2016

Use of a Small Unmanned Aerial System for the SR-530 Mudslide Incident near Oso, Washington

Robin Murphy
Texas A&M University, murphy@cse.tamu.edu

Brittany Duncan
University of Nebraska-Lincoln, bduncan@unl.edu

Tyler Collins
PrecisionHawk, t.collins@precisionhawk.com

Justin Kendrick
PrecisionHawk, j.kendrick@precisionhawk.com

Patrick Lohman
PrecisionHawk, p.lohman@precisionhawk.com

See next page for additional authors

Murphy, Robin; Duncan, Brittany; Collins, Tyler; Kendrick, Justin; Lohman, Patrick; Palmer, Tamara; and Sanborn, Frank, "Use of a Small Unmanned Aerial System for the SR-530 Mudslide Incident near Oso, Washington" (2016). *CSE Journal Articles*. 126.
http://digitalcommons.unl.edu/csearticles/126

Authors

Robin Murphy, Brittany Duncan, Tyler Collins, Justin Kendrick, Patrick Lohman, Tamara Palmer, and Frank Sanborn

Published in *Journal of Field Robotics* (2016), 13pp. doi 10.1002/rob.21586

Submitted 20 June 2014; accepted 18 February 2015; published online 4 May 2015.

Use of a Small Unmanned Aerial System for the SR-530 Mudslide Incident near Oso, Washington

Robin R. Murphy
Center for Robot-Assisted Search and Rescue, Texas A&M University, College Station, TX 77843-3112 email murphy@cse.tamu.edu
[*Corresponding author*]

Brittany A. Duncan
Center for Robot-Assisted Search and Rescue, Texas A&M University, College Station, TX 77843-3112 email bduncan@cse.tamu.com

Tyler Collins
PrecisionHawk, 9001 Glenwood Ave Suite 100, Raleigh, NC 27617 email t.collins@precisionhawk.com

Justin Kendrick
PrecisionHawk, 9001 Glenwood Ave Suite 100, Raleigh, NC 27617 email j.kendrick@precisionhawk.com

Patrick Lohman
PrecisionHawk, 9001 Glenwood Ave Suite 100, Raleigh, NC 27617 email p.lohman@precisionhawk.com

Tamara Palmer
Field Innovation Team, 390 W 910 S, Heber City, UT 84032, United States email tamara@fieldinnovationteam.org

Frank Sanborn
Field Innovation Team, 390 W 910 S, Heber City, UT 84032, United States email fsanborn@fieldinnovationteam.org

Abstract

The Center for Robot-Assisted Search and Rescue deployed three commercially available small unmanned aerial systems (SUASs)—an AirRobot AR100B quadrotor, an Insitu Scan Eagle, and a PrecisionHawk Lancaster—to the 2014 SR-530 Washington State mudslides. The purpose of the flights was to allow geologists and hydrologists to assess the eminent risk of loss of life to responders from further slides and flooding, as well as to gain a more comprehensive understanding of the event. The AirRobot AR100B in conjunction with PrecisionHawk postprocessing software created two-dimensional (2D) and 3D reconstructions of the inaccessible "moonscape" region of the slide and provided engineers with a real-time remote presence assessment of river mitigation activities. The AirRobot was able to cover 30–40 acres from an altitude of 42 m (140 ft) in 48 min of flight time and generate interactive 3D reconstructions in 3 h on a laptop in the field. The deployment is the 17th known use of SUAS for disasters, and it illustrates the evolution of SUASs from tactical data collection platforms to strategic data-to-decision systems. It was the first known instance in the United States in which an airspace deconfliction plan allowed a UAS to operate with manned vehicles in the same airspace during a disaster. It also describes how public concerns over SUAS safety and privacy led to the cancellation of initial flights. The deployment provides lessons on operational considerations imposed by the terrain, trees, power lines, and accessibility, and a safe human:robot ratio. The article identifies open research questions in computer vision, mission planning, and data archiving, curation, and mining.

1. Introduction

The SR-530 mudslide occurred between Oso and Darrington in the state of Washington on March 22, 2014. It killed 43 people, destroyed 49 homes, and disrupted the course and flood zone of the Stillaguamish River. The sporadic river flooding and sloughing of the mudslide posed a threat to recovery workers working downslope, and it continues to influence the future safety of residents along the river.

Small unmanned aerial systems (SUASs) were used to fill in gaps in sensing of the geological and hydrological state of the mudslide during the response phase, which helped to

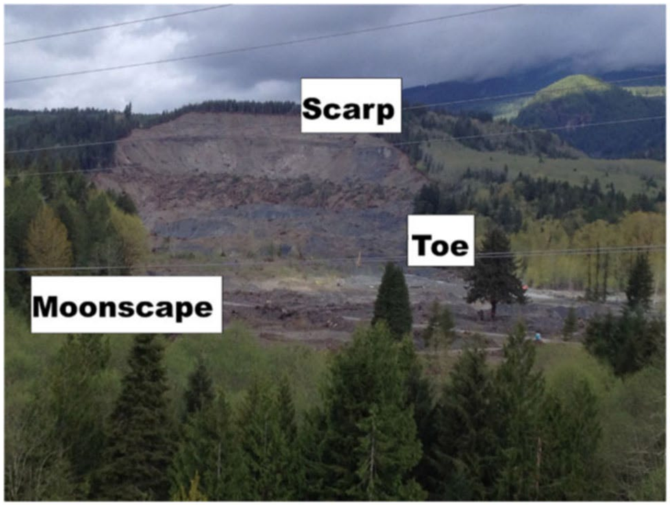

Figure 1. SR-530 mudslide labeled with regions of interest.

protect responders working on recovering victims and mitigating flooding. Figure 1 shows the slide. The riparian section of the slide, dubbed the "moonscape," and the intersection of the scarp and moonscape, called the "toe," were inaccessible by foot or ground vehicle due to quicksand-like mud that was over 6 meters deep. The moonscape, toe, and lower portions of the scarp could not be sensed with satellite remote sensing with sufficient resolution. Manned helicopters could not acquire a complete survey because of the need to stay at altitudes higher than 500 feet for safety reasons, as the narrow canyon produces unpredictable gusts and there was a danger that debris loosened by the rotor wash would be sucked into the rotors and cause a crash. The expense of manned helicopters precluded daily use for a rapidly changing situation: the rule of thumb from the 2014 AUVSI/AIAA Civilian Applications of Unmanned Aerial System (CAUAS) workshop was that manned helicopters cost 10 times more than a SUAS, i.e., about $250 an hour versus $25 an hour. The available LIDAR data from manned assets were taking 2–4 days for processing and subsequent release to the responders in the field.

The Texas A&M Engineering Experiment Station's Center for Robot-Assisted Search and Rescue (CRASAR) provided three commercially available small SUASs—two fixed-wings and one rotorcraft—through its Roboticists Without Borders (RWB) program. The flights make at least three contributions. First, they were the first SUAS flights reported specifically for mudslides. Thus they add another case study to the growing corpus of SUAS applications, as well as providing insight into platforms, operations, and open research questions. Second, the flights exemplify the evolution of SUASs from data collection platforms to data-to-decision systems, where the system collects data and converts it to actionable information readily comprehended by decision makers. Third, the flights illustrate the increasing impact of regulations and societal concerns. SUAS flights for the 2013 floods in Boulder, CO were suspended due to the lack of adherence to regulations (9News, 2013). The SR-530 flights reported in this article occurred under a novel airspace deconfliction plan approved by the Federal Aviation Agency that allowed manned operations in the same area. However, misunderstandings about regulations within the emergency response community and public perception of privacy caused initial flights to be cancelled.

The article is organized as follows. Section 2 reviews previous and related work in disaster robotics. Section 3 describes the general missions and selection of platforms using the criteria established in Murphy (2014). Section 4 describes the initial deployment in March 2014, which resulted in zero flights. The Insitu Scan Eagle could not find a staging area that had sufficient space for launch and landing, the PrecisionHawk Lancaster was not granted an emergency certificate of authorization (COA), and the AirRobot flights were canceled due to concerns over privacy. Section 5 describes how the team returned and on April 23, 2014 flew an AirRobot AR100B quadrotor under an emergency COA with postprocessing by Precision Hawk producing a two-dimensional (2D) mosaic and 3D interactive reconstruction of 30–40 acres of the moonscape with 48 min of flight time and 3 h of processing time on a laptop. The general performance of the SUAS, the lessons learned for operations, the human-robot ratio for the missions, and gaps and open research questions are discussed in Section 6. The article concludes in Section 7 that SUASs are cost- and time-effective for mudslide response.

2. Prior And Related Work

SUAS use has been reported for 17 disasters, including the SR-530 mudslide incident and a subsequent 2014 mudslide in Collbran, CO. Deployments to 11 of the 17 disasters are analyzed in the book *Disaster Robotics* (Murphy, 2014): Hurricane Katrina, USA (2005); Hurricane Wilma, USA (2005); Berkman Plaza II Collapse, USA (2007); L'aqulia Earthquake, Italy (2009); Haiti Earthquake (2010); Christchurch Earthquake, New Zealand (2011); Tohoku Earthquake, Japan (2011); Fukushima Daiichi Nuclear Accident, Japan (2011); Evangelos Florakis Naval Base Explosion, Cyprus (2011); Thailand Floods (2011); and Finale Emilia Earthquake, Italy (2012). The deployment to Typhoon Morakot, Taiwan (2009) is reported in Adams & Friedland (2011). The deployments to Typhoon Haiyan, Philippines (2013) (University of Hawai'i, 2014; UH, 2014); the Boulder, CO floods, USA (2013) (9News, 2013); the Collbran, CO mudslide, USA (2014) (Yoanna, 2014); and the Serbia and Bosnia-Herzegovina floods (2014) (ICARUS, 2014) were reported in the media.

The SR-530 flights differ from prior work. No SUAS deployments prior to the SR-530 event were for mudslides, which consist of a vertical scarp and horizontal deposits of mud downslope. The 2011 Thailand Floods and the 2013 Typhoon Haiyan missions specifically looked at flooding. These deployments are especially relevant because flooding is a continuing consequence of the engagement of the Stillaguamish River in the SR-530 mudslide, and thus they are compared to the SR-530 deployment below. No pre-2014 deployment reported postprocessing for 3D reconstruction of terrain, although 2D mosaics were implied in University of Hawai'i (2014) and UH (2014).

2.1. Relevant CRASAR Deployments

CRASAR deployed SUASs to five of the 17S UAS events (Katrina, Wilma, Berkman Plaza II, L'aquila, and Fukushima Daiichi) prior to the SR-530 mudslide. SUAS protocols developed by CRASAR were used by teams at two other events (Evangelos Florakis, Finale Emilia). CRASAR had also deployed unmanned ground robots to help search collaterally damaged houses at the La Conchita, CA Mudslide (2005). The La Conchita mudslide was significantly different from the SR350 slide in that it was a narrow slide of about 0.035 km^2 with a claylike solid mud that supported the weight of responders and equipment. One of the recommendations from that deployment was to use robots to monitor the mudslide (Murphy & Stover, 2008); the SR-530 deployment is thus a logical extension of the 2005 deployment.

2.2. 2011 Thailand Flooding

The 2011 Thailand Floods was the first event in which SUASs are known to have been specifically used for flood assessment. Siam UAV Industries deployed an eSUAV600 small electric-powered fixed wing with roughly a 2.5 m wing span and video cameras for 3 months in 2011 to assist the Thai government with the major flooding event (Srivaree-Ratana, 2012). The mission was to provide video of the water movement and the status of mitigation work to engineers and officials so that they could better control the flooding and evacuate the population. Siam UAV Industries obtained permission from the government to fly. The airspace was divided by the government into manned and unmanned regions in order to prevent possible collisions with news helicopters flying at low altitudes. The missions were successful, but lessons learned emphasized the need to annotate and curate the large amount of video, as geotagging was not sufficient.

2.3. 2013 Typhoon Haiyan

A set of fixed-wing SUASs with video cameras was deployed by the University of Hawai'i Hilo to the 2013 Typhoon Haiyan (UH, 2014; University of Hawai'i, 2014) for general visual mapping surveys including the Aklan river system at Panay. The team used a custom-built fixed-wing SUAS with approximately a 1.5 m wing span. Work was directed by an organization called Skyeye associated with the Ateneo de Manila University, and the data were provided to local governments. The value of surveying the river system was to understand and prevent additional flooding. The UH Hilo team described that they added "first person view" [generally referred to as *remote presence* (Murphy & Burke, 2008; Tittle, Roesler, &Woods, 2002) in the cognitive engineering and human-robot interaction literature] so that the responders could actively manage missions and for general safety. The team also cited difficulties with the weather and with finding launch sites.

Other SUAS platforms were reported in the media as being used at Typhoon Haiyan for general damage assessment and general mapping, but not flood assessment. Some notable examples are Team Rubicon, which deployed a Huginn X1 quadrotor with a camera and IR (Net Hope Center, 2014), and unspecified humanitarian relief organizations supporting Open Street Maps (OpenStreetMap, 2014). There was no discussion of flight altitudes, airspace regulations, or airspace deconfliction with manned assets operating in the same area, although one website reported that the Philippine Civil Aviation Authority had restricted flights to Tacloban City to relief effort flights only.

2.4. Similarities and Differences with SR-530 Deployments

The SR-530 Mudslide deployments are most similar to the Typhoon Haiyan deployment. They shared a similar motivation to mitigate risk to citizens (and responders) from current and future flooding. Both the RWB and UH Hilo teams had difficulty in finding staging areas and were prevented by weather from flying some flights. In both cases, the platform and payload selection were made on the presumption of mapping missions, but the need for a remote presence emerged in the field.

The SR-530 deployments are different from the Thailand Floods and Typhoon Haiyan deployments. Those deployments relied solely on fixed wing, not rotorcraft, and the visualizations appear to be limited to 2D mosaics versus 3D interactive reconstructions. The airspace in both cases was not restricted in the areas in which they appeared to be working, and thus it was open to news helicopters and other response workers, whereas the airspace in the SR-530 event was under a temporary flight restriction (TFR) barring entry of all aircraft except those authorized through the incident command process. The Asian deployments appeared to have deconflicted airspace either by explicitly sterilizing the airspace or through some informal method.

3. Premission Selection of Platforms

On March 27, 2014, CRASAR received an invitation to fly SUASs in order to provide data for the geological and hydrological teams through the Snohomish County Sheriff Urban Search and Rescue Air Operations branch, facilitated by the field innovation team (FIT), a disaster response nonprofit that delivers innovative solutions, real-time, to help first responders and disaster survivors.

3.1. Tactical and Strategic Mission Objectives

The initial mission scope as described prior to arrival had three objectives, two of which required advanced data processing and visualization for strategic decision makers. The first objective was to aid tactical teams in anticipating and mitigating ongoing flooding by providing comprehensive imagery. The responders were concerned that the continuing rain in the region combined with the dynamically changing river course could lead to significant flooding. Flooding could impact other residents but also the responders working downslope on recovery, creating a second disaster. The second objective was to provide a rapid 3Dreconstruction of the site and then use that to create a 3D printed map of the terrain. FIT provided access to Autodesk as ReCap reality capture, a cloud-point image-based 3D modeling software, and an Objet 500 Connex 3D printer. The 3D printed map would complement a 3D graphics reconstruction and also serve as a physical artifact for the responders to work over together, thus offering a similar but different visualization capability. The third objective was to collect imagery over several days to anticipate further slide movement so as to protect the responders. Note that there was no mission to search for survivors or for victim recovery.

3.2. Platform Selection

Following *Disaster Robotics* (Murphy, 2014), the choice of platforms from within the Roboticists Without Borders membership was based on four questions: *What are the expected (and unarticulated) needs for the robot? What are the transportation and logistical arrangements? How will maintenance and repairs be conducted?* and *Are there any regulatory issues that must be considered?* The answer to the fourth question was that all platforms would require an emergency COA from the FAA to fly. The first three questions produced the following set of criteria:

- *Prior use for geospatial missions.* Reliable platforms that had existing payloads and demonstrated post-processing for accurate, georeferenced 2D tiling and 3D reconstruction were needed.
- *Rapid coverage and reconstruction.* The SR-350 slide was approximately 2.5 km^2. The general expectation was that the entire process—flight and postprocessing—should occur within 1 day, preferably within one 12-h shift so that the data could be used for planning the next day's activities.
- *Portability.* It was expected that SUASs and operator control stations would have to be manually carried to a suitable launch site inside the disaster zone.
- *Ability to fly in regional weather.* Washington State is subject to rain. While SUASs generally are not permitted to operate in rain due to the lack of visibility, it is desirable to be able to operate in light rain so that the platform could get wet as it was returning home.

CRASAR invited Insitu and PrecisionHawk to join the deployment under the Roboticists Without Borders program, where they donate their time and travel costs, and they absorb any damage or loss to the platform. The expectation was to bring two complementary fixed-wings, namely the Insitu Scan Eagle and the PrecisionHawk Lancaster, with geospatial sensing and postprocessing capabilities, and to bring the CRASAR AirRobot AR100B quadrotors as a backup (see Figure 2). It should be noted that over two dozen SUAS systems are commercially available that support geospatial missions; these two can be considered representative of the emerging industry.

The AirRobot AR100B is a man-portable rotorcraft weighing 1.8 kg with vertical takeoff and landing with operations in up to 15 knots, and flight durations of 8–20 min within about 3 km. It is typically used at altitudes between 9 and 122 m AGL. It is used primarily for military or border security applications, where the real-time low-resolution imagery from a RGB camera is used to investigate situations or track activity. The Panasonic Lumix 10 megapixel camera transmits a 640 × 480 viewfinder image over 802.11 b/g/n in real time; this low-resolution viewfinder image is used for teleoperation. The AR100B can take manually high-resolution still imagery, but software upgrades for automated image collection for use with postprocessing software was not available at the time of the deployment. Other payloads, such as fused video and thermal imaging, were not available on loan from the manufacturer. The platform can operate in a light rain. The AirRobot was chosen as a backup platform because it could be launched vertically and because it could provide responders with tactical, on-demand oversight of the general area.

The Insitu Scan Eagle is a fixed-wing UAS with a wing span of 3.1 m and a weight of 14 kg. It requires a short runway to launch and land and is supported by three tractor-trailer units. It was chosen despite its larger size, weight, and staging needs, because it is used extensively by the U.S. Geological Survey, it is arguably the best known UAS for geospatial application, and because the company is based in nearby Oregon and could respond quickly.

The PrecisionHawk Lancaster is a fixed-wing man-portable SUAS with a 1.2 m wing span, weighing 2.5 kg. It is hand-launched with operations in up to 25 knots of wind and the platform belly-lands as opposed to having landing gear unless landing in water, at which time floats can be employed. It can be landed either automatically or manually. The Lancaster is primarily used for agricultural and terrain mapping at altitudes of 30.5–183 m above ground level using video, LIDAR, or thermal payloads. It has flight durations of approx-


(a) (b) (c)

Figure 2. Roboticists Without Borders platforms selected for deployment: (a) the AirRobot AR100B, (b) the Insitu Scan Eagle, and (c) the PrecisionHawk Lancaster.

imately 60 min and can map a 2.6 km^2 area in under 2 h. The reconstructions can be generated from either video or line-scanning LIDAR payloads, with 3 cm per pixel processed in 3–72 h. The LIDAR payload was not available for the mudslide deployments. The Lancaster was chosen because of its high degree of portability and flexibility in staging, postprocessing software for terrain reconstruction, and the ability to fly in light rain.

4. March 2014 Deployment

The team assembled on March 28, 2014, and demobilized on March 30. The team was directed by Robin Murphy (CRASAR), with Brittany Duncan (CRASAR) as the pilot-in-command. Tyler Collins was the lead pilot for PrecisionHawk, with Pat Lohman as field support. Kevin Cole and Travis Cieloha were the lead pilots for Insitu. Frank Sanborn (FIT) served as the liaison with the incident command management team but had no direct responsibilities for the SUAS. Friday, March 28 was spent waiting for the three teams to arrive and scouting staging areas that could serve as takeoff and landing zones and provide visibility for line-of-sight operations. The deployment resulted in zero flights due to environmental constraints eliminating the Insitu and county concerns over safety and privacy, despite meeting FAA regulations.

4.1. Environmental Constraints on Operations

The Insitu Scan Eagle demobilized on the afternoon of March 28 due to a lack of a suitable staging area within the TFR. The temporary heliport at Skagland that was being used by manned helicopters had sufficient space and access, but there was a possibility of radio interference between the Black Hawks and Scan Eagle, as well as complicated coordination issues. No other site was found.

The CRASAR and PrecisionHawk representatives scouted for a location that could be used by both platforms. A temporary emergency access south of SR-530 was ruled out due to radio-frequency interference from overhead power lines [Figure 3(a)]. It also would have required over a 400 m hike over a steep muddy hill; see Figure 3(b). A meadow at the Shunn property off Whitman Road was identified as the best option. It would not require a hike but it did require permission from the landowner, a four-wheel-drive vehicle to go off road, and there was a danger of a secondary slide. The location would also necessitate two safety officers in order to maintain constant line of sight with the SUAS. One would be with the flight team on the west side of the slope, and the second would be stationed on the south side of the slide and communicate with the team via radio.

4.2. Mission Objectives

The mission objectives in order of priority are given below, with the areas for each mission shown in Figure 4. The refinement of missions introduced one surprise: that the quadrotor had a mission and was no longer strictly a backup aircraft. The expectation was to use the PrecisionHawk Lancaster flying at 137 m AGL for priorities 2–4, with follow-up flights if needed by the AR100B rotorcraft to investigate areas of interest from 30.5 m or less. However, for priority 1, the "hover and stare" capability of the AR100B was considered essential in allowing the Army Corps of Engineers to access the flow patterns and general movement of the water. A flight might be able to meet multiple objectives.

- *Priority 1: Riverbed assessment (blue).* Washington Task Force 1, the state team conducting rescue and recovery operations, wanted the river bed cleared so the pond area would drain and they could search the waterlogged area. Low-altitude, high-resolution data would aid hydrologists in making decisions on where blockages are and how to clear them.
- *Priority 2: High resolution of lower slide (yellow).* The geologists wanted a better understanding of the scarp, particularly at the toe. Low-altitude, high-resolution data would aid in identifying potential problem areas that would lead to more slides or make further changes in the river.
- *Priority 3: High resolution of cliff face/upper slide (green).* Washington Task Force 1 wanted to project secondary slides because even a small slide could impact search


(a) (b)

Figure 3. Examples of the difficulty in staging the SUAS: (a) A candidate staging area with sufficient line of sight and minimal risk of flying over responders, but with power lines creating a navigation hazard and radio interference, and (b) the 400 m trail over a muddy hill to reach that site.

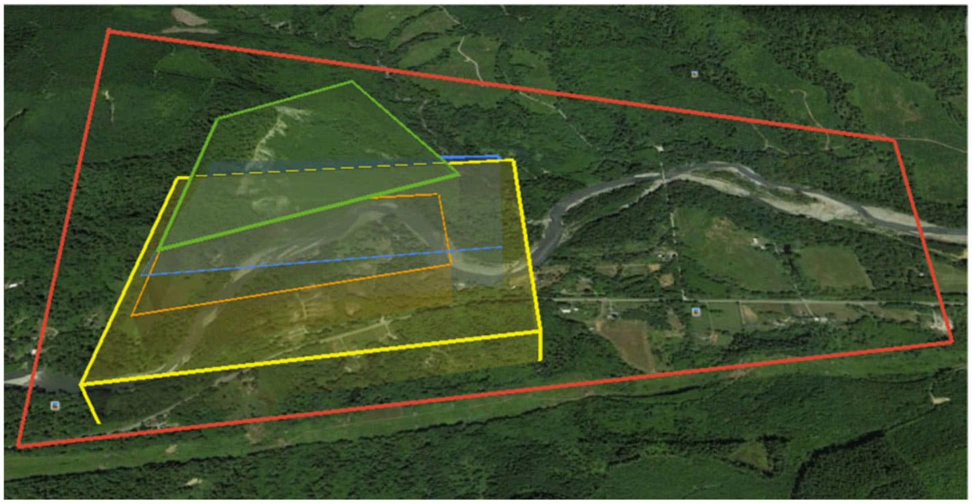

Figure 4. Map of the March 2014 objectives overlaid on a pre-mudslide Google Earth map. The overall boundary is shown in red, with priority 1 airspace in blue, 2 in yellow, 3 in green, and 4 in orange.

operations taking place in water. Low-altitude, high-resolution data would aid in making decisions on where small slides might occur and how to clear them.

- *Priority 4: High resolution of "moonscape" (orange).* The geologists and hydrologists needed clear imagery for planning since the area was inaccessible by foot. Low-altitude, high-resolution data would aid in making decisions on potential access sites (how firm was the ground? was there ponding of water?).

4.3. Regulatory Constraints on Operations

FAA regulations placed constraints on the SUAS operation. To legally fly, an emergency COA had to be issued for each platform. The key component of the emergency COA was a novel airspace deconfliction plan that allowed manned and unmanned aircraft to operate over the same area. The emergency COA required an existing COA for each platform and an airspace deconfliction plan approved by the group responsible for flights in the area. The FAA was extremely supportive and remained on standby 24/7 throughout the weekend and continuously provided feedback as the emergency COA forms were filled in. The emergency COA process also required a separate email from the incident commander to confirm that the SUASs were needed due to eminent risk of loss of life.

Manned aircraft operations were essential at the mudslides. The FAA had already declared a temporary flight restriction (TFR), which serves as an aviation "do not enter" zone to protect the helicopters that were used for extracting survivors; see Figure 5. For the initial phase of the rescue and recovery, responders had to be transported via helicopter until a boardwalk was built through the viscous mud and

Figure 5. Extraction flight showing the low altitude of the helicopter and risk to personnel on the ground from a crash. Courtesy of Northwest Regional Aviation.

remained on standby for emergency extraction. These tactical operations meant the helicopters were operating at 61 m above ground level (AGL), and they were extremely vulnerable to debris being sucked into a rotor. At those altitudes, even a small bird could cause a crash. A crash would not only risk the helicopter's inhabitants, but the survivors and workers in the area below the helicopter as well.

In the event that a helicopter in these situations sees an unknown aircraft or SUAS, the helicopter must discontinue the mission and return to its staging area until the offending aircraft is identified or leaves the airspace. For example, operations at the mudslide were suspended when a manned float plane entered the TFR without permission and landed during the initial rescue operations. Likewise the use of manned helicopters for low-altitude operations at the mudslides was clearly essential but at risk from a SUAS operating in what would normally be an acceptable altitude under 122 m associated with Class G "hobbyist" airspace.

Previously, the most straightforward way to coordinate manned and unmanned aircraft has been to "sterilize" the airspace, allowing only one or the other type of craft to enter the area for scheduled periods. An Air Space Deconfliction Plan was created in collaboration with Snohomish County Sheriff's Office chief pilot William Quistorf and the onsite Air Operations Branch. The Air Operations Branch directly coordinated flights within the TFR and also performed any necessary coordination with the overall Air Traffic Control system through Seattle Center. The primary objective of the plan was to segregate manned and unmanned flights but allow them to fly simultaneously while creating a protocol to discontinue unmanned operations if a helicopter had to fly through the canyon at a low altitude. There were four key elements to the plan:

- *Manned and unmanned aircraft separation.* During any normally scheduled flights, the air space was deconflicted via a "rack-and-stack" approach to maintain 500 feet (152.4 m) vertical separation between aircraft, where the UAVs would not fly above a 500-foot (152.4 m) ceiling and the manned operations would not breach a 1,000- foot (304.8 m) floor. The FAA requires at least a 500-foot (152.4 m) separation between any aircraft.
- *Manned flights take precedence if separation could not be maintained.* To allow for emergency rescue flights by the helicopters, which meant they would have to breach the 304.8 m floor, it was explicitly stated that manned flights took precedence over unmanned flights and that the maximum time to land for any unmanned flights would be less than 1.5 min. This ensured that if a manned helicopter had to perform an emergency evacuation of the responders, the SUAS would be able to land before the helicopters came close enough to be vulnerable.
- *A SUAS team member(s) attend daily Air Branch meetings.* The expected area for SUAS flying and timing were discussed in an early morning meeting with the entire air branch, including all supervisors and pilots so that manned flight teams were aware that there would be unmanned flights below them. The radio protocols were set in this meeting to allow coordination throughout the day as flights were scheduled or requested. Although not required by the emergency COA, the SUAS team representatives also attended the short daily Operations Branch meetings at 0600 to coordinate access to the staging area and to maintain personnel accountability for team safety, i.e., that a

six-person SUAS team with two cars would be working in a particular Division and Section that day. The meetings also made other responders aware that the team was authorized to fly, was not from the media, and what data would be available to them.

- *The SUAS team flew on demand.* The SUAS team was allowed to fly on demand, versus at specifically scheduled times, within the designated area by monitoring the Air Branch radio frequency and broadcasting on the tactical air branch radio channel that they were about to fly and had landed. The team was allowed to change staging areas and move about without reporting in as long as they stayed within the parameters set at the morning meeting.

It should be noted that the emergency COA process did not hold up flights per se, as approval would have been nearly instantaneous given a complete application. The time-consuming element was finding realistic staging sites and communicating them to the FAA. The coordination with the Air Operations Branch was short and straightforward, did not preclude on-demand flights, and should not be used as a reason to argue against SUASs coordinating with manned air traffic control arrangements.

The addition to the emergency COA process of a separate email from the incident commander prevents an agency participating in the response from requesting an emergency COA without the larger incidence command staff approval. This serves two purposes. It explicitly states the relationship of the missions to eminent loss of life, which is required for an emergency COA. It also helps to ensure that the flights are coordinated within the larger use of aerial assets. For example, in a disaster spread over a large geographical area, such as a hurricane, a sheriff's department or other agency may have access to UASs but be unaware that the manned helicopters are being tasked to work at low altitudes in the same area, which was the problem with the Boulder, CO flood flights.

4.4. Cancellation Due to Public Safety and Privacy Concerns

No flights were conducted as the Snohomish Office of Emergency Management internally canceled the flights and the incident commander did not email the FAA. The county held the incorrect perception that manned and unmanned systems could not fly in the same airspace. After meetings with officials on March 30, the team and the Air Operations Branch clarified that the airspace deconfliction plan did allow manned and unmanned aircraft to fly, they rewrote a jargon-free version of the airspace deconfliction plan, and they resubmitted the request for flights. The Incident Commander, Larry Nickey, then formally raised concerns of privacy and viewing of personally identifiable information (PII). Mr. Nickey indicated that at least one family had expressed concerns about drone operators seeing bodies of loved ones, and thus he did not approve the flights, though he might at a future date. It was unclear if the families understood that the SUASs were being proposed to fly over the moonscape in order to protect workers and mitigate further flooding, and they were not being flown over the victim recovery area in order to search for victims.

5. April 2014 Deployment

The team was invited to return on April 17, 2014, and was onsite April 22–24, 2014. Four previous members (Collins, Duncan, Murphy, and Sanborn) returned. Justin Kendrick, PrecisionHawk, was substituted for Pat Lohman. A new member was added, Tamara Palmer, who is a communication strategist with FIT. The FAA did not grant an emergency COA for the PrecisionHawk Lancaster, as a regular COA for the platform had not completed FAA approval at that time, but the AirRobot AR100B emergency COA was approved. The AirRobot AR100B flew seven flights on April 23, but it was unable to fly on April 24 due to weather. A total of 33 GB of data were collected from image and video data from the AirRobot AR100B quadrotor, including raw and postprocessed imagery; photos and video of the robot in flight and the context taken by the team members; and flight logs and ethnographic observations.

5.1. Operational Differences from March Deployment

Staging for the April deployment was easier as the team could drive directly to staging areas without hiking and could use the roadway as a launch and landing zone. A portion of SR-530 on the Darrington side of the slide was now open, and a temporary road from Oso to Darrington had been completed. There was also a temporary road near the river where the Army Corps of Engineers was building dikes to stabilize the river flow. The weather for the April deployment was similar, with intermittent rain and cloud cover. Since the team could drive an SUV to the site, a popup tent was included to protect the base station and SUAS from light rain.

The flights had the same four objectives as Deployment 1, however the priority was changed where Priority 4 Moonscape was number 1 and Priority 1 Riverbed Assessment was demoted to 2. It should be emphasized that the primary objective Moonscape was best suited for the fixed-wing as it could collect a larger amount of overlapping images, and at higher resolutions. The Riverbed Assessment was better suited for the rotorcraft, which could hover and stare at moving water.

The emergency COA was the same as the March deployment since the TFR was still in place, but it was updated to reflect the expected flight period of April 23 and 24. The Snohomish County Department of Emergency Management sent an email to the FAA on April 18.

5.2. Flights

On April 23, 2014, the AirRobot AR100B was flown seven times for a total of 48:18 min over an 8 h period, with a 4 h break for lunch off-site and recharging batteries, approximately 1.5 h waiting for intermittent rain to stop, and 0.5 h spent on the ground waiting for a manned helicopter flight to pass. Time at staging area 1 started at 08:45 and ended at 11:30 for a lunch break and recharging. The team returned at 15:30 to staging area 2 and was in field until 16:45. Multiple staging areas were needed because the short battery flight times of the AirRobot restricted the area that could be covered from a single staging area. The team arrived at a new staging site on a dike at 10:15 on April 24, 2014, but flying was canceled at 11:45 as the winds were gusting to 25 knots, beyond platform rating, and projected to increase throughout the afternoon.

The AirRobot was generally at an altitude of 42 m with 6 knots of wind and overcast conditions and flown from two landing zones along SR-530 about 0.5 km apart. Both were a 3m×3m flat surface on SR-530. The staging area provided a clear line-of-site, and therefore a second observer was not needed. Five of the seven flights (44:50 min) were data collection runs, with two short flights for platform checkout. The longest flight was 10:20 min.

Data Flight 1 provided a 360° view of the site for context.

Data Flight 2 addressed Priority 2. Engineering Branch representative Norm Skjelbreia arrived on site, creating an opportunistic shift in mission plans from surveying the moonscape to conducting the river assessment. He directed the flight and "hover and stare" operations in order to observe the progress of excavators working on the river channel, as well as an additional 360° view of the site.

Data Flight 2 highlighted a disadvantage of using wifi viewfinder cameras as payloads. These are convenient because they transmit real-time video imagery. However, the video is of low resolution, in this case 640×480 pixels, and poor quality. As seen in Figure 6, the real-time imagery was so poor that neither the pilot nor the hydrologist could find the bright orange excavator in the imagery. Data Flight 2 also highlighted the advantage of having a separate mission specialist interface (Peschel & Murphy, 2015). As seen in Figure 7, Skjelbreia is able to view on a separate laptop the real-time video stripped of artifacts for the pilot (e.g., battery life, altitude, GPS satellite coverage, etc.). This also kept him from having to crowd the pilot by looking over her shoulder.

Data Flights 3, 4, and 5 (priority 1) approximated the Lancaster image sampling pattern and constitute the bulk of imagery data used for 3D reconstruction. The pilot manually flew the AirRobot over the "moonscape" area to approximate the pattern flown by the Lancaster while capturing still images with approximately 50% overlap both horizontally and vertically. While it is possible for CRASAR to code the AR100B for autonomous flight and image collection, there was no opportunity to test any code and the risk was too high. This was accomplished by flying using the viewfinder, and it resulted in difficulty navigating back to the stopping point of the previous flight. The imagery captured in these three flights was equal to 30–40 acres of coverage in the resulting stitched images.

5.3. Feedback on Postprocessing

Imagery from the AirRobot was postprocessed by PrecisionHawk using AgiSoft Photoscan software in 3 h on a laptop during lunch. The mosaic and 3D reconstruction are not georeferenced, thus they cannot be imported into Google Earth or similar software, because the AirRobot stills were not geotagged with EXIF data when captured. The data set was incomplete due to limited flight time and missing areas due to errors in manually covering the area. While a georeferenced reconstruction is possible with control points, no survey marks were visible in the imagery as the flights were over inaccessible areas.

The 2D mosaic and 3D reconstructions from the April 23 flights were delivered to the Engineering and Operations Branch at the incident command post at 18:25. Figure 8 shows representative stills. Feedback at that time was that both 2D and 3D visualizations were considered valuable, but the interactive 3D reconstruction was viewed as more useful. The Operations Branch responders indicated that the lower resolution and lack of geotagging was acceptable given that the results could be generated on a laptop in 3 h; this meant that SUASs could be a tactical tool for Operations for immediate decision making in the field. The 3D reconstruction was also valuable to the Engineering Branch, but a higher-resolution, georeferenced reconstruction would be even more useful.

A 3D printed model was delivered to Snohomish County Public Works on July 28, 2014, and it has been used by the County to identify locations for a flooding bypass channel; the feedback has been that the 3D reconstruction and the 3D print have been extremely valuable for strategic decision-making despite the lower resolution.

6. Discussion

Overall, the general performance of rotorcraft, despite being an older model poorly matched for the situation, met the technical objectives. The advances in commercial postprocessing software, in this case AgiSoft Photoscan, added real value to visualization of complex terrain for both tactical (immediate) and strategic (long-term) decision-makers. The performance of the rotorcraft suggests that the difference between fixed-wing and rotorcraft may come down to oper-

(a) (b)

Figure 6. Data Flight 2 showing (a) the low-resolution real-time display where the yellow and orange excavators cannot be seen, and (b) the high-resolution still image where the yellow excavator can be clearly seen on the left and the orange excavator is visible to the right.

(a) (b)

Figure 7. External view of Data Flight 2 showing (a) the AirRobot 100B in-flight and (b) separate displays for the hydrologist Norman Skjelbreia (right) and the pilot Brittany Duncan (left). The yellow cases are the backpackable base stations—the active station and a spare base station not in use except as a table.

ational constraints. The SR-530 deployments reiterated lessons already learned about operational constraints in terms of environments, but they introduced regulatory and societal constraints that could not be overcome. Manpower remains a open discussion; the deployments suggest that a SUAS team for a disaster will continue to have a 3:1 or 2:1 human-to-robot ratio for the near future. The deployments reinforced the need for multisensor payloads for SUASs, which is well-known. However, they also identified gaps in autonomous planning, especially the need to consider landing zone and operational constraints such as time for the return home and maintenance of line-of-sight. Seven short flights produced 33 GB of data, posing challenges in data curation, archiving, and mining.

6.1. General Performance

The performance of the rotorcraft was considered outstanding by the response professionals. The deployments met two of the three original objectives despite only covering about half of the desired area due to the use of an older rotorcraft and flight cancellations due to county concerns, weather, and time constraints. The flights and same-day reconstruction provided data that could be used by tactical responders to anticipate and mitigate flooding as well as to gain situation awareness. Tactical responders saw huge advantages for an organic process that allowed them to collect data and process them on a laptop in less than a day. Here speed and convenience trumps resolution. The imagery plus the AgiSoft Photoscan

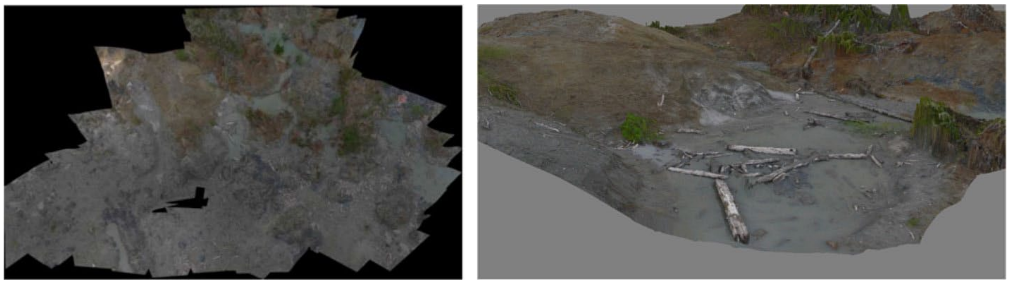
(a) (b)

Figure 8. Example sites for Phase 1 operations: (a) the 2D mosaic showing missing images, and (b) a view from the interactive 3D reconstruction.

postprocessing software produced 3D reconstructions, and later AutoDesk created a 3D printed model that has been used by strategic decision-makers. The 3D software visualization was rated by engineering and operations specialists as a sufficient reason to deploy SUASs. The 3D printed model was viewed as an exciting and desirable tool, especially if it could be generated within 2–4 days. The deployments were unable to meet the third objective of providing multiday series of imagery due to the initial flight cancellations. The flights did help hydrologists better understand the evolving terrain, but flights in March would have been more effective in anticipating and mitigating the initial flooding.

The technical objectives were largely met by postprocessing software, which is independent of platform. While a fixed-wing is better suited for wide-area coverage, sufficient data can be gathered by a rotorcraft. The AR100B quadrotor represents a worst case: it was over five years old, it was not using new batteries, which get over 30 min flight time, and it did not have autonomous flight and imagery collection software. Newer models such as the AR180 can fly in the 20–30 knot regime, which would have allowed an additional day in April.

The real barriers to performance were initially societal and then regulatory. The misunderstanding of regulations and fear of inappropriate use of "drones" caused the cancellation of flights at a time when it would have had a larger impact on the response. Once those issues were rectified, the biggest technical barrier to meeting the objectives was the inability to fly a fixed-wing designed for rapid coverage and geospatial data collection. The core problem was regulatory: the inability to get an emergency COA for the PrecisionHawk platform. The weather produced high winds, rain, fog, and low visibility, which limited the AR100B flights but would have also impacted a fixed-wing.

6.2. Lessons Learned for Operations

The deployments illustrate three general principles in deploying SUASs for disasters (Murphy, 2014): the systems must be portable, the actual missions will be different from the expected missions, so having multiple systems to handle these unanticipated tasks or constraints is important, and responders will always want remote presence capabilities even if the mission is nominally automated data collection. These three principles are not new, but the SR-530 mudslides do pose a warning as to specialization of platforms. The PrecisionHawk Lancaster, like many geospatial and precision agriculture platforms, was specialized for autonomous data collection. It did not allow real-time viewing of the video data. However, when planning the missions with the Engineering Branch on March 29 and April 22, it was clear that the responders had expected to at least passively view what the SUAS was seeing or be able to interrupt the preprogrammed flight path and direct it to a different area. The opportunistic use of the AirRobot to check on the riverbank mitigation efforts was one of five data flights, essentially 20% of the deployment. Not having a remote presence (first person view) capability would not have led to a rejection of the technology, but it would have hampered its utility.

6.3. Human-Robot Ratio

The human-robot ratio was 3:1 in March and 2:1 or 3:1 in April, depending on the mission. In the March deployment, the flight team for the AirRobot consisted of three people: a pilot, a safety officer colocated with the pilot, and a remote safety officer stationed across the slide. The PrecisionHawk team would have consisted similarly of a three-person team. Note that two safety officers were required not only due to the FAA requirements to maintain line-of-sight, which could have been satisfied with just the distributed safety officer, but also to safeguard the pilot. The pilot should not have been deployed alone, and the safety officer would be more alert to warnings on a secondary slide. The manpower could increase if the Engineering Branch sent an engineer to serve as a mission specialist, opportunistically directing data collection, as was seen in the April deployment.

The April deployments had more favorable staging, and there was no need for a second safety officer so the nominal ratio was 2:1. Even with autonomous data collection software, the ratio would still be 2:1 for two reasons. One is that a person looking between a display and the SUAS quickly loses the platform in the background of the mountains; the choice is to maintain constant line-of-sight following FAA regulations or to completely trust the autonomy. The second reason is that teams will work in at least groups of two for personal safety. However, in remote presence, the presence of an engineer changed the ratio to 3:1. In all cases, a safety officer was more than an observer; they needed to understand the normal flight patterns of the SUAS so that they could alert the pilot to subtle, potential problems.

6.4. Gaps and Open Research Questions

The deployments highlight gaps in sensing encountered on previous SUAS deployments (Murphy, 2014). Thermal sensing might have improved the identification of the extent of flooding, as it was difficult to visually distinguish water from the mud. LIDAR would have produced more accurate 3D reconstructions, and miniaturized prototypes suitable for SUASs are coming on the market. Multisensor payloads are needed; given the large area to cover and the need for rapid coverage, it is unrealistic to expect to fly with one payload and then repeat with a different payload.

The mudslide flights also suggest that more work is needed in flexible autonomous systems and planning. It would be useful to divide the site into an optimal set of regions that can be flown from the available staging areas and satisfy constraints such as remaining in visual line-of-sight and being able to return home and land within N minutes, where N is specified by a COA. Planning and geospatial reasoning to determine possible staging areas and observer positions to maintain line of site from *a priori* data would also be desirable.

The data set from just one day of flying was 33 GB, implying that data curation (archiving, retrieval, and data mining) will be problematic. Data were heterogeneous, consisting of video, images, external views, and flight logs. Different cameras and sources used different file-naming conventions. The use of cloud processing services was impractical with a cell phone data connection. The problem will be exacerbated by future planned missions, which will add more data for comparative analysis. Data are currently collected and stored using the RESPOND-R format (Shrewsbury, Henkel, Kim, & Murphy, 2013), where the file names support basic retrieval functions. The data curation functionality will need to address queries such as *all views of a location*, *all data of type* ***d*** *for a short time period* (e.g., a flight or a day), and *all data of type* ***d*** *for a long time period* (e.g., seasons). Accessing data must be complemented with tools to allow analysis, such as how to detect and visualize differences over time.

7. Conclusions

The SR-530 mudslide was the first reported use of small unmanned aerial systems (SUASs) for a mudslide. It adds to the corpus of understanding of robots fielded under extreme conditions, regulatory constraints, and societal confusion and fears of drones. The deployments also contribute a case study of a new style of SUAS missions in which the platform is less important than the postprocessing for visualization of the data. The SR-530 mission exemplifies the evolution of SUAS from platforms enabling data collection to a data-to-decision system, where the system collects data and converts them to actionable information readily comprehended by decision makers. In this case, a low-resolution interactive 3D reconstruction of the site was sufficient for both tactical and strategic decision makers. A 3D printed model was ranked the most valuable outcome. The SR-530 deployments produced a novel airspace deconfliction plan approved by the FAA that allows manned and unmanned aircraft to work in the same airspace.

The choice of platform was based on previously demonstrated geospatial payload and postprocessing capabilities, with the Insitu and PrecisionHawk volunteering to deploy fixed-wing systems used for geological surveys and precision agriculture through Roboticists Without Borders. An older AirRobot AR100B quadrotor was included as a backup platform, although it had not been used for geospatial reconstructions. In the field, the choice of SUAS was limited by the terrain (eliminating the Scan Eagle) and FAA regulations (eliminating the Lancaster). As a result, the AR100B was the only platform suitable for flying. Even though its camera payload was a lower resolution, the images were not geotagged, the image locations were selected manually, and the coverage area was smaller per unit time than a fixed-wing, the data were sufficient for the AgiSoft Photoscan to produce a viable 3D interactive reconstruction of the “moonscape” within a single 12-h shift.

The deployment goes beyond disaster response and recovery and contributes to an understanding of unmanned aerial system design for field applications in remote areas such as environmental protection, fish and wildlife tracking, and assessment of pipelines, bridges, and railways. Small UASs need to have higher-resolution real-time displays and geotagging on all imagery and video. Thermal and LIDAR sensors are desirable, especially if miniaturization supports multisensor payloads. Flight planning needs to consider maintaining a known return-to-home time constraint. Autonomous systems should allow users to interrupt preprogrammed flight paths and use the platform for remote presence. The large amount of heterogeneous data, 33 GB from just 48 min of flight time, suggests that data archiving and curation will become a major issue in the near future.

The deployment also illustrates safety and societal issues impacting the adoption of SUASs. The cancellation of the initial March deployment shows that the public’s perception of unmanned aerial systems in general, particularly with regard to privacy, plays a very real role in SUAS adoption. Regulations prevented the use of a more desirable platform. At the same time, it showed that the SUAS community can work within regulations and why it is dangerous not to. The airspace deconfliction plan shows how accepting minimal coordination with established manned aircraft control procedures can lead to the FAA approving flights in the same airspace as manned systems. The use of manned helicopters for tactical response is an example of why flying under 122 m AGL as in U.S. "hobbyist rules" does not promote safe operations during a disaster, and why it is not permitted by the FAA.

Work is continuing on mudslides, although it is outside of the scope of this article. CRASAR deployed a second time in August, 2014, in order to provide follow-up data for the geologists and hydrologists to use in verifying models of the mudslide and river. These flights were conducted under a normal COA, and both the PrecisionHawk and the AirRobot AR180, a larger SUAS with autonomous data collection, were successfully used.

Acknowledgments — This work was supported in part by a donation from the Field Innovation Team, National Science Foundation Grants IIS-1143713 "EAGER: Shared Visual Common Ground in Human-Robot Interaction for Small Unmanned Aerial Systems," CNS-0923203 "MRI: Acquisition of Mobile, Distributed Instrumentation for Response Research (RESPOND-R)," and EIA-0224401 "R4: Rescue Robots for Research and Response," and a NSF Graduate Fellowship. The authors would like to thank the incident management team, especially Bill Quistorf and the Air Operations Branch, Steven Thomsen and Norm Skjelbreia and the Engineering Branch, and Chiefs Steve Westlake and Steve Mason and the Operations Branch; the FAA, especially Randy Willis, Mark Jordan, Jacqueline Jackson, and Johnny Morrow; the members of FIT, especially Desi Matel-Anderson and Stacy Noland; Kimberly Mallett for coordinating the travel arrangements; the anonymous donors; and the anonymous reviewers. We are honored to have been of some small assistance to the people of Snohomish County, and we continue to express our sympathy for all the victims and their families.

References

9News.com (2013). Colorado floods: Fact check. http://archive.9news.com/news/local/article/355477/222/Colorado-Floods-Myths-debunked , Sept 19.

Adams, S. M., & Friedland, C. J. (2011). A survey of unmanned aerial vehicle (uav) usage for imagery collection in disaster research and management.

Humanitarian OpenStreetMap Team Center. (2014). Support Haiyan/Yolanda reconstruction: Contribute public use uav (drone) imagery. http://solutionscenter.nethope.org/webinars/view/webinar-on-uav-unmanned-aerial-vehicle-drone-use-in-development#45

Net Hope Center (2014).Webinar on UAV (unmanned aerial vehicle) use in development. http://solutionscenter.nethope.org/webinars/view/webinar-on-uav-unmanned-aerial-vehicle-drone-use-in-development

ICARUS (2014). European funded projects team up in response to the worst floods Bosnia-Herzegovina and Serbia have faced in 100 years. http://www.fp7-icarus.eu/news/european-funded-projects-team-response-worst-floods-bosnia-herzegovina-and-serbia-have-faced-10 , May 19.

Murphy, R., & Burke, J. (2008). From remote tool to shared roles. IEEE Robotics and Automation Magazine, special issue on New Vistas and Challenges for Teleoperation, 15(4), 39–49.

Murphy, R. R. (2014). Disaster robotics. Cambridge, MA: MIT Press.

Murphy, R. R.,& Stover, S. (2008). Rescue robots for mudslides: A descriptive study of the 2005 La Conchita mudslide response. Journal of Field Robotics, 25(1-2), 3–16.

Peschel, J., & Murphy, R. (2015). A mission specialist interface for micro unmanned aerial systems. IEEE Transactions on Human-Machine Systems (to be published).

Shrewsbury, B., Henkel, Z., Kim, C.-Y., &Murphy, R. R. (2013). Respond-r test instrument: A summer institute 2013 case study. In IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR 2013) (pp. 1–6).

Srivaree-Ratana, P. (2012). Lessons learned from the great Thailand flood 2011: How a uav helped scientists with emergency response and disaster aversion. In AUVSI Unmanned Systems North America.

Tittle, J. S., Roesler, A., & Woods, D. D. (2002). The remote perception problem. In Proceedings of the 46th Meeting of the Human Factors & Ergonomics Society (vol. 46, issue 3, pp. 260–264). Sage Publications: Thousand Oaks, CA.

UH Chancellors Weblog (2014). UH Hilo chancellor's office helps fund typhoon relief research in the Philippines. http://hilo.hawaii.edu/blog/chancellor/2014/01/28/uav-research-philippines/

University of Hawai'i (2014). Super typhoon Yolanda disaster relief with unmanned aircraft Philippines. http://www.epscor.hawaii.edu/content/super-typhoon-yolanda-disaster-relief-unmanned-aircraft-philippines

Yoanna, M. D. (2014). How mesa county used drones in search and rescue efforts after landslide. http://www.cpr.org/news/story/how-mesa-county-used-drones-search-and-rescue-efforts-after-landslide , June 5.