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Concepts and Applications for Integrating Unmanned Aerial Vehicles (UAV's) in Disaster Management

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Abstract. Over the past few decades, the impact of natural, manmade and natech (natural hazard triggering technological disasters) disasters has been devastating, affecting over 4.4 billion people. In spite of recent technological advances, the increasing frequency and intensity of natural disasters and the escalation of manmade threats is presenting a number of challenges that warrant immediate attention. This paper explores the integration of drones or Unmanned Aerial Vehicles (UAV's) into infrastructure monitoring and post-disaster assessment. Through reviewing some of the recent disasters, effectiveness of utilizing UAV's in different stages of disaster life cycle is demonstrated and needed steps for successful integration of UAV's in infrastructure monitoring, hazard mitigation and post-incident assessment applications are discussed. In addition, some of the challenges associated with implementing UAV's in disaster monitoring, together with research needs to overcome associated knowledge gaps, is presented.

Keywords: Drones, Unmanned Aerial Vehicles (UAV's), Hazard, Mitigation, Disaster Management

1.0 Introduction

Disasters, whether triggered by natural or human factors, have become a growing concern lately. This is due to the fact that between 1994 and 2013, the international disaster database (EM-DAT) has recorded 6,873 natural disasters. These disasters have claimed 1.35 million lives and caused economic losses of more than US$ 2 trillion (Arain et al., 2016; UN, 2012). Unfortunately, the number of disasters has also been shown to rise due to global warming effects, increasing population in urban areas, poor zoning laws, as well as lack of proper risk management and regulations (Gencer, 2013). As the increase in likelihood of more intense disasters is expected, losses in the aftermath of these disasters is increasing as well. For instance, global losses due to natural disasters only were estimated at $175 billion in 2016 (Riley, 2017). Out of this, $46 billion in damages occurred in the US, mainly due to flooding, severe storms and wildfires (see Table 1).

Table 1 Major natural disasters affected the U.S. in 2016 (NOAA, 2017)

Disaster type	Number of events	Adjusted losses *(in billions of dollars)*
Drought	1	3.5
Flooding	4	16.6
Severe Storm	8	14.5
Tropical Cyclone	1	10.0
Wildfire	1	2.0
Total	15	46.0

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A disaster is defined as an occurrence that causes loss of human life, socio-economic damage, ecological disruption, deterioration of health and health services on a large scale to warrant an extraordinary response from outside the affected zone. One example of such a disaster is the Haiti earthquake, which occurred on January 12, 2010. This earthquake had a magnitude of 7.0 (on Richter scale) and was followed by two aftershocks of magnitudes 5.9 and 5.5. This earthquake has caused a death toll estimate of 160,000. In the aftermath of this earthquake, the government of Haiti estimated that 250,000 residences and 30,000 commercial buildings, including 60% of government and administrative buildings (such as presidential palace) to have collapsed or severely damaged. As a result, there were 19 million cubic meters of rubble and debris in Port-au-Prince capital city alone (DesRoches et al., 2011). According to Inter-American Development Bank (IDB), damage from this disaster was estimated at $14 billion, making this earthquake one of the most destructive natural disaster of modern times (Chiaro et al., 2015).

It can be seen that a major disaster can cause substantial damage, especially if occurrence of such disaster is not anticipated or prepared for (DHS, 2013). Thus, it is crucial to implement all possible strategies to minimize damage associated with disasters. Such strategies comprise of developing successful emergency response plans to enable effective early relief operations. However, execution of such strategies is often hindered by the fact that authorities often have little information regarding extent of losses to population and damages to infrastructure (i.e. power plants, transportation grid etc.) in the aftermath of a disaster, mainly due to communication outages and inability to visually assess damage. As a result, conventional manned assessment are often less efficient in the early stages of a disaster. In order to overcome some of these challenges, aerial-based disaster evaluation has become an effective tool to provide authorities with much needed situational awareness in the event of a disaster breakout.

Aerial-based disaster evaluation technique utilizes large surveillance aircrafts to conduct post-disaster assessment missions (Jibiki et al., 2016). However, use of such aircrafts is expensive, require dedicated infrastructure (airports) and can pose threats to human pilots (in case of harsh weather). Further, use of aircrafts may not be applicable where there is lack of airports (especially in developing countries/remote areas) or in cases where airports are severely damaged (i.e. due to earthquake). Another aerial-based disaster evaluation technique utilizes satellites to capture level of damage arising from a disaster. Although satellites can inspect large areas efficiently, footage collected from satellites require sophisticated observatory stations to be processed and analyzed. As a result, use of satellites may not provide precise presentation of zonal damage in a timely manner.

The recent advances in new materials, as well as design and manufacturing technologies have led to rapid advancements of Unmanned Aerial Vehicles (UAV's). The Federal Aviation Administration defines UAV's as an aircraft that can be operated without the intervention of a human pilot aboard. In general, a UAV comprises of an aerial vehicle that can operate either under remote control by a human operator, or fully autonomously by complex automation systems. The fact that UAV's do not require especial infrastructure for deployment or advanced processing equipment to analyze their collected data allows UAV's to provide authorities with accurate and quick representation of disaster magnitude. Perhaps one of the main advantageous of UAV's is the fact that they can be deployed at short notice (in few minutes) and operate without posing any risk to human pilots, especially in harsh weather conditions or in dangerous environment (i.e. radiation related). Further, UAV's are equipped with various sensors and have the ability to perform multi-task operations during same flight. Moreover, UAV's are cheap and fuel efficient, as a

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result they can be deployed more frequently since they have low maintenance cost/requirements (as compared to aircrafts).

From the above discussion, it can be inferred that UAV's have the potential to be an effective tool in disaster management and infrastructure assessment applications. This paper reviews some of the recent disasters in which UAV's were successfully employed so as to demonstrate the effectiveness of utilizing UAV's in different stages of disaster life cycle. The needed steps for successful integration of UAV's in infrastructure monitoring, hazard mitigation and post-incident assessment applications is discussed. In addition, the challenges associated with implementing UAV's in disaster monitoring together with research needs to overcome knowledge gaps is presented.

2.0 Evolution and Classification of UAV's

The earliest recorded use of UAV's dates back to August 22, 1849, when Austrian forces attacked the Italian city of Venice with 200 unmanned balloons. The balloons, which measured at 5.7 meters in diameter, carried 15 kgs of explosives and were armed with timed fuses. These balloons were aimed at targeting critical buildings and lunched towards Venice city. Although some of the balloons did not reach their targets, and those which made it caused minimal damage, this attack marked the feasibility of unmanned aerial vehicles in military applications. It should be noted that a similar attack strategy was also used during the American civil war in 1862. In this war, Northern Union forces used to install incendiary devices on unmanned balloons and release them to start fires on the Southern Confederacy side of battle lines (Sloggett, 2015).

The development of UAV's and implementation for military applications have continued in early 1900's and been well documented during World War I and II (Pearson, 1963; Taylor and Munson, 1977). During this era, production of radio controlled (RC) aircrafts started in the United States (US). Such aircrafts, designated as OQ-2 Radioplane, were specifically designed from low-cost material and used to train anti-aircraft gunners. These Radioplanes were the first mass-produced UAV's for the US army of which fifteen thousand planes were produced during World War II. During the same period, US Navy was able to install a camera in an aerial aircraft, called Curtiss Fledgling N2C-2, which was remotely controlled from a companion Naval Aircraft TG-2 (Fahrney, 1980). The N2C-2 was an anti-aircraft target drone and is considered to be the blueprint for modern UAV's.

The development of UAV's continued for military applications during 1950-1990's and until the end of Cold War. During this period, many UAV's were originally designed to perform aerial photo reconnaissance, deliver equipment, and execute strikes against high-value, and time-sensitive targets (Saxena, 2013). One of the notable UAV's is the Predator RQ-1L which was the first deployed remotely piloted aircraft (RPA) to conduct offensive operations in Balkans war in 1995, Iraq war in 1996 and proved its effectiveness in Afghanistan war in 2003.

After the cold war, much of the classified technology regarding UAV's became open for public. As a result, development of UAV's shifted towards civil and governmental applications. For instance, US Customs and Boarder Protection Agency used several types of UAV's to survey the border between U.S. with Mexico, scout property and locate fugitives (Karp and Pasztor, 2016). In addition, UAV's and Unmanned Ground Vehicles (UAGs) were extensively used in search and assessment missions in Ground Zero after 9/11 in 2001 and over New Orleans after Hurricane Katrina in 2005. In 2006, the Federal Aviation Administration (FAA) authorized the use of specific types of military-grade UAV's (i.e. General Atomics MQ-9 Reaper) within U.S. civilian airspace. The MQ-9 Reaper was supplied with digitally enhanced

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infrared camera capable of identifying heat signature of human body from an altitude of 3000 m, as a result, MQ-9 Reaper was successfully used in number of search and rescue missions.

Unmanned aerial vehicles are classified based on their engine type i.e. fixed wings (i.e. has wings like conventional airplane) or rotary motors (can be with single or multiple rotor blades, see Fig. 1). In general, UAV's designed with fixed wings have efficient aerodynamics and high endurance. As a result, they can fly at high altitudes and long flight times. However, theses UAV's require take-off/landing facilities and are prone to high maintenance and refueling costs. On the other hand, the main advantage of rotary UAV's is their ability to vertically take-off and land (VLOT), high capacity to hover, and maneuverability especially in narrow spaces (NASA, 2017; Roberts, 2017; Watts et al., 2012). Unlike fixed wing UAV's, rotary UAV's have relatively short flight times (ranges) and low speeds since they are often designed with electric motors and have limited battery power.

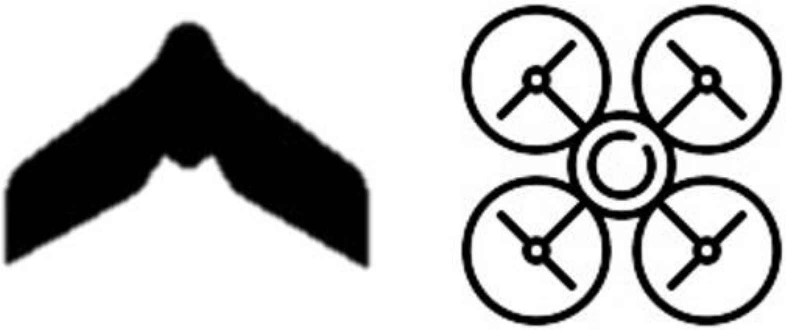

Fig. 1 Illustration of a fixed wing and rotary UAV

UAV's can also be grouped under other metrics such as size and operation range/endurance. For example, UAV's classified by size (i.e. wing span) are referred to as nano/micro (300-500 mm), small (500-2000 mm), medium (5000-10000 mm) and large (greater than 10000 mm) UAV's. Further, UAV's classified by operation range/endurance can also be categorized as UAV's with close range (5 to 50 km and endurance time of 20 min to 6 hours), short range (50 to 50 km and endurance time of 8-12 hours), mid-range (with working radius of 650 km and endurance time of 12 to 24 hours) and large range (more than 1500 km and endurance time of 24 to 36 hours).

Prior to 2010, different branches of the US military (Air Force, Marine Corps, and Army) separately classified UAV's as "Tiers" or "Classes". However, the department of defense has recently established a more homogeneous classification system known as the "Group System". In this system, UAV's are classified into five groups based on their weight, operating altitude and speed. This classification system is adopted for military-oriented UAV's and can be extended to civilians UAV's as well. Typical example of each UAV group is listed in Table 2.

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Table 2 Generic classification of UAV’s

UAV group	Description	Weight lb (kg)	Altitude ft (m)	Speed (knots)	Example
Group 1	UAV’s in this group are typically light, can be hand-launched, portable systems that fly at low speeds and altitudes and/or within a structure.	0-20 (0-10)	< 1200 (400) AGL[*]	100	WASP, AeroVironment RQ-11 Raven
Group 2	These are typically small to medium sized UAV’s that fly at low-to-medium altitudes. They typically perform special purpose operations or routine operations within a specific set of restrictions. These UAV’s are typically launched via catapult.	21-55 (10-25)	< 3500 (1000) AGL	< 250	Boeing Insitu ScanEagle
Group 3	These UAV’s operate at medium altitudes with medium to long range and endurance.	<1320 (600)	< FL 180[**] (55)		AAI RQ-7 Shadow
Group 4	These are relatively large UAV’s that operate at medium-high altitudes and have extended range and endurance.	>1320 (600)		Any airspeed	General Atomics MQ-1 Predator
Group 5	These are large UAV’s that operate at medium-high altitudes and have the largest range, high endurance, and speed capabilities. Typically these perform specialized missions such as broad area surveillance or penetrating attacks.		> FL 180 (55)		General Atomics MQ-9 Reaper

[*] AGL: height above ground level

[**] FL: flight level at nominal altitude in multiples of 500 ft (150 m).

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It is worth noting that UAV’s are the aerial-based counterpart to unmanned ground vehicles (UGV’s) and more recently developed remotely operated underwater vehicles (ROUV’s). Although UGV systems, can carry much larger loads than UAV’s, still they require to be transported and placed very close to disaster source/location. However, this may not always be applicable and can pose threat to first responders. Further, UGV’s have number of mechanical challenges especially over uneven terrain or movement across rubble. It is due to these issues that UAV’s are considered superior to UGV’s. Since UAV’s are usually equipped with similar instruments to that of UGV’s, with the exception that UAV’s can fly to cover large areas, UAV’s can be best suited for disaster management operations and assessment of infrastructure post-incident.

3.0 Successful Use of UAV’s in Recent Hazard Incidents

The first high-resolution aerial image of a major disaster was a black and white picture of San Francisco, CA, taken three weeks after the devastating earthquake that occurred in 1906. This photograph was taken by a camera raised 300 m above San Francisco Bay using a train of large Conyne kites (Harris, 2017). Although the concept of aerial reconnaissance and photography for military application started in mid-1800’s, the use of UAV’s in global disaster aid is relatively new (Reich, 2017). For instance, hurricane Katrina saw the first deployment of UAV’s for relief aid in 2005. UAV’s were also deployed during the 2007 southern California wildfires. These UAV’s were well-equipped with infrared cameras that were able to penetrate layers of smoke as to provide information on the size and direction of fire. In order to further illustrate the feasibility of utilizing UAV systems in disaster aid and assessment mission, details of two recent major disasters and how UAV systems were applied to aid first responders in rescue missions and infrastructure assessment are discussed herein.

3.1 Nepal Earthquake

The Nepal earthquake (also known as the Gorkha earthquake) occurred on April 25, 2015 and had a magnitude of 7.8 on Richter scale. This earthquake was the worst natural disaster to strike Nepal, since 1934, and caused $7 billion in losses (which is estimated to be 40% of Nepal's nominal GDP (see Table 3)). This earthquake has led to a large number of casualties including 9,000 deaths, 22,000 injuries and has left 3.5 million people homeless. In the aftermath of this disaster, more than 600,000 structures in Kathmandu capital city and other nearby towns were either damaged or destroyed including 80% of the houses in rural areas. This large number of collapses is attributed to the fact that most residential structures constructed in Nepal are non-engineered buildings made of masonry and concrete. These buildings lacked sufficient reinforcement and detailing and were built under the advice of mid–level technicians and masons, without a professional structural design background (Chiaro et al., 2015).

Table 3 Damage assessment in Nepal earthquake (in $US million) (Chiaro et al., 2015)

Sector	Damage cost	Additional loss	Total disaster effect
Housing	3,036	467	3,503
Education	280	3.2	283.2
Industry	174	168	342
Transportation	171	49	220
Others	5,532	1,473	7,005

The Nepalese army air service has limited resources, thus only 4 aircrafts and 17 helicopters were allocated for transport and assistance in the aftermath of this earthquake. Thus, in order to estimate the size

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and magnitude of this earthquake, a fleet of Canadian UAV's was deployed to survey affected regions between India and Tibet and collect thousands of high-resolution ortho-images to help streamline repair and rescue missions. In addition to sending UAV's in relief missions, several TV news networks have utilized UAV's in news coverage since large portion of Nepalese telecommunication grid was damaged (Tompkins, 2017).

3.2 Super Typhoon Haiyan

Super Typhoon Haiyan was a tropical cyclone which devastated portions of Southeast Asia, particularly the Philippines, on November 8, 2013 (Harris, 2017). This super typhoon had an estimated "maximum two-minute sustained winds" of 280 km/h and a "one-minute sustained winds" of 315 km/h. It was the deadliest Philippine typhoon on record, killing at least 10,000 people and causing $2.86 billion in losses especially in Tacloban and Ormoc cities (where 90% of the structures were reported to have been either destroyed or severely damaged). As a result, the Philippines faced a humanitarian crisis with 1.9 million homeless people and more than 6,000,000 people displaced.

Although local and national agencies deployed a collective of 18,177 personnel and 844 vehicles to perform relief operations, the extreme damage to infrastructure throughout the region posed logistical problems and significantly slowed relief efforts. Though aid was flown into local airports, most of it remained there as roads were closed and/or blocked. In order to overcome some of these complexities, UAV's were deployed in routinely operated missions to provide non-governmental organization (NGOs) with needed "real-time" information and pinpoint alternative routes and potential base locations for aid workers. In addition, advanced UAV systems, such as those equipped with Sky-Watch system, were also utilized in infrastructure assessment operation and helped engineering teams to evaluate structural damage of Tacloban City Airport (Kim and Davidson, 2015).

4.0 Strategies for Effective Integration of UAV's in Disaster Life Cycle

From the above review on previous disasters, it can be inferred that significant losses can occur during and in the aftermath of major catastrophes. Such losses can be mitigated, to some extent, if vulnerable communities (and cities) are better prepared. Due to recent technological advancement, it is quite possible to predict breakout (or arrival) of some disasters (such as tsunamis) through early warning systems i.e. satellites. However, these systems are still not effectively and fully implemented in disaster management and require sophisticated processing and communication facilities to operate efficiently. These early warning systems are also costly and have limited accessibility to poorer countries. In order to overcome some of these limitations, integration of UAV's is currently being considered for use in conjunction with early warning systems.

The versatility of UAV's makes them a feasible tool that can be used in various stages of disaster life cycle. For example, UAV's can be deployed to identify vulnerable infrastructure and foresee possible extent of damages before disaster season arrives. Further, UAV's can closely monitor formation of tsunamis/hurricanes and update authorities with disaster development through livestreams. Also, UAV's are quite inexpensive, readily available and easy to operate. Although it is clear that UAV's have high potential for use in disaster management, unfortunately, there are very limited provisions or guidance on use of UAV systems to detect or monitor disaster evolution nor to perform infrastructure assessment during or in the aftermath of a disaster. To bridge this knowledge gap, some of the strategies for effective integration of UAV's in three stages of a disaster (see Fig. 2), are presented here.

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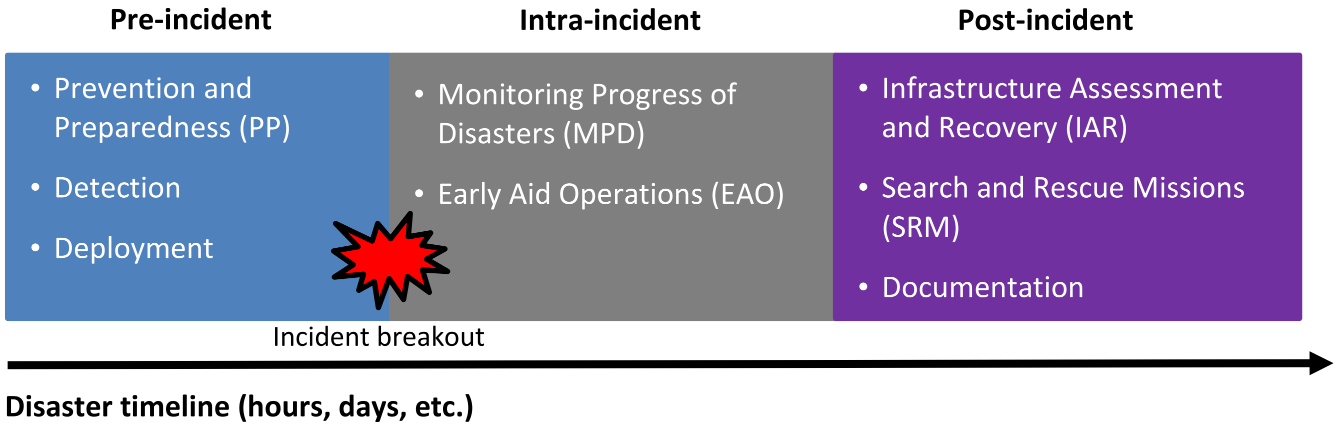

Fig. 2 Application of UAV's in different stages of disaster life cycle

In general, disaster life cycle comprises of three stages namely, pre-incident (before disaster arrival/breakout), intra-incident (during disaster impact) and post-incident (after impact). In the "pre-incident" stage, UAV's can be used to identify and prepare disaster prone regions to develop effective strategies that can be used to minimize adverse effect of natural and manmade disasters. As a result, UAV's can collect needed data to authorities to develop prevention and preparedness measures to be used when a disaster breaks out.

The "intra-incident" stage refers to the duration during which disaster occurs and the timeline starts the moment a disaster breakout and continues until it ends. Based on the duration, a disaster can be short or long. Disasters of short nature (duration) are those which last from few minutes to few hours i.e. earthquakes, fires and terrorist attacks. The other type of disasters occurs over longer periods and can extend to few days/weeks. Example of this are wildfires, floods, tsunamis etc. Since it has been shown that much of damages occur during "intra incident" period, UAV systems can be deployed to monitor progression of disaster (Gencer, 2013; Riley, 2017). Through such monitoring, authorities can quantify size/magnitude of disaster on "real-time basis" to identify severely damaged areas and accordingly distribute resources to optimize aid operations.

Finally, during the third stage, in the aftermath of a disaster, UAV's can be highly effective in post-incident assessment and damage estimation to infrastructure. Data collected from UAV's during this stage can be of significant importance to first responders, survivors, governmental agencies and humanitarian organizations. During the third stage, UAV's can also be used in search and rescue missions as well as monitoring of rehabilitation progress. Further, analysis and documentation of collected data can be important for training, education, and research purposes.

4.1 Stage I – Use of UAV's in Pre-incident Stage

The main strategies for effective integration of UAV's in detection of disasters, as well as proposed mechanisms for optimal deployment of UAV's during pre-incident stage, are discussed herein.

4.1.1 Prevention and Preparedness (PP)

According to the Federal Emergency Management Agency (FEMA), risk and disaster assessment is the evaluation of different types of disasters and consequences to define associated risk as to prepare appropriate procedures for use when a disaster occurs. These procedures are applied to reduce vulnerability of communities and ensure that authorities and general population can make informed decisions at the right

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time. Hence, disaster mitigation strategies aim at directly preventing future breakouts or minimizing their negative effects.

Such strategies can be achieved through effective deployment of UAV systems in disaster management. For example, UAV’s can be deployed to assess condition of critical infrastructure, defined as facilities that are essential for the functionality of society and economy (i.e. nuclear power plants, bridges, airports etc.). Any interruption or failure in operations in such facilities can severely hinder rescue and rehabilitation operations and also would lead to substantial monetary losses. For instance, once an area prone to flooding is identified, UAV’s can be effectively deployed to assess current state of dams to warn authorities or people in low laying areas for developing precautionary measures. Through such inspection, resiliency assessment can point out the need for any repairs, upgrades or strengthening necessary to ensure optimal performance of critical infrastructure before a flood/tsunami incident occurs.

4.1.2 Detection

As discussed earlier, satellite systems have been applied for wildfires detection and hurricanes formation over the last few years. However, these systems have some drawbacks such as time delays, low resolution and need for intensive computational capacity to process collected footage (Chuvieco et al., 1994; Sá et al., 2017). In essence, utilizing a UAV can lead into “faster” and “convenient” access to imagery than that to be obtain via satellites. Since UAV’s are often supplemented with a complete processing package that is able to analyze images and videos collected during a flight (in real-time) this is considered an advantage over utilizing satellite images that require special access and processing of large streams of data (Matese et al., 2015). As a result, current methods of detecting natural disasters, especially wildfires, rely heavily on human efforts. Depending on such measures, is not only unreliable, but can also pose large threats to first responders and people in the region as shown in recent statistics from the U.S. Fire Administration (Fahy et al., 2016). According to recent statistics, wildfires have caused 68 firefighters deaths and 68,085 injuries in 2015.

The fact that UAV’s can fly lower than manned aircrafts (and in reduced visibility) to detect local fire ignition areas, and with less risk to pilots, infers that deploying specialized UAV’s can reduce the frequency of contact between firefighters and wildfires. Not only that, but UAV’s can also be deployed to detect development of other disasters as well. For example, UAV’s can be utilized to monitor formation of tsunamis/typhoons which is safer than deploying manned coast guard helicopters and/or ships. Furthermore, UAV’s have also been used to monitor landslides and act as early warning systems to pinpoint vulnerable regions and infrastructure (Casagli et al., 2017; Erdelj and Natalizio, 2016). The above discussion clearly shows the feasibility of integrating UAV’s into disaster early detection systems.

UAV’s can be also effective to detect, and to some extent, prevent vandalism incidents. UAV’s can supplement conventional surveillance systems (such as CCTV, infrared cameras etc.) in monitoring critical structures. Since conventional surveillance systems require to be installed at visible spots, and to be connected through hard wiring, they are easily accessible and can be susceptible to sabotage. Such limitations can be overcame through use of UAV’s since they are hard to detect and do not require direct contact with infrastructure (i.e. “hard wiring”). Hence, UAV’s can provide additional layers of security that outperform conventional detection systems.

Further, integrating UAV systems equipped with infrared sensors or sniffing devices can be deployed in routine patrols to detect possible terrorist threats (i.e. bombs) near critical infrastructure (i.e. nuclear power plants etc.) or large gatherings of people (sporting events). Such UAV’s are also able to identify criminals through facial recognition systems, and communicate with fugitives and/or victims (in

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cases of hostages). In these unique situations, UAV's can have the ability to release tear/sleeping gas to prevent casualties. It is clear that not only UAV's can provide significant amount of information that can prevent, to some extent, occurrence of an incident, but they can also perform basic tasks without exposing human operators to any danger.

4.1.3 Deployment

In order to provide first responders with updates and livestream footages, especially during early stages of a disaster, quick deployment of UAV's can be highly effective. In current practice, fixed wing UAV's can be deployed from ground control stations (GCS) or through portable launching systems (PLS). A ground control station is a land or sea-based command center that provides facilities needed for human operators to deploy and control UAV's. Such a station is often located in a well-protected secure zone such as military base (and away from any areas prone to hazards). Thus, when a disaster breaks out, fixed-wing UAV's are deployed towards affected regions which can be hundreds of kilometers away. In another deployment system, a team can be dispatched, from a ground station, to get as close as possible to the damaged region to deploy a UAV using a pre-assembled lunch pad system (see Fig. 3). Unfortunately, both of aforementioned deployment systems only utilizes fixed wing UAV's, can take long duration to reach affected zones and may jeopardize safety of UAV deploying team.

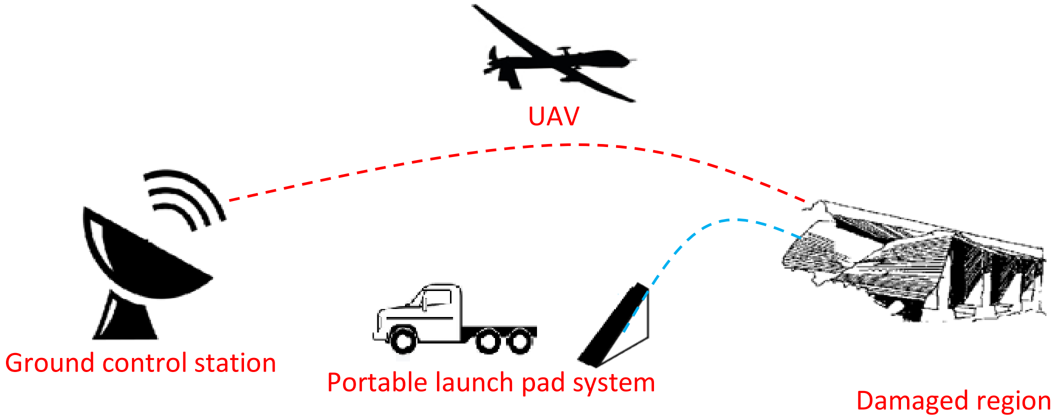

Fig. 3 Illustration of current UAV deployment systems

To overcome the above limitations, rotary UAV's can be used for more effective deployment. In this concept, rotary UAV's can be deployed through number of mechanisms. In the first mechanism, micro-rotary drones, manufactured with low cost materials and be equipped with limited transmission devices, can be transported by a large fixed wing UAV. These rotary drones are released upon reaching a certain destination or along a predefined path. Once released, these micro-drones can cover large areas to collect information and provide logistic awareness to local stations and ground personnel. At the same time, these micro drones can feed information to the large fixed wing drone which then transmits this data to control command center to aid authorities in decision making.

Another alternative is to install small UAV remote stations in predetermined locations. In this concept, remote stations are designed to be located in infrastructure or regions of critical importance such as nuclear plants, coastal areas, offshore oil rigs etc. (see Fig. 4). These remote stations can house one to two small or medium sized rotary UAV's. In this system, a UAV is placed in a station and can be remotely-

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activated (by operator) or through self-activating mechanism. In the first case, once a disaster occurs (i.e. wildfire), a remote pilot activates the UAV to survey and monitor the development of such disaster.

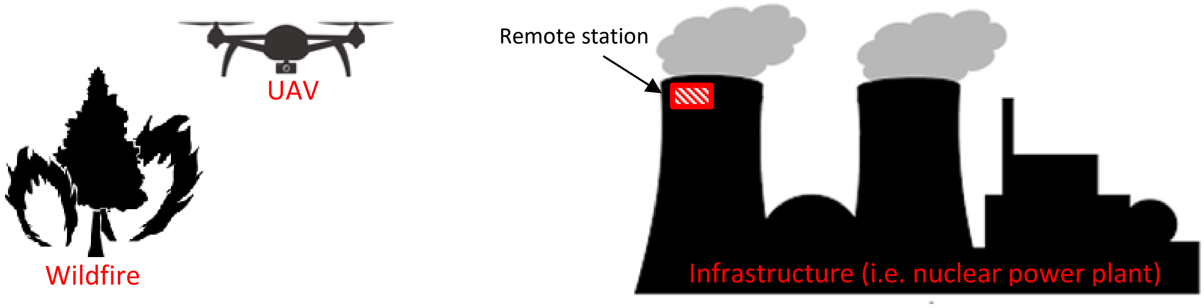

Fig. 4 Illustration of a remote station

In case of a self-activating UAV, a UAV is only activated if certain parameters exceed a predetermined threshold and/or upon receiving feedback from "onsite sensors" installed in critical infrastructure. For example, if vibration level (or wind speed) near an offshore oil rig that houses a UAV deploying station exceeds a certain limit (due to an earthquake or tsunami formation), a UAV gets self-activated, notifies control station and performs a pre-programmed task (see Fig. 5). This task can be in terms of a short flight in the vicinity of the deploying station. During this flight, UAV operators can analyze livestreams and sensors readings to assess state of emergency. When needed, the UAV can use these stations to recharge, return collected samples or wait for further instructions.

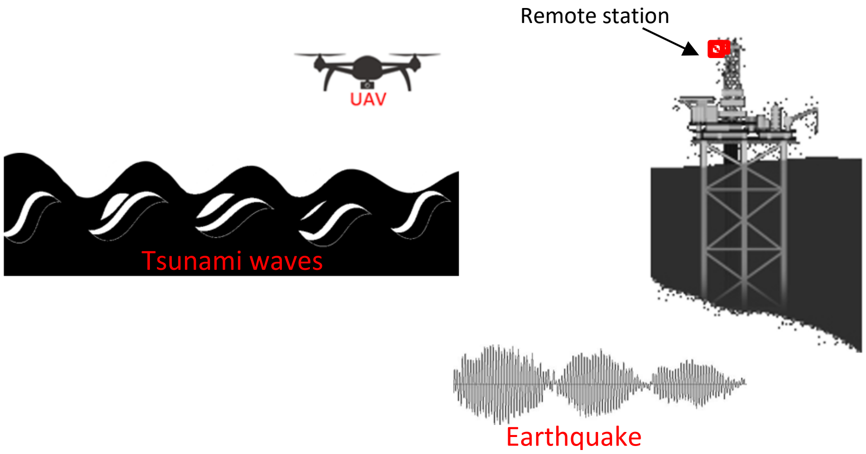

Fig. 5 Illustration of deployment of UAV from an oil rig to monitor formation of tsunami waves post-earthquake incident

4.2 Stage II - Role of UAV's during an Incident

In Stage II, "during/intra incident" period, UAV's can be effectively utilized to monitor the progression of disaster, as well as to provide critical information to agencies/first responders which can aid in organizing early relief operations.

4.2.1 Monitoring Progress during a Disaster (MPD)

Much like how bomb disposal robot provides law enforcement with a closer look at a dangerous situation from a remote location, medium-to-large sized UAV’s can be deployed to provide first responders with better view of a disaster scene without placing operators at risk or having to rely on helicopters, or aircrafts which can be can be expensive and/or inapplicable (in cases of low visibility or damage/absence of airports). In particular, use of UAV’s can be helpful during the course of a dynamic disaster; those that can change direction, speed and intensity with time, such as hurricanes and wildfires. For instance, since UAV’s can be equipped with sensors to measure wind speed, smoke density etc., they can collect data on gust speed and direction, combustion rate in a fire, etc. and predict imminent progression of such a disaster. As such, UAV’s can also be effective in monitoring development of wildfires and associated resident evacuation (Casbeer et al., 2005; Moore, 2011).

To illustrate the use of UAV’s in monitoring the development of a disaster formation, Fig. 6 shows progression of a hurricane affecting Area (A). As this hurricane is developing, there is a possibility for this hurricane to grow and move towards Areas (B) or (C). Thus, an UAV system can be deployed to continuously monitor and provide “real time updates” on development (and movement) of this hurricane. Through these updates, UAV operators can be able to predict future path of this hurricane (i.e. towards Area B) and notify residents and authorities of Area B to evacuate and head towards the safer area (Area C).

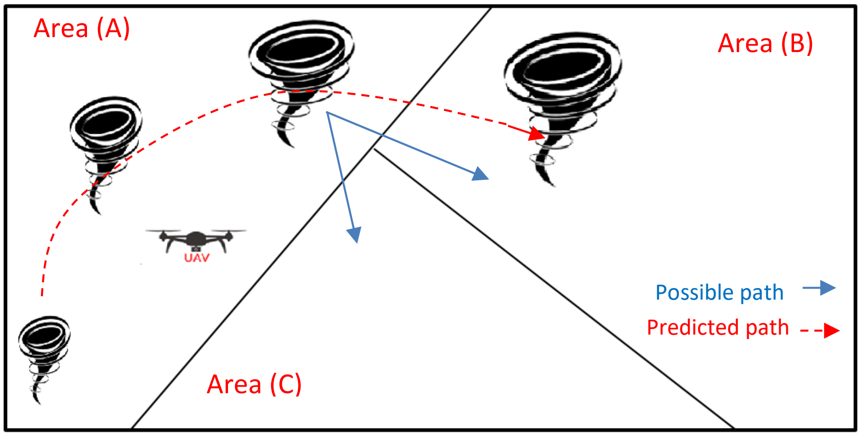

Fig. 6 Use of UAV in monitoring development and pathing of a hurricane

4.2.2 Early Aid Operations (EAO)

As discussed earlier, monitoring of a dynamic disaster, through satellites, although applicable, may not provide in-depth details on number of survivors, their locations or progress of aid operations. Further, a dynamic disaster, such as typhoons and floods, can cause significant damage to communication towers and powerlines. As a result, communication between survivors, relief personnel and control stations can be limited. Thus, large UAV’s can be deployed to establish temporary communication coverage between ground teams and control stations. Similarly, medium-sized UAV’s can be also deployed, by ground teams/survivors (or from nearby UAV deploying “remote” stations), to deliver messages, instructions and updates.

In cases of small scale disaster, i.e. building fire, nearby fire station can deploy a medium-sized UAV to collect information on fire cause, scale, and extent of damage. Since UAV controllers (operators) have access to livestreams, they can decide on number/type of needed firefighting equipment as well as best location to set-up firefighting equipment before first responders arrive to the scene. Not only that, but with the aid of UAV feedbacks, analysis of fire growth (and spread) to adjoining buildings as well as state of traffic at that location can be very helpful to first responders.

Once firefighters arrive at the fire scene, micro-sized UAV's equipped with thermal imaging equipment can also be deployed to provide firefighters with real-time visuals about where the fire is burning most intensely. These drones can fly through building interiors, passing through floors to search for trapped victims and assess structural damage. Search for victims using micro UAV's can save time by pointing location of victims to firefighters or by pointing trapped victims to egress paths (this concept can also be applied in hostage situations, tracing terrorist hideouts etc.). In cases where fire extends through number of floors, conventional firefighting equipment may not be able to reach such levels. As a result, large-sized drones, with heavy lifting abilities, can spray fire retardant directly into higher floors, deliver firefighters to floors above the fire, and/or rescue trapped survivors. It can be seen that integrating various types of UAV's can significantly improve conventional aid and rescue operations.

4.3 Stage III - Use of UAV's Post-incident Stage

In recent years, UAV's have been exclusively used in the aftermath of disasters, especially earthquakes, to perform qualitative damage assessment only. However, data collected by UAV's can be also utilized for education, training, and research purposes.

4.3.1 Infrastructure Assessment and Recovery

In post-incident stage of a disaster, UAV's can be deployed over affected regions to collect information on estimated number of casualties and damage scale, through advanced imaging technology, to generate 3D images and virtual systems of these regions which then can be used to develop repair maps as shown in Fig. 7. Once repair maps are developed, government agencies can deploy rehabilitation missions to target infrastructure with high priorities. Development of damage virtual systems can help understand disaster timeline, and collapse mechanism of infrastructure to prevent future losses. This aspect has been examined by Lattanzi and Miller (2017) as well as Montambault et al. (2010), with special application in transportation and power generation and supply infrastructure.

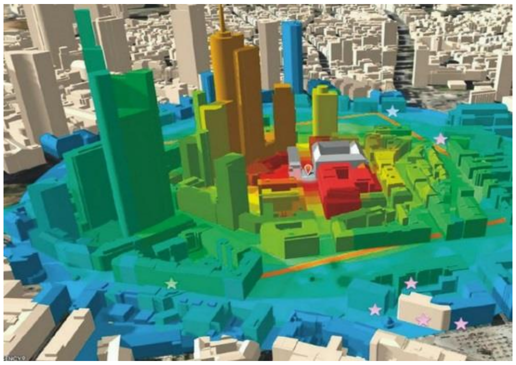

Fig. 7 Virtual system of a typical damaged area in a major city post disaster (Trometer, 2016)

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Furthermore, UAV's can fly near critical infrastructure such as a bridge, oil refinery or a nuclear power plant to analyze any damage/leakage and provide needed data to carryout initial resiliency assessment of the faulty structures (see Fig. 8). This analysis can be performed by visual inspection or through connecting to impeded sensors within infrastructure to collect recordings (i.e. strain/vibration measurements) and check high radiation level and/or leakage (Pöllänen et al., 2009; Spranger et al., 2016). In such assessment, a UAV is able to detect location and size of any defects, damage, or leakage by processing visual data or shearography (i.e. speckle pattern interferometry techniques).

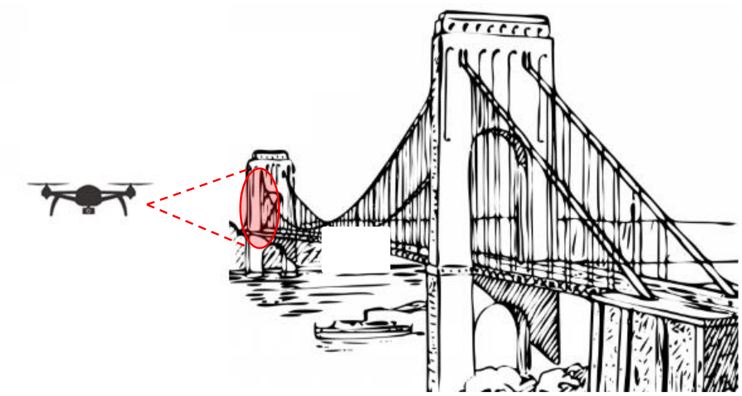

Fig. 8 Visual assessment of bridge post-earthquake event

Based on this resiliency assessment, an informed decision can be made whether to shut down the specific infrastructure (i.e. nuclear plant or bridge) to prevent possible meltdown or collapse. Results of such analysis can prevent escalating existing conditions and ensure safety of nearby survivors or rescue workers. Most importantly, if no damage is detected, the structure can continue to operate for power generation or aid delivery etc. which can accelerate rescue operations by not shutting down the critical infrastructure for inspection which can last for few days/weeks especially in the aftermath of a major disaster.

4.3.2 Search and Rescue Missions

UAV's can be deployed over severely damaged regions to look for survivors and initiate search and rescue missions, especially during post-earthquake scenarios. Further, UAV's can guide survivors to safe zones or emergency centers (survival camps). As a result, use of UAV's can reduce the needed number of first responders to be dispatched to survey a particular location and time, especially in harsh environment (i.e. radiation zones). This can reduce cost and risks associated with search and rescue missions as shown by Doherty and Rudol et al. (2007) and Goodrich et al. (2008).

Besides locating and guiding survivors, UAV's can be also used to drop emergency supplies to unreachable locations. For example, a drone can deliver medical supplies and survival kits, food survivors before rescue crews reach them as explored in recent years (Nedjati et al., 2016). When transmission lines are damaged, UAV's can be locked into a zone (i.e. maintain specific altitude and latitude) to provide a temporary local Wi-Fi network that can be helpful to initiate communication services and coordinate ground search teams. Further, rotary UAV's can provide logistical support to volunteers and rescue workers through providing thermal imaging feedback and lighting which can be helpful in overnight search and rescue efforts where survival rate is high during first few hours of post-earthquake, terrorist attacks etc.

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4.3.3 Documentation

Perhaps one of the most important aspects of using UAV's is the ability to document disaster effects (damage) and emergency response so as to learn lessons for improving disaster response in future incident. Since UAV's can be deployed within few minutes of an incident, they can capture disaster evolution (development) as well as human behavior and response to an incident breakout. These "raw" footages are hard to replicate in controlled experiments (or simulation programs) and are quite useful for education and research purposes. For instance, data collected from UAV's can help understand the behavior of disasters, reaction of victims, efficiency of disaster fighting operations and structural performance of infrastructure. Through data collected from UAV's, investigation teams can reconstruct disaster site, to develop and validate computer models. For example, UAV's have been used in post-incident investigation of nuclear meltdown such as Fukushima Daiichi nuclear disaster and/or air crashes i.e. crash of Germanwings Flight 9525 (Spranger et al., 2016).

Moreover, analysis of UAV's livestreams can aid in training of first responders, and spreading awareness in communities prone to disasters. These recordings can also be used to improve evacuation facilities and to develop better evacuation procedures. It should be noted that recorded footage can be used to develop case studies and point out mistakes and poor decisions taken in previous incidents. Such footage can be analyzed to evaluate current provisions employed in hazard mitigation and in developing new protocols to be used in case of future disasters.

5.0 Needs for Effective Implementation of UAV's in Disaster Mitigation

Findings presented in this paper clearly infer that integration of UAV's as part of disaster management can complement manned relief operations. However, such implementation can be more effective if some of the challenges and limitations associated with the current adoption of UAV's is overcame. Such challenges (and proposed solutions), together with research and development needs, are highlighted herein.

5.1 Technological Challenges

There is a clear need to further improve design, reliability and operating systems of UAV's, especially for disaster management applications. Such UAV's need to be able to endure longer flights while maintaining fuel efficiency. These UAV's also need to be able to fly in harsh weather with the ability to automatically plan flight paths (and maneuver against debris) with minimum or no supervision. Further, UAV's utilized for disaster management need have the ability to be fitted with various sensors so that they are able to perform multi-task operations such as identifying human subjects (trapped or injured) through smoke, while assessing structural damage etc.

Other needs also include addition of safety features that can be automatically enabled in case a drone malfunctions; gets damaged by debris or loses contact with its operator. These features need to be facilitated by a separate operating system, mechanical system and fuel source to ensure safe performance. For example, UAV's can be equipped with an airbag or parachute to be inflated before it (UAV) crashes and have the ability to automatically activate emergency alarms/lights to alert surroundings and minimize damage/casualties upon crashing. In case UAV malfunctions or gets hit by debris, a UAV need to be able to identify areas of "low risk of impact" i.e. water bodies where it can fall and cause minimal damage.

Another technological challenge that needs to be addresses is maintenance requirements of UAV's. Since UAV's are unmanned systems, they often do not undergo frequent maintenance as compared to manned aircrafts. Due to this negligence, the current accident rate for UAV's is about 100 times than that of manned aircraft (King et al., 2005). However, despite this high accident rate, few have resulted in third-

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party losses (DeGarmo, 2004). It should be noted that as the case with other unmanned devices (i.e. robots), the design and manufacturing of UAV's is still evolving and future models of UAV's are expected to have improved performance, lower maintenance requirements and low incident/malfunctioning rate.

5.2 Regulatory/Policy Issues

In recent years, regulations specific to UAV's use have been derived parallel to those applied to manned aircrafts (Haddon et al., 2015). However, these regulations do not account for wide range of UAV's nor for their applications (i.e. disaster management, infrastructure monitoring etc.), therefore, expectations that all types of UAVs can conform to existing regulatory requirement may not be realistic. In order to enable successful integration of UAV's into disaster management applications, development of air traffic management, airworthiness and flight operation regulations are required. Such regulations, need to involve interconnected policies at local (i.e. city/state), regional (i.e. federal), and international levels (i.e. for cross-border operations) to cover number of policies associated with integration of UAV's in disaster management such as technical requirements, pilot competency, data protection and specifically to privacy issues etc.

Since there is no central national standard for UAV privacy controls, privacy emerges as the most important civil right concern that needs to be addressed for large scale deployment of UAV's (Price, 2016). This is due to the fact that when UAV's are deployed for any purpose, they can collect, process, record, and store personal data allowing the identification of people/properties. Further, UAV's used in surveillance applications are instrumented with sophisticated imaging technology (such as Gigapixel cameras) that have the ability to obtain detailed photographs and videos of people, properties, and other objects. Not only that, but in the near future facial recognition technology can be implemented into UAV systems to remotely identify and track individuals. Such technology may provide criminals with needs to "cyber espionage" i.e. blackmail, stalking etc.

Since UAV's are non-detectable, and can be fitted with advanced imaging and hearing devices, UAV's can be utilized to undertake persistent surveillance that conventional surveillance methods (i.e. CCTV, satellites etc.) are unable to achieve (DeGarmo, 2004). As a result, UAV's may present a unique threat to privacy that needs to be addressed. Although there have been few attempts to address such concern, specifically by the induction of the 2015 Presidential Memorandum that aims to verify drone operators observe all applicable local, state, and federal privacy laws (*Policy Memorandum 15-002, "Guidance for the Domestic Use of Unmanned Aircraft Systems,"* 2015). Still, detailed legislations and polices need to be enforced to ensure integration of UAV's proceeds in a safe and legal manner.

5.3 Guidelines for Design and Deployment of UAV's

In the event of a disaster breakout, emergency response and relief operations follow certain codes and acts such as disaster relief act, disaster mitigation etc. (FEMA, 1980), to ensure efficient utilization of available resources. However, current regulations and procedure do not address use of UAV's in case of disasters and many of them do not provide any guidance on successful use of UAV's for disaster management. For instance, there is lack of provisions on required features needed to enable effective use of UAV's, specifically as part of disaster mitigation measures, i.e. conduct infrastructure assessment, and/or search and rescue missions.

Further, there are currently no published guidelines specific to design requirements of UAV's (i.e. including performance, reliability, stability, and control), operation nature of UAV's (i.e. infrastructure assessment, search and rescue etc.), operators qualifications of UAV's (i.e. educational background, licensing etc.) or for UAV's deployment in disaster management. As a result, there is urgent need for developing appropriate guidelines that address aforementioned issues and then incorporate them into relevant codes and standards. Such guidelines can be developed by professional societies or trade organizations. Once developed and approved, these provisions can then be incorporated into current disaster acts to enable effective design and deployment of UAV’s.

6.0 Conclusions

Based on the results of the analysis presented herein, the following conclusions can be drawn:

1. UAV systems can be used in different stages of natural or man-made disaster since they complement, and in some aspects, outperform traditional manned relief operations.
2. Aerial search-based disaster evaluation using UAV’s can provide authorities and disaster management personnel with accurate and quick representation of damage magnitude, without jeopardizing safety of first responders.
3. Since UAV’s can be equipped with different sensors, these devices can perform visual or thermal imaging assessment of a region or damaged infrastructure.
4. Integration of UAV’s into disaster management can be more effective once challenges and limitations associated with their adoption and deployment is overcame through developing relevant technologies, policy issues and associated deployment guidelines.
5. There is a need for specific requirements, laws and regulations for optimal (and safe) integration of UAV systems into disaster management and civilian applications.

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