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A review of rotorcraft Unmanned Aerial Vehicle (UAV) developments and applications in civil engineering

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Abstract. Civil engineers always face the challenge of uncertainty in planning, building, and maintaining infrastructure. These works rely heavily on a variety of surveying and monitoring techniques. Unmanned aerial vehicles (UAVs) are an effective approach to obtain information from an additional view, and potentially bring significant benefits to civil engineering. This paper gives an overview of the state of UAV developments and their possible applications in civil engineering. The paper begins with an introduction to UAV hardware, software, and control methodologies. It also reviews the latest developments in technologies related to UAVs, such as control theories, navigation methods, and image processing. Finally, the paper concludes with a summary of the potential applications of UAV to seismic risk assessment, transportation, disaster response, construction management, surveying and mapping, and flood monitoring and assessment.

Keywords: unmanned aerial vehicle; UAV application; automatic control; artificial intelligence navigation; image processing and analysis; nuclear power plant; transportation; disaster response; construction management; mobile mapping; flood monitoring and assessment

1. Introduction

An unmanned aerial vehicle (UAV) is an aircraft without a human pilot on board. The vehicle is controlled either autonomously by attached microprocessors or telemetrically by an operator on the ground. UAVs can be used to execute observation or detection missions through automatic or remote control. They are mainly used in mapping applications, environmental change monitoring, disaster prevention response, resource exploration, etc. Compared to other flying vehicles and satellite remote sensing technology, UAVs have two advantages when capturing aerial photographs: low cost and high mobility. However, they have many environmental restrictions on their use due

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to low flight stability. Therefore, how to use UAVs in different scenarios so that spatial information for qualitative and quantitative analysis can be reliably processed and produced is an important issue impacting their application.

Recently, many researchers have been focusing on applications of UAVs to cope with disasters and conduct regular infrastructure inspections. For example, Murphy *et al*. (2008) used unmanned sea-surface and micro-aerial vehicles jointly after Hurricane Wilma in 2008. Rathinam *et al*. (2008) proposed a single structure detection algorithm, employed using an autonomous UAV and based on visual feedback. Campoy *et al*. (2009) discussed applications in the field of computer vision related to civilian tasks, in which UAVs can be utilized. Murphy *et al*. (2011) also used UAVs in robot-assisted bridge inspection. Having abound potential opportunities of applications, there are still challenges encountered for certain limitations of applying UAV (Perry and Ryan 2011).

This paper provides an overview of UAV technology. It begins with a detailed introduction of a typical UAV. Then, the latest developments in UAV-related technologies are reviewed, such as control, navigation, and image processing. The last part of the paper will summarize the application of UAVs for the purposes of disaster mitigation and infrastructure inspection.

2. A Typical UAV

There are a wide variety of UAV shapes, mechanisms, configurations, and characteristics. Since UAVs are usually developed for specific purposes, their hardware and software design can be varied depending on task requirements. The following sections summarize the system design, implementation, and software of a typical present-day UAV.

2.1 System design

The system design of a typical UAV includes the following: (1) frame structure, (2) electromechanics, (3) flight controller, and (4) telemetry control system.

2.1.1 Frame structure

The frame structure is the shape of the aircraft. It is usually designed according to an aircraft’s dynamic lifting method. For instance, fixed-wing aircraft (e.g., gliders) are able to fly using wings that generate lift via forward airspeed and wing shape. Another example is rotary-wing aircraft (e.g., helicopter, quadcopter, etc.), which use spinning rotors with aerofoil section blades to provide lift. The International Civil Aviation Organization (ICAO) defines a rotary-wing aircraft as being "supported in flight by the reactions of the air on one or more rotors" (2009). Rotary-wing aircraft generally include those aircraft where one or more rotors are required to provide lift throughout the entire flight.

2.1.2 Electromechanics

Electromechnical components of a typical UAV include the following components: flight controller with multiple sensors (including GPS, gyroscope, barometer, and accelerometer), motors, propellers, speed controllers, and batteries (Fig. 1; example UAV is a hexacopter). Different motor speeds and propellers provide different performance. For example, the combination of high-speed motors and short propellers brings more agility and mobility for this aircraft, but lower efficiency and shorter battery life.

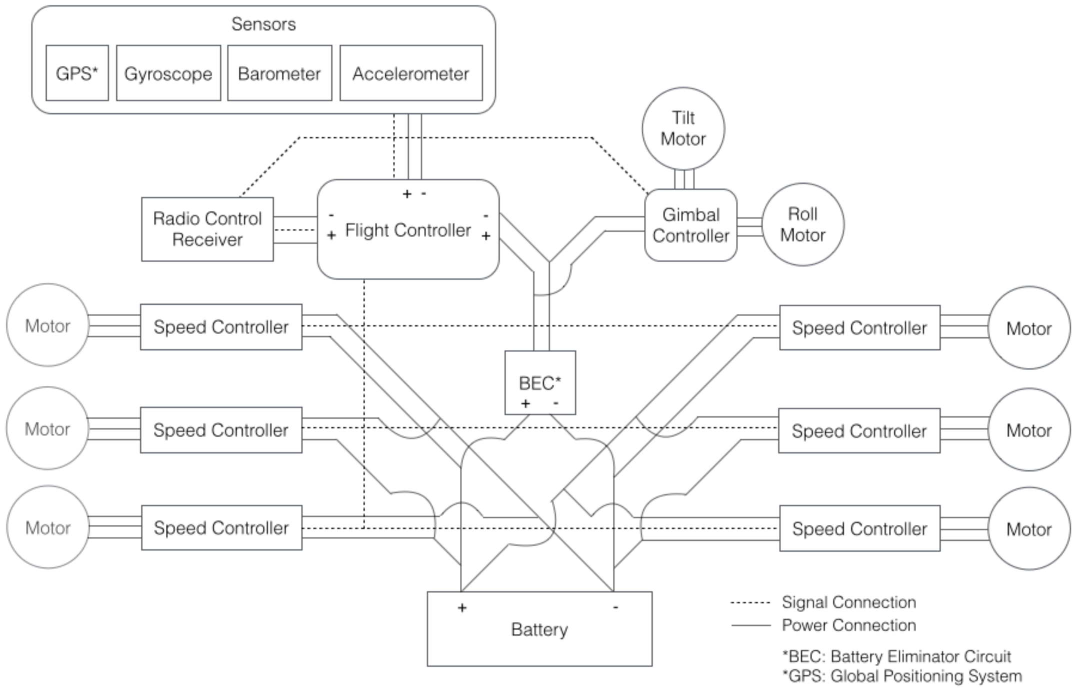


Fig. 1 Hardware assembly of a hexacopter

2.1.3 Flight controller

A flight controller is a microprocessor on the aircraft that manipulates the power output of each motor to stabilize flight and respond to operator orders. There is a variety of control algorithms, such as variable pitch and servo thrust vectoring. Variable pitch models usually applies the cyclic differentially to non-coaxial propellers, which allows for agile control and the potential to replace individual electric motors with belt-driven props hooked to one central motor (Cutler and How 2012). Servo thrust vectoring utilizes differential thrust as well as at least one motor mounted on a servo, which is free to change its orientation. This kind of algorithm is often used in bicopters and tricopters.

2.1.4 Telemetry control system

Common telemetry control systems currently in practice use radio frequencies in various bands such as FM, Wi-Fi, and microwave. The first general-use radio control systems in UAVs used single-channel analog equipment, which allowed for simple on-and-off switch control. In recent years, systems have emerged that use pulse-code modulation (PCM) features to provide a computerized digital stream signal to the receiver, instead of analog-type pulse modulation.

2.2 System implementation

When implementing a typical UAV (again taking a hexacopter as our example), we can divide the process into four main steps: frame assembly, electronics assembly, flight controller tuning, and optional equipment mounting. First, the frame includes the body (to mount the flight controller and other electronics), arms (to mount the motors and speed controllers), and landing gear. Common materials for the frame assembly are aluminum and carbon fiber, which are light but have sufficient strength. Second, electronic components include dynamic systems (propellers and motors), power connections (batteries and wiring), the flight controller, and telecommunication devices (e.g., radio system) (Fig. 2). Third, once the flight controller is well mounted, variables must be tuned in order to adapt the controller to the frame and electronics assembly. PID (proportional-integral-derivative) is a generic control loop feedback mechanism widely used in UAV control systems. The PID controller attempts to minimize error by adjusting the process control inputs. Finally, when the aircraft is ready to fly, various kinds of equipment can be mounted depending on the task requirements. For example, a laser rangefinder and GPS (Global Positioning System) unit integrated with a UAV affords the possibility of fetching 3D terrain information for geodesy inspection. UAVs carrying a digital camera and image telecommunication system allow practitioners to observe objects from high viewpoints and to explore unreachable or dangerous areas (Fig. 3).

Fig. 2 An example of a telecommunication control system

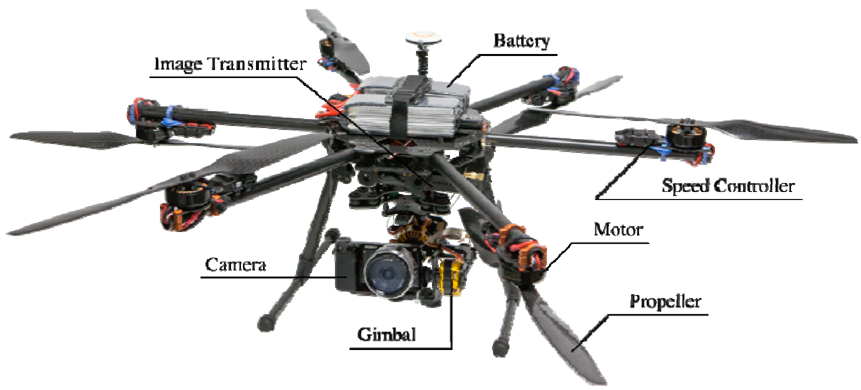


Fig. 3 An example of a hexacopter with a mounted digital camera

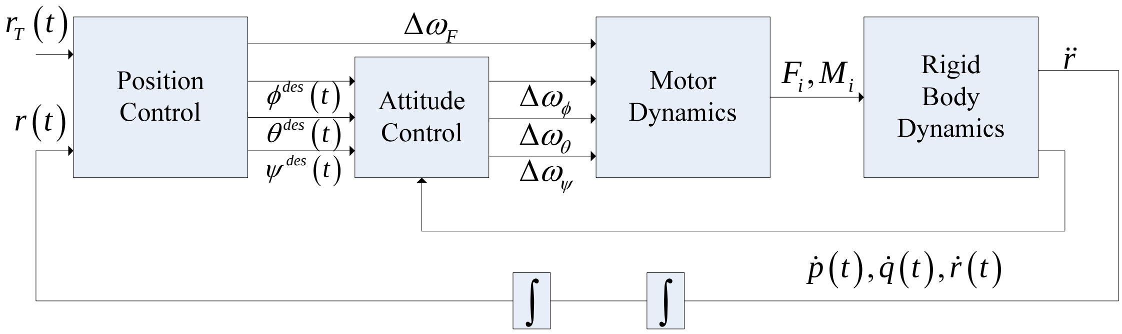


Fig. 4 A general attitude control architecture for UAVs

2.3 UAV control

Four UAV control problems need to be considered in implementing UAV applications: (1) the number of UAVs to be utilized to achieve a task, which can be either single or multiple (two or more); (2) whether the application is model-based or model-free: i.e., whether a mathematical dynamic model or control law for the UAV should be derived; (3) which of various control goals to pursue (e.g., stabilization/estimation of position or attitude, planning/tracking of path or target, obstacle/collision avoidance, cooperative formation flight, air/ground coordination, surveillance, or combinations thereof); and (4) whether the device will be fossil-fuel- or electric-powered.

As an example, we illustrate a general attitude control architecture for UAVs in Fig. 4. From Fig. 4, the overall control system is a combination of reference position $r_T(t)$; the position controller; desired dynamics $\phi^{des}(t)$, $\theta^{des}(t)$, $\psi^{des}(t)$; rotor speed differences between the nominal values $\Delta\omega_F$, $\Delta\omega_\phi$, $\Delta\omega_\theta$, $\Delta\omega_\psi$; motor dynamics; vertical force F_i and moment M_i generated by the i-th rotor; rigid body dynamics; components of angular acceleration $\ddot{\gamma}$, $\dot{p}(t)$, $\dot{q}(t)$, $\dot{r}(t)$ of the UAV in the body frame; and the actual position feedback $r(t)$.

2.4 Software

Software is important in controlling an UAV to acquire information from an aerial perspective; such software is also known as a Ground Control Station (GCS). A GCS is typically a software application running on a computer on the ground that communicates with a UAV via wireless telemetry. It displays real-time data on the UAV's performance and position and can serve as a remote cockpit. A GCS can also be used to control a UAV in flight, uploading new task commands and parameter configurations. Monitoring the live video stream is also a common function of GCSs.

For example, Stroumtsos *et al*. (2013) developed GCS software for military use in order to eliminate risk of disorientation and misreading of numerical data by designing a graphical user interface. In addition, GCSs have been designed by applying other technologies such as helmet-mounted displays (HMDs). The design of one GCS by Morphew *et al*. (2004) showed the application of HMD to a target search task was more advantageous than using conventional computer monitors and joysticks. For some critical cases, simulation functions are required for

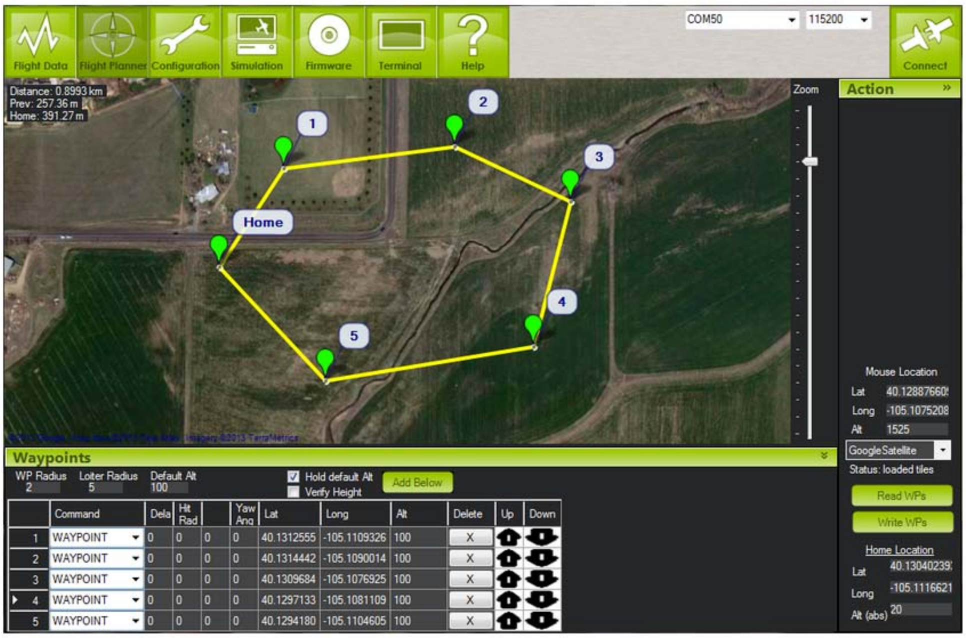


Fig. 5 A representative software interface for flight control (http://copter.ardupilot.com/)

GCS software. Reductions of schedule time, risk, and number of required test flights for complex aerospace tasks is a well-recognized benefit of utilizing prior simulation (Johnson and Mishra 2002). Commercial UAV software is usually used to route craft through waypoints and provide functions such as fail-safes, return-to-home, and route editing (Fig. 5). Recently, such software has also been released on mobile device platforms such as tablets and smart phones.

3. UAV-related technologies

The common goal that all UAVs share is to achieve autonomy without any human intervention whatsoever. We can achieve this goal by applying control technologies throughout the system. In the following sections, we will categorize technologies related to UAVs from the existing literature and highlight their main aspects, which include control, coordination, power management, navigation, and image processing functions.

3.1 Model-base control

The first step of model-based control of UAVs is to reflect their dynamic characteristics as a set of ordinary differential equations (ODEs). The derived dynamic model can be either linear or nonlinear (Kim *et al*. 2002). The advantage of model-based control is that the stability of the closed-loop systems they utilize is backed by rigorous mathematical proof. Ren and Beard (2004) simplified a 12-state nonlinear model into a 6-state one with altitude, heading, and velocity command inputs to achieve trajectory tracking while taking into account constraints on velocity and heading rate. Metni *et al*. (2006) proposed a nonlinear complementary filter to estimate attitude and gyro bias for vertical take-off and landing (VTOL). Note that VTOL performance plays a critical role for civil and military UAV applications in urban environments (Abdessameud and Tayebi, 2010). Azinheira and Moutinho (2008) used a back stepping-based controller with input saturations to achieve hover flight of a UAV. Lee et al. (2009) used an adaptive sliding mode controller to cope with the underactuated property of their helicopter, sensor noise, and uncertainty. Bruggemann *et al*. (2011) proposed automated flight of semicoupled 6-state nonlinear-modeled fixed-wing inspection aircraft to track approximately linear infrastructure, where a guidance law approach was used to attempt to maintain aircraft trajectories with desirable position and orientation properties relative to the infrastructure under inspection. Central to many nonlinear model-based controls is the Lyapunov function-based design, where global stability of objectives (such as stabilization, regulation, and tracking) can be achieved (Azinheira and Moutinho 2008, Metni and Hamel 2007, Guenard *et al*. 2008, Salazar-Cruz *et al*. 2007, Lawrence *et al*. 2008, Park *et al*. 2007, Cai *et al*. 2008, Peng *et al*. 2009).

Many works have utilized model predictive control (MPC, also known as receding horizon control or moving horizon control)—such as Kim and Shim (2003), Shim *et al*. (2006), Wang *et al*. (2007), Kang and Hedrik (2009), Alexis *et al*. (2011) and Riehl *et al*. (2011)—which has the ability to handle constraints, non-minimum phase processes, and changes in system parameters (robust control), and can be applied straightforwardly to large, multivariable processes.

Visual servoing/tracking control methods have also been widely applied, such as in: a proposed control strategy for a class of under-actuated rigid body systems, taking into account the full dynamic system incorporating all degrees of freedom (DOF) and not requiring measurement of the relative depths of the observed image points (Hamel and Mahony 2002); bridge inspection with bounded UAV orientation to maintain camera field of view (Metni and Hamel 2007), stationary or quasi-stationary flight with targets consisting of a finite set of stationary and disjoint points lying in a plane (Guenard *et al*. 2008); a robust visual lock-on framework that uses geometric relations between the UAV pose and the 3D local map defined by the positions of the target and natural landmarks (Min *et al*. 2012); the searching and mapping of river boundaries, bridges, and coastlines (Rathinam *et al*. 2007).

3.2 Model-free control

Intelligent control methods such as fuzzy logic, artificial neural networks (ANNs), and evolutionary computation (or combinations thereof) are typically used in model-free control of UAVs. The advantage of model-free control is the robustness of the controller in the presence of unmodeled dynamics or disturbances.

Nho and Agarwal (2000) used fuzzy logic to design an automatic landing system. Hong (2003) proposed a closed-loop strapdown attitude reference system (SARS) algorithm where fuzzy logic-aided estimation results achieved greater accuracy than conventional fixed parameter filtering estimators. Kadmiry and Driankov (2004) proposed a fuzzy flight controller, which combined a fuzzy gain scheduler and linguistic (Mamdani-type) controller that achieved stable and robust maneuverability for an unmanned helicopter. Kurnaz *et al*. (2009) developed three fuzzy logic modules under a main navigation system for the control of altitude, speed, and heading, through which the global position (in terms of latitude–longitude) of the vehicle was controlled.

Some researchers (Kim and Calise 1997, Leitner *et al*. 1997, Johnson and Kannan 2005) used

ANNs to represent nonlinear inversion modeling as required for flight control. Buskey *et al*. (2002) used ANNs that needed only inertial navigation system (INS) data without state history to achieve stable autonomous hover control for a helicopter. Pesonen *et al*. (2005) employed ANNs to cope with modeling errors in the inverse controller and adapt to sudden failures during flight. Wang et al. (2007) proposed a modified Grossberg neural network (GNN) for the obstacle/collision avoidance problem of UAVs flying in formation. Dierks and Jagannathan (2010) put forward a nonlinear controller for a quadrotor UAV using ANNs and output feedback, which allowed all six DOF of the UAV to be controlled using only four control inputs. Kurnaz *et al*. (2010) proposed an adaptive neuro-fuzzy inference system (ANFIS) based autonomous flight controller.

Nikolos *et al*. (2003) utilized genetic algorithms (GAs) to design an offline/online path planner for UAV autonomous navigation. Yokoyama and Suzuki (2005) proposed a modified GA for constrained trajectory optimization that robustly achieved global optimization of the objective function and feasibility search, even with a large penalty parameter. Shima *et al*. (2006) put forward a genetic algorithm for assigning cooperating UAVs to perform multiple tasks on several targets taking into account unique scenario requirements such as task precedence and coordination, timing constraints, and trajectory limitations. Eun and Bang (2009) proposed using a GA to achieve concurrent task assignment and path planning for a multiple-UAV group mission considering: i) timing constraints on simultaneous attacks and ii) multiple consecutive tasks with specified time delays. Yang *et al*. (2012) used particle swarm optimization (PSO) with a global search scheme and modified simulated binary crossover (MSBX) to enhance controllability of distributed networks, revealing interesting findings concerning pinned nodes, coupling strengths, and their eigenvalues and applying them to UAV coordination problems.

3.3 Coordination of multiple UAVs

Compared with a single UAV performing a task, multiple UAVs have the advantages of greater efficiency and operational flexibility when coordinated behavior among the team is present. To achieve such coordinated behavior, individual vehicles must have knowledge of the joint goals and their relationship with the environment. The guarantee of vehicles sharing consistent information over a noisy time-varying network topology is defined as information consensus (Fax and Murray 2004, Olfati-Saber and Murray 2004, Murray 2007, Ren *et al*. 2007). Note that the design of consensus algorithms operates under the assumption that the UAVs are distributed: i.e., that vehicles are only interacting with neighbors. Stipanović *et al*. (2004) used decentralized overlapping feedback control to achieve formation flight under the assumption that each vehicle (excluding the leader) only detects the vehicle in front. Samad *et al*. (2007) provided an important survey on network-centric UAV applications in urban military operations, with topics covering guidance and control for autonomous operation, multi-UAV coordination and route optimization, and ad-hoc networking with UAV nodes. Karimoddini *et al*. (2011) proposed hybrid supervisory control for inter-collision avoidance in a two-dimensional leader–follower formation scenario.

The general formation flight control of multiple UAVs can be modeled as

$$\dot{x}^i = f^i(x^i, u^i) \qquad x^i \in R^m \qquad u^i \in R^m \tag{1}$$

$$y^i = h^i(x^i) \quad \in SE(3) \tag{2}$$

where x^i, u^i, and y^i, are the state equation, control input, and position/attitude output of the i-th UAV; $x = [x^1\ x^2 \dots x^N]$ represents the state vector of N UAVs; and f^i and h^i are smooth nonlinear functions. The coordination of behavior between the N UAVs can be defined as optimal function

$$J = \int_0^T L(x, \alpha, u)dt + V[x(T) + \alpha(T)] \tag{3}$$

where T is the horizon time over which the task should be accomplished; L represents the incremental cost of the task; V represents the terminal cost of the task; and $\alpha = [\alpha^1\ \alpha^2 \dots \alpha^N]$ is a collection of the roles of the N UAVs. The controller may be derived by many of the methods mentioned in Sections 3.1 and 3.2.

3.4 Power management of UAV

For surveillance tasks using electric-powered UAVs, power management plays an important role in the optimization of flight time under limited power capacity. Many researchers have discussed maximization of the power supplied by solar energy. One such work was conducted by Shiau *et al*. (2009), which proposed a solar power management system (SPMS) consisting of maximum power point tracking (MPPT), battery management, and power conversion stages, which provide the power required for on-board electronic systems. In addition, many UAVs use batteries as the main power source, and so optimal battery usage is yet another important issue to overcome in order to achieve long-lasting flight.

3.5 UAV navigation

In civil engineering applications, the survey area can be large. Relying on remote control of vehicles by operators may not suffice. It is necessary to employ technologies for automatic and semi-automatic navigation. UAV navigation technologies fall into two notable groups: motion-planning methods and mapping methods.

3.5.1 Motion-planning methods

The first notable UAV navigation technology group is motion-planning methods. They are computational methods for determining a continuous route of a vehicle from a start position to the goal position while avoiding collision with known obstacles. Many algorithms in this group have been developed and applied in the field of robotics. One major planner is the Probabilistic RoadMap (PRM) (Kavraki *et al*. 1996, Hsu *et al*. 1999, Sanchez and Latombe 2002, Akinc *et al*. 2005). This method often finds possible connections between feasible robot motions by connecting the configurations sampled according to some probability distribution (Hsu *et al*. 2006).

Grid-based search is another approach, in which a grid is overlaid on a configuration space: i.e., a set of all possible configurations, where every grid point represents a possible configuration. Then, a search algorithm is required to plan an appropriate path from the start to the goal after determining all possible configurations. Many applications have utilized the grid-based search approach (Deng *et al*. 2008, Moghadam *et al*. 2008, Bayili and Polat 2011, Kala *et al*. 2011, Sturtevant 2012); however, it has some obvious shortcomings such as exponential increases in calculation time as dimensions grow, and searching repeatedly when the configuration space changes. Therefore, grid-based search approaches have been developed into many specialized algorithms. Thrun (1998) combined grid-based methods and topological methods to improve accuracy and efficiency. Carsten *et al*. (2006) extended 2D grid-based path planning to 3D grids. Willms and Yang (2008) implemented a distance-propagating dynamic system to achieve real-time robot path planning.

Another group of broadly used methods to calculate planned motion is potential field approaches, which combine attraction to the goal and repulsion from obstacles. Many applications incorporate potential field methods (Barraquand *et al*. 1992, Prandini *et al*. 2000, Ge and Cu 2002, Mezouar and Chaumette 2002, Wee *et al*. 2013). Potential fields can reduce computational effort, but fields may drop into local minima and become unable to find the original path. Ge and Cui (2000) created an improved potential field approach so that the goal position is ensured to be the global minimum. Zhao *et al*. (2010) developed a grid-based potential field method by combining grid-based and potential field techniques. Padula and Perdereau (2013) implemented potential field techniques in an on-line path planner.

A variety of search algorithms, such as A* (Jia *et al*. 2010, De Filippis *et al*. 2011), D* (Cagigas 2005, Guo and Liu 2010), Field D* (Ferguson and Stentz 2006, Ma *et al*. 2012), Theta* (Daniel et al. 2010), Vector Field Histogram (Borenstein and Koren 1991, Chung *et al*. 2013), are often applied in solving motion planning problems.

3.5.2 Mapping methods

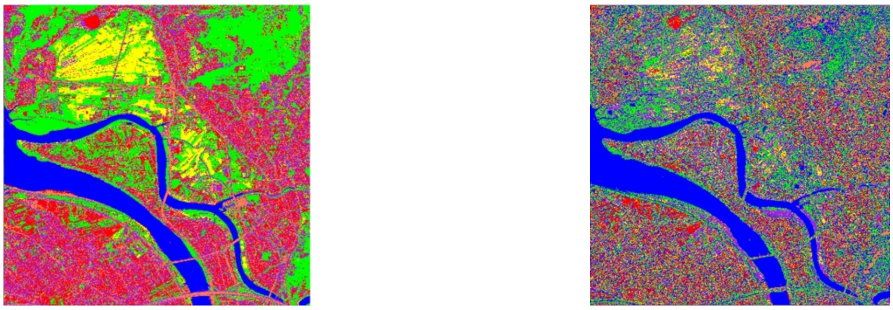
The second group of technologies related to navigation is mapping methods. An autonomous UAV needs to construct or use a map to localize itself. Simultaneous localization and mapping (SLAM) is one of the most popular and advanced techniques used by autonomous vehicles to build up a map within an unknown environment (Bailey and Durrant-Whyte 2006, Durrant-Whyte and Bailey 2006, Max and Andreas 2013). This method can also update a map within a known environment while at the same time keeping track of the current location.

Many researchers have started to integrate SLAM algorithms with UAVs. For example, Barber *et al*. (2006) presented a method, which can determining the GPS location of a ground-based object by integrating SLAM algorithms. Artieda *et al*. (2009) used the images taken from harsh environment by UAVs to test their SLAM algorithms. Huh and Shim (2010) implemented a vision-based landing system, which combined the GPS technique and SLAM algorithms to achieve the goal of accurate localization.

3.6 Qualitative analysis using image processing

The main advantage of a UAV platform is its highly flexible capability of acquiring spatial observations in various scenarios. Although many types of spatial information can be obtained, images are the most frequent choice for a UAV application since they provide a complete and intuitive representation of the object under investigation. The usage of UAV images can be divided into qualitative and quantitative analyses.

In a qualitative analysis, spectrum information is used to identify specific targets in an image and/or to monitor their variations over time (Fig. 6). In the field of remote sensing, this type of analysis is typically referred to as image classification (Jensen 1996). Depending on the presence or absence of training samples, an image can be analyzed using a supervised or unsupervised classification approach (Keuchel *et al*. 2003, Richards 2013). Maximum likelihood, minimum distance, parallelepiped, neural network, and binary encoding methods can be grouped under supervised classification approaches (Donoghue and Mironnet 2002, Lim *et al*. 2003, Kotsiantis *et al*. 2007). In these approaches, sample pixels of target objects are manually selected and trained to provide a reference spectrum so that all other pixels of the same target can be identified from the entire image. The accuracy of a supervised classification is highly correlated to the appropriateness of the training samples, and thus experienced personnel are required to accomplish this task. Additionally, the manual selection of training samples makes this analysis less efficient and automatic. On the other hand, unsupervised classifications—such as K-means, ISODATA, and histogram-based methods and sequential clustering—do not require the input of training samples, but automatically find appropriate reference spectra based on the desired number of target types being classified (Dhodhi *et al*. 1999, Wagstaff *et al*. 2001, Mitra *et al*. 2002). Their common foundation is to locate the spectral boundaries so that the distance between different target spectra can be maximized. This type of classification evidently requires less human intervention and thus contributes to fully automatic image classification analysis. However, because unsupervised classification approaches determine the spectral boundaries automatically, one has less control over the target types to be extracted. This is a drawback when a specific target is required in an analysis.



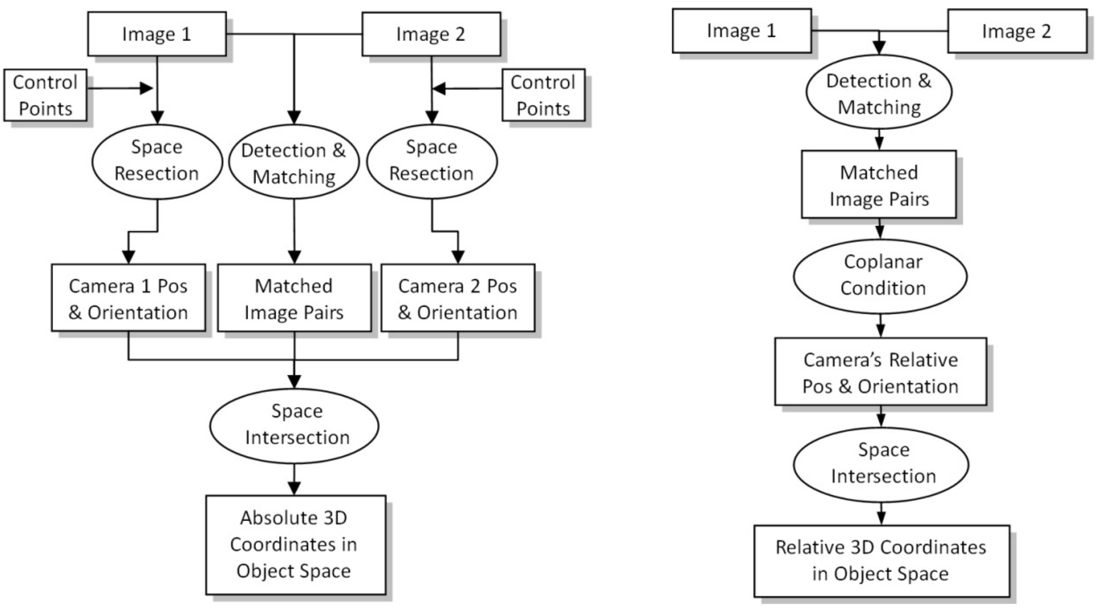
(a) supervised classifications (b) unsupervised classifications

Fig. 6 Qualitative image analysis

3.7 Quantitative analysis using image processing

The quantitative analysis of UAV images is necessary to determine the geometry (e.g., size, shape, and position) of a target object. To accomplish this task, one must account for image distortions due to projective geometry and find their correct coordinates in object space. This is typically done by employing well-known collinearity equations, which provide rigorous mathematical relationships between the image points, object points, and camera position (Schenk 1999, Mikhail *et al*. 2001). Based on these equations, high-quality ground control points (with known coordinates in object space) must be given so that the camera's position at the instant of exposure can be precisely determined. When two or more consecutive camera positions are obtained, the object coordinates for any image point existing in the overlapping region of the images can then be solved. This type of analysis is also referred to as an absolute orientation approach, in which the absolute geometry of the system is what is to be determined (Heipke 1997). Although rigorous, problems may be encountered when it is applied to real scenarios. First, the original collinear equations will take a non-linear appearance, meaning that an appropriate set of initial values for the camera's position and orientation is always required if a reliable solution is to be obtained. This becomes particularly problematic for an UAV, since its trajectory is less stable compared with other larger-sized and better-equipped (i.e., with sophisticated navigation devices) pilot-controlled aerial platforms. Obtaining good approximated values for camera positions and orientations on a UAV platform at every instant of exposure is thus a challenging task. Additional efforts have been made to obtain appropriate initial values using the so-called direct linear transformation (DLT) technique (Kobayashi and Mori 1997). However, this alternative requires more ground control points and is sometime unstable due to singularity issues.

Second, the resulting quality of an absolute orientation approach is highly dependent on the quality and distribution of ground control points. Obtaining accurate ground control points requires careful ground surveys and is thus costly and even impossible for areas inaccessible to surveying operators. These limitations would give UAV images limited applicability in quantitative analyses. On the other hand, if one is only concerned with the relative geometry (i.e., size and shape) of a target object, a relative orientation approach could be applied. This approach does not require ground control points, but can still reconstruct relative positions and orientations between consecutive camera stations (McGlove *et al*. 2004). A linear model to solve for the relative orientations has also been developed recently (Han *et al*. 2012), making it possible to determine the relative geometry of target objects from photographic images without the need for ground control points or additional efforts to find good initial values. Once the object coordinates of target objects have been determined using either an absolute or relative approach, other products (e.g., ortho-images, digital elevation models, or 3D inventory models) representing correct geometries can then be produced.



(a) absolute orientation approach (b) relative orientation approach

Fig. 7 Geometric analysis steps for UAV-acquired images

4. UAV Applications in Civil Engineering

UAVs provide new opportunities for civil engineers, giving aerial views that are difficult to obtain using traditional civil engineering tools. Below, we summarize scenarios across various sub-disciplines in which UAV applications can yield great benefit. The challenges facing, and opportunities afforded by, each application are also summarized.

4.1 Seismic risk assessment

The magnitude-9 Tohoku earthquake and tsunami of March 11, 2011 seriously damaged four of the six power reactors at the Fukushima Daiichi nuclear power plant (NPP). Hydrogen explosions destroyed the roofs of the reactor buildings for Units 1 and 3. Before the earthquake, Unit 4 was already shut down for inspection and all fuel rods had been transferred to the spent fuel pool on an upper floor of the reactor building. However, an explosion occurred close to the spent fuel pool and caused a great concern for the release of a large amount of radiation and toxic material. Residents within 20 km from the plant, at least 170,000 people, were evacuated from the area.

The high radiation of the Fukushima Daiichi NPP made human inspection very difficult. Tokyo Electric Power Company (TEPCO) successfully used a "T-Hawk" UAV, a US-made micro air vehicle commonly used to search for roadside bombs in Iraq, to photograph the nuclear power plant from above, providing images for the interior damage a month after the disaster.

UAVs have more advantages than simply investigating a site that people cannot enter or stay close to. They also provide a relatively cheap, fast, and weather-independent solution for post-disaster investigation compared with satellite photographic technology, and have thus played an increasingly important role in post-event reconnaissance. Gathering the investigating data in the real-time may significantly benefit the tasks in cleaning, rehabilitation, and retrofitting.

The importance of UAVs in reducing risk precipitated from natural or man-made disasters can be further expanded if their application is extended to other stages of risk mitigation and not limited to post-event investigation. The rest of this subsection presents some opportunities for UAVs to play a role in seismic risk assessment of buildings and infrastructure. Such assessment is important for the insurance industry, since estimated average annual seismic loss of buildings or infrastructure is essential information for premium calculation.

4.1.1 Opportunities

UAV technology can provide new solutions to enhance the efficiency of seismic risk assessment. Three possible directions are discussed herein.

New solution for the collection of building inventory data

Building inventory data are essential for seismic risk assessment, but not easy to access when the data belongs to a government. Consultant firms for risk assessment either develop technology to identify important risk parameters for buildings, such as dimensions and the number of stories, using satellite image and GPS technology, or hire people to collect the data through visual inspection. Since requisite building inventory data are project-specific, applying UAV technology in combination of image identification technology offers a third solution that is cheaper, faster, and less labor-intensive than the other two approaches.

Enhancement of the efficiency of post-earthquake reconnaissance

Post-earthquake reconnaissance provides valuable information to governments, research institutes, and insurance companies for emergency responses, observations of structural damage, and claim settlements, respectively. Traditionally, the reconnaissance is performed by humans and is very labor-intensive. With proper planning and coordination, the tasks of post-earthquake reconnaissance can be conducted more efficiently via the application of UAV technology. The cleaning, rehabilitation, and retrofitting are also benefit by the powerful technology.

Establishment of reliable seismic fragility databases for buildings and infrastructure

Reliable seismic fragility databases for buildings and infrastructures increase the reliability of risk assessments. For small-scale assessments for individual structures, the development of fragility functions relies heavily on experimental data and expert opinions and will not benefit directly from UAV technology. However, the development of fragility functions for regional (large-scale) assessments often involves data obtained from post-earthquake reconnaissance and, as mentioned earlier, is labor-intensive. Systematically collecting image data for buildings and infrastructures in a region before and after an earthquake can greatly increase the sample size of fragility databases for such large-scale assessments and therefore improve the reliability of assessment results.

4.1.2 Challenges

Two major challenges facing UAV technology implemented in response to these opportunities are described below.

The ability of UAVs to investigate inside a damaged structure

The UAV "T-Hawk" mentioned in the beginning of this subsection investigated the reactor buildings of the Fukushima Daiichi NPP from above. For a regular building heavily damaged by an earthquake, or a building that may collapse, UAVs can be used to observe the damage to a building in lieu of human inspection. In both cases, more information regarding the damage of the buildings can be obtained if UAVs can enter the buildings and collect images from within. This is important especially in post-disaster rehabilitation stage.

The application of image processing and recognition technology to the identification of the damage level of structures

All three opportunities listed above require the image data taken by an UAV be processed if they are to deliver useful information. The UAV needs to take photographs at meaningful positions of a structure so that the data can be used to correctly assess its damage state. Moreover, methodologies should be developed to extract useful parameters from image data (such as dimensions and numbers of stories) without requiring human judgment.

4.2 Transportation

Some research has focused on using UAV as the medium for the collection of transportation-related information (Peng *et al*. 2012). As transportation-related information is very often widely spread in terms of geospatial area, it creates challenges to data collection, especially when a time constraint on the process is involved. Naturally, UAVs provide an advantage for this kind of task. When using an UAV, its route for the operations must be planned (Liu et al. 2012), as mentioned previously. Applications in which UAVs have been implemented range from roadside asset patrol and condition assessments (Nygard *et al*. 2007, Hart and Gharaibeh 2011), traffic management (Harman *et al*. 2002, Heintz *et al*. 2007, Puri *et al*. 2007), specifically for the surveillance of traffic (Srinivasan *et al*. 2004, Coifman *et al*. 2006, Liu et al. 2012, Liu *et al*. 2013), pavement condition assessments (Zhang and Elaksher 2012), and emergency situations (Kaaniche *et al*. 2005, Zhang *et al*. 2013).

4.2.1 Opportunities

The high mobility of UAVs has created new possibilities in terms of data acquisition and processing methodologies. The following are opportunities in transportation-related operations in which UAVs can be applied.

Midscale and fine-grain information

As UAVs have much more flexible motion planning than other types of data acquisition media, they can potentially be deployed to spatial areas where other types of sensors could not collect data. Basically, they could fill in the gaps of large-scale aerial imagery and on-site spot sensors. UAVs could collect information on an intermediate scale to identify potential problems in transportation networks. If a particular spot is identified as problematic, UAVs could be dispatched to the physical location and collect on-the-spot data with better image quality, enabling much finer-grain information.

Abundant detailed information

With the UAVS collecting more-detailed data, the entire transportation network and geospatial space are enriched with information that enables better decision-making. In other words, the image data collected by UAVs creates a very detailed and rich data set about an area of interest. This allows for the mining of spatial and temporal information. Patterns of data could be identified, such as traffic behavior of a collection of intersections with specific vehicular travel-route patterns.

On-demand applicability

UAVs can collect data on demand for unexpected situations. For example, if abnormal behavior arises in the traffic flow of some sections of a transportation network, UAVs could be sent out to scout those sections. In addition, their mobile nature creates the opportunity to collect information for spatially moving phenomena, such as the propagation and oscillation of traffic, and to guide or follow emergency vehicles.

4.2.2 Challenges

For the application of UAVs to probe data in transportation-related operations, there are challenges that must be considered to fully utilize their potential.

Large amounts of data

With the detailed and fine-grain data collected by UAVs for transportation problems, the amount of data can be enormous. For applications that require real-time or near-real-time judgments, the large amount of data means the analytical model employed must be robust. As a result, machine learning approaches must be efficient enough for data analysis. Tradeoffs and selections between batch training and online training approaches must be considered. For situations when multiple UAVs perform data collection, data coordination and synchronization must also be taken into account. Additionally, how UAV data are collected by existing sensor technology should be studied, since different data sources have different types of noise and error caused by the specific data collection medium.

Real-time concerns and communication

For those applications in transportation that have time constraints on data delivery and analysis, the communication system of the UAVs plays an important role on the judgment validity. With more-detailed and finer-grain information, the amount of data being sent through the communication system becomes larger. In other words, there is a throughput requirement on those UAV communication interfaces. Unlike spot sensors installed on transportation networks, wireless communication is required and thus more limitations on the throughput are expected. This also leads to power issues, as communication is one of the main sources of power consumption.

4.3 Disaster response

There are great opportunities for UAVs to be deployed for disaster response, as on-demand data collection is usually required in large volume in order to gain and maintain situational awareness. There have been research initiatives using UAVs in disaster responses, such as sensing fire (Maza *et al*. 2011), assisting shipment operations (Bernard *et al*. 2011), and supporting reconnaissance along transportation lines (Hu *et al*. 2012). Additionally, disaster response operations usually have time pressures for urban search-and-rescue. As a result, the detail and rapid data collection afforded by UAVs are great boons to such operations.

4.3.1 Opportunities

Initial assessment

In disaster response, the objective in the initial stage is to know the condition of the disaster. UAVs could be sent to locations where high impact is expected and perform the first assessment, before any response resources are deployed. The initial assessment would include induced damage in the disaster zone, as well as the condition of the transportation network. This would enable a better overview of the disaster and assist in the planning of resource deployment; destinations could be set up and routes planned based on this initial assessment. Additionally, the rapid structural assessment of damaged buildings could be screened first by UAVs before the structural triage and the ATC procedures. This would enable a more efficient deployment of the urban search-and-rescue teams.

Detailed information

UAVs can provide more-detailed information by capturing images of zones affected by disasters. In other words, they generate first-hand, on-site information. More-detailed assessments regarding civilians needing assistance, disturbed critical transportation links, and critical power and communication infrastructure could be enabled. Decision makers would thus have a better understanding of the on-the-ground situation. In addition, the updating of information throughout the response operation could also be performed by the UAVs.

Tracking of people and resources

For the evacuation of the population in the damage zone, UAVs could capture the traffic information during rehabilitation phase. The traffic flow through transportation links could be observed and recorded. This information could help with the arrangement and placement of traffic conductors. UAVs could also be used for searching for civilians in need of evacuation transportation. For critical resources such as heavy construction equipment and buses, UAVs could help with seeking out available resources and tracking these equipment and vehicles.

4.3.2 Challenges

Infrastructure-based communication

In disaster response scenarios, infrastructure-based communication is often not available, and cellular networks and Wi-Fi may go down. As a result, the transmission of real-time information is problematic. As UAVs are capable of collecting image streams of high quality, their prompt communication becomes challenged when information transmission is unreliable. The establishment of ad hoc networks and efficient network protocols for UAVs could potentially mitigate this challenge.

Prioritization and identification of critical information

The mobility of UAVs enables data collection in disaster response operations. However, the prioritization of what should be collected first must be decided. The wide range of disaster response organizations at the local, state, and federal levels, private organizations, and non-governmental organizations mean that the objectives of each organization can diverge from the others. Priority should be established for UAVs to collect data in the different phases of disaster response. Additionally, particular objects (or sets of objects) for each objective should be set up. These objects constitute critical data to be collected by the UAVs, and UAVs can search for their target when these decisions are properly established beforehand.

Information dissemination

As there are many first-response organizations working on any disaster-affected zone, the dissemination of information about the area can be challenging. Data collected by UAVs should be made available to those organizations for analysis as needed. A platform that supplies data to authorized organizations should be established for the sharing and transmission of critical data.

4.4 Construction management

Large construction projects such as bridges, highways, and plants usually require the coordination of hundreds of workers and pieces of construction machinery. With UAVs, construction managers can monitor an entire site without accessibility constraints. Additional views provide better site visibility, which may allow supervisors to be more informed about project progress. Flight capacities and control mean cameras can be flexibly deployed to positions where CCTV cannot reach.

4.4.1 Opportunities

Visibility enhancement

An UAV allows us to view a location from a high vantage point. A global view of a construction site is more helpful than local views for managers who want to gain a clear perspective of the whole project. Furthermore, we can plan routes so that UAVs travel through critical, hard-to-reach viewpoints. Especially for engineering projects during disaster recovery, UAV technology can provide precise judgment for available paths almost immediately.

Representation

Common representations of construction sites often use photography, 3D models, and computer-generated imagery. With UAVs, we can model a site using aerial photography in isolation or combined with image and virtual technology, such as by using augmented reality to render mixed scenes toggled between virtual and real views.

Risk management

Ensuring field staff safety is an imperative topic to consider in construction. With UAVs, we can build assumed models to lay out complex (i.e., wide variety of) information in a job or site environment. These can help engineers create reliable plans and improve management efforts and quality, reducing production risks and enhancing on-site productivity.

4.4.2 Challenges

Flight reliability

Flight reliability is a critical issue to address if UAVs are applied in construction sites. Sites might present restrictions such as obstacles and unstable airflow, which increase uncertainty for flight controllers. A reliable algorithm that can deal with many situations needs to be developed to ensure UAV safety and enhanced applicability.

Visibility optimized path planning

Since a full construction site layout usually cannot be captured in just one viewpoint, a waypoint solution is a common method permitting the acquisition of more aspects of the site. The energy capacity of a flight (e.g., electricity or fuel) is always limited, so we must optimize waypoint paths to achieve the best visibility.

Real-time image transmission quality

Real-time image quality is the key to better representation and on-site planning. Current solutions on the market use analog signals for low-bandwidth transmission, which lower the actual image quality obtained from cameras. Other telecommunication technology has potential to provide increased bandwidth for better real-time image quality.

4.5 Surveying and mapping

A UAV provides a flexible and economical mobile platform for acquiring spatial information on objects of interest. Compared with those obtained by traditional aerial or satellite platforms, UAV-acquired datasets have better resolution in both temporal and spatial aspects (Turner *et al*. 2013). Furthermore, due to lower flight height and agile posture, a UAV is less affected by cloud shadows and is capable of collecting multi-view spatial datasets. Consequently, UAVs are regarded as an efficient platform for mapping and monitoring applications. For typical mapping tasks, their geometry and associated attributes should be identified and corrected first. Changes in them can then be further analyzed in a monitoring task when multiple observations across time are available. Applications of this kind are growing in number and are used in diverse fields. Some of the latest examples include: Laliberte and Rango (2009), who mapped the land cover of an experimental range in New Mexico; Wallace *et al*. (2012), who conducted forest inventory in the University of Tasmania in Australia; Lucieer *et al*. (2011) and Turner *et al*. (2012), who mapped and monitored moss beds in the Antarctic area; and Abdelkader *et al*. (2013), who conducted real-time flash-flood monitoring in the Jeddah hydrological basin in Saudi Arabia. In addition to the above-mentioned environmental applications in wide areas, UAV technologies are also employed for small-area, larger-scale detection and monitoring tasks. One novel application is on-ground vehicle identification and tracking for traffic controls (see, e.g., Dobson *et al*. 2013, Kanistras *et al*. 2013, Moranduzzo and Melgani 2014). More applications of a similar kind can evidently be expected in the near future.

4.5.1 Opportunities

Considering their high mobility and real-time capability, UAV technologies should be able to contribute to the following opportunities in mapping and monitoring applications.

Detailed 3D modeling

Traditional aerial surveying techniques only collect information on the top facades of target objects, while ground surveying techniques usually limit the data acquisition to the side facades. The agile mobility possessed by UAVs makes multi-view spatial data collection possible. Furthermore, a UAV can access a target object more closely than any other remote sensing platform. Consequently, complete and high-spatial-resolution observations can be easily obtained. This eliminates the gap between current aerial and ground platforms, and thus contributes a new vision for constructing high-fidelity 3D models.

Fast and highly frequent mapping

A UAV can be operated without much preparatory work or regulative constraints. It is a good candidate for tasks requiring prompt responses such as the emergent mapping of unexpected events, such as flash floods or wildfires. Additionally, its relatively low operating costs mean that frequent operations become affordable for civilian purposes. In other words, shorter revisit periods can be achieved and the target objects can be monitored at a higher temporal rate. As a result, the time-variant behaviors of those fast-changing phenomena will be better captured, contributing to in-depth understanding of the matter under investigation.

Mapping in hostile environments

Owing to its small size and remote maneuvering capabilities, a UAV can collect spatial observations in a hostile environment that is too dangerous or inaccessible for other traditional mapping platforms. Applications indoors or at toxic or radiation-contaminated sites become readily possible when using UAV technologies. Operators do not need to jeopardize their lives but can still acquire the essential spatial information necessary for completing a mapping task. Both geometric modeling and qualitative evaluations under those difficult scenarios become achievable in a safe and cost-efficient manner when a UAV platform is adopted.

4.5.2 Challenges

In order to make full use of the advantages afforded by a UAV platform in mapping and monitoring applications, we suggest further consideration of the following challenges to minimize the barriers to their implementations in various field scenarios.

Intelligent data acquisition

A large number of spatial datasets can be acquired by a UAV platform. However, their volume does not necessarily equate to a quality mapping result. Depending on the types of spatial analyses being performed, different requirements for spatial data acquisition must be fulfilled in order to guarantee analysis validity. For example, flight height, incidence of the camera optical axis, and overlap ratio of adjacent images are all key factors affecting the final results of geometric analysis of UAV images. An intelligent system for spatial data acquisition should be devised in order to optimize field data configurations and to automatically trigger data collection procedures.

Rapid data processing workflow

One challenge common to mobile mapping platforms is tackling the huge amount of datasets being collected. This is a particularly major issue for a UAV mapping platform, since its primary advantage over other platforms is its fast responsiveness. Using UAV technologies, a very large amount of observations can be obtained within a very short period, but the subsequent analyses still require extensive and complicated processing before the final mapping products can be obtained. The delayed processing of UAV-acquired datasets diminishes the superiority in temporal efficiency characteristic of UAV technologies. To facilitate a rapid mapping workflow, all the steps of the processing should be fully automatized, avoiding the need for any human intervention. Recent advances in computer vision and artificial intelligence technologies may provide opportune support and constitute an effective solution for UAV mapping and monitoring applications.

Multi-sensor implementation

A digital camera is the most frequent choice of mapping sensor used in UAV platforms. It records both the geometry and spectral information of target objects and provides necessary information for completing mapping tasks. However, camera sensor limitations are often readily apparent. First, the mapping results from photographic images are usually less accurate along the direction parallel to the camera's optical axis. This is a common problem in photogrammetry arising due to information compression along this optical direction. Second, ordinary photographic images are vulnerable to ambient light conditions. Shadow effects are a serious problem that diminishes the quality of recorded images. Finally, common RGB images do not provide sufficient spectral information for distinguishing among various target objects, such that automatic identification and processing become less possible. To overcome these problems, other mapping sensors could be employed: laser scanning, radar, and multi-spectral image sensors are all potential candidates. However, considering the budget constraints and payload limitations of a UAV platform, carrying all these mapping sensors on board is infeasible since they are currently still too heavy and expensive. Future development of sensor adaptation techniques should aim at reducing their size and cost so that these advanced mapping sensors can be realistically implemented.

4.6 Flood monitoring and assessment

With heavy rainfall, flooding may occur as flowing over the levees to produce widespread flood damage over lowlands. Flood is one of the most destructive natural disasters, which has claimed more lives lost, damaged more properties in urban and agricultural lands than any other natural hazard in recent decades. To manage flood hazards, it is vital to implement an effective flood risk management with appropriate actions for decision makers to reduce exposure and vulnerability of people and property in a flood (Chang *et al*. 2013). Real-time monitoring and mapping of flood extent are crucial to assess damage losses in both spatial and temporal measurements. Using traditional survey of flood inundation extent always encounters the difficulty in harsh environments such as inaccessible road due to severe weather conditions. UAV can serve as a powerful tool for spatial data access, real-time image transmission, detection of high-risk inundation areas, low cost and flexibility advantages of satellite or aerial remote sensing for flood monitoring and assessment (Niethammer *et al*. 2010, Ajibola and Mansor 2013). In flood hazard, flood monitoring and mapping information obtained from UAV operation has direct implications to the public safety responses (Rahmeyer 2011). Although abound potential applications of UAV, there are still challenges encountered in flying fragile small-scale aircraft with low weight limits and narrow center of gravity tolerances (Perry and Ryan 2011) for certain limitations of applying UAV due to hostile weather conditions and commercially available sensors.

4.6.1 Opportunities

Flood inundation and damage assessment mapping

Accurate mapping of the inundation areas from flooding is critical to save lives and property, which relies on real-time high-resolution digital elevation of surface. The construction of flood extents and the estimation of both area and depth of inundation provide the assessment of damage during a flood event, especially for the inaccessible flooding areas due to hazardous environments. To monitor flood rising and recessing in the inundation areas, rapid mapping of the fast-changing flood flow phenomena requires a quick-response task for the emergent events. Without much preparatory work or regulative constraints, UAV can be operated by a lower cost with frequent revisit operations which are affordable and beneficial for tracking the entire flood event. For example, when the river flow exceeds the design flood discharge of the levee, water stages may be higher than the top of the levee and the flood can overflow and propagate to the surrounding wide lowlands over complex topography. Detailed flow spreading information for flood inundation and damage assessment mapping can be processed by utilizing UAV technologies.

Flood protection structure monitoring

Flood hazard may damage infrastructure and utilities. Monitoring flood flow conditions around the flood-affected facilities and structures can provide important information for emergency management, which includes water level, flow velocity, floating debris around bridge, levee, river bank, floodplain or other critical hydraulic structures. Moreover, to monitor and identify river bank erosion, bridge and road damage, broken oil or gas lines, downed power lines, loose tanks, victim and property lost, etc. are also important (Rahmeyer 2011). The ability to survey and monitor by UAV can provide quick assessment of emergency response to plan and coordinate for damaged facility inspection and rescue operation during a flood event.

Flood emergency management

During storm with heavy rain, flooding may create the loss of property and the potential loss of life. The emergency agencies who respond to flood disaster events usually encounter significant uncertainties regarding flooding situations of threats to public safety. However, accessible paths to flooded areas are frequently be impeded, making it difficult or impossible to acquire information on the public safety threats in the state of the flooded system. A comprehensive emergency response can save lives and property effectively. To provide in-situ mapping about the details of the flooding location and extent is crucial for planning and coordinating a real-time response to threatening conditions. With UAV, we can rapidly explore the potential utility to gather real-time data during or just after emergency flooding situations in support of flood emergency management decisions.

4.6.2 Challenges

Operation reliability in severe weather conditions

During the flood event, flight reliability of UAV operation can be an essential issue for the flight controller due to gustily strong wind and intensity rainfall which may disrupt the planned path and stableness of telecommunication. There are certain limitations of applying UAV in the severe weather conditions. Nevertheless, the need to identify and inventory areas of potential hazards can serve as pre-flood and post-flood monitoring before and after flooding, respectively. For example, debris removal at a bridge may considerably reduce damage in pre-flood monitoring. The use of UAV for post-flood damage assessment and surveys is also a beneficial operation for search and rescue in flood emergency response.

Mapping flow pattern and water quality

Flood flow patterns around the flood-affected structures can provide important information for emergency management. Water level and flow velocity are the crucial factors to determine the potential failure of bridge pier, bank erosion, levee scour, etc. If UAV can be applied, images taken from the flooding river channel may be analyzed by using particle image velocimetry (PIV) technique (Fujita and Hino 2003) to map the flow field and near bank water levels which should be helpful for the prediction of structure safety. Moreover, remote sensing has been widely used to monitor water quality by analyzing data products and imagery from spectral sensors (Wang *et al.* 2004, Steissberg *et al.* 2010, Allan *et al.* 2011, Papoutsa and Hadjimitsis 2013). To monitor water quality in a flood is increasingly important for conservation efforts on eco-environment. Without the need of costly in-situ sampling in the flooding extent, it is beneficial of adopting a UAV carrying spectral sensors for water quality monitoring such as total suspended sediment, solid suspension and turbidity for further applications. However, the challenge of applying UAV for monitoring water quality may be limited due to the availability of spectral sensors.

In summary, UAVs have great potential to facilitate Civil Engineering applications such as, but not limited to, Seismic Risk Assessment, Transportation, Disaster Response, Construction Management, Survey Engineering, and Flood Monitoring and Assessment. The advantage of UAVs in comparison to traditional data acquisition mediums is the timely, versatility and flexibility to collect detailed imagery data in a wide geospatial extent. In other words, efficient decisions could be made to enable tasks such as post disaster debris cleaning, rehabilitation, and structural retrofitting. As the starting point for research and applications for UAVs, the authors recommend to explore the opportunities and to tackle the challenges aforementioned.

5. Conclusions

UAVs have been in development for years and their technology is becoming more mature. Civil engineering usually involves large-scale surveys to cope with uncertainties occurring before, during, and after construction. UAVs provide new opportunities for civil engineers to understand their projects or the problems they face. This paper summarizes state-of-art technologies related to UAVs, including control, navigation, power management, and image processing technologies. It also lists many possible opportunities where UAVs can be employed in civil engineering applications. However, many challenges still remain and need to be explored further.

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