Unmanned Aerial Vehicles for Power Line Inspection: A Cooperative Way in Platforms and Communications

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Abstract—The emerging technology of unmanned aerial vehicle (UAV) has become more affordable and practicable for power line inspections. In this paper, we propose a multi-platform UAV system and multi-model communication system for highly efficient power line inspection tasks in China. The different UAVs cooperatively serve as long-distance imaging, short distance imaging and communication relay. The high quality image/video is transmitted in realtime to the on-site control station for UAV navigation and far end office for analysis. Our experience shows that the cooperative inspection for multi-UAVs can achieve a much higher efficiency than traditional inspection methods.

Index Terms—UAV, hexrotor, fixed wing, tethered rotor, power line inspection, communication relay, datalink

I. INTRODUCTION

In this new era of smart grid, the technology of unmanned aerial Vehicle (UAV) for power line inspection is drawing increasing attentions from power industry [1]-[4]. The inspection team carries the UAV on-site, conducts the flight tasks, acquires high definition pictures/videos from airborne camera and sends them back to office for defect analysis. By replacing tenuous human labor power inspection (distant picturing using telescope or walk close to the objects), UAV have conspicuous superiority in quality, cost and effectiveness, especially in graphically tough areas such as southwest of China [5]-[6]. Along with the advancement of unmanned aerial vehicle technology, the cost of UAV has become affordable for civil and industrial applications [7]. There are more enterprises in China nowadays in power industry using UAV for power line inspection as a piloting technology than that in the past. In different enterprises, a variety of UAV platforms are being used in practice from fixed wings, helicopters to multi-rotor aircrafts [8]-[11]. The different types of UAVs can cope with different scenario in power inspection depending on the weather, terrains, inspection objects and tasks. These applications in UAV have been demonstrated as an effective way in power line inspection and may partially substitute the human labor.

However, the current applications of UAV in China are still in a piloting stage and facing many unsolved challenges which prevent them from daily services. The first challenge is the application modality. In most enterprises, only a single type of UAV is being used in a power line inspection task. Due to the different characteristics of UAVs, a single aircraft cannot cope with a typical power line inspection task in most time. A fixed wing (both gas fueled and lithium battery) is flying high and fast. It is very suitable for a rough overview inspection over a long power line but it cannot observe the details of those subtle defects in electric towers, wires and insulators. The helicopter and multi-rotor aircrafts can acquire the detailed pictures by hovering in the air at a closer distance to the objects, but their patrol distance and time duration from the ground control station are much smaller than fixed wings due to limited power supply of the battery. There are barely few reports and literatures in using multiple types of UAV platforms to cooperatively perform the inspection tasks. How to cooperate the different UAV in a single regular task to fully substitute the human labor is still unsolved.

The second challenge is that the communication and control system for UAV are not effectively integrated to adapt the power line inspection. For fixed wing, the traditional way is to setup flight plan into its autopiloting system before it takes off and obtain the pictures and videos from the camera memory stick after landing. There is no realtime communication datalink during the whole flight for control and datalink. For helicopters and multi-rotors aircrafts, the regular way is to use a remote controller by using a pulse mode modulation 2.4GHz uplink, whose transmitting distance is typically within visual range. There is often a 2.4/5.8GHz downlink for realtime video transmissions, helping pilot control the aircraft. The line of sight (LOS) transmission characteristic of 2.4/5.8GHz and the multipath effect of complicated task environment will degrade the transmission distance and video quality greatly. In practice, the patrol distance for helicopters and multi-rotors is very limited, often ranging from 100m to 1km depending on the environments, within the eye view distance of the pilot to keep the aircrafts safe.

The third challenge is the gap time between the on-site picture/video acquirement and afterwards analysis. The high-quality pictures and videos in the airborne camera

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memory are acquired after aircraft landing. These videos are often handed in for expert analysis after the on-site crew finishing the on-site tasks and going back office by automobiles. In many cases, the on-site place is hundreds or thousands kilometers away from the office and it may takes a substantial time for picture/video analysis after the on-site work. It greatly delays the progress of the whole power line inspection task. The lack of communication between the on-site and the office greatly degrades the effectiveness of the whole workflow.

In this paper, we will tackle the above mentioned challenges by proposing a new cooperative operation workflow for power line inspection by multiple UAV platforms and multiple communication modalities in section II. We also propose an improved design for UAV communication systems to control the UAV and transmit the picture/video in a realtime, reliable and high-quality way in section III. A comparison between our proposed workflow and traditional inspection workflow is also conducted in section IV. Section V concludes the paper.

II. System Configuration

In this section, we will propose a cooperative power line inspection paradigm using multi-platform UAVs. Different types of UAVs serve as different functionality in the whole inspection task. The communication and control systems are also integrated into the cooperative UAV systems, achieving the optimal transmission quality and distance, thus improve the inspection efficiency.

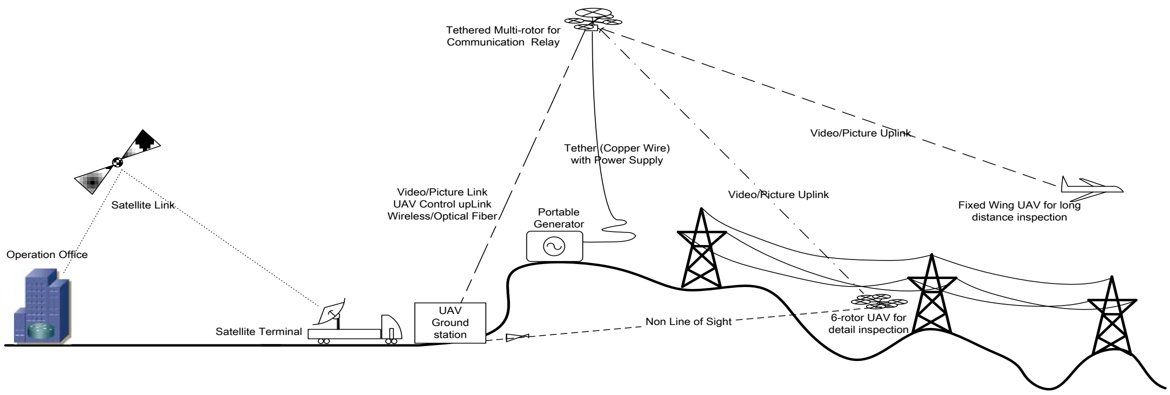

Fig. 1. The proposed cooperative UAV systems for power line inspection

Fig. 1 shows the overall deployment of the UAV systems along with its communication and control solution. Three types of UAVs are being used in this configuration, serving as the function for long-distance sketchy inspection, short-distance closer inspection and communication relay.

A. Fixed Wing UAV

Fig. 2. Fixed wing UAV for power inspection

Fig. 2 shows the fixed wing being used. This Li-battery powered fixed wing has a patrol distance of 50km at average speed of 70km/h. It is made of engineering plastics with a brushless DC motor powered by a 16000mAh Lithium battery. The autopilot system is incorporated into its body, controlling the flight path, position and attitude. A high-definition ultra-wide angle video camera is added to the head of the plane, allowing a very wide bird-eye vision to include any possible abnormalities along the transmission line [12]. The flying height is normally 100-200 meters above the transmission line, from where the overall condition of power towers, wires and insulators can be observed. The collapse of towers or the breakage of wires can be easily identified from the images. The flight distance has a very good coverage of a typical 220kV or 500kV transmission line between substations.

B. HexRotor UAV

After the sketchy inspection of fixed wing, the defects of the power transmission lines are identified and located. A hexrotor UAV is then used for a further inspection for detail recording. The picture of the hexrotor is shown in Fig. 3.

Fig. 3. Hexrotor vertical takeoff UAV

Thanks to its simplicity in structure and control, the hexrotor is very easy to manipulate with the autopilot system. The autopilot system uses a combined GPS/IMU navigation system. By using a remote controller, this aircraft can automatically take off and land at any geographical condition with toy-like easy manipulation. It is also very light weighted and easy to carry. The major superior of hexrotor over fixed wing is that it can hover in the air, allowing plenty of time for crew to thoroughly check the point of interests. The only drawback of this aircraft is the patrol time. The limitation of battery power density allows the aircraft to fly up to 25minutes and a distance of 5km. In this situation, we suggest a last-mile solution to use hexrotor only the crew cannot get closer to the objects due to environment constraints such as gorge, cliff, flood or landslide where human treading is almost impossible. Our experience shows that most of the power tower and wires are within the flight range from the human accessible point and the typical working time with and without the aircraft can be a huge contrast: 15 minutes versus 8 hours.

Fig. 4. A tethered multi-rotor UAV. The black and red wires on the ground are the power supplying cable.

C. Tethered Multi-rotor UAV

A third type of UAV is shown in Fig. 4. This kind of multi-rotor aircraft serves as an in-the-air platform. It consists of small 4 rotors in a plane and a big rotor upon it, driven by electrical motors [13], [14]. The big rotor accounts for the major elevating force and the four smaller one account for balance control [15]. The 100 meters long wire is directly attached to the electrical motor in the aircraft supplying the power for the aircraft. By using gas generator or other power supplies, this kind of aircraft can hover in the air for infinite time. The allowable payload is also much larger than hexrotor, up to 10kg at maximum, allowing the aircraft carry more payloads for multi functionality. In most time, the aircraft carries the communication module for signal relay between the aircrafts and ground station. This is necessary because in many environments the signal transmission path between the aircraft and the ground station is NOT line of sight, leading a communication failure. The tethered UAV is in use when the on-site geographical condition is too hard for line-of-sight communications. In practice, it has been used for over half of the tasks due to the complicated graphical areas in southwest China.

D. Cooperative Operation of UAVs

The different UAVs serve as the different functionality in a single inspection task. This cooperative operation of UAVs can greatly expand the inspection range and improve the inspection quality. The parameters of the UAVs are shown in Table I.

We introduce a standardized workflow for a typical power line inspection task. A typical UAV inspection crew consists of six persons, including experts in the field of UAV operations, transportations and communications. The crew is equipped with 4 to 5 UAVs, including 1 fixed wing, 3 hexrotor and 1 tethered multi-rotor depending on the need for communication replay.

From the start point, we first use fixed wing to obtain the overall condition along the transmission line. The realtime videos/pictures are transmitted through the datalink to the ground station. These videos are further transmitted through satellite communication to the back operation office for fast analysis and further inspection decisions. The specialists in the back office will identify the specific tower or transmission line to be further inspected. Once the specific inspection task is made, the on-site crew will carry the hexrotor UAV to the designated area for further detail inspection. The crew may dispatch multiple hexrotors for different sites at a time. The detailed videos from hexrotor UAVs are also transmitted to the back office for realtime analysis.

III. COMMUNICATION DESIGN

The transmission of realtime images is the indispensable part of the UAV inspection system. The quality of imaging devices and wireless communication system is the essential factor for the UAV inspection efficiency. We managed to realize the realtime high quality image/video transmission from the UAV, on-site ground station and back office, by multi-modality wireless communication systems. The details of the communication systems are elaborated below.

TABLE I: PARAMETERS FOR THREE TYPES OF UNMANNED AERIAL VEHICLES

UAV type	Power Supply	Size	Max Take of Weight	Max Flight Duration	Max Patrol Distance	Flight Speed	Flight Ceiling (altitude)	Max Flight Height (to the ground)
Fixed Wings	Electrical	1.8m (wing span)	3 kg	50 min	50 km	70 km/h	4000 m	500 m
Six-rotor UAV	Electrical	0.8 m (diameter).	6 kg	25 min	10 km	30 km/h	3000 m	200 m
Tethered multi-rotor UAV	Electrical	1.5m (diameter)	15 kg	depend on power supply	---	---	3000 m	300 m

A. UAV Datalink

The goal of UAV inspection system is to transmit images or videos of inspection objects in a realtime, reliable and high quality way. To achieve this goal, the communication must be digital, low latent and high throughput. As UAV are often used in geographically tough areas, the multipath effect is also a challenge which degrades the transmission quality. Furthermore, since UAV flight duration is very sensitive to its payload weight, the communication module on the UAV must be as light as possible. The requirement of high performance and the low weight leads to a tremendous difficulty in designing UAV transceiver in practice.

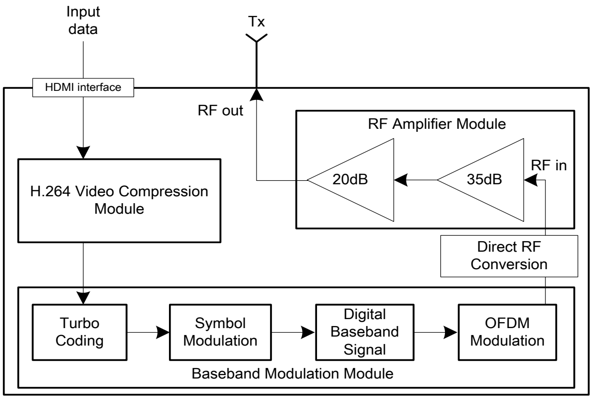

Fig. 5. UAV transceiver configuration

Based on the above requirements, we have designed a wireless transmitting module, with very low weight, power consumption, latency and high video definition and data throughput, as shown in Fig. 5. The realtime video data streams are compressed by H.264 standard at first. Then the compressed data streams are passing channel coding module for error correcting encoding. To achieve the both high error-correcting performance and low latency, we use the turbo code as the channel coding solution [16]. Then the data streams are mapped into frames and ready for channel modulation. The coded orthogonal frequency division multiplexing (COFDM) is used for modulation to multiplex a high rate data stream into multiple low data streams on orthogonal subcarriers for transmissions [17], [18]. The baseband modulation of each carrier can be selected among BPSK, QPSK, 8PSK, 16QAM and 64 QAM depending on the channel condition. The othogonality of subcarriers guarantee the minimum inter-symbol interference, thus greatly improve the transmitting quality [19]. The modulated signals are then directly converted into radio frequency band for wireless transmitting. A two-stage power amplifier solution is used at the RF end, with 35dB at stage 1 and 20dB at stage II. We managed to control its overall weight in 200g, power consumption in 0.5 watt and data throughput in 5Mbps with 8MHz bandwidth. The transmitting distance can reach over 5km under non-line of sight (NLOS) in geographically tough areas and up to 30km under LOS.

B. Communication Relay

When the UAVs are operating at a long distance from the ground station, the communication relay is often necessary to overcome the NLOS environment. The relay module is equipped to the tethered UAV and stay at a height in the air, allowing for LOS transmission of wireless signals.

The function of relay module is to receive the signals from UAV transceiver and forward the signal to the ground station in a lossless way [20]. It is extremely hard to direct repeat the signal at radio frequency level, due to the difficulty in designing high amplitude low noise RF amplifier. In our design, we first decode the received RF signals to baseband. The configuration is similar to the UAV transceiver, just in a reversed order. The RF signal is amplified through the low noise amplifier. Then the amplified RF signals are demodulated into baseband and are forward to another stage of transceiver module. The error correcting codes during the demodulation process can guarantee the minimum bit error rate due to the RF noises. As a substitute, after the signal is demodulated, we can also use a tethered optical fiber to transmit the signal to the ground, if the ground station is close to the tether UAV. In this case, the possible signal degradation at the relay transmitting is avoided.

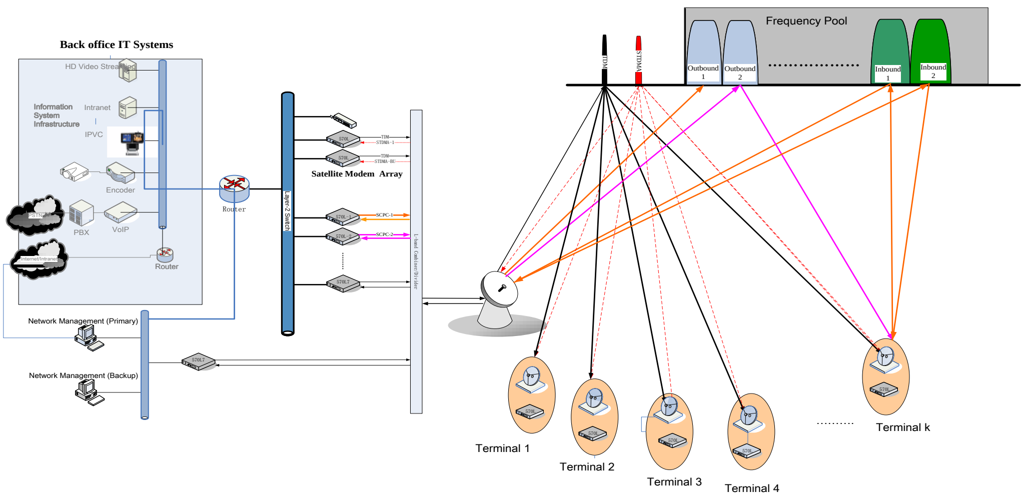

Fig. 6. Satellite communication configuration

C. Satellite Communication

The last stage of communication is to transmit the real-time videos/pictures to the far-end back operation center or office for realtime analysis. We use the very small aperture terminal (VSAT) satellite communication for the broadband communication [21].

The satellite communication system is an IP based comprehensive network as shown in Fig. 6. In our enterprise, a multiple of portable VSAT satellite stations are deployed to different inspection crew teams. All end terminals are sharing an 8MHz satellite bandwidth, allowing 4 HD video streams for simultaneous transmission. When there is no task, the terminal is in standby status. As the need for remote transmission is initiated, the end terminal will automatically switch the satellite link from standby status to transmission status. When the remote transmission is finished, the satellite link will automatically switch back to standby mode, sparing the bandwidth for other usages. This operation mode can utilize the limited and expensive satellite resources in an optimum way.

D. Cooperative Communication Practice

In our practice, the designed communication system can be coordinated smoothly. The design of the communication module is in a standardized way. All the interfaces of 200-800MHz COFDM wireless communication, optical fiber communication and satellite communication are using the standardized design, making the module substitutable in a fast and easy way. We also design a customized shelter for all the UAVs and communication equipments. The shelter can be easily transported through the truck. The integrity of the inspection team equipment is well preserved in our design.

IV. Performance Evaluation

In this section, we will evaluate the above cooperative inspection paradigm for feasibility and performance in a practical 500kV transmission line in Sichuan Province, southwest of China. The line starts from a hydro power plant and ends at a 500kV substation, across a mountain ridge as shown in Fig. 7. The overall length of the line is about 70km with 43 towers named J1 to J43. The elevation range of all 43 towers is among 400 to 1500 meters in altitude.

Fig. 7. A 500kV transmission line for inspection

An inspection team of 4 crew members is sent to inspect the transmission line, with 2 multi-rotors and a tethered multi-rotor for communication relay. The on-site position of operation base station is determined in the place close to the tower J25, which is vehicle accessible and is also the highest in elevation with the altitude of 1587 meters. The UAV ground station, satellite communication terminal and tethered communication relay UAV are deployed in this area. The deployment and preparation time is about 2 hours. Two flights of the fixed wing are then conducted, with first flight from J25 to J1 and the second flight from J25 to J43. The roundtrip distance and the flying time of the flights are 38km/58min and 18km/22min, respectively. The realtime video is sent back to the analysis office through satellite communication and a possible landslide at J3 is spotted from the analysis. Then a crew member is sent by vehicle to J3 for further inspection. A hexrotor is taken with the crew member from the on-site ground station to the nearest possible take-off place of J3, where a county road is passing by. The distance of the takeoff place of hexrotor is just 850 meters away from J3. Thus, the hexrotor only takes 9 minutes to fully inspect J3 tower and its surrounding environment. The pictures and videos taken are transmitted to the relay point at the on-site operating point and then to the back office for further analysis and recording. Then the crew member goes back to the on-site operation point, with a roundtrip travel time at 90 minutes. The whole inspection time for this cooperative operation is less than 3 hours. This is a tremendous time reduction by using cooperative UAVs. In comparison, the traditional inspection method may take over a week in finishing the all inspection tasks. We must be noticed that, the UAV inspection cannot fully substitute conventional methods but it indeed greatly improves the inspection efficiency, especially in emergent inspection during the natural disasters.

V. Conclusions

In this paper, we propose a new paradigm of power line inspection by using cooperative UAVs. The details of UAV functionality and communication systems are introduced and discussed. Our practical experience shows that by this cooperative operation the time taken for inspection can be greatly reduced and the efficiency can be improved tremendously. The feasibility and superiority of UAV inspection is demonstrated. The further work may include the optimization of UAV configuration in crew team.

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