Toward Autonomous Rotorcraft Flight in Degraded Visual Environments: Experiments and Lessons Learned

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ABSTRACT

Unmanned cargo delivery to combat outposts will inevitably involve operations in degraded visual environments (DVE). When DVE occurs, the aircraft autonomy system needs to be able to function regardless of the obscurant level. In 2014, Near Earth Autonomy established a baseline perception system for autonomous rotorcraft operating in clear air conditions, when its m3 sensor suite and perception software enabled autonomous, no-hover landings onto unprepared sites populated with obstacles. The m3's long-range lidar scanned the helicopter's path and the perception software detected obstacles and found safe locations for the helicopter to land.

This paper presents the results of initial tests with the Near Earth perception system in a variety of DVE conditions and analyzes them from the perspective of mission performance and risk. Tests were conducted with the m3's lidar and a lightweight synthetic aperture radar in rain, smoke, snow, and controlled brownout experiments. These experiments showed the capability to penetrate through mild DVE but the perceptual capabilities became degraded with the densest brownouts. The results highlight the need for not only improved ability to see through DVE, but also for improved algorithms to monitor and report DVE conditions.

Keywords: degraded visual environment, lidar, radar, unmanned aerial system, helicopter, brownout

1. INTRODUCTION

The deployment of unmanned rotorcraft reframes the problems caused by degraded visual environments (DVE) and raises new questions. When operating in DVE, pilots have limited ability to detect obstacles in time to avoid them. Irrespective of being a person in the cockpit or an automated control system, pilots loose their situational awareness and spatial orientation when their sensors become obscured. This can occur suddenly as the weather shifts due to environmental conditions like low light, fog, rain, and snow (Fig. 1). The helicopter also can induce a DVE when the rotor downwash blows particulates, like dust (brownout) or snow (whiteout), into the air during landing.

For human pilots, obscurants are a leading cause of death and rotorcraft accidents. NATO reports that 75% of rotorcraft accidents[1] in arid climates like Afghanistan and Africa have been caused by DVE brownout condition. Similarly, in the civilian world, flying into inadvertent instrument meteorological conditions (IIMC) accounts for 5% to 9% of all accidents.[2]

Unmanned aerial systems (UAS) are a natural tool for handling this danger. A UAS goes one step beyond pilot's aids by removing the pilot entirely from risky situations. Unmanned cargo missions through DVE only risk damage to the helicopter and cargo and no longer risk the loss of the pilot's life.

The limiting factor which will prevent application of UAS in DVE environments is the performance of the UAS perception system. The perception system uses raw data from sensors such as lidar, radar, and cameras to interpret the world. These sensors can be obscured just like human vision. The amount that they are affected by DVE depends on the sensing modalities and the algorithmic design as well as the specific type of obscurant.

Near Earth Autonomy has started to measure the effects of DVE on its functioning, state-of-the-art, UAS perception system composed of the m3 sensor suite and custom perception software. The system was built for the Office of Naval Research (ONR) Autonomous Aerial Cargo/Utility System (AACUS) program. This program funded technology development to allow an untrained Marine to call an unmanned rotorcraft for resupply in an

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Figure 1: Near Earth Autonomy m3 sensor suite installed on the nose of a Boeing H-6U Unmanned Little Bird (ULB). It enabled the ULB to perform autonomous, no-hover landings.

unprepared location. A remote operating base would then dispatch the helicopter. The UAV would navigate to the Marine's location while avoiding obstacles and selecting a safe place to land. In February 2014, m3 empowered the Tactical Autonomous Aerial LOgistics System (TALOS)[3] helicopter to perform 23 autonomous missions to an unprepared landing zone (Figure 1). As the helicopter flew, m3's scanning lidar swept over the helicopter's potential path to identify any hazards. During final approach m3 focused on the target landing zone to measure the undulations of the ground to find level, safe locations to touch down. This architecture defined a baseline level of performance against which the effects of DVE on perception algorithms and interfaces can be understood.

2. PERCEPTION SYSTEM

2.1 m3 Sensor Suite

The perception suite is designed to maximize mission performance. The prototypical AACUS mission requires no-hover landings from a flight speed of over 100 kts. This requires sensing hardware which can keep the helicopter safe in flight and analyze the terrain en route. These requirements inspired the m3 sensor suite's integration of a nodding 2D lidar, inertial navigation system, and cameras. The lidar is the primary sensor for safe flight; it scans a 100° horizontal field-of-view while the active sensor planning[4] focuses scanning vertically on regions of interest. This allows wide sweeps to clear the flight path as well as focused scanning on far-away terrain. The sensor scans for hazards at 42k measurements per second with a typical maximum range of 1.1 km.

The sensing hardware sitting on the nose of the helicopter feeds perception software running on an onboard computer. The perception software system interacts with the rest of the autonomy software by mapping all obstacles in up-and-away flight and analyzing terrain for landing. The obstacle mapping and landing zone evaluation modules are the principal components will be effected by DVE.

2.2 Obstacle Mapping

The obstacle mapping module generates a 3D map of hazards to flight. The hazards must be mapped at far enough range for the planner to correct its commanded trajectory and for the helicopter controls to react. Typical hazards include wires, trees, towers, buildings and terrain.

The core obstacle mapping algorithm discretizes the world into a set of 3D boxes, or voxels. For each voxel, the system estimates the likelihood of occupancy by fusing the sensor data over time. This map is initialized with

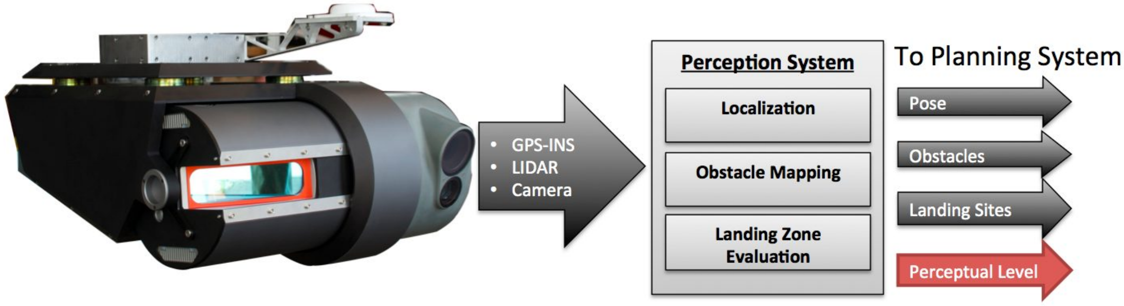


Figure 2: Near Earth Autonomy's m3 sensor suite uses m3's nodding 2D lidar as its main sensor. Additional cameras are used for advanced perception development. The perception system analyzes the data to output locations of obstacles and safe landing locations. Algorithms monitoring performance of the perception system in response to DVE are being developed. This Perceptual level, shown in red as a future addition, will be added to allow operation in the full range of DVE situations.

any available prior database of obstacles and terrain, but it relies on real-time sensor updates for true safety. In flight, m3's lidar scans continually update this map using a probabilistic sensor model. Each lidar beam provides measurements of likely free space and space occupied by a potential hazard. By tracing along each lidar beam, the algorithm updates each cell the lidar passes through as unoccupied. Any cell in which the lidar reflected an echo is measured as occupied by a potential hazard.

2.3 Landing Zone Evaluation

The landing zone evaluation module uses the geo-registered lidar data to find safe locations to land. The most basic evaluation algorithm performs purely geometric checks for a location's safety. The location must be neither too sloped, nor be too close to any obstacle. This analysis is performed continually during an approach to landing. m3's nodding lidar scans a target landing area and generates 3D point cloud models of increasing accuracy and resolution as the helicopter gets closer. The evaluation algorithm fits a terrain model to the lidar point cloud. Obstacles are then identified by analyzing lidar returns above the terrain model.

3. DVE EXPERIMENTS

Near Earth performed experiments at several points along the DVE continuum to understand how the m3 perception suite would function when installed on a fielded UAS. The DVE continuum extends from the clearest day with extreme visibility to the densest dust-filled brownouts. At each point along the continuum, the decreased level of visibility and increased particulate concentration causes decreased perceptual level. The perception system has reduced sensing range and increased noise in its obstacle detection measurements.

3.1 Clear Air Conditions

The least degradation and peak perceptional performance occurs during clear air conditions. m3 has been tested in over 100 hours of flight testing in clear air conditions and it is in these conditions that any autonomy architecture achieves peak performance. In 100 kts flight, m3's lidar begins to see obstacles at 1.1 km and fully maps the typical large obstacles like towers, trees, or terrain by 800 m. During approaches to landing, it can analyze the terrains shape and map 60 cm obstacles by 200 m from the landing zone.

This peak performance extends to clear air conditions at night time or in dull light. m3 uses an active sensor, lidar, to perceive. It does not need ambient lighting. It is therefore unaffected by low or dull light that can be dangerous to human pilots who need ambient lighting to see hazards.

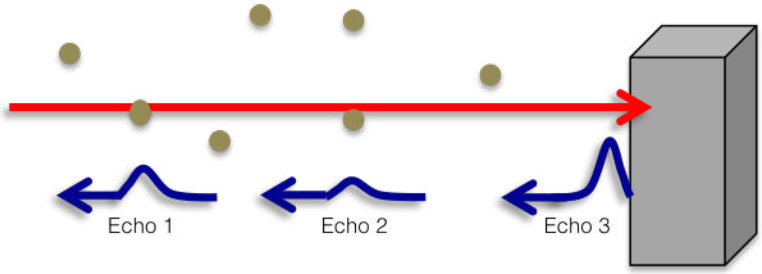


Figure 3: A cartoon of full wave form lidar processing. The lidar simultaneously detects the particulates in the air and the obstacle they are obscuring. The red lidar beam passes through the dust cloud and is first reflected by the dust particles. This causes echoes one and two. The last echo reflects off of an obstacle. All of the reflected echoes are extracted and used by the perception software.

3.2 Haze, Mist and Fog

Haze, mist, and fog are among the meteorological conditions that reduce visibility due to fine particulates suspended in the air. Haze occurs from pollution while mist and fog occur as water saturates the air. Entering dense fog is like entering a low stratus cloud. Visibility can change from over 50+ km in exceptional clear air to fewer than 50m in dense fog.

For autonomy, the primary effect of this diminished visibility is a reduction in the speed at which the helicopter can safely fly. A helicopter's perception system must sense, identify and communicate a hazard with enough time for the helicopter to maneuver to avoid it. If visibility is reduced, the look-ahead time for that warning is reduced and the flight speed must be lowered to compensate. In severe conditions this may require a slower flight speed than is possible given other aerodynamic or mission constraints. As a result, the autonomy will need to choose the more dangerous situation: flying blind or flying too slow.

The secondary problem for autonomous systems is that current state of the art does not account for environmentally changing sensor visibility models. Research and development systems have only operated in relatively clear air conditions where it is possible to define a single static model for the range to which the sensor can see. The Laser Obstacle Avoidance Marconi (LOAM)[5] were designed to a minimum visibility operating requirement but did not track decreased performance as visibility changes. The unmanned Rascal,[6] RMax,[7] and m3 used a single probabilistic model to update their map of safe, unoccupied space. In m3's obstacle mapping algorithm the problem appears in its notion of measuring free, safe space by emitting a laser shot but receiving no return echo. Since there is no echo, this is no range measurement. The system needs to make an assumption about the distance along the lidar beam to which to measure as free space. If this assumed range is a static quantity, it will always be an over estimate during reduced visibility DVE. This will make the system mistakenly confident that space it has never seen is free of obstacles.

3.3 Low to Moderate Density Particulates

Large particulates in the air cause degradation of perceptual capabilities by blocking a scene and distracting sensors. These particulates can be rain, snow, smoke, dust, etc. With low levels of particulates, the majority of the scene is still visible and the particulates themselves are detected by the sensor. As the concentration of particulates increases more of the scene is blocked and the particulates make up a larger portion of the sensor data.

At the lowest level, m3's lidar was designed to robustly operate in the presence of particulate noise. The particulates appear in the sensor data as spurious points in the air but the scene behind the particulate is still measured. m3 uses a technique called full wave form processing (Figure 3) to analyze its lidar returns. Its lidar emits a short burst of laser light which can shine on multiple surfaces as it travels. The sensor continuously samples the reflected signal and can detect each individual echo from the particulates or obstacles. This technique was developed in the surveying lidar world to see through vegetation to terrain and it is invaluable for seeing through low to moderate density clouds of particulates.

Figure 4: m3 guided the Unmanned Little Bird to land even in the presence of snow. m3 scanned and remembered the landing site before it became obscured.

The perception system then uses preprocessing algorithms to filter the particulate noise. Particulates are easily identifiable by being the first or middle along a lidar beam. Large obstacles and terrain reflect the entire lidar beam. They provide the final return from the lidar beam. Additionally, the particulates are filtered as high frequency spatial noise. This filtration occurs both as an individual scan line is processed and after the lidar is added to the obstacle map. Along a lidar 2D scan line, consecutive points assumed to be physically close to one another if they are scanning the same, smooth surface. Large jumps of single points are likely particulates in the air rather than obstacles. These large jumps are filtered. At the obstacle mapping level, voxels only occupied by particulates are marked as unoccupied because the majority of other lidar beams pass through the voxel.

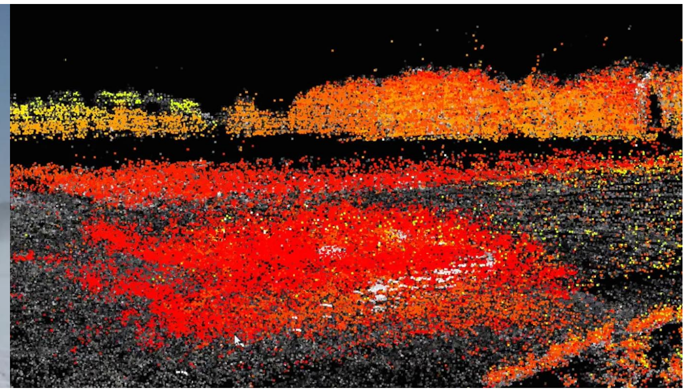
These techniques were opportunistically applied in the presence of light snow. Tests in light snow occurred during demonstrations with the Unmanned Little Bird helicopter (Fig. 4). m3 applied the see-and-remember strategy for DVE. m3 scanned the landing zone over 250 m away. The system then decided where to land and ignored the increased snow particulates during landing. Another test was conducted after heavy snow in Pittsburgh, PA. In this test, data was collected to analyze performance in whiteout conditions. An obstacle was placed on a snow covered grass runway as a Bell-206 came to a hover (Fig. 5). The induced whiteout visually obscured the hazard. In the raw point cloud from m3's scanning lidar, the obstacle was present and surrounded by snow points floating in the air. However, after applying m3's filtering to remove the snow particles, the obstacle was obvious.

Similar controlled tests were conducted with light to moderate density smoke. They were performed by detonating a smoke pot (Fig. 6). These commercial smoke pots were designed to simulate smoke in city block sized areas. They released $14,000\ m^3$ of white dense smoke during a five- to six-minute burn time. The smoke contained 0.1 to 0.001 mm diameter particulates. Near Earth conducted perception flight tests with these pots during landings on to a grass runway. On approach to landing, the white smoke was released while the lidar scanned. The lidar penetrated the less dense smoke and could detect box obstacles on the runway. The same filtering algorithms that allowed the lidar to see obstacles through snow allowed the lidar to operate in the presence of the smoke. However, the lidar was blocked by the densest concentrations of smoke.

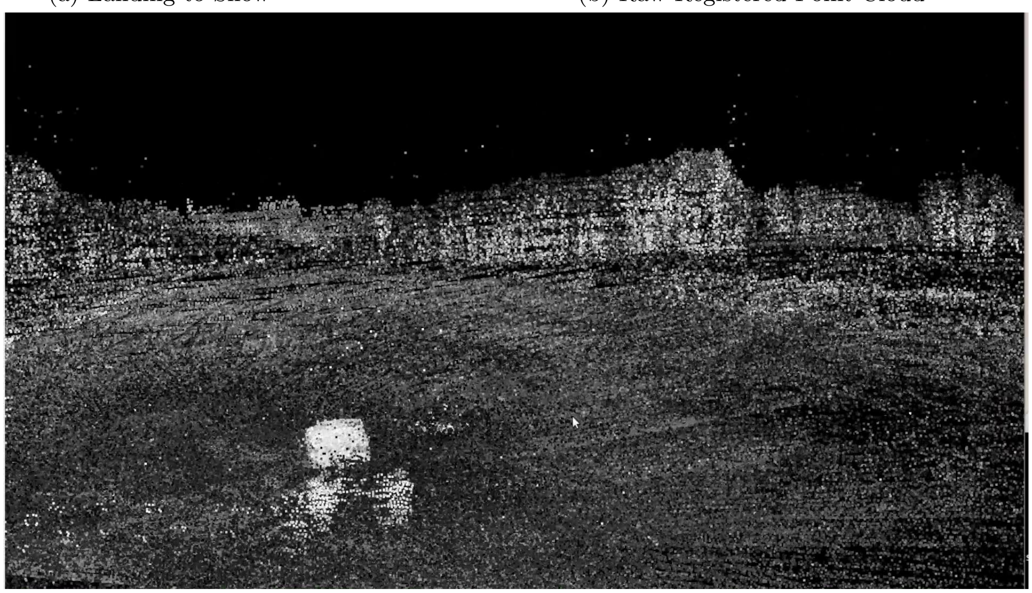
3.4 High Density Particulates

The worst degradations and highest risk of accidents occur during missions through high concentrations of particulate DVE. These are meteorological conditions like heavy snow, heavy rain, dense smoke or aircraft induced conditions like brownout or whiteout. In these situations the particulates block visibility completely for small wave length sensors. Human sight, visibile range cameras, long wave infrared cameras, and lidar can all be

(a) Landing to Snow

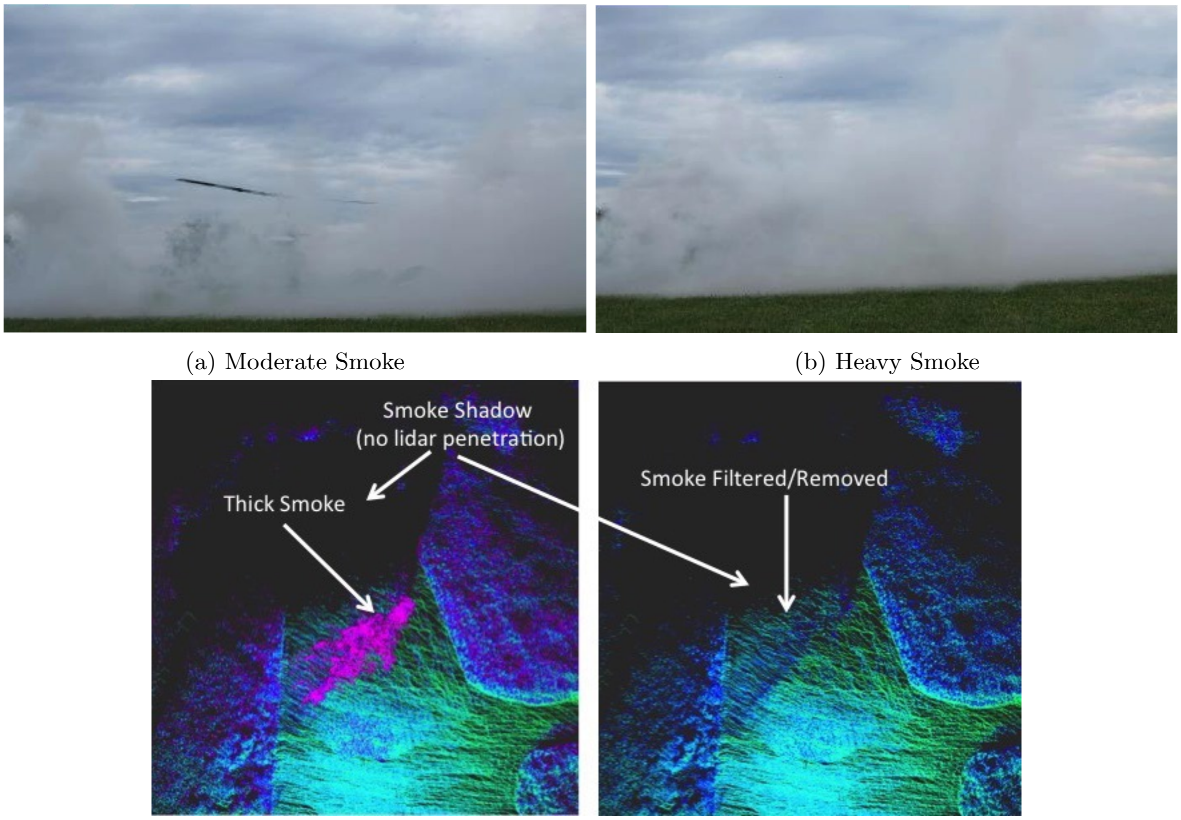


(b) Raw Registered Point Cloud



(c) Point cloud after filtering algorithms removes the snow.

Figure 5: Tests to snow covered runways allow safe testing in whiteout like conditions. The hovering helicopter blows up snow which can hide obstacles in a 3d point cloud (3d). Through smart filtering algorithms, these obstacles are uncovered (c).



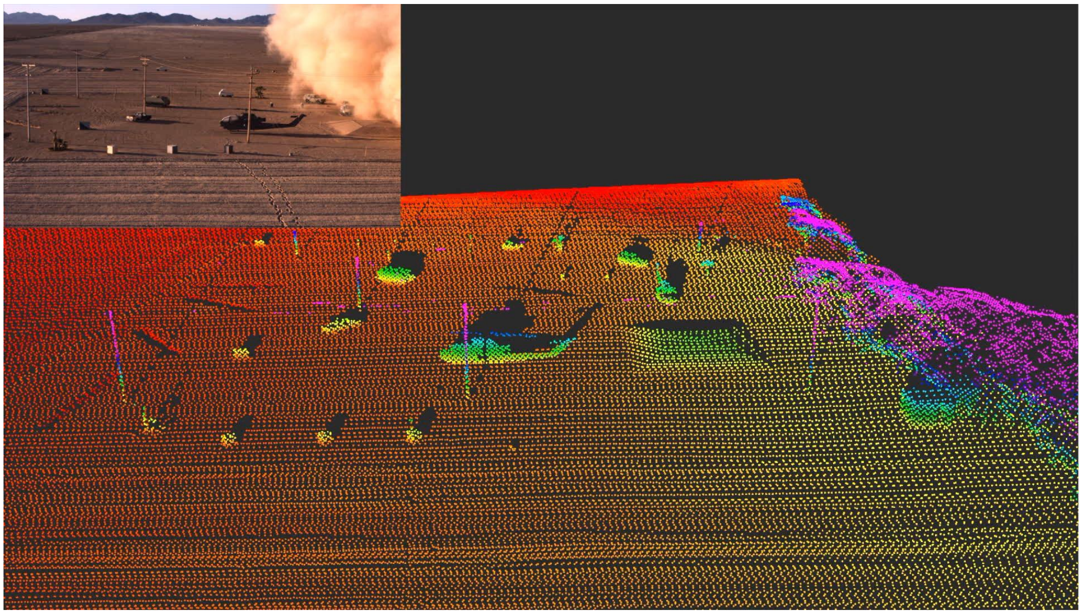
(a) Moderate Smoke (b) Heavy Smoke

Figure 6: Near Earth conducted experiments with seeing through smoke at landing zones. Advanced filtering techniques remove smoke particles from the lidar and allow m3 to see through smoke. The above are rendered point clouds from the scanner during smoke testing. The lower left image shows the raw lidar while the lower right image has been processed to remove the smoke. The heavy smoke is too thick for lidar to penetrate.

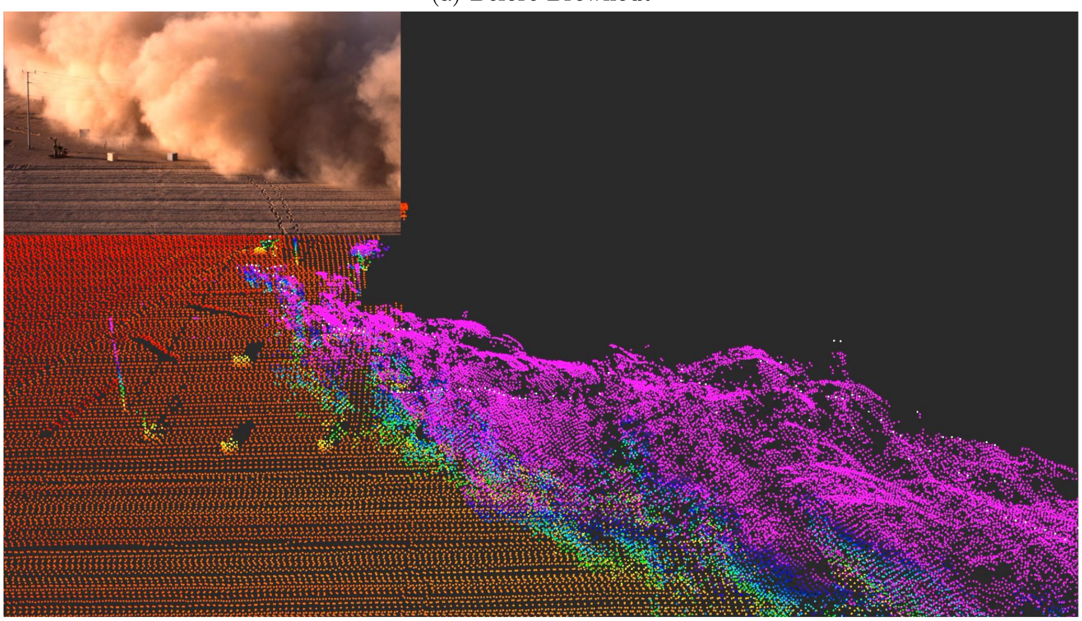
completely obscured. This makes these conditions the most important DVE types to test against but also the most dangerous.

The United States Army Research, Development and Engineering Command developed a safe testing regime as a part of their DVE Mitigation (DVE-M) program. They invited Near Earth Autonomy to Yuma Proving Grounds (YPG), Arizona, to perform ground based brownout testing. YPG staff created DVE-LZ in the middle of the Arizona desert. DVE-LZ is a prepared 308 m x 298 m obstacle field surrounded by finely raked dust. As test sensors scanned the obstacle field, a EH-60L Blackhawk helicopter fouled the obstacle field by maneuvering over the dust to blow up a brownout. The sensors were mounted on a 30 m tall tower over looking prototypical obstacles like utility poles, wires, mounds, helicopters, and trucks. These obstacles are arrayed at distances of roughly 100 m, 200 m, and 500 m to test the ability of the sensors to resolve hazards at different distances. The program tested the sensors in three different conditions: clear air, brownout, and chalk 2. Clear air conditions had no obscurants and provided a base line for detections. During brownout the sensors witnessed the field before being obscured as if they belonged to the first helicopter landing to a dusty site. This allowed see and remember techniques to scan the field before full dust coverage. Chalk 2 tests were analogous to sensors viewing a landing zone already fouled by earlier helicopters landing to the dusty site. The sensors had no time with clear air with which to remember the landing zone.

Theoretical analysis and prior experimentation had shown that lidar alone would not allow an autonomous system to see through dense brownout. Studies of the DVE pilot assist SFERION lidar[8] and Opal lidars[9] showed moderate to heavy brownout drastically reduces the range of the 1550 nm lidar. Lidar can see through dense concentrations of dust but only because there are local low density windows allowing the lidar through.



(a) Before Brownout



(b) During Brownout

Figure 7: Brownout experiments performed at Yuma Proving Grounds. Color imagery from m3's forward visible imager are overlaid on 3D point cloud from m3's lidar. The point cloud is colored by elevation. During clear air and brownout experiments (a) m3 generates accurate 3d models of the obstacle field which can be remembered after obscurance. During brownout, the dense dust blocks the lidar. Obstacle shown are in the near field, approximately 100 m away from the sensor.

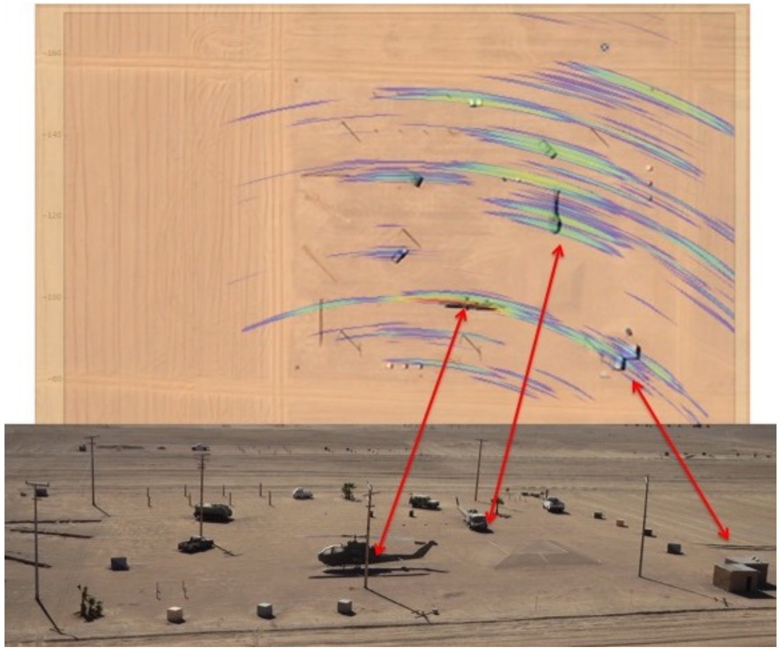


Figure 8: (Top) IMSAR radar results during full brownout of the YPG obstacle field. IMSAR's radar returns are overlaid an orthographic view of the YPG testing field. The radar was unaffected by the dust and clearly picks up on the large obstacles. The synthetic aperture radar only received a yawing motion over the field which only enabled sensing a limited spatial resolution.

Near Earth Autonomy partnered with IMSAR to test a low SWaP-C millimeter wave radar along side m3 during brownout conditions. Unlike fielded 94 GHz DVE radar systems, IMSAR offers a Ku-band (12-18 GHz) synthetic aperture radar (SAR) that could be easily integrated into the m3 sensor suite as a complementary sensor. Each radar measurement has a large beam width, 6°, but the SAR technique allows fusing measurements as the helicopter moves to create spatial high resolution models. Typically SAR is used as side looking SAR where the radar scans perpendicular to the direction of travel. This geometry generates the highest resolution model but would require dedicated survey over-flight to utilize in DVE. However, the radar can also be used as forward looking SAR to enable no hover direct landings. This can be performed can be performed at the cost of model resolution. In both cases, the radar acts as a lower resolution fall back sensor for the lidar to enable safer flight in the presence of DVE.

During clear testing both sensors demonstrated the expected, nominal performance. m3 was able to scan the obstacles to sub-centimeter accuracy (Figure 7). Even the smallest obstacles, the wires running across the utility poles were identified. As expected, the radar solution had low angular resolution and could not detect the smallest obstacles like wires (Figure 8). The expected low resolution was due to the lack of translational movement of the radar. This lack of movement prevented creation of the synthetic aperture for the radar. However, with the minimal movement the radar was still able to clearly detect the large hazards in the scene like helicopters, trucks, barrels and poles.

During brownout the lidar became obscured while the radar remained unaffected. Before the dust cloud moved in m3 generated detailed a detailed map. Then as the thickest dust cloud blew over the obstacle fields, m3's lidar was entirely obscured. During one tests where the concentration dust blown by the helicopter was lower, m3 was able to see through the dust cloud to the obstacles in the 100m range field. The full wave form lidar simultaneously captured the dust, the terrain, and obstacles behind the cloud (Figure 9). On the other hand, throughout the brownout and chalk 2 experiments the radar was entirely unaffected by the dust. No matter the brownout dust concentration the radar provided real time feed back of the world.

Experiments at Yuma Proving Grounds confirmed that a UAS equipped with an existing m3-like perception system would mitigate much of the risk of landing in brownout. In a future mission, the UAS would load the

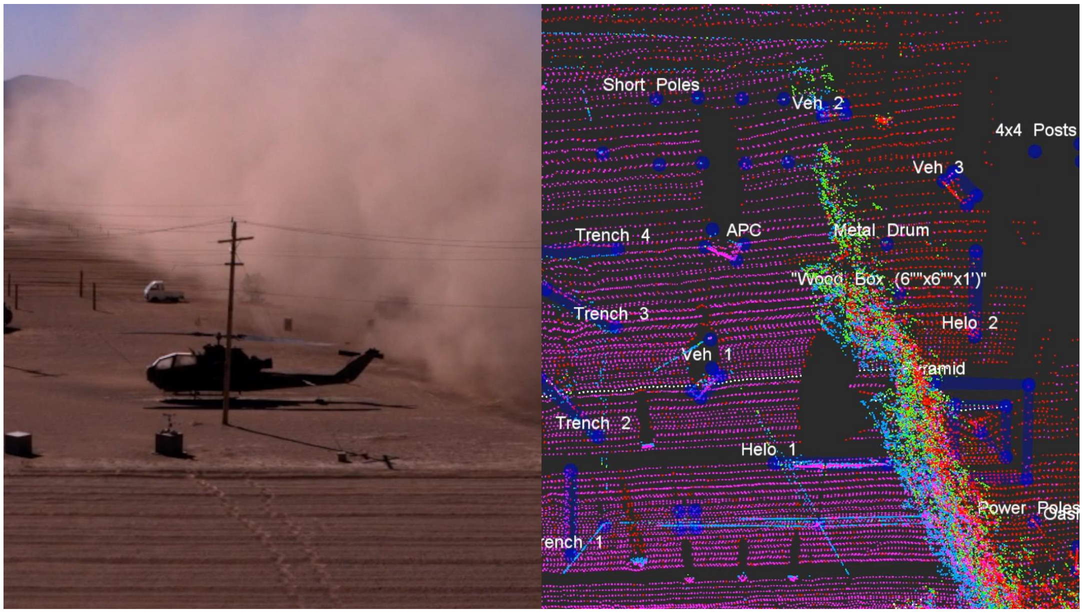


Figure 9: During brownout experiments, m3's lidar could see through low to moderate levels of dust but was blocked by dense levels of dust. Above is an example of the lidar penetrating the dust cloud to see obstacles behind it. (Left) A visible imagery from m3 taken at the same time as the lidar point cloud (Right). Ground truth hazard locations are marked in blue on the lidar along with each obstacles identifier.

latest terrain and hazard database for its target location and use that to plan its initial flight. As it neared the landing zone, the UAS's lidar would focus on the terrain and update its 3D map based on realtime scans. By 250 meters from the touch down location, the sensor would have created its detailed model of the terrain, identified the obstacles, and selected a landing site. As the brownout dust blew into the air, the system filters the dust, looses lidar visibility, but remains unaffected. Unlike human pilots, it would not experience spatial disorientation. It automatically falls back to using information collected before the brownout and proceeds to land safely.

Scenarios with dynamic landing zones or obscurance before the helicopter arrives require modification to acceptable mission risk and sensor hardware. Small radar have the potential to provide see through capabilities during obscurance when lidar sensors are blind. The wide beam width radar can be used to detected moving large obstacles like trucks or other helicopters. If the area is already obscured on arrival, a survey overflight to perform SAR imaging can be used to generate a minutes old 3D map for the landing helicopter. Integration of a low SWaP-C into an m3 style sensor suite enables sensor fusion to achieve peak performance with fallback solutions for harsh DVE.

4. AUTONOMY OPERATION IN DVE

Large scale robustness to DVE will require significantly more development from both the hardware and software of unmanned systems. Large scale robustness requires recognizing that perception will get degraded by environmental conditions. No sensor suite and set of processing algorithms will achieve peak performance in all conditions. In fact, there exists a continuum of perceptual ability that should be continually translated into mission risk for the planning algorithms and human mission commanders (Figure 10). Through their choice of sensors and algorithms, system designers define an operational range for the perception system. The system's peak performance occurs during exceptional clear air. Every other operational moment is some level of degradation. Planning algorithms need to use this perceptual feed back to compensate for worse perceptual performance. This could mean adjusting the aggressiveness of their trajectories or performing maneuvers to better perceive the environment (like survey over flights) rather than directly accomplishing its mission. Human mission planners

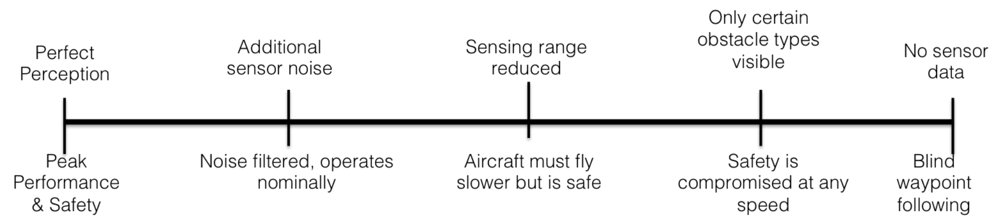


Figure 10: The operational effects of perceptual degradation due to DVE are spectrum. While a UAS can operate anywhere along the spectrum, the risk of accident must be understood and acceptable to a mission commander. During blind waypoint following a UAS can only use a prior database model of the world and is vulnerable to unexpected obstacles.

need to understand the perceptual level and risk such that they can decide if the mission is still worth the risk of accident.

Perceptual performance level should be become a part of every open interface for future UAV perception systems (Figure 2) because the measure is intrinsic to the processing algorithm and sensor. The effects of DVE on derived outputs like landing zone locations or an obstacle maps are non-intuitive and dependent on the sensor used to generate the output. For example, a UAV with a sensor suite which combines lidar and radar enters a dust storm. The lidar portion of the sensor has drastic reduction in visibility and increase in noise due to the dust. The radar remains relatively unaffected. The net perceptual output would still detect large obstacles at a far range, but could no longer detect structures with as fine a resolution. This means that obstacles like wires would become hidden hazards for the system.

Near Earth Autonomy has already begun development of the infrastructure and algorithms to estimate this perceptual performance. For systems like the m3 perception suite, the lidar visibility range and sensor noise can be easily estimated. For example, the expected lidar sensing range can be estimated by comparing measurements with a prior terrain database. If a real lidar beam fails to return an echo but the simulated beam hits the terrain of the database, then real visibility is lower than the simulated lidar beam's range. Each comparison is a measurement in a filter estimating the lidar's range regardless of the conditions.

5. CONCLUSIONS

Even small-scale robustness to DVE on an unmanned cargo aircraft greatly expands the system's operational envelope by allowing operation in dust, fog, snow, and rain. Through DVE experimentation, m3 has demonstrated that it already has the hardware and much of the software capabilities required for low to moderate levels of obscurants. It can see through particulates, filter them, and identify the obstacles or terrain behind the cloud. Future work will move these tests from off-line validation to integrated testing on UAS.

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