The use of unmanned aerial vehicles and drones in search and rescue operations – a survey

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Please consider this paper for the Doctoral Consortium.

Abstract

Governmental organizations, nongovernmental organizations (NGO), and inter-governmental organizations devote considerable resources to preventing, mitigating, preparing, responding, and recovering from the effects of disasters. Preparing for and responding to disasters is a major logistical challenge. Many organizations are now considering the use of drones in search and rescue operations in the disaster responder's toolkit. This paper aims at exploring the latest literature in the use of unmanned aerial vehicles in search and rescue operations. We find that gaps exist in the use of these unmanned aerial vehicles in urban search and rescue environments, the use of wireless sensors to detect cell phones in a disaster context, and the incorporation of stochastic optimization techniques in flight operation optimization.

1 Introduction

Preparation for and responding to natural disasters, manmade or natural, is a major logistical challenge. Governmental organizations, nongovernmental organizations (NGO), and inter-governmental organizations devote considerable resources to preventing, mitigating, preparing, responding, and recovering from the effects of disasters. A disaster is, "a shocking event that seriously disrupt the functioning of a community or society, by causing human, material, economic or environmental damage that cannot be handled by local agencies through standard procedures" (Galindo & Batta, 2013). Disaster response is considered a "growth industry" (Altay & Green, 2006). When a disaster occurs, organizations begin to mobilize their disaster response plans. Disaster response are the operations whose objectives is the deployment of resources to provide immediate relief to a population (Galindo & Batta, 2013; United Nations, 1992).

In recent years, technological advances in unmanned, autonomous and semi-autonomous vehicles have reduced their cost while increasing their utility and ease of use. The increased development and use of unmanned aerial vehicles (UAVs), commonly and colloquially known as drones, have added a new dimension to SAR operations. UAVs and drones are currently being developed for applications in construction, mining, journalism, security, and even pizza delivery. In practice, the use unmanned vehicles can be beneficial in situations where the use of human manpower can be dangerous, limited, or rapid decisions are required.

The first notable example in disaster response was the CASPER project using land-based robots to assist rescuers in locating victims after the September 11th terrorist attacks in New York City (Casper & Murphy, 2003). The development of cheaper devices allows for the development of swarm robotics methods. The typical definition of swarm robotics is to allow for many small, cheap devices to accomplish a task, in this case cover a larger search area. That is, we can cover a search area in less time and more efficiently than a single manned aircraft or unmanned aircraft can. The use of aerial vehicles (manned or unmanned) is ideal for search and rescue efforts as it allows for searchers to traverse uncertain and often impassable terrain to locate individuals in need of aid. In addition, the maneuverability of quadcopters UAVs and drones allows for these devices to get close to structures for SAR missions.

The traditional sensors that SAR personnel use in their efforts are acoustic sensors, optical cameras, infrared (heat sensing) cameras, and trained dogs. With the exception of using infrared cameras, many of these tools require a line-of-sight or require the detection device to be within close proximity of the target. This limits the UAV to assess destruction of disasters rather than aid rescuers in locating victims. However, in the past decade, there has been an explosion in the adoption and use of the personal cell phone around the world. In 2015, there were approximately 95 mobile subscriptions per 100 people in the world (International Telecommunications Union, 2015). Cellphones emit a host of signals by being on and active. Some authors have begun to explore the ability to passively or actively detect in interact these signals. In general, the wireless sensor is a general term for a device that attempts to detect the existence of wireless signals, much the same way a laptop can seek Wi-Fi signals and attempt to connect to them. With the proliferation of and the ability to detect the presence of cellular devices, in addition to the increase in the popularity of drones; it is at this intersection of technologies and need there is the opportunity for incorporating the wireless sensor technology into the SAR toolbox. Installing the wireless sniffer on a drone, or several drones, could give responders a means to quickly scan a disaster area and identify potential victims.

This document is a literature review on the use of UAVs and drones, their sensors, and flight operations optimization in the event of their need in SAR operations. It was the aim of this paper to attain the recent and relevant literature in the domain of using UAVs in search and rescue operations with an emphasis on exploring what sensors are being used by the UAVs (and in some cases, land-based robots) and search path optimization procedures. After breaking down the search methodology (Section 2), we will begin to dissect the literature along six axes (Section 3). Then, we will expose the potential gaps in the literature (Section 4). Finally, we will conclude with recommendations for future research (Section 5).

2 Search Methodology

The objective of this paper is to assess utility and use of the UAVs and drones, their sensors, and flight operations optimization in search and rescue operations. We have used the words UAV and drone interchangeably, as is the case in reality. In general, a UAV or drone is, “any fixed or rotary winged aircraft or lighter than air vehicle (e.g. blimp) capable of flight without an onboard pilot or crew” (Dempsey, 2010). For the remainder of this paper, we will use the colloquial drone in lieu of UAV when appropriate to indicate the use of a commercially available quadcopter device. It is the aim of this literature review to assess the use of the more commercially available quadcopter devices (such as a DJI Phantom) instead of the more prohibitively expensive equipment (such as the Predator that is in use by several governments around the world). The academic literature reflects this decision we make here as when an author makes reference to a *drone* as their tool of choice, they are most often referring to a commercially available *quadcopter drone*. Conversely, when the author is using a vehicle such as a *Predator* or other fix winged large aircraft often used by militaries, the term is always *UAV*. There is a subset of papers where the authors use the term UAV to reference the more commercially available quadcopter drone. This is not an incorrect term. However, we will refer to these devices as drones as well to ensure clarity and consistency with our paper.

In this section, we will define and break down the recent research in managing and optimizing operations of the use of robots – with emphasis on flying vehicles – in disaster operations – with an emphasis on sudden onset disasters. We will discuss the latest research and break down the literature as follows:

- Environment – the type of environment that the search robots will operate (for example: urban, wilderness, combat). Each environment has a distinct set of objectives that need to be accomplished, such as the number of victims to be found.
- Equipment – the type of devices used (UAV, Drone, land based, swarm). Fixed wing aircraft have a different set of flight characteristics versus a rotor wing aircraft.
- Sensors – the specific types of sensors indicated by the researchers. Often, sensors are undefined in the literature; however, some sensors do provide specific information to the robot and rescuers.
- Optimization Procedures – the procedure used to optimize their problem. Due to the size and complexity of the constraints, often heuristics and metaheuristics are used.
- Optimization Goal and model formulation – the goal of the optimization procedure; for example: minimize flight time, ensure adequate coverage, etc.
- Uncertainty – the uncertainty accounted for in the optimization model or method, such as flight time uncertainty (between waypoints) or fuel consumption uncertainty.

To begin the literature search, we executed a keyword search with the keywords outlined in Table 2.1. The keywords were executed in Engineering Village's search engine using the three databases Compendex, Inspec, and Knovel. After the initial search, manually combing through the abstracts was a method of eliminating irrelevant papers. A common keyword that yielded irrelevant papers was SAR. In addition to search and rescue, SAR is also the acronym for, "synthetic aperture radar," which is a method of creating a map by moving a radar antenna over or by a target area. These articles, among other irrelevant articles, were manually removed. After the manual removal of the irrelevant literature, the remaining papers were cataloged based on the criteria outlined above. Papers were then selected from the criteria that matched the environment (USAR operations), equipment (UAVs or drones), or used sensors (wireless sensors). If a paper was, say for example, a WiSAR operation with land-based robots and a heat sensing camera, it was not considered unless it had some unique aspect in its optimization procedures, optimization goals, formulation, or uncertainty.

Table 2.1 - Selected keywords for initial literature search

Robotics	Optimization	Disaster Relief Planning
drone*; robot*; UAV*; unmanned aerial vehicle*; unmanned air*; UA*; UMA*; uninhabited aerial vehicle*; uninhabited air*; pilotless; aircraft*	"operations research"; "operations analysis"; "operational research"; optimisation*; optimization*	crisis situation*; "disaster relief"; "disaster operations"; "disaster recovery"; "humanitarian aid"; "humanitarian assistance"; "humanitarian logistics"; "emergency response"; "emergency intervention"; "emergency management"; "emergency preparedness"; "reliability planning"; SAR; Search rescue; air-sea rescue; air sea rescue

3 Analysis and gaps in the literature

We will break down the literature along the following lines: environment, equipment, sensors, optimization procedures, optimization goal and model formulation, uncertainty.

3.1 Operational Environment

In the literature, there were six main operational environments that were used by authors to help contextualize their problems. Locating people in need of aid is known as a SAR mission. The SAR mission can be broken down further into three subtypes; they are urban SAR (USAR), wilderness SAR (WiSAR), and air-sea rescue (ASR) operations. These three are all SAR missions in an urban, wilderness, and maritime context, respectively. USAR operations (our focus here) aim to locate and provide aid to multiple, stationary victims in a constrained search environment. This differs from a wilderness SAR (WiSAR) or air-sea rescue (ASR, the maritime equivalent) as USAR is tasked at locating, likely, a multitude of stationary victims who may be trapped in collapsed structures or vehicles. WiSAR and ASR operations often have open-ended search locations and are tasked to locate a known number of mobile, or semi-mobile, victims. At present, members of a USAR team often conduct searches with sniffing dogs, heat sensing cameras, and possibly acoustic sensors (FEMA, 2017).

In addition to the three, some authors contextualized their paper by assessment operations. Here, assessment operations are defined as investigating a region in the event of a disaster or other event. Some examples may be assessing a hydroelectric dam after a storm. There is no, 'search for missing people,' tasks that we see in the various SAR missions. Other assessment operations explored in the literature was assessing an archaeological dig. Another term classified as assessing is remote sensing.

Another mission classification observed in the literature is surveillance. Surveillance operations are tasks by which a target, usually a person or vehicle, is identified and must be monitored (or followed). The papers taking on this designation typically do not search for their target the way SAR missions are conducted. Surveillance missions are usually conducted by sending a drone or UAV to a coordinate where they are likely to expect an encounter with the target.

The last designation the literature contains is UAVs, drones, and robots being used in combat environments. The combat environment undertakes the mission of assisting military personnel to conduct their missions.

When we place an emphasis on USAR operations, we are left with Casper & Murphy (2003), Hatazaki, Konyo, Isaki, Tadokoro, & Takemura (2007), Loukas & Timotheou (2008), Zhang, Wu, Peng, & Jiang (2009), Fard, Parvar, Shiri, & Soleimani (2010), Pishkenari, Mahboobi, & Alasty (2011), Ding & Pan (2011), Choi & Zhu (2012), Olson et al. (2012), Liu, Nejat, Liu, & Nejat (2013), Mirowski, Ho, Saehoon Yi, & MacDonald (2013), Özgelen & Sklar (2015), Pineda, Takahashi, Jung, Zilberstein, & Grupen (2015), Elbanhawi et al. (2017), and Mouradian, Sahoo, Glitho, Morrow, & Polakos (2017). Papers that will be worth considering would be Wang, Joshi, Kulkarni, Leong, & Leong (2013) and Acuna, Kumbhar, Vattapparamban, Rajabli, & Guvenc (2017) for their studies using mobile phone detection in aerial search and rescue operations. Both these studies are in the WiSAR context. Also Sardouk, Mansouri, Merghem-Boulahia, Gaiti, & Rahim-Amoud (2010) proposes a crisis management tool that contains multi-target tracking. There is also Hayat, Yanmaz, Brown, & Bettstetter (2017) who uses a team of UAVs in WiSAR operations. Recchiuto & Sgorbissa (2017) use drones in post-disaster structural analysis. Finally, Senthilkumar & Bharadwaj (2012) and Couceiro, Rocha, & Ferreira (2013) explore the use of, "autonomous agents," to map out an area. A complete table breakdown of the environments in the literature can be seen in ground-based multi-robot solutions overwhelmingly outnumber the aerial based tools. As mentioned previously, UAVs and drones have the ability and opportunity to traverse uncertain and impassible terrain by flying over buildings, lakes, and other obstacles. This may mean we can simplify the methods and models in the ground-only based solutions. A complete table breakdown of the equipment in the literature can be seen in Table 3.1.

3.2 Sensor technology in use

The majority of articles in the literature either referred to sensor technology in the abstract sense, such as in in some papers like Hayat et al. (2017) where the UAVs have homogeneous and 100% accurate sensors, without any indication to what they are. Other papers, such as Mufalli, Batta, & Nagi (2012) where their formulation considers a set of sensors (undefined) and their model formulation attempts to allocate appropriate sensors to appropriate tasks. As referenced in the introduction, the most common sensors used in USAR operations (and similarly in WiSAR operations) are optical sensors (cameras) and heat sensing cameras (or infrared cameras). Part of the inspiration for this research proposal, however, was the use of wireless sensors to detect electronic devices on persons. One of the earliest papers was in Loukas, Timotheou, & Gelenbe (2008) where they proposed a method to use the wireless sensors to establish a connection with a trapped civilian population. More recently, (Zhongli Liu et al., 2014) create their UAV to detect a lost person (WiSAR).

The key pieces of literature in this domain is in Wang et al. (2013) where they analyze the feasibility of using WIFI detection in WiSAR operations. Most importantly, the authors deem the technology feasible. In Sardouk et al. (2010), they use wireless sensor networks to help in crisis management. Another is in Acuna et al. (2017) where the authors use the wireless sensor to develop a probability map of the location of a lost individual. Zhongli Liu et al. (2014) denote the make and model of their wireless sensor (a Nokia N900 wireless sniffer) in their method to create an uncertainty map. A complete table breakdown of the sensors in the literature can be seen in Table 3.1

3.3 Types of equipment in use

For the purposes of this literature review, we will briefly look at the literature which emphasizes aerial devices (UAVs and drones) over land based or maritime devices. However, there is plenty of research into land-based robotics which cannot be ignored, such as the feasibility studies into wireless sensing technologies appear to be on land-based robots. Some of the methods and models outlined in the literature for land-based robotics USAR can potentially be adapted and simplified when the ability to ignore terrain and unforeseen obstacles can be removed.

Authors who use multiple UAVs or drones to accomplish their goals are Hayat et al. (2017), Zillies et al. (2016), and Recchiuto & Sgorbissa (2017). Using a single UAV or drone exists in Jevtiü, Andina, Jaimes, Gomez, & Jamshidi (2010), Acuna et al. (2017), Zhongli Liu et al. (2014), and Deng, Zhao, & How (2009). When expanding the search to land-based robots (i.e. multiple robots working together to achieve a goal), we can include Bakhshipour, Jabbari Ghadi, & Namdari (2017), Beck, Teacy, & Rogers (2016), Casper & Murphy (2003), Couceiro, Rocha, & Ferreira (2011), Couceiro et al. (2013), Fard et al. (2010), Liu et al. (2013), Loukas & Timotheou (2008), Mirowski et al. (2013), Mouradian et al. (2017), Olson et al. (2012), Pasqualetti, Durham, & Bullo, (2012), Pineda et al. (2015) Senthilkumar & Bharadwaj (2012), Straub, Marsh, & Mohammad (2013), and Zhang et al. (2009). Clearly the ground-based multi-robot solutions overwhelmingly outnumber the aerial based tools. As mentioned previously, UAVs and drones have the ability and opportunity to traverse uncertain and impassible terrain by flying over buildings, lakes, and other obstacles. This may mean we can simplify the methods and models in the ground-only based solutions. A complete table breakdown of the equipment in the literature can be seen in Table 3.1.

3.4 Model formulation and optimization goals

When formulating the problem as a mathematical optimization problem, the most common formulations appear to be in the form of a traveling salesman problem (Jevtiü et al., 2010; Pasqualetti et al., 2012), a vehicle routing problem (Zillies et al., 2016), or as a simpler shortest path problem or path-finding problem - where returning to the start is unnecessary (Bakhshipour et al., 2017; Ganesan, Shakya, Aqueel, & Nambiar, 2011; Hayat et al., 2017; Senthilkumar & Bharadwaj, 2012). While the latter papers in the literature may on the surface appear simple, the goals put forth in the papers often are to create a coverage network in an attempt to identify victims and find paths to them (Olson et al., 2012; Senthilkumar & Bharadwaj, 2012), or to set up a connectivity network to a victim (Hayat et al., 2017; Loukas & Timotheou, 2008).

After graph-based formulations, another common model formulation is set covering methods (Couceiro et al., 2011; Fard et al., 2010). It is a formulation well suited to monitoring procedures as set covering formulations attempt to allocate the robots over a disaster scene to ensure connectivity (Couceiro et al., 2011) or to ensure an area is adequately searched (Fard et al., 2010).

In addition to the mathematical optimization models proposed, several robot task allocation models and methods were used in the literature (Beck et al., 2016; Choi & Zhu, 2012; Mouradian et al., 2017; Straub et al., 2013). Robot task allocation can be implemented in a decentralized way and enable real time reactions to new information present in the environment. For a breakdown of the literature, see Table 3.2

3.5 Optimization Procedures

When it comes to a centralized method for optimizing the formulations outlined in the previous subsection, ant colony optimization (ACO) appears to be a common method (Ding & Pan, 2011; Ganesan et al., 2011; Jevtiü et al., 2010; Zhang et al., 2009). The ACO method uses multiple agents (ants) to find an optimal path from a start to a goal objective. Both (Ding & Pan, 2011; Ganesan et al., 2011) use ACO to optimize multiple land robots to find a specific target location. (Jevtiü et al., 2010) uses ACO to find the most efficient traversal of a tour in their TSP formulation.

Table 3.1 – Environment, Equipment, and Use of sensors in drone and UAV SAR literature

	Environment							Equipment						Sensors				
Citation	USAR	WiSAR	ASR	Assessment	Surveillance	Combat	Undefined	Drone	UAV	Land-based	Maritime	Single	Many	Wireless Sensor	Optical (camera)	Infrared (Heat Sensing)	Acoustic	Undefined
Acuna, Kumbhar, Vattapparamban, Rajabli, & Guvenc (2017)		X							X			X		X				
Bakhshipour, Jabbari Ghadi, & Namdari (2017)							X			X			X			X		
Beck, Teacy, and Rogers (2016)	X									X			X		X			
Casper & Murphy (2003)	X									X			X			X		
Choi & Zhu (2012)	X								X				X					X
Couceiro, Rocha, & Ferreira (2011)							X			X			X					X
Couceiro, Rocha, & Ferreira (2013)					X					X			X					X
Deng, Zhao, & How (2009)					X			X				X				X		
Ding & Pan (2011)	X									X			X		X			X
Elbanhawi et al. (2017)	X					X		X										X
Fard, Parvar, Shiri, & Soleimani (2010)	X									X			X					X
Ganesan, Shakya, Aqueel, & Nambiar (2011)	X									X			X		X	X	X	
Hatazaki, Konyo, Isaki, Tadokoro, & Takemura (2007)	X									X		X			X			
Hayat, Yanmaz, Brown, & Bettstetter (2017)		X							X				X					X
Jevtiü, Andina, Jaimes, Gomez, & Jamshidi (2010)							X		X			X						X
Liu, Nejat, Liu, & Nejat (2013)	X									X			X		X		X	
Loukas & Timotheou (2008)	X									X			X	X				
Macwan, Nejat, & Benhabib (2011)		X								X			X					X
Mirowski, Ho, Saehoon Yi, & MacDonald (2013)	X									X			X	X				
Mouradian, Sahoo, Glitho, Morrow, & Polakos (2017)	X									X			X					X
Mufalli, Batta, & Nagi (2012)						X			X				X					X
Olson et al. (2012)	X									X			X		X			
Özgelen & Sklar (2015)	X									X			X		X			
Pasqualetti, Durham, & Bullo, (2012)							X	X				X			X			
Pineda, Takahashi, Jung, Zilberstein, & Grupen (2015)	X									X			X		X			
Pishkenari, Mahboobi, & Alasty (2011)	X									X		X			X			
Recchiuto & Sgorbissa (2017)				X				X					X					X
Sardouk, Mansouri, Merghem-Boulahia, Gaiti, & Rahim-Amoud (2010)	X									X		X		X				
Senthilkumar & Bharadwaj (2012)					X					X			X		X			
Straub, Marsh, & Mohammad (2013)	X									X			X					X
Wang, Joshi, Kulkarni, Leong, & Leong (2013)		X						X				X						X
Xia, Batta, & Nagi (2017)						X			X				X		X			
Zhang, Wu, Peng, & Jiang (2009)	X									X			X					X
Zhongli, Yinjie, Benyuan, Chengyu, & Xinwen (2014)							X	X				X		X				
Zillies et al. (2016)							X		X				X					X

Table 3.2 – Optimization procedures, model formulation, presence of uncertainty in the literature

	Optimization	Model	Uncertainty	Notes
Acuna, Kumbhar, Vattapparamban, Rajabli, & Guvenc (2017)	Random Forest Search	Decision Tree		
Bakhshipour, Jabbari Ghadi, & Namdari (2017)	Evolutionary optimization	Minimize time to victim		Modifies robot positional vectors, objective to "find person"
Beck, Teacy, and Rogers (2016)	Robot Task Allocation	Task Allocation	Anticipated future information gains in executing a task	
Casper & Murphy (2003)				One of the first papers using robots in USAR
Choi & Zhu (2012)	Robot Task Allocation, Auction	Task Allocation		
Couceiro, Rocha, & Ferreira (2011)	Particle Swarm Optimization	Ensure inter-robot connectivity		
Couceiro, Rocha, & Ferreira (2013)	Particle Swarm Optimization	Ensure inter-robot connectivity		
Deng, Zhao, & How (2009)				A paper on target tracking of an individual
Ding & Pan (2011)	Ant Colony Optimization	Decision tree to find individual		
Elbanhawi et al. (2017)				Literature Review
Fard, Parvar, Shiri, & Soleimani (2010)	Particle Swarm Optimization	Set covering		
Ganesan, Shakya, Aqueel, & Nambiar (2011)	Ant Colony Optimization	Graph		
Hatazaki, Konyo, Isaki, Tadokoro, & Takemura (2007)	Simultaneous Location and Mapping			
Hayat, Yanmaz, Brown, & Bettstetter (2017)	Genetic Algorithm	Graph		
Jevtiü, Andina, Jaimes, Gomez, & Jamshidi (2010)	Ant Colony Optimization	Travelling Salesman		
Liu, Nejat, Liu, & Nejat (2013)	Simultaneous Location and Mapping			A survey from the Control Perspective
Loukas & Timotheou (2008)	Distributed Greedy Heuristic	Directed Graph		
Macwan, Nejat, & Benhabib (2011)	Use of Iso-probability Curves	Set Covering		
Mirowski, Ho, Saehoon Yi, & MacDonald (2013)				Feasibility study of using wireless sensors in WiSAR
Mouradian, Sahoo, Glitho, Morrow, & Polakos (2017)	Robot Task Allocation	Task Allocation		
Mufalli, Batta, & Nagi (2012)	Column generation	Tool selection and routing over a graph		
Olson et al. (2012)	Simultaneous Location and Mapping	Graph	Uncertainty in future node (vertex) selection	
Özgelen & Sklar (2015)	Robot Task Allocation	Task Allocation		
Pasqualetti, Durham, & Bullo, (2012)	Distributed heuristic	Travelling Salesman		
Pineda, Takahashi, Jung, Zilberstein, & Grupen (2015)	Markov Decision Process	Decision Tree	Robot observations	
Pishkenari, Mahboobi, & Alasty (2011)	Differential Evolution and Genetic Algorithms	Graph		
Recchiuto & Sgorbissa (2017)	Node Count Algorithm; Edge Counting Algorithm	Graph	Inconsistent images relayed	
Sardouk, Mansouri, Merghem-Boulahia, Gaiti, & Rahim-Amoud (2010)	Bayesian methods	Multi-Agent system		
Senthilkumar & Bharadwaj (2012)	Spanning Tree Coverage	Graph		
Straub, Marsh, & Mohammad (2013)	Robot Task Allocation	Task Allocation		
Wang, Joshi, Kulkarni, Leong, & Leong (2013)				Feasibility study of using wireless sensors in airborne WiSAR
Xia, Batta, & Nagi (2017)	Decomposition Method; Markov decision process	Decision Tree		
Zhang, Wu, Peng, & Jiang (2009)	Ant Colony Optimization	Directed Graph		
Zhongli, Yinjie, Benyuan, Chengyu, & Xinwen (2014)	Preplanned Route			An example using specific equipment in the use of detecting an individual using wireless sensor technology
Zillies et al. (2016)	Column Generation	Vehicle Routing Problem		

Another optimization procedure that makes multiple appearances is particle swarm optimization (PSO) (Couceiro et al., 2011, 2013; Fard et al., 2010; Mouradian et al., 2017). PSO is a subset of population-based algorithms that is based on how animals will work both cooperatively and competitively to find food in an environment. The agents of the population will alert the population to the most optimal solution, and then the agents will make a decision to improve their optimal value. In addition to the PSO method, Hayat et al. (2017) and Pishkenari et al. (2011) explores a genetic algorithm method and differential evolution to optimize the path-finding mission outlined in their paper.

In a decentralized manner to solve the robot task allocation methods, auction based optimization methods appears to be a common choice (Choi & Zhu, 2012; Korsah, Stentz, & Dias, 2013; Loukas & Timotheou, 2008). They are commonly used as they are easy to decentralize (each agent of a robotic swarm makes their own decision) and easy to implement (one asks the robot to predict how much it will cost to perform a task, the cheapest one executes the task). In addition to the well-established procedures outlined previously, some authors attempt simulation techniques such as Markov Decision Process (Acuna et al., 2017; Pineda et al., 2015; Sardouk et al., 2010; Senthilkumar & Bharadwaj, 2012). For a breakdown of the literature, see Table 3.2.

3.6 Uncertainty

While looking for a lost person is inherently an uncertain endeavor, most authors do not account for uncertainty in the sense of, say, battery drain or the time it takes to search a region. With respect to uncertainty, it is indicated that authors also claim that their sensors are 100% accurate (Hayat et al., 2017). In other cases, authors plan on "incorporating uncertainty" in the future in some unknown form (Ganesan et al., 2011). Incorporating some element of quantifiable uncertainty, such as estimations in deployment time, estimations in scanning time, and others, has potential to be explored.

One unique take on uncertainty is found in the literature can be found in (Beck et al., 2016) where they cite attempting to minimize the need for future information gains by incorporating a list of dependent, yet uncertain tasks, in the optimization methods. The method is more formally called the Uncertain Multi-Robot Task Allocation (UMRTA). UMRTA has a collection of tasks, denoted as T , and a set of uncertain tasks $\mathcal{T}$. The uncertain set of tasks is a collection of tasks that can be executed after a task. The tasks in $\mathcal{T}$ are given a probability of needed to be executed. The uncertain tasks are explicitly associated with the rescue tasks (such as dig rubble or administer aid). For a breakdown of the literature, see Table 3.2.

4 Analysis and gaps in the literature

We, as a society, are at the precipice of having widescale use of these drones with wireless sensors. The literature does indicate that such a device has the potential to be feasible addition to the SAR toolkit for organizations in disaster response such as FEMA or the Red Cross. This has been answered in Mirowski et al. (2013) and Zhongli Liu et al. (2014) as well as a few others. The authors of those papers give a yes for the potential of using wireless sensing networks in use for SAR operations, specifically WiSAR. Sardouk et al. (2010) and Loukas & Timotheou (2008) apply the wireless sensor and connectivity tools to a USAR operations, but also are attempting to develop a tool in conjunction with the devices (i.e. the user's phone) to establish a communication link with rescuers. While a tool such as this could be immensely valuable in the future, as it stands right now, the tool outlined in those papers requires the users to 1) own a modern phone with the software installed, 2) have the knowledge to set up an ad-hoc network on their phone in the event of a disaster, or 3) have the foresight to install the application on the smartphone to enable the ad-hoc communication with rescuers before a disaster occurs. There is a significant and current benefit to detecting cellular devices as-is.

Since the use of wireless sensor has not been widely used in the manner of USAR missions, there is a gap when it comes to planning the flight operations for this tool. As the literature shows, drone and UAV literature has become more commonplace in the last five years. There are few VRP style formulations in the literature for routing UAVs/drones, but none in a post-disaster context. Robot task allocation formulation, an extension of task allocation, and auction based solution method has been the de-facto standard optimization procedure for swarm robotics as the auction method and it's variants lends itself well to decentralization of the decision making process and works well in practice as it is robust to communication issues (Korsah et al., 2013).

It has been cited by some authors that disasters have the opportunity to incorporate stochastic programming or stochastic decision making due to the uncertainty that occurs after the event of a sudden onset disaster (Galindo & Batta, 2013; Kara & Savaşer, 2017; Leiras, de Brito Jr, Queiroz Peres, Rejane Bertazzo, & Tsugunobu Yoshida Yoshizaki, 2014). Some examples of uncertainty can be in discharge rate of a drone's batteries (or fuel burn for the combustible fuel counterparts), time it takes to scan or triangulate a person in the field, the location and number of people in a search area (in an urban context).

Finally, in their literature review, Galindo & Batta (2013) cites that an underrepresented part of the disaster operations management literature is the, "search for an entity in (such as an injured person) after a disaster." Any use of drones in search and rescue operations could begin to fill that gap identified by those authors.

5 Conclusions

Sudden onset disasters, such as hurricanes, earthquakes, and wildfires, have claimed many lives and incurred billions in damages. In the aftermath of these disasters, search and rescue crews will attempt to find trapped and injured individuals. Rescuers are usually equipped with some tools such as sniffing dogs and heat sensing cameras.

The use of cheap and easy to operate drones has exploded in industry and the consumer markets. The use of aerial vehicles allows for searchers to traverse uncertain and impassable terrain to locate individuals in need of aid. The relative inexpensiveness of drones means these devices can blanket a search area: a more timely and efficient search and rescue mechanism than a single manned or unmanned aircraft. In addition, cell phones have become more prolific in recent years. Devices exist that can passively detect active cell phones much the same way a laptop detects Wi-Fi. Attaching these devices to a drone, a new tool has the potential of being used that can remotely sense and approximate the location of individuals who may be trapped in structures after a disaster.

After executing a literature search outlined from Section 2, we see such a tool beginning to be explored, but lacking in the use of drones in urban search and rescue operations. In addition, the use of wireless sensors to detect cell phones has been explored, but its use in urban search and rescue operations has been underexplored. Other gaps in the research and literature exist in broad scoping optimization procedures and accounting for uncertainty in aspects of the search procedures (not accounting for the location of the individual).

It is the aim of research inspired by this literature review to incorporate drones into the search and rescuer's toolkit. With online and real-time optimization techniques, SAR drones will begin to have the ability to relay information back to rescuers and allow for the drones and rescuers begin to react to victims' needs in a rapid amount of time.

It is the hope of this research going forward that we better account for the uncertainty in scan times and search times in the use of drones in search and rescue operations. In particular the use of wireless sensors has a potential to add a mode of detection of victims in SAR operations.

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