Architectures and Algorithms for Multiple UAV Cooperative control: A Review

Nelson Muchiri, Kamau S.I and Ikua B.W

***Abstract*—**For multiple unmanned Aerial Vehicles to collaborate in execution of a mission, a design of the mission, tasks and way points is first developed. Core to the design is determination of proper architecture and practical algorithms for the whole system. The architecture helps in integration of sensing, control, communication and planning while the algorithms are necessary for information sharing, task assignment and conflict resolution. In this paper a review of the principles of cooperative architectures and algorithm is presented. It hopes to extrapolate their importance in design hence provide essential knowledge to designers with interests in multiple vehicle cooperative control.

***Keywords*—** Control Algorithms, Cooperative control architectures, Multi Vehicle Cooperative control.

I. Introduction

APPLICATIONS of Unmanned Aerial Vehicles (UAVs) in military and civilian applications are on the rise in recent years. Such applications include exploration and mapping, search and rescue, reconnaissance, surveying, detection and monitoring in dangerous scenarios [1]. Deployment of collaborating Multiple UAVs is inevitable in most of these applications mainly because a team of cooperating UAVs offers the following advantages over single UAV [2]. First, it is possible to execute multiple simultaneous observations collect information from disparate points unlike when single UAV is deployed. Then efficiency is greatly improved by use of multiple UAVs in that tasks are executed faster. Furthermore, reliability and robustness are improved since members of the UAV team can complement each other making the entire system fault tolerant [3].

Control of multiple UAVs however is a has challenges, mainly to derive desirable collective behaviors through the design of individual agent control algorithms [4]. This has triggered research leading to the development of various architectures and algorithms for information sharing and task assignment.

II. Multi-Vehicle Cooperation Architectures

Cooperation is defined as a joint collaborative behavior that is directed toward some goal in which there is a common interest or reward [1, 5]. UAV cooperation requires the integration of sensing, control, and planning in an appropriated decisional architecture. According to wenjing, there are three cooperation architectures applied to multi-UAV research [6]. Multi-agent based architecture, work-flow based architecture and control-station based cooperation architecture.

A. *Multi-agent Based Cooperation Architecture*

This has been widely studied in the works of [7, 8] and by Maza [2] in which they classified various multi-agent cooperation systems based on the coupling as: Physical coupling, Formations, Swarms and Intentional cooperation.

i. *Physical Coupling*

Here UAVs are physically connected to each other hence their motions are constrained by forces that depend on the motion of other UAVs. This approach is mainly applied in transport problem as in the works of Bernard et-al [9, 10]. As shown in Fig 1 where a leader-follower structure is adapted for coordination.

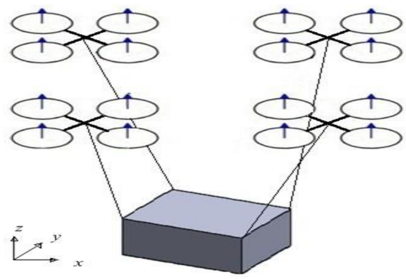

Fig 1: Load Transport with four Quadrotors

ii. *Formations*

Here each member of the team must keep user-defined distances with other members. Member ‘s motions are strongly constrained to keep the formation. This structure has been widely researched in the recent years and UAV aerial shapes as shown in Fig 2 have been achieved.

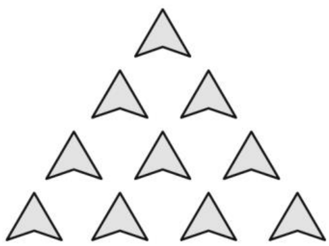

Fig 2: UAV Shape formation

For example, in research done by Turpin *et al* [12] formations strategies were developed for a team of quad-rotors following a group trajectory. The UAVs could maintain a shape or transform from one shape to another. In the works of Han *et-al* [13], Multiple UAV formations were applied for cooperative source seeking and contour mapping of a radiative signal field where they analyzed different scenarios for formation. Further research in formation has been done by Zhao *et-al* [14], where collision avoidance strategies were developed for multiple vehicles in a formation.

Nelson Muchiri, Department of Electrical Engineering, Kirinyaga University 0728073139; e-mail: ngachoki@kyu.ac.ke).

S. I. Kamau, Department of Electrical Engineering, JKUAT, Ikua B.W, Department of Mechatronic Engineering, JKUAT.

iii. Swarms

According to Maza *et al* [15], swarms are defined as teams of many vehicles in which interactions generate emerging collective behaviors. It is a concept derived from biological behaviors and typically involves a large number of homogeneous individuals [16]. Characteristics of a group of animals are imitated in coordination of a group of robots without a central supervisor, by using only local interactions between the robots as shown in Fig 3

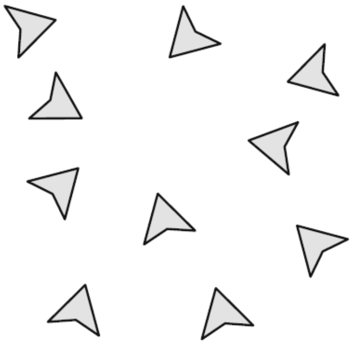

Fig 3: UAV Swarm

This has motivated development of multi-agent robotics and intelligent swarms like in the research by Vincent *et al* [17], where a framework was developed for a cooperative strategy for multiple agents searching for moving and evading targets. This was further researched by Altshuler *et al* [16] in analysis of *Cooperative Hunters Problem* where a swarm of UAVs were utilized for searching and intercepting a set of evading targets. Further applications of UAV swarms are in the works in references [18, 19, 20].

iv. Intentional Cooperation

In intentional cooperation, the UAVs of a team move in trajectories defined by individual tasks that should be allocated to perform a global mission [11]. Each UAV executes a set of tasks explicitly allocated to perform a given mission. the concept of intentional cooperation is illustrated in Fig 4. Each UAV executes its own path for accomplishment of the group objective while avoiding conflicts with other UAVs in the group.

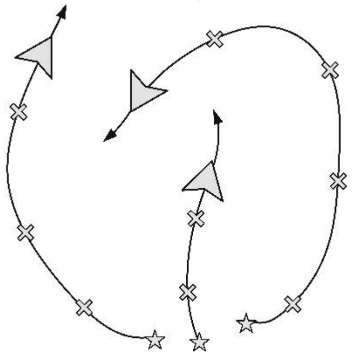

Fig 4: Intentional cooperation

This has been researched widely in works of Parker *et al* [21], Viguria *et al* [22] and Jian *et al* [8]. In design of this architecture, the main issues are task allocation, motion coordination and collision avoidance. Addressing these are emerging algorithms such as ant colony algorithm [23, 24] and others as documented in the works of Goerzen *et al* [25].

B. Other Recent Architectures

i. Hierarchical architecture

Owing to general weaknesses of the above multi-agent based cooperation architecture such as long time negotiation and reaction delays, recent research has proposed a hierarchical model of UAV coordination. developed by Pawel and Wojciech, [1] the framework is based on human organization where there is workers and superiors. The worker UAVs perform mission specific tasks such as image acquisition, while the superior UAVs are (*watching over)* supervising the function of multiple workers. This framework is illustrated in the Fig 5. Each level has its functions defined as follows, level A UAV coordinates all members of the team,

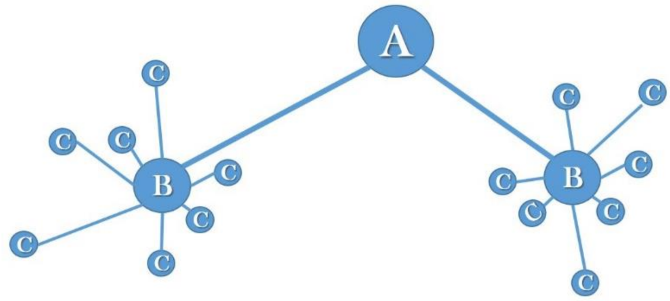

Fig 5: Hierarchical Model

level B UAV coordinates level C members in a small team and also communicates with level A. Unlike in swarms, in this model level C members cannot directly communicate with each other.

ii. Work-flow Based Architecture

This architecture has been recently proposed by Wenjin *etal* [26], where all UAVs execute tasks synchronously according to the same work flow [6]. Each UAV commands the related devices to execute tasks with the decision outputs as inputs. Therefore, because of the identical decision inputs and the same decision event, decision outputs of each UAV are same. It eliminates the need for negotiation on decision output and improves on practical time of response.

iii. Control-station Based Cooperation Architecture

With this architecture, UAVs perceive the environment, then transmit these data to the control station [6]. It has been researched previously by Jian *et al* [27] and applied in fire control by Cao *et al* [28]. The control station makes cooperative decision but UAVs make no decisions on their own.

III. Multi-vehicle Cooperation Algorithms

The principles behind operation of Cooperation algorithms is mainly dependent on the tasks being carried out by the team. For multiple air vehicles to collaborate, issues regarding information sharing, task assignment and conflict resolution are key.

A. Information Sharing

Shared information is a necessary condition for cooperation therefore information exchange among UAVs is central in their collaboration. A thorough understanding of information flow and sharing among multiple vehicles in a group is key in design of collaborative UAV systems [29]. First, the design should define the information to be communicated then decide on how to manage the information. This information may be communicated between vehicles using a wireless network, or joint knowledge might be pre-programmed into the vehicles before a mission begins [30]. The information could be about vehicles relative position, team objectives or common control algorithms. The algorithms must make vehicles to come to an agreement commonly referred in literature as consensus. Information sharing topologies manages the exchange of local and global information among vehicles in a team [31]. The operations of team communication topology have been widely studied and can be represented by a directed graph [32, 33]. Directed graph is an approach of analyzing switching topologies by use algebraic graph theory, which associates each graph topology with an algebraic structure of corresponding matrices [29]. In these graphs, the agents are the nodes of the graph and an edge between two nodes represents an ability to communicate [34]. In a dynamic network, all nodes move and the distances between them vary with time. Such multi-agent system corresponds to a time-varying information exchange topology, and the related graph involves fixed number of nodes. In a decentralized network of multiple agents, the group performance and task accomplishment depend on agents information sharing ability to their neighbors. The algebraic connectivity, is a measure of connectivity and plays vital role in group dynamics as it determines how well the agents can communicate to each other. Team communication topologies for small teams can be demonstrated by considering a team of three members shown in Fig 6. The team members can communicate either as in (a) with a weak connection or (b) where member 1 and 2 have weak connection but member 2 and 3 have strong connection. All of them can be strongly connected as shown in (c).

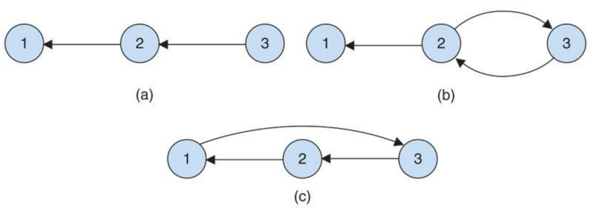

Fig 6: Different communication topologies for three vehicles

Information sharing is applied in cases of pattern formation where local information is shared between neighbors to maintain prescribed distances. In task assignment, global information helps in confirmation of overall mission.

B. *Role Sharing*

Another key issue in multiple vehicle collaboration is sharing of roles. Each member of a team has a role in the entire mission. The role needs to be assigned in real time, in case of a faulty member this information is shared and other members take up the role of the faulty member hence most cooperative systems are fault tolerant. If a fault happens in formation application, an algorithm repositions its neighbors to maintain the pattern. In applications where cooperative task assignment is needed, an algorithm can reassign the task aborted by a faulty member to another member in the team.

Several algorithms have been proposed for this, are broadly classified as either centralized algorithms or distributed algorithms [35]. some of the centralized algorithms include branch-and-bound procedure, enumeration method and dynamic programming. In the works of Chandler, centralized control mechanism was used to solve task allocation problem in optimization model and proposed solution approaches based on utilizing mixed integer linear programming, dynamic programming and genetic algorithms [36, 37, 38, 39]. Recent research has seen development of intelligent algorithms, such as genetic algorithm (GA) [40], particle swarm optimization (PSO), ant colony optimization (ACO) [35], wolf pack algorithm (WPA) and cat swarm optimization. Compared to distributed algorithms, the performance of the results obtained by centralized methods are generally poor in the dynamic environment.

Distributed algorithms include decentralized Markov decision process (Dec-MDP), distributed model predictive control (DMPC), dynamic distributed constraint optimization (DDCOP), contract net (CN), auction algorithm [35]. They are preferred because of their simple calculation, quick response to dynamic events, and little computation overhead and good robustness and are widely used to solve complex task allocation problems [11].

C. *Consensus and Conflict Resolution*

The consensus problem is to have a group of UAV reach a common assessment or decision based on distributed information and a communications protocols [31]. A consensus algorithm or protocol is an interaction rule that specifies the information exchange between an agent and all of its neighbors on the network [41]. It has been formulated as a coordinated control problem by Fax and Murray [42] where they considered a control law in which each system attempts to stabilize itself relative to its neighbors.

IV. Conclusion

In this paper a review of core issues in design of multiple cooperating UAV are presented. They include the principles of cooperative architectures and algorithms. The architectures are mainly multi-agent based which include formations, physical coupling and intentional cooperation. Algorithms development issues are information sharing, task assignment and conflict resolution. It is anticipated that the work presented here will elaborate critical issues in multiple UAV cooperation design hence provide essential knowledge to designers with interests in multiple vehicle cooperative control.

References

[1] P. Rotter and W. Chmiel, "A framework for a hierarchical model of cooperation between unmanned airplanes," *European Journal of Remote Sensing*, vol. 51, no. 1, pp. 276–284, 2018.

[2] I. Maza, A. Ollero, E. Casado, and D. Scarlatti, "Classification of multi-uav architectures," in *Hand- book of Unmanned Aerial Vehicles*. Springer, 2015, pp. 953–975.

[3] T. H. Summers, M. R. Akella, and M. J. Mears, "Coordinated standoff tracking of moving targets: Control laws and information architectures," *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 1, pp. 56–69, 2009.

[4] J. Shamma, *Cooperative control of distributed multi-agent systems*. John Wiley & Sons, 2008.

[5] T. Shima and S. Rasmussen, *UAV cooperative decision and control: challenges and practical ap- proaches*. SIAM, 2009.

[6] Wenjing and X. Shenghong, "Comparison of multi-uav cooperation architectures," in *Information Management (ICIM), 2017 3rd International Conference on*. IEEE, 2017, pp. 500–505.

[7] L. Merino, F. Caballero, J. R. Mart´ınez-de Dios, J. Ferruz, and A. Ollero, "A cooperative perception system for multiple uavs: Application to automatic detection of forest fires," *Journal of Field Robotics*, vol. 23, no. 3-4, pp. 165–184, 2006.

[8] J. Han, C.-h. Wang, and G.-x. Yi, "Cooperative control of uav based on multi-agent system," in *Industrial Electronics and Applications (ICIEA), 2013 8th IEEE Conference on*. IEEE, 2013, pp. 96–101.

[9] M. Bernard, K. Kondak, I. Maza, and A. Ollero, "Autonomous transportation and deployment with aerial robots for search and rescue missions," *Journal of Field Robotics*, vol. 28, no. 6, pp. 914–931, 2011.
[10] S. Aghdam, M. B. Menhaj, F. Barazandeh, and F. Abdollahi, "Cooperative load transport with movable load center of mass using multiple quadrotor uavs," in Control, Instrumentation, and Au- tomation (ICCIA), 2016 4th International Conference on. IEEE, 2016, pp. 23–27.
[11] M.-H. Kim, H. Baik, and S. Lee, "Response threshold model based uav search planning and task allocation," *Journal of Intelligent & Robotic Systems*, vol. 75, no. 3-4, pp. 625–640, 2014.
[12] M. Turpin, N. Michael, and V. Kumar, "Decentralized formation control with variable shapes for aerial robots," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. IEEE, 2012, pp. 23–30.
[13] J. Han and Y. Chen, "Multiple uav formations for cooperative source seeking and contour mapping of a radiative signal field," *Journal of Intelligent & Robotic Systems*, vol. 74, no. 1-2, pp. 323–332, 2014.
[14] I. Zhao, S. Li, J. Hu, Q. Pan, Z. Xu, Y. Lvy, and W. Meng, "A study on uav formation collision avoidance," in *Control Conference (CCC), 2017 36th Chinese*. IEEE, 2017, pp. 8743–8747.
[15] Maza, J. Capit´an, L. Merino, and A. Ollero, "Multi-uav cooperation," *Encyclopedia of Aerospace Engineering*, 2016.
[16] Y. Altshuler, V. Yanovsky, I. A. Wagner, and A. M. Bruckstein, "Efficient cooperative search of smart targets using uav swarms," *Robotica*, vol. 26, no. 4, pp. 551–557, 2008.
[17] P. Vincent and I. Rubin, "A framework and analysis for cooperative search using uav swarms," in *Proceedings of the 2004 ACM symposium on Applied computing*. ACM, 2004, pp. 79–86.
[18] J. Hu, J. Xu, and L. Xie, "Cooperative search and exploration in robotic networks," *Unmanned Systems*, vol. 1, no. 01, pp. 121–142, 2013.
[19] Undeger and F. Polat, "Multi-agent real-time pursuit," *Autonomous Agents and Multi-Agent Systems*, vol. 21, no. 1, pp. 69–107, 2010.
[20] Y. Altshuler, A. Pentland, and A. M. Bruckstein, "The cooperative hunters–efficient and scalable drones swarm for multiple targets detection," in *Swarms and Network Intelligence in Search*. Springer, 2018, pp. 187–205.
[21] L. E. Parker, "Distributed intelligence: Overview of the field and its application in multi-robot systems."
[22] A. Viguria, I. Maza, and A. Ollero, "Distributed service-based cooperation in aerial/ground robot teams applied to fire detection and extinguishing missions," *Advanced Robotics*, vol. 24, no. 1-2, pp. 1–23, 2010.
[23] W. Cao and W. Yang, "A survey of vehicle routing problem," in *MATEC Web of Conferences*, vol.100. EDP Sciences, 2017, p. 01006.
[24] M. Dorigo and L. M. Gambardella, "Ant colony system: a cooperative learning approach to the traveling salesman problem," *IEEE Transactions on evolutionary computation*, vol. 1, no. 1, pp. 53– 66, 1997.
[25] Goerzen, Z. Kong, and B. Mettler, "A survey of motion planning algorithms from the perspective of autonomous uav guidance," *Journal of Intelligent and Robotic Systems*, vol. 57, no. 1-4, p. 65, 2010.
[26] W. Cao and S. Xu, "A new multi-uav cooperation method," in *Computational Intelligence and Design (ISCID), 2016 9th International Symposium on*, vol. 2. IEEE, 2016, pp. 231–234.
[27] J. Li, X. Fu, and X. Gao, "Cooperative multi-uav path planning with communication constraints, "*Electronics Optics & Control*, vol. 20, no. 6, pp. 29–33, 2013.
[28] J. Cao and X. Gao, "Agent-based design for multi-ucav intelligent command and control cooperative system," *Fire Control & Command Control*, vol. 28, no. 5, pp. 22–24, 2003.
[29] W. Ren and R. W. Beard, *Distributed consensus in multi-vehicle cooperative control*. Springer, 2008.
[30] W. Ren, R. W. Beard, and E. M. Atkins, "A survey of consensus problems in multi-agent coordina- tion," in *American Control Conference, 2005. Proceedings of the 2005*. IEEE, 2005, pp. 1859–1864.
[31] R. M. Murray, "Recent research in cooperative control of multivehicle systems," *Journal of Dynamic Systems, Measurement, and Control*, vol. 129, no. 5, pp. 571–583, 2007.
[32] W. Ren, R. W. Beard, and E. M. Atkins, "Information consensus in multivehicle cooperative control," *IEEE Control Systems*, vol. 27, no. 2, pp. 71–82, 2007.
[33] C. Godsil and G. F. Royle, *Algebraic graph theory*. Springer Science & Business Media, 2013, vol.207.
[34] R. Dutta, "Cooperative control of autonomous network topologies," Ph.D. dissertation, The Univer- sity of Texas at San Antonio, 2016.
[35] H. Wu, H. Li, R. Xiao, and J. Liu, "Modeling and simulation of dynamic ant colony's labor division for task allocation of uav swarm," *Physica A: Statistical Mechanics and its Applications*, vol. 491, pp. 127–141, 2018.
[36] K. E. Nygard, P. R. Chandler, and M. Pachter, "Dynamic network flow optimization models for air vehicle resource allocation," in *American Control Conference, 2001. Proceedings of the 2001*, vol. 3. IEEE, 2001, pp. 1853–1858.
[37] Schumacher, P. Chandler, M. Pachter, and L. Pachter, "Uav task assignment with timing con- straints via mixed-integer linear programming," in *AIAA 3rd" Unmanned Unlimited" Technical Conference, Workshop and Exhibit*, 2004, p. 6410.
[38] T. Shima, S. J. Rasmussen, A. G. Sparks, and K. M. Passino, "Multiple task assignments for co- operating uninhabited aerial vehicles using genetic algorithms," *Computers & Operations Research*, vol. 33, no. 11, pp. 3252–3269, 2006.
[39] V. K. Shetty, M. Sudit, and R. Nagi, "Priority-based assignment and routing of a fleet of unmanned combat aerial vehicles," *Computers & Operations Research*, vol. 35, no. 6, pp. 1813–1828, 2008.
[40] M. Darrah, W. Niland, B. Stolarik, and L. Walp, "Uav cooperative task assignments for a sead mission using genetic algorithms," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2006, p. 6456.
[41] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 215–233, 2007.
[42] J. A. Fax and R. M. Murray, "Information flow and cooperative control of vehicle formations," *IEEE transactions on automatic control*, vol. 49, no. 9, pp. 1465–1476, 2004.