A new Rechargeable WSNs based Multi-UAVs Network and Topology Control Algorithm

Li Li, Xu Yixiang, Hu Xiaoguang, Duan Haibin, Zhang Hanyu
School of Automation Science and Electrical Engineering
BeiHang University，Beijing, China
lilihe@buaa.edu.cn

Che Jun, Liang Jin
Science and Technology on Aircraft Control Laboratory
FACRI, Xi'an 710065
keylab@facri.com

Abstract—Multi-UAVs network technology is now one of the key directions of the UAV development. The primary needed research of network technology is the topology control technology. Firstly, we analyses the research status of the heterogeneous Multi-UAVs network which consisted of manned aircraft and UAVs. Secondly, we proposed the Multi-UAVs Network based Heterogeneous Rechargeable WSNs. In this paper, a real-time wireless recharging technology architecture and a Multi-UAVs Network based Heterogeneous Rechargeable WSNs are proposed, which are used in UAV in the air, and proposed.

Keywords—UAV, Rechargeable Wireless Sensor Network, Topology Control Algorithm，Multi-UAV

I. Introduction

UAV (Unmanned Aerial Vehicle, UAV) driven without staff, working in harsh environments, has notable features of high maneuverability, stealth, economy and so on. In civilian areas, the UAV can fight border smuggling, perform communications relay and detect agricultural condition, etc. It can also perform tasks in nuclear, chemical, raw and other hazardous environments, such as disaster relief, forest fire control, nuclear accident emergency and other complex and dangerous tasks. In the military field, UAVs will play an important role in future wars ,such as improve the battle space situational awareness, high-risk target penetration capability, communications and navigation support capability, electronic warfare capabilities, the ability to suppress enemy air defense systems, fixed and mobile target attack capability, combat survival capacity and joint combat capability. Therefore, many countries are giving priority to developing UAV technology, and put forward network-centric warfare, quick decisive battle and new operational concepts. As UAV's ability to complete reconnaissance and combat missions is limited, the tendency is to combine multiple UAVs into UAV cluster, namely UAV collaborative network, which collaboratively works together to accomplish more complex tasks[1].

Early UAVs cooperative network is generally controlled by the ground control station, which is restricted by the communication distance, delay and UAV dynamic flight and other conditions. Sometimes it can't achieve good control of the UAV cooperative networks. Hence there are many scholars that have proposed manned aircraft should be added to the UAV collaborative network, in which manned aircraft with a long-range detection capability leads a group of UAVs to work together and fights and the manned aircraft out of the enemy firepower loop is responsible for communications, directs and controls UAVs group with the ground station. When clustered UAVs are working or combating in the front, thereby they can implement more flexible combat tactics and enhance the operational effectiveness of the entire system, which deserves significant military value[2].

UAV collaborative network composed of manned and unmanned aircraft fleet, in essence, is a heterogeneous wireless sensor network, in which the manned and unmanned aircraft are nodes in the network. Heterogeneous network refers to the nodes in the network are not exactly same as other nodes in the communication distance, energy and other aspects. UAV collaborative network based on heterogeneous Sensor Network has important practical significance to improve the application level, and achieve better future network-centric warfare. Constitution diagram of a heterogeneous UAVs cooperative network is shown in Figure 1.

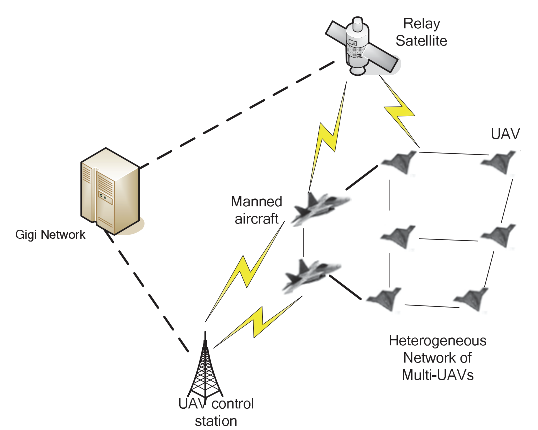

Fig. 1. Heterogeneous networks of Multi-UAVs

Multi-UAV cooperative network requires communication quality and invulnerability to be high enough, and the battery power carried by the small UAV is limited, while mobility of UAV leads UAV collaborative network topology to change frequently, so UAV collaborative network topology control research is very important.

II. MULTI-UAVS NETWORK BASED WIRELESS RECHARGEABLE SENSOR NETWORK

Multi-UAV cooperative network is essentially a wireless sensor network and a network node refers that small UAV's battery energy is limited, how to improving the UAV voyage is a hot spot of the research in recent years [3-6]. The present relevant research work can be divided into two categories. One is the use of energy-efficient protocols and optimization topology control, route planning algorithms etc. to save energy and improve flight time[3], the other is using a variety of charging technology or rechargeable batteries techniques to improve flight time, such as solar cell technology[4], the microwave power charging, fuel cell technology and so on [5].

UAV solar charging technology stores energy collected by the wafers covered in UAV surface solar into batteries to supply energy storage, which needs to work in place with sufficient sunlight, while the solar cell covering the surface of UAV makes UAV stealth poor. Fuel cell technology can achieve high efficiency and long-endurance, but poor stealth. Besides, the cost is more expensive and high heat generated during fuel combustion will bring some security issues[6]. If the UAV can be charged at the time of flight, the flight time will be greatly extended and the operational performance of the UAV can be significantly improved.

In recent years, the development of wireless charging technology makes electric vehicle, electronics and other long-distance wireless charging becoming a reality and it also brings a new technological revolution at the same time. Wireless Sensor Networks based on wireless recharging (Wireless Rechargeable Sensor network)[7-9] has gradually got attention and been extensively studied in recent years. Multi-UAV cooperative network adopting battery-powered is a mobile Wireless Sensor Network on the nature, so when we put the wireless charging technology for multi-UAV cooperative network to extend UAV flight time, expand UAVs cooperative network work scope, and extend its life cycle.

The trial of electric vehicles based on wireless charging has achieved success. According to January 26, 2015 report of the Economic Daily News, on January 23, 2015, Chengdu, Sichuan Province electric buses have been put into use, which can make a round trip with only 5 minutes wireless charging [10]. In recent years, the United States, Sweden, the United Kingdom, Japan and South Korea and other countries have also successfully adopted wireless charging technology in the city bus system[11-15]. Current wireless charging cars adopt magnetic resonance wireless charging frequently. According to a magnetic resonance wireless charging technology showed by Witricity in Watertown, Massachusetts, USA, coil with a diameter of 50cm can cover the range of 1 meter to 1.5 meters, or even up to 2 meters[16]. The coil with 2 meters in diameter can charge the target away from 4 to 8 meters. The distance meets manned aerial vehicle carrying large amounts of electricity to wireless charging small battery powered UAV closely. Due to the relatively large size and load of manned aerial vehicle, wireless charging coil with a diameter of 1.5 meters to2 meters can be entirely possibly placed at the bottom or side of manned aircraft. According to the situation, UAV will be scheduled to fly near to manned aerial vehicle to be wireless charged, as is shown in Figure 2. This technology is same with electric vehicle wireless charging principle and is technically feasible.

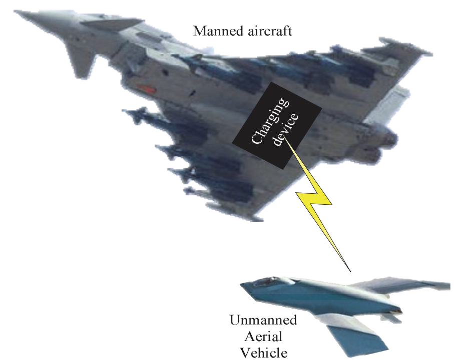

Fig. 2. Heterogeneous networks of Multi-UAVs

Wireless charging technology of UAVs in the air is more easily operated and realized than traditional aerial refueling technology. Using UAV wireless charging technology can greatly improve the flight time, expand the scope of the UAV clusters, improve its long-range detection and operational capabilities and save the cost of replacing the UAV.

The new technology, wireless charging to multiple UAVs cooperative network, brings some new changes. All kinds of the existing network protocols and algorithms need to be amended. The primary one is its topology control algorithm. For moving charging can cause the UAV topology changes and fast movement of UAV can result in links broken, it is great important to re-join the UAVs cooperative network. Researching the technology will also play a positive role in the development of multi-UAV cooperative network technology and lay a solid foundation for enhancing the UAV cluster operational capabilities of military and civilian.

III. RESEARCH STATUS OF UAVS COOPERATIVE NETWORK TOPOLOGY CONTROL ALGORITHM

At present, both the type and quantity of US drone is the top in the world. The development trend of the US drone represents the UAV development direction in the world. In order to guide the development and planning of the US drones, between 2000 and 2007, the US Department of Defense published the four official documents: *From 2000 to 2025 US UAV Roadmap*, *From 2002 to 2027 US Drone Roadmap*, *From 2005 to 2030 US UAS Roadmap* and *From 2007 to 2032 US Unmanned Systems Roadmap*[17]. US drone control technology development plan is shown in Figure 3.

As shown in the figure, US government focuses on the development of various technologies of UAV cluster from around 2005. From UAV clusters coordination, UAV tactics re-planning, tactical objectives assigned to networking distributed control and to around 2025 completely independent cluster control, the US drone cluster technology development plan have very important reference value for the development direction of China's unmanned aerial vehicles. UAV collaborative network technology is an important part and network infrastructure of the UAV cluster technology, including the use of optimized network topology control to optimize collaborative network which is part of the primary consideration.

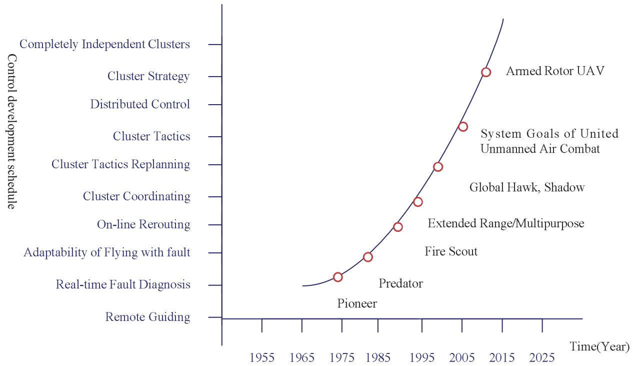

Fig. 3. UAV control technology development plans of US

Currently, a series of research work on topology control algorithm for UAV cooperative network has emerged in China and other countries. The research work is mainly carried out on several aspects. They are minimum energy control, control of the mobile network connectivity, routing based control etc.

Jinhai et al and Bekmezci et al describe a UAV's Mobile Ad Hoc Network structure that can provide greater reliability and a wider range of the wireless network, with which it has higher communication quality among the UAVs and less errors in communication. For every UAV acts as a relay node, the mobile Ad Hoc network structure is optimized. It has three new features, increasing action parameter, requiring more communication resources and more mission and mobile mode[18,19].

In the traditional barrier-free environment, the UAV control program is a series of navigation points and speed monitoring issues. Kuochu proposed a new routing algorithm, so that the UAV has a strategy to avoid obstacles [20]. The algorithm combines the tangent guide algorithm and the Lyapunov algorithm and proposes a theoretical shortest path to the UAV based on the state of motion and target location.

MECN (Minimum Energy Communication Network) algorithm [21] is the classic topology control algorithm, of which the design idea is to use a layered approach to build subnets with the fewer number of nodes where the energy consumption is very small in transferring data between two nodes. Through the local searching for subnet, the global minimum energy route can be found without making all the nodes traversing. SMECN (Small Minimum Energy Communication Network) algorithm [22] is optimized for MECN, which fully considered the possible barriers that lead to the situation of the direct communication failure between any two nodes. SMECN algorithm achieves the lowest energy consumption route through calculating and constructing the subnet, whose energy performance is superior to MECN. Both algorithms initially assumed that all nodes have the same maximum power consumption and low energy transmission efficiency. Liu and Li propose a distributed topology control algorithm based on the shortest route tree, whose tree algorithm determining the shortest route transport energy consumption of each node according to the local topology[23]. This algorithm is suitable for static topology for the higher energy efficiency. With the algorithm, the calculation from the beginning is needed if the network topology changes, so it is not suitable for the UAV dynamic topology control[4].

In the aspect of clustering topology control algorithms, Ehssan S et al [25] supposed that the aircrafts could be divided into groups according to fly destination and proposed a dynamic Doppler value clustering algorithm. The algorithm establishes groups based on Doppler frequency shift amount of data packets between aircrafts, so the number of re-election of cluster head node is reduced and the stability of the cluster is improved. Mario G et al also proposed clustering algorithm based on random competition against communicate among multiple aircrafts, which can save the cost of network[26]. Liu Kai et al proposed an adaptive stable clustering algorithm and constructed a single node mobility and cluster moving function named willingness factor[27]. Cluster parameters established and maintained according to the willingness factors can be adapted to the node's mobility and topology's changes [28].

OLSR (Optimized Link State Routing) is a routing protocol that is earlier and available for multi-UAV network[29]. It is a routing protocol of table-driven optimization link-state. In OLSR, each node selects a part as its MPR (Multi Point Relay) node in the neighbor nodes. The node becoming a MPR node will be responsible for transmitting topology control packets to the nodes of the whole network. By using MPR mechanism, OLSR reduces the overhead of protocol, thus routing protocols were optimized. Then, many scholars have made further optimization for OLSR and proposed OLSFR (Optimized Link State Forecast Routing) [30], HOLSR (Hierarchical Optimized Link State Routing Protocol) and so on. But OLSR essentially is table-driven and still belongs to the static routing topology. So it is not suitable to the dynamic topology caused by UAV mobility.

Dynamic topology generation and maintenance algorithms caused by UAVs movement generally generate dynamic topology path by on-demand routing protocol. The current main demand routing protocols applied to a multi-UAV cooperative network are AODV (Ad hoc On-Demand Distance Vector Routing), AODV protocol improvements, dynamic source routing protocol DSR (Dynamic Source Routing) and so on.

Zanxin et al simulated the performance of DSR, OLSR and AODV routing protocols by using UAV cooperative networks scenarios. AODV routing protocol is much better than the other two in aspect of network transmission speed and throughput, especially when network node is large. But the initial network delay of AODV is relatively high. If it can be improved, AODV is an excellent routing protocol which can be used in multi-UAV cooperative networks[31].

Many researchers have adopted the improved reactive routing protocol AODV in UAVS collaborative network. Li Zhihua et al solved the problem of long-distance data transmission in highly decentralized Ad Hoc network by using UAVs as a relay node and combining AODV with DTN routing protocols. Wang Ding put forward an improved algorithm of AODV routing protocol which uses mobile information and the number of available neighbors of Ad Hoc network nodes and chooses reliable route by setting the threshold value to determine the link quality[32]。

Reactive-Greedy-Reactive (RGR) is proposed to enhance the performance of the original AODV protocol, which combines the mechanisms of the Greedy Geographic Forwarding(GGF) and reactive routing[33]. The proposed RGR employs location information of UAVs as well as reactive end-to-end paths in the routing process. Simulation results show that RGR outperforms existing protocols such as Ad-hoc On-demand Distance Vector(AODV) in search UAVs network missions in terms of delay and packet delivery ratio. Its overhead is similar to traditional mechanisms. Although the RGR protocol improves the packet delivery ratio, the overhead and delay are higher when compared to AODV.

Li, Y. proposed a scoped flooding and mobility prediction based RGR to enhance the performance of the original RGR protocol[34]. In addition to the location information, this mechanism takes advantage of the velocity vector of the nodes to predict their current locations. Unlike other mobile nodes, the trajectories of UAVs are less prone to abrupt changes, so it might lead to very good prediction accuracy. Mobility prediction then allows the protocol to monitor the status of the reactive routes and chooses appropriate neighbors during the GGF phase of the protocol. At the same time, two different scoped flooding methods are utilized to reduce the overhead messages generated by the original RGR protocol during the route discovery phase by exploiting location information. The new protocol can effectively enhance the performance of the RGR protocol in terms of packet delivery ratio, overhead and delay.

Currently the improved AODV algorithm applied to UAV network still has not solved the problem of high initial network latency. The best way to solve this problem is to establish global network topology with priori routing protocol at the beginning of network. Only when UAV's movement leads to network topology's change, we need to start the dynamic topological path established on demand. This will not only retain the advantage of on-demand routing protocol to quickly generate dynamic topology, but also solve the problem of high initial network latency, which uses hybrid routing protocol of a priori type and on-demand type to control the topology and generation of network. HWMP (Hybrid Wireless Mesh Protocol) is successfully applied in improved hybrid routing protocol which is based on AODV. It is the default routing protocol on the standard of wireless Mesh network standard IEEE802.11S and it is applied widely. HWMP was originally applied in the wireless Mesh network, of which the node energy is not restricted. It is different to UAVs cooperative network which is generally battery-powered and the node energy is limited. Therefore HWMP cannot be directly used in UAVs cooperative network. It must be improved and optimized[35].

IV. Research Status of Wireless Recharging Sensor Networks

The earliest idea on wireless charging came from wireless power transmission and wireless transmission test which was proposed by Nikolas Tesla in 1890s. In twenty-first century, wireless charging research has been a hot spot and been widely applied in portable consumer electronics products.

Marin MarinSoljacic (2007) in MIT used two copper coils with 50cm diameter to power a 60W electric light which is two meters away from the power transmitter by adjusting the transmitting frequency[36]. This is the WiTricity device to generate power with magnetic resonance. In 2008, Intel also developed a resonance type wireless charging device and lit a lamp successfully.

Currently, wireless charging technology is mainly divided into three types, electromagnetic induction charging, electric magnetic resonance charging and radio frequency or microwave wireless charging. Microwave wireless charging is mainly used in long-distance power transmission such as microwave charging power plane, satellite solar power station and so on. The principle of mainstream microwave charging power plane is using microwave energy wireless technology to receive the radiation of microwave beam in the distance through receivers on the plane and convert microwave into electricity.

Canada is the first nation to develop microwave powered aircraft. In October 1978, Canadian scientists have designed a high-altitude unmanned microwave aircraft, which was used as microwave communications relay station. In September 1987, another unmanned microwave aircraft successfully flied to the sky on the airport in outskirts of Ottawa. The transmitter on the ground converted electrical energy into microwave and transmitted microwave energy into the sky. The energy is converted into electricity to drive the propeller for flight after being received by aircraft [37]. Soon after, the United States developed an unmanned microwave surveillance aircraft. This flying device was powered by 2 MW microwave transmitted by terrestrial station. The receiver on aircraft converted received microwave energy into electrical energy to supply power to the motor[38].

In 1993, a microwave propelled unmanned aircraft (MILAX) model was developed in Japan. The bottom surface of the aircraft was almost completely covered by microwave rectenna(i.e. composed of 120 circular micro-strip antenna). The received ultra-high frequency waves was converted into electrical energy and stored in the battery. The biggest work rate of the translator is 80 W.

Although the microwave charging power UAVs has many advantages, there are still many problems that cannot be completely realized. Firstly, in order to enable the aircraft to get enough power and greater flight range, a series of high-power microwave transmitter stations must be set to gather all microwave beams to aircraft by directional antennas. When the aircraft is in flight, ground directional transmitting antennas have to track them to focus the microwave to the moving aircraft. Secondly, radiation of high-power microwave station is harmful for the nearby residents, so not too much microwave transmitter stations can be built. Consequently there is no ensurance to provide continuous wireless charging power for microwave aircraft. In recent years, the development of microwave charging power UAV encountered insuperable problems and gradually fade out of sight. It is no longer a hot topic.

With the emergence of collaborative networks of heterogeneous UAVs, the problem of UAV wireless charging mode can be solved in another way. Wireless charging device can be installed on some manned vehicle and UAVs flight can be charged by manner of flying close to the manned vehicle. This is similar to the electric vehicle charging technology, electric magnetic resonance wireless charging.

Compared to the electromagnetic induction type, transmitter coil of magnetic resonance wireless charging technology need not to be consistent with the receiver coil completely, so the charging range could be extend in this approach. The maximum charging range of electromagnetic induction covers from a few centimeters to tens of centimeters and the changing range of electromagnetic resonance can reaches several meters. For magnetic resonance works strictly in excitation frequency, the safety can be improved by setting a reasonable excitation frequency.

The network combined by manned and unmanned aircraft is essentially a heterogeneous wireless sensor networks. Unmanned aircraft can be managed by manned aircraft in the network and charged wirelessly, so it is actually a wireless charging sensor net.

The concept of wireless charging sensor network attracted a large number of research institutions and scholars to study it in depth as it was proposed. After 2007, a large number of domestic and foreign research articles began to emerge according to SCI Citation Reports. Current research trends of wireless sensor charging networks are shown in Figure 4.

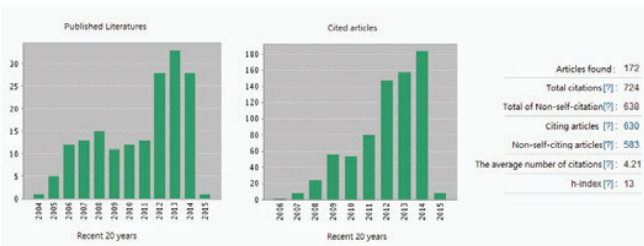

Fig. 4. The research trends of Wireless Rechargeable Sensor Network

From currently retrieved paper, researches on wireless charging wireless sensor networks mainly focus on scheduling of wireless charging node, path optimization of vehicle charging, movement path of charging car (robot), algorithm optimization of charging time scheduling and so on.

Liguang Xie in Virginia Tech University studies on wireless charging of multi-node sensor network, energy transmission and path planning of charging vehicles which is based on wireless charging sensor network[7, 39-42]. He adopts discretization and an improved-linearization technology (RLT) to build an optimization algorithm according to joint optimal operation path, flow routing and charging time. This algorithm is based on the assumption that multiple nodes can be charged simultaneously.

Xu et al proposed optimized approximation algorithm on the application of vehicle routing problem in data collection and wireless sensor networks wireless charging. The core algorithms are composite property of development issues and utilization of tree decomposition[8].

Weifa etc. studied in using a minimum wireless charging mobile vehicle to charge the sensors in sensor network and proposed a flexible on-demand wireless charging mode to optimally schedule the charging node by data routing protocol design. And he designed an optimization program to charge the key sensor for the problem of the least amount of scheduling moving vehicles[9].

Zhao et al used SENCAR control liquidity advantages to study the joint optimization of efficient energy charge and high performance of data collection. A distributed algorithm was proposed for stochastic general topology network to adjust the sensor to SENCAR, link scheduling, traffic routing and delivery of buffered data rate[43].

Gao et al pursuit the minimum sleep latency from the node to the receiving point by increasing high transmission power nodes in the minimum number of parameter h and propose an end-to-end delay-maintenance solution for rechargeable wireless sensor networks[44].

V. Conclusion

A new idea is introduced in this paper. Heterogeneous wireless charging sensor networks composed of manned vehicles and rechargeable UAVs is directed by manned aircraft. The manned vehicle with wireless charging device conducts the unmanned aerial vehicles and the unmanned aerial vehicles can be charged near the manned vehicle in safe area. It is a new solution of heterogeneous UAVs collaborative networking. One of its key technologies is the study and optimization of their network topology control algorithm. This study for the subject has an important significance for the promotion of the development of heterogeneous UAVs cooperative network and the improvement of the application in the field of military and civilian.

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