Humans and Robots in Off-Normal Applications and Emergencies

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Abstract. Unmanned systems are becoming increasingly engaged in disaster response. Human error in these applications can have severe consequences and emergency managers appear reluctant to adopt robots. This paper presents a taxonomy of normal and off-normal scenarios that, when combined with a model of impacts on cognitive and attentional resources, specify sources of human error in field robotics. In an emergency, a human is under time and consequences pressure, regardless of whether the mission is routine or whether the event requires a change in the robot, the mission, the robot's work envelope, the interaction of the humans engaged with the robot, or their work envelope. For example, at Hurricane Michael, unmanned aerial systems were used for standard visual survey missions with minor human errors but the same systems were used at the Kilauea volcanic eruption for novel missions with more notable human errors. An examination of two cases studies suggests the physiological and psychological effects of an emergency may be the primary source of human error.

Keywords: Human Factors · Systems Analysis · Human error analysis · Extreme environments · Uninhabited aerial vehicles

1 Introduction

Ground, aerial, and marine robots are being used at disasters, public safety incidents, and other non-routine, also called "off-normal" events. Unmanned systems for off-normal events are unlikely to be fully autonomous. As noted by Murphy and Burke [1], many missions are intended to provide humans with real-time remote presence, not taskable agency, and thus no advances in autonomy would eliminate the human. Even fully autonomous missions, such as photogrammetric mapping with unmanned aerial vehicles, still involve human supervision and a human is always on call in case of a problem. Although robot deployments have generally been successful, some failures do occur and human error is responsible for over 50% of those cases [2]. While not related to human error, we have witnessed firsthand a hesitancy by managers to deploy robots for off-normal events.

In order to reduce human error and foster appropriate adoption of robots for off-normal events, this paper poses a taxonomy of off-normal events as either novel or an emergency. The paper uses this framework to discuss a model of human resource constraints and demands on the human in off-normal events, inspired by multiple resource theory [3]. An off-normal event increases the resource demands due to changes in the robot, the mission, the robot and human work envelopes, or the humans' cognitive capacity, while at the same time decreases the available resources due to changes in the physiological and psychological state of the humans. The human factors between a novel event and an emergency is that an emergency always diminishes the capacity of the humans due to unfavorable changes in physiological and psychological state. The paper then presents two cases studies of the use of small UAS during emergencies, describing how the resources demands and state changed and the human errors. The paper concludes with a discussion of ramifications of the taxonomy and model for reducing human error and increasing trust.

2 Taxonomy of Normal and Off-Normal

There appears to be no formal definition of normal and off-normal use of robots in the literature, therefore, this paper provides the following definitions and taxonomy. A robot can be used in one of three types of events: normal, off-normal due to an emergency, or off-normal due to novelty.

An off-normal event due to an emergency is when a robot is being used to respond to or mitigate an abnormal situation that is declared by the responsible authority to be time-critical. Emergencies are generally extraordinary. A hurricane is an emergency, an emergency room in a hospital is not. In an emergency event, the robot may be used for a normative application, but the humans must perform under pressure from time and consequences. For example, a small unmanned ground robots (UGV) for bomb squads and military operations were used during the Fukushima Daiichi nuclear accident for missions routinely encountered in those applications (open a door, go inside, look around, pick and examine an object, etc.) [2], but a failure in completing the mission or taking too long to complete the mission would have significant consequences. More often than not, a robot is used during an emergency for a novel application. For example, during the Fukushima nuclear accident, a small unmanned aerial system (UAS) typically used to track vehicle movement in the desert was used for inspection of the reactor buildings [2]. Both examples illustrate how emergencies stress the humans interacting with the robot.

However, an off-normal event can be different due to novelty, that something has changed about the normal way of working. There are five ways in which a routine can be disrupted:

- *Robot:* The robot platform and its capabilities has changed. This may be due to the replacement of an existing robot with a new or upgraded robot, the addition of a payload, the change in software, etc.
- *Mission:* Either the objective or the set of tasks the robot will perform has changed. This could be due to a new mission or use for the robot. It can also be due to a new workflow for accomplishing an existing mission, such as adopting a new set of best practices. Since the applications for robots is still formative

- *Robot Work Envelope:* The physical environment in which the robot will perform the mission has changed. In a building collapse, the physical environment is now spatially restricted and cluttered with debris.
- *Humans:* The composition of the operators, mission specialists, and any other humans directly involved in using the robot for the mission changes, either new people are introduced or roles change, or the skills and cognitive capacity of the humans change. A robot operator may not be trained for a new mission or may be ill. A structural inspection mission may require an engineer who has never worked with the operators to help direct the robot.
- *Human Work Envelope:* The physical environment in which the humans directly involved in using the robot for the mission are working has changed. The changes might be due to weather (humans used to working in warm weather are now working in bitter cold), safety (humans have to wear gas masks or hazmat suits), or background distractions (humans have to work in an unusually noisy or distracting setting).

The first three factors on the list above--- Robot, Mission, and Robot Work Envelope-- are generally referred to as the ecology of the robot in behavior-based robotics [4]. The other two factors capture how the human fit within the larger human-robot ecology.

3 A Model of Cognitive and Attention Resources in Field Robotics

The taxonomy presented in the previous section identifies types of influences on the overall human-robot interaction in a robot but falls short in connecting those influences to human error. This section introduces a model of cognitive and attention resources for field robots, describes how the five attributes of a human-robot system contribute, in conjunction with physiological and psychological drains, to cognitive and attentional deficits, which in turn increase the potential for human error.

Our model groups the drain on the cognitive and attentional resources for a human directing a robot into three broad categories: task demands, perceptual demands, and team work demands. These are described as follows.

Task demands stem from how the robot is used to accomplish the tasks. A human can be presented with a new robot, upgrades or software that changes how a task is performed. A new mission can either uses existing tasks and skills but in different ways or it can require new tasks and new skills. A mission can be performed under notably different environmental conditions, such as flying a small UAS during the day and flying the same mission at night. Using the taxonomy, changes in task demands would be seen as changes in the Robot (change in platform, sensors, or software), Mission (changes in tasks), Robot Work Envelope (changes in environment), and Human (changes in requisite skills).

Perceptual demands stem from the challenges of perceiving a distal environment, and actions upon said environment, that is mediated by a robot and interface. The human users are trying to comprehend an environment that may have changed and is being viewed from unfamiliar angles, such as from very near to the ground or a bird's eye view. Perception of the distal environment is further impacted by the design of the user interface, which may not display all relevant data or display it poorly. Using the taxonomy, changes in perceptual demands would be seen as changes in the Robot (change in sensors or sensor placement), Robot Work Envelope (operating in a deconstructed environment), and Human Work Envelope (change in the user interface).

Team work demands stem from the interaction between the human and robot, but also the interactions between multiple humans. Many robot missions benefit from multiple humans working together, for example, experiments show that two responders using a single robot to find a victim are nine times better than a single responder using the robot [5]. Regulations may require multiple operators, such as Federal Aviation Regulations for visual observers to assist pilots in safe UAS operations. An off-normal event is often characterized by additional personnel, for example, experts or decision makers looking over the shoulder of operators, as seen at Hurricane Harvey [6], or operators working in teams rather than solo during training to maximize teaching efficiency. Using the taxonomy, changes in team work demands would be seen as changes in mission and in humans.

Following Wickens Multiple Resource Theory [3], if the sum of these demands exceed the current capacity of the human, then increases in human error are expected to result. However, off-normal events may decrease the inherent capacity of the human through physiological and psychological effects. In an emergency, responders, including robot operators, get very little sleep, perhaps only 3 hour power naps [7]. The operators may be asked to work a 24-hour or longer shift, as we witnessed at the 2018 Kilauea volcanic eruption where a small UAS crew worked a full day shift but were then called out for a night shift. The responders have less quality of rest, essentially camping out in harsh conditions. In addition, the graveness of emergencies imparts a psychological burden on responders; it is impossible not to think about the disaster and its impacts or not to worry about the robot's performance [7].

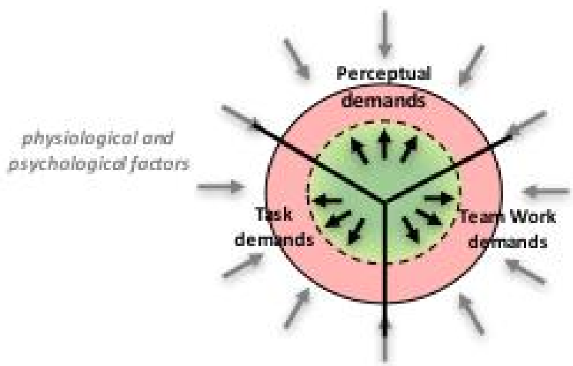

Figure 1: A model of cognitive and attention resource demands in field robotics.

Figure 1 provides a graphical metaphor. The outer concentric circle represents the absolute fixed amount of an individual human's cognitive and attentional resources. The inner circle represents the actual resources consumed to meet the task, perception, and team work demands. If the task, perceptual, and team work demands (arrows radiating out) are low, shown in green, then human error due to these demands (as opposed to human error for other reasons) would be less likely. If the demands are high and approach the human's limits, shown in red, the cognitive pre-conditions for human error will increase. However, the size of the outer circle can be diminished due to physiological and psychological pressures (arrows directed inward). This means that even if the task, perceptual, and team work demands remain the same as for a normal event, it is possible that physiological and psychological pressures of an off-normal event can drive the human into a region of high likelihood of making an error.

The model of cognitive and attention resource constraints and demands helps solidify the differences in potential for human error between novel and emergency events. In both an emergency and novel event, one or more of attributes of a robot system (the robot, mission, robot work envelope, humans, or human work envelope) changes. These changes may or may not lead to an increase demand on cognition and attention that exceed resources. A novel event may have some physiological and psychological costs that decrease the available resources, but in general, since it is not an emergency, the humans would be expected to be well-rested, in good health, can arrange to be in a work-conducive setting, and can control when they take breaks and pace of work. However, in an emergency, the humans operating the robot will always experience physiological and psychological deficits due to the nature of emergencies. These deficits go beyond apprehension of trying something new or being inserted into a new group of people or location.

4 Two Case Studies of Emergencies

Our participation as part of the Center for Robot-Assisted Search and Rescue (CRASAR) for its two most recent deployments to federally declared disasters provides case studies that illustrate how emergencies increase the likelihood of human error. CRASAR has participated in 30 disasters since 2001, for the sake of space, only the two are discussed.

4.1 2018 Kilauea Volcanic Eruption

CRASAR deployed to the Kilauea volcanic eruption to assist the Hilo, Hawaii, Department of Civil Defense with small UAS from May 14 to May 19, 2018. The team flew a total of 28 day time flights and 16 night time flights to fulfill three types of missions: debris/damage/flood estimation, strategic situation awareness/reconnaissance/survey, and tactical situation awareness. The team did not have a predictable schedule and worked more than 12 hours on May 14 and more than 24 on May 17-18. The team had to carry, and often wear, respirators to protect from SO2 emissions as shown in Figure 2. The human work envelopes were generally stationed close to the volcano, on the order of 0.1 mile to 0.25 miles; this was considered outside of the range of lava and debris explosions but the noise was deafening.

Figure 2: Pilot and visual observer wearing respirators during exposure to SO2 at Kilauea volcanic eruption.

CRASAR provided four models of small UAS and five pilots, three of whom had flown at multiple disasters and all but one were cross-trained on all models. The team members were all proficient with the robots, and had flown together in exercises. The team divided into three squads, with two of the squads consisting of a pilot, visual observer, and data manager, and one a pilot and visual observer. The team members had flown from Texas, Florida, and Utah, and arrived with jet lag from long flights and the three- to five-hour time difference. The squads travelled approximately 1.5 hours between the affected areas and a rented house, where team members each had a bed and most had a private room.

The high potential for human error was observed on one occasion. On the night of May 14, the team was given a routine survey mission, requiring the use of a new DJI Zenmuse XT2 thermal sensor on the DJI Inspire. The pilot had not used the Inspire in over a month and had to fly the first mission at night from a small landing zone surrounded by difficult to see power lines. The Inspire evinced a platform problem on the first flight, was landed successfully and fixed. On the second flight, the platform encountered electromagnetic interference to the compass and inertial measurement unit which caused the UAS to randomly change direction. This forced the pilot to put more effort into navigation. The mission was successfully completed. Note that Robot had changed from normal operations (new sensor), Robot Work Envelope had changed (more constrained than normal, night), the Humans had changed (skills were rusty), and the Human Work Envelope had changed (wearing gas masks, night, noisy explosions).

On the night of May 16, the team was given a routine mapping mission from a previous site. It was flown with the DJI Inspire but now operations were routinized. The mission had to be repeated three times as the platform did not correctly record imagery on the first two flights. The cause was presumed to be human error: that the data manager or pilot had done something wrong in setting up the autonomous software or the data transfer process and, through increasing the level of detail of the methodical check and confirmation of each step in the process, finally performed the correct sequence. While this could have been a software error, the error never reappeared. Note that the only change from the previous two days was the humans' degraded physiological condition from lack of sleep and rest.

During the day of May 17, one of the pilots had a problem with a software program that allowed autonomous image collection; it would not reach altitude and collect pictures but would simply hover. Eventually the pilot determined that the altitude limit from a previous flight in the continental US had not been reset on the configuration menu to the appropriate limit for the volcanic event. The autonomous program then performed correctly. Again, the only change was the humans' degraded physiological condition from lack of sleep and rest.

4.2 2018 Hurricane Michael

Figure 3: Typical human work envelope at Hurricane Michael.

Hurricane Michael made landfall on October 10, 2018. CRASAR, under the direction of the Center for Disaster Risk Policy, a member of the State of Florida Emergency Response Team, deployed to Hurricane Michael with small UAS. The team flew a total of 80 flights to fulfill 26 missions from Oct. 11 to Oct 14. at Panama City and Mexico Beach. Small UAS were used for three types of mission: debris/damage/flood estimation, strategic situation awareness/reconnaissance/survey, and ground search. The squads flew a predictable schedule, from early morning to sun down each day, and conducted one mission at night, and from much less restrictive work envelopes (see Figure 3).

The deployment was different Kilauea in many ways, most notably that the response had a predictable pace. The model of robots used were different, but the pilots were expert in their use. The missions, with the exception of ground search for missing people, were identical to Kilauea, but more of the missions involved photogrammetric mapping surveys. The robot work envelope was smaller, as temporary flight restrictions limited flights to 200 feet AGL versus 1, 000 feet AGL.

There were 11 pilots forming 6 squads, everyone on a squad knew each other and had flown together. Four of the five pilots from Kilauea participated, along with two other pilots who flew regularly with CRASAR. However, five additional pilots had not flown with the CRASAR pilots before, and only one of the four had post-disaster flying experience. Two of the eight pilots were unfamiliar or rusty with the DroneDeploy photogrammetric mapping software for survey missions. Four of the pilots traveled from Texas, 2 pre-deployed and the other two drove for about 18 hours after the landfall. Eight of the team slept on cots in the Walton County Emergency Operations Center, about a two-hour drive from the affected areas; the rest stayed in hotels similarly far away. The teams were divided into 6 squads. Five of the squads included a Pilot and usually a Visual Observer due to high density of manned aircraft and other UAS from news organizations and from unauthorized flyers. If a squads had multiple pilots, they turns flying to give each other rest breaks.

Human error was observed on two occasions. Several squads had task errors where they mislabeled data, which was corrected by the data manager. The error was possibly due to lack of familiarity with the protocols, but the need to finish the flights before night fall and the distracting excitement of participating in a disaster, plus fatigue, probably heavily contributed to disregarding the protocols.

A more serious error was the generation of an overlap in the areas of two different UAS and the failure of one squad to detect a potential midair collision. In this situation, one of the two squads working in adjoining areas specified a region for their UAS to map that overlapped the region assigned to the other squad. By coincidence, both squads specified the starting point for the flight paths such that both UAS happened to be flying in the area of overlap at the same time at the same altitude. Fortunately, one squad saw the other UAS and changed altitude and aborted their mission to avoid a collision. It was unclear that whether the other squad was aware of the proximity of their UAS to the other. The squad that detected the problem was more experienced that the team in the adjacent sector. Note that the Robot Work Envelope had changed from normal situations (other UAS in the vicinity, which is uncommon) and the Humans had changed (one squad was not experienced).

5 Ramifications and Recommendations

Off-normal operation of robots should be of high interest to the human factors community because these deployments have high consequence if they are for an emergency and because off-normal conditions occur frequently due to upgrades, new features and best practices, and the identification of new applications for unmanned systems.

In terms of minimizing human error in emergency off-normal events, there are at least three non-exclusive approaches. One is to pro-actively minimize the novelty of the human-robot system being deployed. Three possible methods are below:

- Humans should have expert skill in normal conditions and, ideally, experience or training in novel and emergency conditions.
- Deployments should avoid the insertion of new technology, software updates, or anything else that could increase the potential for human error. This may

not be possible. For example, the use of the XT2 and the toxic gas sensors were essential to the missions. However, these were minor modifications. One of the pilots had experience with the XT2 so it was not particularly novel and the toxic gas sensor was flown in benign conditions. On the other hand, during Hurricane Harvey, a UAS manufacturer put out a mandatory software update which introduced a dangerous bug.

- A "warm-up" area should be set aside to allow operators to refresh rusty skills or try out a new sensor before the actual mission. This may not be possible due to the location of the event or time pressures.

A second approach is to minimize unfavorable conditions for the humans. Perhaps the most obvious is to specify crew rest requirements. However, any such policies may have to be violated due to the exigency of the emergency. Sometimes responders simply have to work day and night. Also, the risk of a robot failure may be acceptable; the loss of a platform over a lava field is a relatively small monetary loss versus the reward of safely evacuating civilians.

A third approach is to mitigate the unfavorable conditions for the humans. Mitigations might be:

- Training individuals and teams for resilience.
- Minimizing the number of new members in a squad so as to preserve established norms.
- Require crew resource management protocols, such as having checklists, mission rehearsal, verbal protocols, a "sterile cockpit" with no unnecessary conversation, keeping observers or non-essential personnel out of the personal zone of the pilot to prevent distractions, and so forth.
- Increased autonomous capabilities, but these should be normative rather than only for use when the human's cognitive and attentional resources are depleted. The human may not trust a transfer of the autonomy and supervising the autonomous capability may further overtax the team. Also, if the autonomy was sufficiently good to be used to replace a person, why would it be used only in extraordinary situations?

A related topic is fostering trust in the unmanned system by explicitly considering whether the off-normal event significantly changes the normal use patterns of the robot. To date, managers are reluctant to use a robot for an off-normal situation. However, the use of a robot for a situation where it is performing an identical mission and a similar work envelope with trained, rested operators working in favorable conditions would not be expected to increase the frequency or severity of human error. The likelihood of a mission failure would be similar to the likelihood of a failure for the normal case. Given that the robot is used for normal events, the risks should be well understood.

The growing use of unmanned systems, and the continuous beta product development cycle, means that off-normal events will become more prevalent. This is an opportunity for the human factors community to investigate how to design autonomous capabilities or decision support for off-normal events, what training will produce resilient operators, and what mitigations are effective (crew rest schedules, checklists, crew resource management, protocols, and so forth).

Our current research efforts, with colleagues Drs. Ranjana Mehta and Camille Peres at Texas A&M, are focusing on quantifying the difference between normal and off-normal events, analyzing data from CRASAR deployments to inform crew rest requirements and mitigations, and creating resilience training for robot operators.

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