the four attributes of formation flight, namely: formation rendezvous, formation hold, formation reconfiguration, splinter activities.

Another key challenge for a reliable and efficient Loyal Wingman from a global perspective will be to successfully scan the environment, create scenarios (including dynamic as indicated by Humphreys, Cobby, Jacques & Reeger (2016), evaluate the best of those scenario, simulate combat, and assess the impact and vulnerability. In other words, a Loyal Wingman must possess the ability to handle the primary idea, particularly C2, intellect, mobility, protection, logistics, and effect (Stensrud, Mikkelsen, Betten & Valaker, 2021).

Other frameworks involve the UAV serving as the second formation's central planner. A system like this would take into account a conglomerate of tasks. In that case, a computer on board in a single UAV computes mission paths for all UAVs in formation and communicates these paths to other UAVs in the formation to complete all mission tasks. Another scheme would be a collaborative control environment resembling swarming behaviors, in which all UAVs in formation are continuously communicating with one another to determine which vehicle is carrying out which task and to find the best way to complete all mission objectives.

Finally, in addition to the challenge of information systems, the Loyal Wingman is also a purely aeronautical problem. Indeed, this UAV will have to act in team with fighter planes, especially of the last generation, which supposes that it will be able to offer the same capacity of flight, velocity and agility. In fact, the development of information systems must be coupled with the development of aeronautical technology which puts defense industries in competition.

3- MANAGING THE MAIN ATTRIBUTES OF FORMATION FLIGHT

To become efficient pilot partners, Loyal Wingmen have to be able to manage the main attributes of formation flight and then to fulfill technical missions which request calculating and planification. This road planification implies to master the outer-loop control that includes Path planning control using graph theory, the Dijkstra algorithm, proportional navigation, line of sight, sliding mode terminal guidance, and artificial potential functions

3.1.- Formation Rendezvous

This idiom recovers the coming together of two or more vehicles leaving from physically separate locations in a formation intended to last for a given amount of time.

This idea has to be completed by another, the rendezvous target, which addresses the issue of multiple vehicles arriving from various physically colliding locations (Giulietti, 2000). By assuming that each aircraft is a node and that the communication paths between them are the edges connecting the nodes, graph theory is used. The issue is solved by reducing it to a shortest path problem and providing a set of assumptions. The Dijkstra algorithm was chosen because it is deterministic, only has polynomial complexity, and ensures optimality (Smith, 2008; Park, 2003 ; Tahk, Park & Ryoo, 2005). Sliding Mode Terminal Guidance (SMTG) to rendezvous aircraft is used because communication is not needed when using sliding mode (Harl & Balakrishnan, 2008). Proportional Navigation (PN) produces control accelerations proportional to the interceptor-target line-of-detected sight's rate of rotation and directs these forces to slow down or maintain that rate constant. By designating the constraint function as a repulsive force and the objective function as an attracting force, artificial potential functions may be used. This makes it possible to steer the vehicle so that it is drawn to goals and rejected by restrictions (Stickney, 2014; Garcia, Barnes & Fields, 2012).

3.2.- Formation hold

After the Formation Rendezvous, the aim is to maintaining the formation. That implies to build a 3D potential field which will be part of the outer-loop control category defined for sequential path planning. That will resort to graph theory again (Tanner, Jadbabaie & Pappas, 2003; Garcia, Barnes & Fields, 2012). UAVs swarm, as Loyal Wingmen, as supposed to behave as groups of animals and swarms. Consequently engineers worked on modeled real swarm behaviors especially their *"ability to accomplish complex objectives through synergistic interactions of simple reactionary components »* (Kovacina et al., 2002), and also developed methods such as Multiplexed Model Predictive Control -MMPC- (Weihua & Go, 2011; Ling et al. 2012). This approach is still developed (Yan, Yu & Wang, 2022), in order to increase anomaly detection problem as well as to coordinated UAVs and UAGs (Chen, Li, Wang & Wang, 2022).

3.3.- Formation Reconfiguration

Because of the changes implied by leading an action or by the incorporation of new vehicles, the formation flight may require a formation reconfiguration. This re configuration is largely dependent on communication systems, sensors, flight path restrictions as well as the system managing the collaborative flight such as Particle Swarm Optimization -PSO- (Hu & Eberhart, 2002) as defined and develops by Duan, Ma & Luo (2008) and Duan & Liu (2006), or direct orthogonal collocation (Ma, Huang & Zhuang, 2010), and is still progressing and subject to current research (Zhang et al., 2019 ; Li, B., Zhang, Dai Teo & Wang, 2020 ; Liu, Li & Ji, 2022).

3.4.- Formation Activities

Formation may have to manage different kinds of activity including splinters ones. Swarming and emergent behaviors are pertinent to splinter activity performance. But Kovacina et al. (2002) mentioned that traditional control methods *"do not provide the flexibility and efficiency needed to meet the commercial and military demands placed upon UAV swarms*". Consequently, he creates a control algorithm and uses a simulation of a swarm of vehicles in a perspective of emergent behavior control algorithm that can be divided into different technics (Russell & Lamont, 2005 ; Teodorovic & Dell'Orco, 2005 ; Wang, Yadav & Balakrishnan, 2007 ; Sammut & Webb, 2011 ; Xie, Han, Dong, Li & Ren, 2021) Splinters activities, as all reconfiguration activities have to minimize the time necessary to create a new formation which is another challenge (Fukurawa et al, 2002).

4.- KEY CHALLENGE FOR A RELIABLE AND EFFICIENT LOYAL WINGMAN

But talking of Loyal Wingman involved in integrating specific issues that are not always a matter for others UAVs. According to Humphreys, Cobby, Jacques, and Reeger (2016), a technique must be developed that enables the production of quick, autonomous solutions for the optimal control of Loyal Wingmen. This must be for a unique mission path, but Loyal Wingmen must be capable of generating a new mission path in a changing environment. Humphreys, Cobby, Jacques, and Reeger (2016) suggest creating a heuristic Particle Swarm Optimization (PSO) algorithm tailored to a dynamic threat environment as a conclusion to their study. With this paper's suggestion, it seems that fighters who become Loyal Wingmen may use the same concept.

A behavior tree (BT) was the primary technique used to in the recent research by Giacomossi, Schwanz Dias, Brancalion & Maximo (2021) to make decisions in a decentralized way. They employed the PSO optimization technique to achieve this goal. Their studies were able to demonstrate a 93% threat removal efficiency. Alongside, a strategy of manned fighters and UAVs cooperating in air combat with intelligent decision-making based on the deep deterministic policy gradient (DDPG) algorithm was proposed by Li, Han, Zhong, Ji, and Mu in 2022.

Besides these technical issues, MUM-T implies that the human agrees not to interact with the UAVs. Many researches studies showed that technology acceptance is linked to trust placed in the system by the human using it. Since it is not based on an interpersonal relationship, trust in AI and other robotic systems will have to be built between a person and the machine. Thus, the trust link between the technology provider (especially if it is innovative) and the actor could be interdependent (Wang & Siau, 2020) and depends, in particular, on the transparency and "explainability" of the new systems. For these authors, trust in technology is based on three types of characteristics: human, environmental and technological.

Consequently it appears that, additionally to the technical issues related to AI design dedicated to Loyal Wingmen, these drones have to inspire trust in their pilot partner in order to be completely accepted and thus fully used.

DISCUSSION - just needed in manned-unmanned teaming (MUM-T) and development proposal

As mentioned earlier, Loyal Wingmen are a technological challenge, a main piece of the future of air forces and a challenge in terms of acceptability both because they have to comply with technological, human and environnemental characteristic (which included explainability, the estimated competence of the object, and task nature assigned to the drone) and because they must not be felt as a threat for pilots' professions. If explainability may be increased by training and pilot IS education focusing on some of the methods exposed in this paper, it won't solve the estimated competence of the object which is correlated to the pilot's willingness to trust.

Keeping those challenges in mind, we postulate that future research could address the proposal to reuse fighter aircraft well known to pilots to develop AI dedicated to the Loyal Wingman.

Indeed, this proposal can be a way to save time by developing the aircraft concurrently and the inserter system that can be tested in real flight conditions as well as using a large data set.

Thus, reusing fighter aircraft for which the financial cost has already been amortized and for which cruise and combat flight databases are available could be an opportunity. Indeed, by equipping them with AIs allowing them to be transformed into Loyal Wingmen could have a triple advantage.

First, it would enable the development of a dedicated and efficient AI at low cost.

Secondly, considering that their flight and combat skills are known to the pilots, it will help increase one of the pillars of trust mentioned above, allowing a natural and progressive shift towards new designs of Loyal Wingmen.

Then, as they have been financially amortized, their possible loss would be more sustainable, as drones can have a very limited combat life (sometimes barely more than one day for the drones used in Ukraine, which are certainly not Loyal Wingmen).

Finally, this AI deployment would allow to save development time by not waiting for the finalized development of the drone to be equipped with this AI, thus allowing the industrialists not to fall behind schedule. Any delay could then be difficult to overcome.

CONCLUSION

In conclusion, drones have recently played a predominant role in modern conflicts, whether in the war between Azerbaijan and Armenia (Hecht, 2022 ; Kinik & Çelik, 2021) or since the invasion of Ukraine by Russia in February 2022 Chavez, 2023 ; Dugoin-Clément, 2023). With this recent conflict, Western countries are considering with more willingness to rebuild their armies. Equipping themselves with drones which can surpass human skills while protecting lives, is becoming more and more attractive. This attraction is reinforced by the development of capabilities and computing power that allow the development of more and more successful AI dedicated to the piloting of drones, including UAVs.

However, developing AIs in line with the flight characteristics of fighter aircraft presents a set of complexities. This UAV must behave as a team partner, be able to perform planning, surveillance and tracking missions. it also has to but also to interact in real time in aerial combat within a team mixing piloted aircraft and Loyal Wingmen.

In addition to this, if human technologies' acceptability and trust oblige us to think of AI as explainable, security needs are crucial. Consequently IA has to be "hardened", in particular in order to counter cyber attacks (especially spoofing) and to reduce the surface of vulnerability.

Finally, these drones have to be designed to be able to be accompanied by 5th and 6th generation fighter planes, which implies having more or less the same capacities in flight and fight actions. But, they also have to be capable of being expendable as they may be forced to sacrify themselves in order to protect the human-piloted jetfighter, which implies sustainable production costs.

Finally, the literature has several times described that to be exploited the systems that they must be accepted by their users. This acceptability is based on several characteristics, including the willingness to trust the systems themselves and trust in the skills of the systems.

It seems relevant to us to wonder about the possibility of reusing old fighters to train AI. It could be an interesting option in that they would facilitate the confidence of pilots as they know the fighter perfectly well, which is the carrier of the new AI-partner. Moreover this could be a transition enhancing/meant to enhance the pilots trust in the system before moving to a drone with a completely new design, and therefore with poorly known flight skills and in any case not experienced empirically by the pilots.

In addition, the training time of the AIs could be shorten if it uses existing databases, collected during past mission made by the already exploited jetfighters. That could make it possible to develop AIs that are both explainable (Gunning, Stefik, Choi, Miller, Stumpf & Yang, 2019; Arrieta et al., 2020; Tjoa & Guan, 2020; Meske, Bunde, Schneider & Gersch, 2022; Dwivedi et al., 2023) especially as conceptualized by the US DARPA (Gunning & Aha, 2019), and hardened, without waiting for the finalization of the UAVs on which they will have to be installed. This time saver will represent a significant advantage for the military-industrial complex within which the competition on these development projects is particularly stiff.

Finally, if Loyal Wingmen refer directly to developments are meant to be developed for military use, it is appropriate to think of similar developments that could be implemented for security purposes but also for civilian use. Indeed, in those others fields, technology's acceptability and production cost control will also be an issue.

BIBLIOGRAPHY

- Altmann, J. & Sauer, F. 2017. Autonomous Weapon Systems and Strategic Stability *Survival*, Vol. 59, No. 5, pp. 117–142, https://doi.org/10.1080/00396338.2017.1375263.
- al-Garni, A. D. 2022. Drones in the Ukrainian war : will they be an effective weapon in future war? Rasanah study

- Arrieta, A. B., Díaz-Rodríguez, N., Del Ser, J., Bennetot, A., Tabik, S., Barbado, A., ... & Herrera, F. (2020). Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Information fusion*, *58*, 82-115.
- Brumfield, E. 2014. Armed Drones for Law Enforcement: Why It Might Be Time to Re-Examine the Current Use of Force Standard. *McGeorge Law Rev, 46*, 543
- Bryen, S. 2017. Armed Drones Revolutionizing the Future of War, *Asia Times*, December 9, 2020, https://asiatimes.com/2020/12/armed-drones-revolutionizing-the-future-of-war/.
- Calcara, A., Gilli,A., Gilli,M., Marchetti,R., Zaccagnini, I. 2022. Why Drones Have Not Revolutionized War: The Enduring Hider-Finder Competition in Air Warfare. *International Security* 2022; 46 (4): 130–171. doi: https://doi.org/10.1162/isec_a_00431
- Cansell,P. & Desmoulin, L. 2017. De la RMA à la guerre infocentrée : retours d'expérience sur les promesses inaccomplies de la numérisation et du big data. COSSI - Méthodes et stratégies de gestion de l'information par les organisations : des "big data" aux "thick data, May 2017, Montréal, France. p.50-61. .hal-02984391.
- Chávez, K. (2023). Learning on the Fly: Drones in the Russian-Ukrainian War. *Arms Control Today*, *53*(1), 6-11.
- Chen, M., Li, B., Wang, J., & Wang, G. (2022, November). A Formation Control Algorithm for Air-Ground Cooperative UAV. In *2022 14th International Conference on Wireless Communications and Signal Processing (WCSP)* (pp. 741-747). IEEE.
- Davis, N. C. (1997). An information-based revolution in military affairs. RAND-PUBLICATIONS-MR-ALL SERIES-, 79-98.
- de Henning Michaëlis, S. (2023). Turkey's And Iran's Drone Supply In The War In Ukraine. *Policy,* (21).
- Duan, HB., Ma, GJ. & Luo, DL. 2008. Optimal formation reconfiguration control of multiple UCAVs using improved particle swarm optimization. Journalof Bionic Engineering, 5(4):340-347 doi:10.1016/S1672-6529(08)60179-1.
- Duan, HB. & Liu, SQ. 2010. Non-linear dual-mode receding horizon control for multiple
- unmanned air vehicles formation flight based on chaotic particle swarm optimisation. Control Theory & Applications, IET, 4(11):2565{2578, 2010.
- doi:10.1049/iet-cta.2009.0256.
- Dugoin-Clément. C. 2023. Ukraine-Russie : un an de guerre des UAVs. *DSI*
- Dugoin-Clément, C. 2023. Ukraine, Russie et high-tech, un an après le déclenchement de l'invasion. *Revue Défense Nationale*, (2), 37-42.
- Dwivedi, R., Dave, D., Naik, H., Singhal, S., Omer, R., Patel, P., ... & Ranjan, R. (2023). Explainable AI (XAI): Core ideas, techniques, and solutions. *ACM Computing Surveys*, *55*(9), 1-33.
- Eslami, M. 2022. Iran's drone supply to Russia and changing dynamics of the Ukraine war. *Journal for Peace and Nuclear Disarmament*, 5(2), 507-518.
- Fuhrmann, M. & Horowitz, M.C. 2017. "Droning On: Explaining the Proliferation of Unmanned Aerial Vehicles," *International Organization,* Vol. 71, No. 2, 397–418, https://doi.org/10.1017/S0020818317000121.
- Furukawa,T., Durrant-Whyte, HF., Bourgault, F. & Dissanayake, G. 2003. Time-optimal coordinated control of the relative formation of multiple vehicles. *In*

Computational Intelligence in Robotics and Automation, Proceedings 2003 IEEE International Symposium on, volume 1, 259-264. IEEE, 2003. DOI: 10.1109/CIRA.2003.1222099.

- Garcia, RD., Barnes, L & Fields, MA. 2012. Unmanned aircraft systems as wingmen. The Journal of Defense Modeling and Simulation: Applications, Methodology, *Technology,* 9(1):5{15, 2012. doi:10.1177/1548512910391217.
- Giacomossi, L., Schwanz Dias, S., Brancalion J. F. and Maximo, M. R. O. A. 2021 "Cooperative and Decentralized Decision-Making for Loyal Wingman UAVs," 2021 L*atin American Robotics Symposium (LARS), 2021 Brazilian Symposium on Robotics (SBR), and 2021 Workshop on Robotics in Education (WRE),* Natal, Brazil, 2021, pp. 78-83, doi: 10.1109/LARS/SBR/WRE54079.2021.9605468.
- Giulietti,F., Pollini, L & Innocenti, M. 2000. Autonomous formation flight. Control Systems, *IEEE,* 20(6):34{44, 2000.
- Gunning, D., Stefik, M., Choi, J., Miller, T., Stumpf, S., & Yang, G. Z. (2019). XAI—Explainable artificial intelligence. *Science robotics*, *4*(37), eaay7120.
- Gunning, D., & Aha, D. (2019). DARPA's explainable artificial intelligence (XAI) program. *AI magazine*, *40*(2), 44-58.
- Harl , N. and Balakrishnan, SN. 2008. Coordinated rendezvous of unmanned air vehicles
- to a formation: A sliding mode approach. *In AIAA Guidance, Navigation and Control Conference, 2008.*
- Hecht, E. (2022). Drones in the Nagorno-Karabakh War: Analyzing the Data. *Mil. Strateg. Mag*, *7*, 31-37.
- Houck, M. R., Whitaker L. A. and Kendall, R. R. 1992 "A cognitive classification of pilot performance in air combat," *Proceedings of the IEEE 1992 National Aerospace and Electronics Conference@m_NAECON 1992, Dayton, OH, USA, 1992,* pp. 503-509 vol.2, doi: 10.1109/NAECON.1992.220524.
- Hu, X. & Eberhart, R. 2002. Solving constrained nonlinear optimization problems with particle swarm optimization. In Proceedings of the Sixth World Multiconference on Systemics, Cybernetics and Informatics, volume 5, pages 203-206. Citeseer, 2002.
- Humphreys, C. J. (2016). Optimal control of an uninhabited loyal wingman.
- Kinik, H., & Çelik, S. (2021). The Role of Turkish Drones in Azerbaijan's Increasing Military Effectiveness. *Insight Turkey*, *23*(4), 169-192.
- Kunertova, D. 2023. The war in Ukraine shows the game-changing effect of drones depends on the game. *Bulletin of the Atomic Scientists,* 79(2), 95-102
- Kovacina MA., Palmer, D., Yang, G. & Vaidyanathan, R. 2002. Multi-agent control algorithms for chemical cloud detection and mapping using unmanned air vehicles. *In International Conference on Intelligent Robots and Systems, volume 3, 2782-2788. IEEE, 20*02. doi:10.1109/IRDS.2002.1041691.
- Li, B., Zhang, J., Dai, L., Teo, K. L., & Wang, S. (2020). A hybrid offline optimization method for reconfiguration of multi-UAV formations. *IEEE Transactions on Aerospace and Electronic Systems*, *57*(1), 506-520.
- Ling, KV., Maciejowski,J., Richards,A. & Wu, BF. 2012. Multiplexed model predictive control. *Automatica,* 48(2):396-401.
- Liu, G., Li, B., & Ji, Y. (2022). A modified HP-adaptive pseudospectral method for multi-UAV formation reconfiguration. *ISA transactions*, *129*, 217-229.

- Losing, S. 2023. US Air Force eyes fleet of 1,000 drone wingmen as planning accelerates
- *Defense News, March 8th*
- Ma, G., Huang, H. & Zhuang, Y. 2010. Time optimal trajectory planning for reconfiguration of satellite formation with collision avoidance. *In Control and Automation (ICCA), 2010 8th IEEE International Conference on,* 476-479. IEEE, 2010.
- Mahadevan, P. 2010. The military utility of drones. *CSS Analyses in Security Policy*, *78*.
- Marin, L.; Krajčíková, K. 2016. Deploying Drones in policing southern European borders: Constraints and challenges for data protection and human rights. In *Drones and Unmanned Aerial Systems*; Springer: Berlin/Heidelberg, Germany, pp. 101–127
- McDermott, R. 2021. Moscow Forming First Robotic Military Units, *Eurasia Daily Monitor* Volume: 18 Issue: 64
- Meske, C., Bunde, E., Schneider, J., & Gersch, M. (2022). Explainable artificial intelligence: objectives, stakeholders, and future research opportunities. *Information Systems Management*, *39*(1), 53-63.
- Mohanavelu, K., Poonguzhali, S., Adalarasu, K., Ravi, D., Chinnadurai, V., Vinutha, S., ... & Jayaraman, S. (2020). Dynamic cognitive workload assessment for fighter pilots in simulated fighter aircraft environment using EEG. *Biomedical Signal Processing and Control*, 61, 102018.
- Park, S. 2003. *Avionics and Control System Development for Mid-Air Rendezvous of Two Unmanned Aerial Vehicles.* PhD thesis, Massachusetts Institute of Technology, 2003.
- Ree, M. J., & Carretta, T. R. (1996). Central role of g in military pilot selection. *The International Journal of Aviation Psychology*, *6*(2), 111-123.
- Roma, A. 2017. Drones and popularisation of space, *Space Policy, 41*, 65–67
- Russell, MA. & Lamont, GB. 2005. A genetic algorithm for unmanned aerial vehicle routing. In *Proceedings of the 7th Annual Conference on Genetic and Evolutionary Computation, 1523-1530. ACM.*
- Sammut, C & Webb, GI. 2011. Encyclopedia of Machine Learning. S*pringer Science & Business Media*.
- Shishkov, B.; Hristozov, S.; Janssen, M.; van den Hoven, J. 2017. Drones in Land Border Missions: Benefits and Accountability Concerns. In Proceedings of the 6th International Conference on Telecommunications and Remote Sensing, Delft, The Netherlands, 6–7 November 2017; p. 77–86.
- Siau, K & Wang W. 2020. Building Trust in Artificial Intelligence, Machine Learning, and Robotics, *Cutter Business Technology Journal,* Vol. 31, No. 2
- Sloan, E. C. 2002. Revolution in Military Affairs (Vol. 5). McGill-Queen's Press-MQUP
- Smith.AL. 2008. Proportional navigation with adaptive terminal guidance for aircraft rendezvous. Journal of Guidance, Control, and Dynamics, 31(6):1832{1836, 2008. doi: 10.2514/1.33535.
- Stelmack, K. 2014. Weaponized Police Drones and Their Effect on Police Use and Force. *J. Technol. Law Policy*, *15*, 276
- Stickney., HM 2014. Performance characterization, development, and application
- of artifcial potential function guidance methods. *Technical report, DTIC Document*, 2014.

- Stulberg, AN. 2017. Managing the Unmanned Revolution in the U.S. Air Force," *Orbis*, Vol. 51, No. 2 (2007), pp. 251–265, https://doi.org/10.1016/j.orbis.2007.01.005
- Tahk, MJ., Park,CS and Ryoo. CK. 2005. Line-of-sight guidance
- laws for formation flight. J*ournal of Guidance, Control, and Dynamics*, 28(4):708{716, 2005. doi: 10.2514/1.9605.
- Tanner, HG., Jadbabaie,A and Pappas, GJ. 2003 Stable flocking of mobile agents, part i: Fixed topology. *In Decision and Control, Proceedings of the 42nd IEEE Conference on, volume 2, pages 2010{2015.* IEEE, 2003.
- Teodorovic , D & Dell'Orco, M. 2005. Bee colony optimization{a cooperative learning approach to complex transportation problems. *In Advanced OR and AI Methods in Transportation, Proceedings of 16th Mini EURO Conference, 51-60. Poznan Publishing House of the Polish Operational and System Research.*
- Tikanmäki, I.2011. *Possibilities to Operational Use of Remotely Piloted Aircrafts in Finland.* Master's Thesis, Laurea-ammattikorkeakoulu, Vantaa, Finland, 2011.
- Tjoa, E., & Guan, C. (2020). A survey on explainable artificial intelligence (xai): Toward medical xai. *IEEE transactions on neural networks and learning systems*, *32*(11), 4793-4813.
- Tsiamis, N., Efthymiou, L., & Tsagarakis, K. P. 2019. A comparative analysis of the legislation evolution for drone use in OECD countries. *Drones*, *3*(4), 75.
- Villasenor, J. 2014. "Drones" and the future of domestic aviation. *Proc. IEEE*, *102*, 235–238
- Wang, X., Yadav, V., & Balakrishnan, S. N. (2007). Cooperative UAV formation flying with obstacle/collision avoidance. *IEEE Transactions on control systems technology*, *15*(4), 672-679.
- Weihua, Z. &Go, TH.2011. Robust decentralized formation fliight control. I*nternational Journal of Aerospace Engineering*.
- Witt, S. 2023. The Turkish Drone That Changed the Nature of Warfare, *the NewYorker, May 16th, 2022.*
- Xie, Y., Han, L., Dong, X., Li, Q., & Ren, Z. (2021). Bio-inspired adaptive formation tracking control for swarm systems with application to UAV swarm systems. *Neurocomputing,* 453, 272-285.
- Zhang, B., Sun, X., Liu, S., & Deng, X. (2019). Adaptive differential evolution-based receding horizon control design for multi-UAV formation reconfiguration. *International Journal of Control, Automation and Systems*, *17*(12), 3009-3020.