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Safe2Ditch Autonomous Crash Management System for Small Unmanned Aerial Systems: Concept Definition and Flight Test Results

Louis J. Glaab and Patricia C. Glaab
Langley Research Center, Hampton, Virginia

Parker C. Lusk
Brigham Young University, Provo, Utah

Bryan J. Petty
Analytical Mechanics Associates, Inc., Hampton,Virginia

Randall W. Beard
Brigham Young University, Provo, Utah

Chester V. Dolph and Robert G. McSwain
Langley Research Center, Hampton, Virginia

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Available from:

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NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Abstract

Small unmanned aerial systems (sUAS) have the potential for a large array of highly-beneficial applications. These applications are too numerous to comprehensively list, but include search and rescue, fire spotting, precision agriculture, etc. to name a few. Typically sUAS vehicles weigh less than 55 lbs and will be performing flight operations in the National Air Space (NAS). Certain sUAS applications, such as package delivery, will include operations in the close proximity of the general public. The full benefit from sUAS is contingent upon the resolution of several technological areas in order to provide an acceptable level of risk for widespread sUAS operations. Operations of sUAS vehicles pose risks to people and property on the ground as well as manned aviation. Several of the more significant sUAS technological areas include, but are not limited to: autonomous sense and avoid and deconfliction of sUAS from other sUAS and manned aircraft, communications and interfaces between the vehicle and human operators, and the overall reliability of the sUAS and constituent subsystems. While all of the technological areas listed contribute significantly to the safe execution of the sUAS flight operations, contingency or emergency systems can greatly contribute to sUAS risk mitigations to manage situations where the vehicle is in distress. The Safe2Ditch (S2D) system is an autonomous crash management system for sUAS. Its function is to enable sUAS to execute emergency landings and avoid injuring people on the ground, damaging property, and lastly preserving the sUAS and payload. A sUAS flight test effort was performed to test the integration of sub-elements of the S2D system with a representative sUAS multi-rotor.

Nomenclature

Ah	Amp hour, unit of measure of the amount of battery capacity
AOSP	Airspace Operations and Safety Program
AGL	Above Ground Level
ATC	Air Traffic Control
BVLOS	Beyond Visual Line of Sight
BYU	Brigham Young University
CERTAIN	City Environment Range for Testing Autonomous Integrated Navigation
CONOPS	Concept of Operations
DSS	Ditch Site Selector
FAA	Federal Aviation Administration
FOV	Horizontal Field of View
FMEA	Failure Mode and Effects Analysis
fps	Frames Per Second
GA	General Aviation
GCS	Ground Control Station
GCSO	Ground Control Station Operator
GPS	Global Positioning System
HMI	Health Monitor Interface
IH	Intelligent Hub
LaRC	Langley Research Center
LSV	Landing Site Verifier
MR	Multi-Rotor
NAS	National Air Space
NASA	National Aeronautics and Space Administration
NRO	Nav/Route Optimizer
ppd	Pixels per degree
R-RANSAC	Recursive-Random Sample Consensus
SAA	Sense and Avoid
SP	Safety Pilot
sUAS	Small Unmanned Aerial System
R/C	Radio Control
ROI	Region of Interest
RSO	Range Safety Officer
RTL	Return to Launch
S2D	Safe2Ditch or Safe2Ditch
TOD	Top of Descent
UTM	UAS Traffic Management
VAL	Vision Assisted Landing
WVLOS	Within Visual Line of Sight

Introduction

Small unmanned aerial systems (sUAS) have been studied by private industry and government and the results indicate a large array of potentially-beneficial applications. It is widely recognized that sUAS (i.e.; those that weigh less than 55lbs) can provide significant benefit. Those benefits include a growing array of applications from traffic monitoring to fire spotting and even small package delivery.

The introduction of sUAS into the National Airspace System (NAS) has been an objective of several research efforts. In order for sUAS to reach their full potential, multiple technological issues must be resolved, along with a comprehensive assessment of risk from these new and revolutionary vehicles, in order to avoid exposing the public to undue risks from sUAS operations. These risks could involve mid-air collisions of sUAS with each other or with manned aircraft, or risks associated with direct collision of sUAS with people and property on the ground.

One area of technology development is in a traffic management system that can deconflict sUAS while imposing limitations to where the vehicles can operate to help mitigate, but not eliminate, the risk to manned aircraft. The NASA UAS Traffic Management (UTM) project has been developing a traffic management system for sUAS along with a concept of operations (CONOPS) as described in Reference 1.

Within Reference 1 several differences between traditional manned aircraft and sUAS are noted, such as the absence of an onboard pilot to detect and avoid other vehicles. Second, there is a wide range of new and unknown sUAS performance characteristics, and third, sUAS are by definition small and lightweight and do not have the capability to carry heavy or power-intensive equipment regardless of the equipment’s function. Finally, Reference 1 states that while sUAS may fly very close to each other under certain circumstances, the biggest risk is to the people and assets on the ground, and to manned aviation.

Other significant differences between manned aviation and sUAS also need to be noted. For example, it is also important to note that the role of the pilot in manned aviation extends beyond avoiding other air traffic and also includes aeronautical decision-making (Reference 2) both for nominal and off-nominal or emergency operations. Manned aircraft pilots are continuously monitoring the vehicle’s flight path, performance, and status of subsystems with consideration of deteriorating weather, failing/off-nominal system performance, and other circumstances.

SUAS offer many benefits as previously presented. However, many of the benefits of sUAS can be provided by manned aircraft or from other transportation methods, such as ground transportation for package delivery. Therefore, a critical enabling characteristic of an sUAS transportation systems is the potentially low-cost of acquisition and operation of these vehicles. Highly expensive sUAS will not likely be commercially viable as their costs could be commensurate with manned aviation. While sUAS provide risk mitigation to loss of human life due to the absence of a pilot, more widespread and prolific implementation of sUAS requires monetary commercial benefits and/or massive improvements in convenience and service.

Another significant difference between sUAS operations and manned aircraft operations is the lack of reliability data for critical systems and subcomponents. Small, lightweight, and low-cost sUAS vehicles are comprised of many new and revolutionary components. For example, autopilots and attitude reference systems are based on micro-sensor technologies and augmented with GPS adjustments. Data for these systems is limited compared to their manned aircraft counterparts, and mean-time-to failure data does not exist.

In the event of an emergency, such as an engine failure for a single-engine aircraft, the manned aircraft pilot executes a specific list of actions to optimally configure the aircraft for an emergency landing and rapidly determines and selects an adequate (or the best) emergency landing location. Successful emergency landings of manned aircraft in open fields or roads are examples of pilots saving themselves, avoiding injury to those on the ground, and often also saving the aircraft as discussed in Reference 3. As a result, the risk of manned aviation to the general public is significantly mitigated through the pilots' actions in emergency situations.

While the accident rate for general aviation as performed and tracked under the Federal Aviation Administration (FAA) FAR Part-91 and commercial transport operations performed under Part-135 is not, it is still considered an acceptable form of transportation to air travelers and to the general public on the ground because the risk is similar to other forms of transportation. For sUAS to be fully-accepted as a means of transport, risk from these vehicles must also be similarly commensurate with other forms of transportation.

Presently, the FAA permits limited operations within-visual-line-of-sight (WVLOS) under Part-107 regulations to manage risks from sUAS operations. SUAS operators are permitted to operate their WVLOS aircraft at altitudes less than 400ft above ground level (AGL), at speeds less than 100mph, and at operational locations sufficiently far away from airports. General WVLOS visual limitations range out to ~1 mile depending on the size of the vehicle.

While WVLOS operations can provide substantial benefit and include applications such as construction monitoring, real estate, limited precision agriculture and infrastructure monitoring and other d beneficial applications require sUAS operations beyond-visual-line-of-sight (BVLOS) and/or include multiple sUAS operated by a single person. The FAA does permit some very limited BVLOS operations through a waiver process that requires applicants to perform extensive safety and risk analysis of the specific proposed flights.

During WVLOS operations, the human operator is responsible for visually assuring that the sUAS will avoid manned aircraft and other sUAS, avoid overflight of unprotected people on the ground, and be able to intervene in the event of vehicle system issues to mitigate risk. BVLOS operations place an added emphasis on the vehicles' systems as real-time human intervention is much harder or even impossible in some situations due to time constraints.

Risk for sUAS operations needs to be quantified and managed in order to permit routine BVLOS flight operations. The risk from sUAS operations to people on the ground and manned aviation can be assessed through traditional risk assessment procedures as described in References 4 and 5. Within these references the risks are analyzed through a probability and threat methodology. Failure Mode and Effects Analysis (FMEA) is one method of assessing risk as defined in Reference 5. Critical ingredients to successful risk assessment are valid and accurate probabilities for a subcomponent or system failure to occur along with realistic effects. Given the new and untested nature of sUAS, both the probabilities of failure and effects are largely unknown as discussed in Reference 5. Also given the low cost and light weight typical of sUAS designs, the failure rate of sUAS subsystems is assumed to be very high, potentially several orders of magnitude above manned general aviation.

The combination of the anticipated high rates of sUAS failure with their envisioned use cases to frequently bring the vehicles in close proximity to the public require the mitigation of risk of sUAS operations. Risk mitigations can take many forms. Some, such as redundant systems or emergency systems like parachutes, can lead to significantly increased weight and decreased payload that limits vehicle performance.

Autonomous emergency landing systems have been proposed and defined previously in References 3, and 6 through 9. The systems defined in these references provide various methods for providing the pilot with situational awareness regarding available landing locations along with automated systems to route vehicles to usable roads and potential runways.

The Safe2Ditch concept

Autonomous emergency landing systems as described in References 3, and 6 through 8, provide significant safety benefits to piloted aircraft while also largely avoiding weight impact to the vehicle. An autonomous crash management system is proposed and referred to as Safe2Ditch (S2D) and is designed to provide this same benefit for unmanned aircraft, including response to emulate that of a pilot.

The S2D system provides autonomous crash management capability for sUAS to identify an emergency in progress, locate a viable landing/crash site, and fly the vehicle to the ground while maneuvering to avoid people in its path if necessary. For a pilotless vehicle, the risk to people on the ground from overflights of sUAS is potentially mitigated by providing a level of contingency management onboard the vehicle, mimicking the role of the pilot for manned aviation. The S2D system's priority order is 1) the safety of people on the ground, 2) safety of property on the ground, and 3) the safety of the vehicle, itself. The system provides an alternative to having the sUAS simply fall out of the sky at random locations when failures occur or potentially heavy safety systems such as parachutes.

By residing directly on the vehicle, S2D can respond immediately to off-nominal situations without having to communicate with remote personnel. This minimizes requirements to the vehicle's communication system as well as accelerates response time. The S2D system was also designed to leverage components already resident on many sUAS vehicles, which is critical to minimizing weight to preserve payload capacity of the host vehicle. In early discussions with potential commercial customers, weight of such a system was the single most important criteria for acceptance of a safety system like S2D because of the potential impact to payload. This makes one potential configuration of S2D as an auxiliary autopilot mode particularly impactful since it could be implemented simply through software resulting with no additional weight penalty to the vehicle.

The Safe2Ditch system is comprised of several functionalities as portrayed in Figure 1. At the center of S2D is the Intelligent Hub (IH). The IH serves to integrate information from the other subsystems and performs timing and communication. The Health Monitor (HM) processes inputs from onboard sensors and systems and compares that data to expected states to identify impending emergencies. The HM triggers S2D engagement when needed, provides an estimate of the remaining time-to-fly, and identifies vehicle maneuvering limitations.

The Ditch Site Selector (DSS) triages a list of landing site options to determine the best site based on the vehicles' condition and estimated flight time remaining. If no pre-determined sites are within the disabled vehicle's range, the vehicle immediately begins its descent from the current location. The DSS may dynamically change sites if needed as the flight progresses.

The Nav/Route Optimizer (NRO) generates the best flight plan to the selected ditch site to conform to vehicle or airspace constraints and to maximize the view of the ditch site by the on-board camera. The NRO provides a set of waypoints to the autopilot to fly to.

If the vehicle is equipped with a camera system, the Vision Assisted Landing (VAL) scans the ditch site during approach and looks for unexpected occupancy, particularly by people. If the vehicle is equipped with an infrared camera, this could also be inferred from heat signatures. It is assumed that many vehicles will be equipped with at least low-cost electro optical cameras. The VAL in the current S2D prototype identifies objects in motion, which implies people, animals, or vehicles. The potential use of an audible warning could help incite the movement. The VAL passes this information to the DSS which may decide to re-route to another ditch site if deemed a better choice. If the vehicle is unable to re-route, S2D uses its own "steer-to-clear" mode to avoid the obstacles.

Adaptive controls are also included within the S2D concept. Within this context adaptive controls can provide an array of potential needed vehicle functionality. For example, it has shown in Reference 5 that during engine failure conditions for multi-rotors, vehicles can still maintain controlled flight within limited conditions. These limits include limiting, or avoiding, any rotational heading control of the vehicle, which is a possible mode of operations. S2D would need to inform the autopilot to operate in a controlled-limited manner. Adaptive controls can also provide many other positive attributes for fixed-wing vehicles where all available controls can be used in non-traditional means (i.e. flaps providing limited pitch and/or roll control). The objectives of the adaptive controls would be to provide limited, but useful, control of the vehicle to execute safe emergency landings.

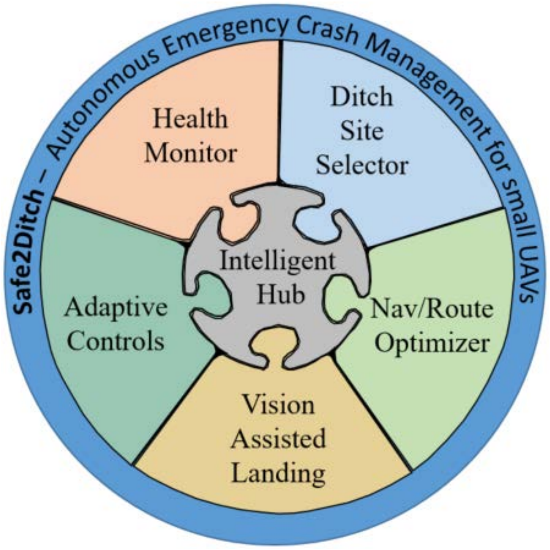

Figure 1 - S2D functional system portrayal.

Developmental and integration testing was performed in 2016 through 2018 at NASA Langley Research Center (LaRC) in Hampton, VA. The objectives of the testing were to 1) demonstrate the feasibility of the S2D system on a representative sUAS, 2) evaluate the performance of a prototype VAL, and 3) evaluate the integration of S2D elements along with a representative autopilot.

Method and approach to integrated flight testing

A prototype S2D system was developed, installed and tested on a representative sUAS. All of the S2D subsystems were included in the test effort. Resource and time constraints prevented prototyping of a full system, so these tests prioritized systems considered to pose the greatest risk to the concept's success, with minimal functionality included for low-risk components. For example, the earliest software prototype version demonstrated selection of a site by the DSS and navigation to that site by the NRO using available interfaces to existing inexpensive commercial off-the-shelf (COTS) autopilots. The second version added the VAL recognition of moving ground objects, and the third integrated that visual recognition to the DSS rerouting capability.

Flight vehicle

The vehicle selected for initial prototype testing was a 3DR Y-6 hexacopter shown in Figure 2. It was selected because it represented the small, inexpensive vehicle style targeted for the S2D concept, and because of its availability as an existing sUAS at LaRC (N516NU). The Y-6 meets the research payload requirements while also achieving flight endurance objectives of typical sUAS missions (e.g. infrastructure inspection). This vehicle was also capable of carrying the required research equipment while maintaining minimum endurance performance. The Y-6 was equipped with a Pixhawk autopilot running APM v3.5.4 firmware with standard Pixhawk/Ardupilot configuration.

The Y-6 was also equipped with a Spektrum 2.4 gHz R/C communication link for safety pilot control and 900 mHz telemetry link for ground station monitoring of future waypoints and mode changes. A ruggedized laptop interfaced with the Pixhawk autopilot and operated the vehicle in auto mode. The stock weight of the Y-6 is approximately 4.5 lbs with an approximate 16-minute endurance using a 4-cell 6.8 Amp hour (Ah) battery. The on-board research system was comprised of a Jetson TX-2 computer and camera that weighed approximately 1 lb. The resulting vehicle configured for research operations weighed approximately 5.5 lbs with 8 minutes endurance and 30% battery reserve in the research configuration.

Figure 2- 3DR Y-6 research vehicle with research computer and camera installed.

Camera assembly

The camera and lens used for testing was an Imaging Development Systems UI-1250ML shown in Figure 3. The camera features a USB 2.0 interface to provide easy access to camera parameters, supply power to the camera, and transmit the image data. The camera is an industrial compact design and provides high-resolution imagery (1600x1200) at up to 17 frames per second (fps). The UI-1250ML features a global shutter to minimize imagery distortion due to vehicle motion and vibration. A 12 millimeter lens was selected that provided a 30-degree horizontal field of view (FOV). Overall weight of the camera and lens was 70 grams or approximately 2.5 ounces. A 3D printed nylon camera mount was designed, fabricated, and installed with rubber vibration isolators as shown in Figure 2 located at the front of the vehicle. The mount orients the camera downwards at an angle of 45 degrees. The camera orientation provides a potential worst-case sUAS camera system due to limited fixed FOV and lack of hardware implemented (i.e. camera gimbal) image stabilization. For the testing the camera was operated at a resolution of 800x600 at 30 fps. This was important to stay consistent with limitations expected in small commercial applications for concept feasibility. The resulting pixel per degree (ppd) was 27.

Figure 3 - UI-1250ML camera and lens

Jetson TX-2 research computer

The Jetson TX-2 features an integrated 256-core NVIDIA tm Pascal General Processor Unit (GPU), hex-core ARMv8 64-bit CPU complex, and 8GB of LPDDR4 memory with a 128-bit interface. The CPU complex combines dual-core NVIDIA Denver 2 alongside a quad-core ARM Cortext-A47. The Jetson TX-2 fits a small size, weight, and power (SWaP) footprint of 50x87mm (2”x3.4”), 85 grams (3 ounces), and requires only 7.5 watts of power. The TX-2 was configured with an Orbitty carrier board to provide required input and output interfaces. The entire assembly was contained in a 3D printed nylon vented enclosure and Velcro strapped to the top of the vehicle. Interfacing with the Pixhawk was via a UART cable into the Pixhawk’s telem 2 port. Figure 4 shows the TX-2 research computer alongside the 3D printed enclosure. The WiFi antennas were used for ground system development and not used for flight testing.

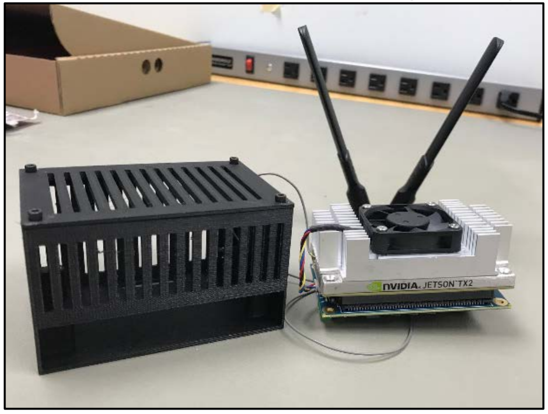

Figure 4 - Jetson TX-2 research computer along with 3D printed enclosure and WiFi antennas.

Human motion simulator

A primary testing goal was the performance evaluation of the VAL S2D subsystem. This required a way to create motion within the targeted ditch site for the VAL to detect and report. In order to achieve this without exposing team members to undue risk, a radio controlled (R/C) car was employed. The R/C car selected was the Traxas Xmaxx all-terrain truck. This vehicle used electric power, weighed approximately 19 lbs, and had a top speed of ~50 mph. For S2D testing, speeds were limited to less than 10 mph. A 1” thick foam board was attached to the top of the truck to provide a visual cross section approximating that of a human being. Figure 5 presents a photo of the R/C car human motion simulator.

Figure 5 - R/C car used for S2D testing.

Safe2Ditch software components

Time and funding limited the scope of NASA’s S2D prototype development and forced judicious choices for the subset of functions targeted for prototype testing. A layered implementation plan began in 2015 with each iteration created to demonstrate feasibility for key systems, and each building on prior work. The first tests in 2015 implemented a basic ditch site selector (DSS) component, a minimal navigation/route optimizer (NRO), and enough communication in the intelligent hub (IH) to access state data from the autopilot and to send guidance commands back.

The 2017 version of the prototype focused on the assessment of vision assisted landing (VAL) software. These tests informed changes to the vision software and supported the planned integration of the DSS and VAL components.

Testing in winter 2018 integrated the prototype versions of the DSS and VAL for initial flight testing. While the component integration worked, it was not user-friendly and design changes in the startup sequence later facilitated configuration changes. The winter 2018 tests were also adversely impacted by hardware issues which caused intermittent lost link with the transmitter to trigger return-to-land (RTL) mode. Software startup was redesigned between the winter and spring 2018 test cycles, and the faulty hardware components were replaced. These changes significantly streamlined the spring tests, which yielded the results later in this report.

It is important to note that while the current version of the prototype is the most complete to date, it still represents only a small subset of the functionality of the complete Safe2Ditch concept design. The following sections describe the envisioned functional behaviors of each component, with clarification of the subset implemented in the current prototype vehicle.

Health Monitor (HM)

The health monitor (HM) is responsible for identification of an imminent emergency to trigger engagement. An imminent emergency means the vehicle's current performance capability no longer allows the vehicle to meet its mission. The HM determines the presence of an off-nominal condition and attempts to estimate the time remaining for the disabled vehicle and provides this to the DSS for use in calculating the subset of ditch sites that are reachable. Time remaining could be estimated through battery monitoring and voltage trends along with other potential parameters. The HM also informs the NRO of any performance limitations that could impact path construction choices.

Detection of emergencies due to mechanical failures (e.g., servos or motors), power system anomalies (e.g., unexpected battery or fuel depletion), and severe weather that degrades performance (e.g., extreme headwinds) are envisioned for a full implementation of the S2D concept. However, the HM in the current prototype does not yet contain failure detection algorithms. The HM triggers S2D engagement when it detects a positive value on a specific transmitter switch. This gives the safety pilot direct control over the timing of system engagement to simplify testing of the DSS and VAL while delaying development of those algorithms to future work.

Ditch Site Selector (DSS)

The ditch site selector (DSS) determines the best ditch site to target under the current situation. It receives the engagement signal from the HM, along with the estimated flight time left for the vehicle (the "time-to-crash"). It also receives the current vehicle location from the autopilot. The DSS uses a performance database for the host vehicle, which for the prototype simply estimates the cruise, climb, and descent speeds. The performance data and the time-to-crash allow the DSS to compute the range potential of the vehicle at S2D engagement.

The DSS also uses a database of optional ditch sites, which describes the location and size of each site, and each site's probability of being clear of occupants. The vehicle's location and the range potential allow the DSS to identify which sites are within range. Of those sites that are within range, the DSS identifies the site it considers to be the "best" option. Note that the best site may not be the closest because distant sites with a higher probability of being clear may offer a lower risk, if the vehicle has the power to reach them. The triage algorithms assign weighting to individual factors for range to the site, size of the site, and probability of being clear, which are configurable before startup and support the selection.

A mature ditch site database would ideally use polygons to define ditch sites. However, the prototype version of the ditch site database uses a simple latitude/longitude centroid and a radius to describe the sites to facilitate setup and analysis. During flight tests, these centroids were located with GPS and circles were painted on the grass at the defined radii. These circles provided a visual reference in the on-board videos and identified the site locations to the R/C car driver.

Once a ditch site was selected, the centroid was set as the region of interest to the autopilot, which caused the autopilot to rotate the vehicle for camera sighting. When the vehicle was close enough to the targeted sight to allow imaging, input from the VAL was used to trigger a new site selection by the DSS for re-routing the vehicle if needed.

Vision Assisted Landing (VAL)

The vision assisted landing (VAL) subsystem was developed by Brigham Young University (BYU) under a grant to NASA. BYU leveraged its Recursive-Random Sample Consensus (R-RANSAC) multiple target tracking algorithm. For this effort, R-RANSAC was configured and optimized to run on the Jetson TX-2 research computer platform. R-RANSAC uses a visual measurement front-end to process incoming video data and generate measurements that can be given to the Recursive-RANSAC Tracker. The Recursive-RANSAC algorithm values many low-quality measurements over few high-quality measurements for robustness. The vision processing was performed with a calibrated camera in a three-step pipeline to find feature correspondences between images, compute a homography, and detect true object motion. Further information regarding the development of the VAL and R-RANSAC can be found in References 9 through 11 and in a future Journal publication.

The VAL continually scanned for moving objects during the vehicle's flight, though the prototype only used the object location data after S2D engagement. The VAL was responsible for the axial transformation from the camera FOV to north-east-down (NED) axis, and relied on vehicle location and attitude data from the autopilot to support this transformation. The prototype vehicle used a fixed-mounted camera angle of 45 degrees (as described earlier) which adversely inhibited the camera from imaging the ditch site selected until it was within a lateral range of the site approximately equal to the vehicle altitude, plus/minus the camera FOV. The VAL calculated the distance between each motion object and the ditch site centroid and tallied that object as an "intruder" in the site if the computed distance was less than the site's radius. For these tests, a single intruder triggered a re-route request to the DSS.

Nav Route Optimizer (NRO)

The Nav Route Optimizer (NRO) creates the flight plan to the selected ditch site. In a mature S2D concept implementation, this could include optimization of vehicle performance, risk assessment, or area avoidance. For the prototype vehicle, the camera view angle was the only contributor to the optimization. The path to the ditch site was created as a straight line from the engagement point to the ditch site centroid and maintained the altitude of the vehicle until it reached a range equal to the vehicle's altitude (to match the 45 degree angle of the camera mount). This point was stored as the top-of-descent (TOD) waypoint (Figure 6). The bottom-of-descent (BOD) waypoint was set to the centroid of the site.

Each target waypoint as the flight progressed was supplied to the autopilot for vehicle steering in GUIDED mode. Before reaching the TOD point, the vehicle cruised at its maximum speed. After crossing the TOD, the vehicle descended at 1.5 m/s, 4.9ft/s. If the selected ditch site changed for re-routing due to motion, the NRO created a new path to the alternate site using the vehicle's altitude at re-route as the new cruise altitude. Motion was only created in the primary site for the tests performed.

Intelligent Hub (IH)

The intelligent hub (IH) provides the configuration, communication, and timing services needed between components. It also creates the subsystems and interfaces needed to communicate with external parts of the system. For the current prototype, this included only the autopilot and the camera.

Adaptive Controls (AC)

The adaptive controls (AC) component in the prototype is simply a place-holder for future development. The mature S2D concept envisions this component to inform control requirements for a disabled vehicle using information received from the HM. For example, rotor power balancing for a vehicle with a seized motor. The AC would be responsible for communicating additional performance changes to the NRO and the DSS since the adapted state may impact path optimization and the vehicle's range capability.

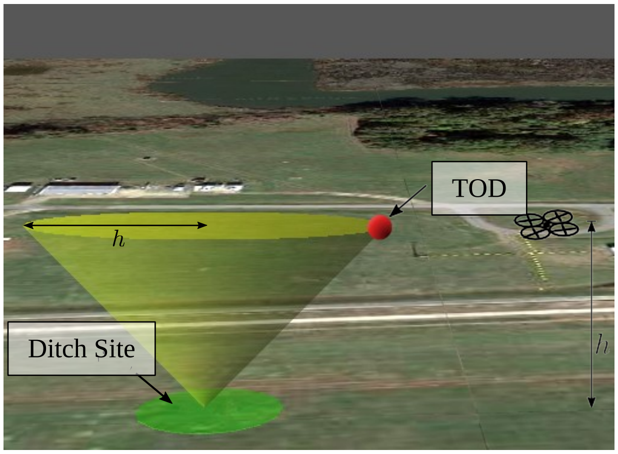

Figure 6 - Location of Top of Descent waypoint as generated by the NRO.

Test site

The test location was the City Environment Range for Testing Autonomous Integrated Navigation

(CERTAIN) range in Hampton, VA, which is located at NASA Langley. Operations of sUAS are permitted WVLOS up to an altitude of 400ft AGL. Range 1 of CERTAIN was used for the current testing effort as illustrated in Figure 7. Weather limits required a visibility minimum of 3 miles with a minimum 1,000 ft AGL ceiling. Wind limits were set at 20 mph, though most testing occurred in winds at 10 mph or less.

Figure 7 - CERTAIN Range-1, NASA LaRC, Hampton, VA. (image approximately 1,500 ft by 800 ft).

Flight test operations

Flight test operations spanned several days. After an airworthiness preflight, a nominal flight plan was loaded into the Pixhawk as illustrated in Figure 8. The flight initiation point in the figure is denoted by the green balloon icon, and available ditch sites are denoted by the green circles. The red-cross indicates the approximate S2D engagement location.

The flight test team included a safety pilot (SP), ground control station operator (GCSO), R/C car driver, and range safety office (RSO). The SP was required for all CERTAIN flight operations to mitigate unexpected flight issues, and was responsible for the safe operation of the vehicle in flight. In addition, the SP engaged S2D with a switch on the R/C transmitter. The RSO provided range oversight and the required interface to the Langley Air Force Base tower. The GCSO supported the preflight checklist and monitored vehicle systems during flight. The GCSO was also responsible for transferring data from the research computer after each flight. The R/C car driver drove the car in laps in and around the ditch site to induce motion for detection by the VAL.

Once the vehicle was ready for takeoff, the Y-6 was manually flown to an altitude of approximately 50ft. After the vehicle was stable at 50ft, a post-liftoff checklist was performed to again ensure that GPS, battery voltage, and 900 mHz telemetry links were in behaving nominally. The Y-6 was then transitioned to auto mode and began to climb towards the designated cruise altitude to fly the predetermined flight path starting at waypoint 1 at the desired altitude. The nominal cruise speed selected was 10 m/s (22.4 mph). Maximum descent speed was 1.5 m/s (5 ft/sec). Testing was performed at cruise altitudes of either 60 m (197 ft) or 120 m (394 ft). The higher altitude represents potentially the highest altitude an sUAS would use for cruise conditions as described in Reference 1.

These flight tests required the moving car operating in the primary selected ditch site as soon as the S2D system engaged, so the ditch site database was limited to include only two sites, with one substantially better than the other to trigger selection as the primary site choice. Having S2D select one specific ditch site for all testing facilitated use of the R/C car to simulate motion within the selected ditch site. The primary ditch site was located approximately 200 ft east of the launch location. The alternate ditch site was located approximately 400 ft west-northwest of the launch location. Total flight times for the research flights were approximately 3.5 minutes.

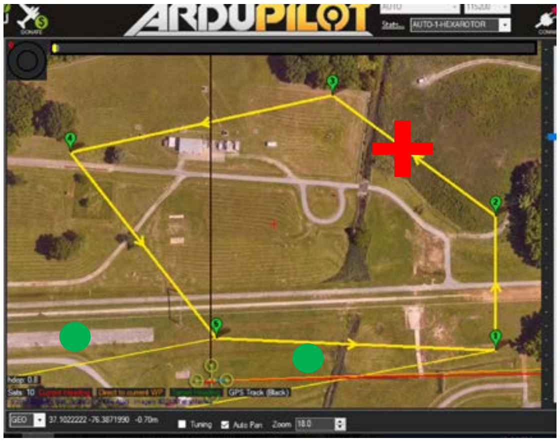

Figure 8 - Nominal flight path used for S2D testing along with primary and alternate ditch sites (green circles), and S2D engagement location (red cross).

Test matrix

A total of 13 data flights were conducted over two days. The R/C car was driven in the expected primary ditch site for approximately half of the tests. Tests conducted without the car were intended to test for false positives. The test matrix is provided in Table 1.

Table 1: Test Matrix

Altitude	With Motion	Without Motion
60 m (197 ft)	3	3
120 m (394 ft)	4	3

Results and discussion

Tests of a prototype S2D system were performed at NASA LaRC during the late spring, 2018. The objectives of the testing were to 1) demonstrate the feasibility of S2D system on a representative sUAS, 2) evaluate the performance of a prototype LSS, and 3) evaluate the integration of S2D elements along with a representative autopilot.

Results indicate that the S2D correctly selected the best ditch site and the S2D VAL system had zero false positives over the conditions tested. For the 6 test cases without the R/C motion present, the Y-6 research vehicle descended to an altitude of approximately 2m (6.6 ft) at which point the SP took control and landed the vehicle. This is considered a significant result in that an effective S2D system should not re-route without a reason to do so. Given the emergency situations possible during S2D engagements, needless re-routing could expose people to increased risk due to unnecessary flight of a potentially crippled aircraft.

Results for motion detection are presented in Table 2 as well as Figures 9, 10, and 11. Table 2 presents the time required for the S2D VAL system to detect the presence of the R/C car human motion simulator from the time the car was observable in the camera's field of view for both the 60 m (197 ft) and 120 m (394 ft) cruise altitudes. Table 2 also presents the time required for the S2D system to determine that the detected motion was within the primary ditch site and trigger a re-route to the alternate ditch site. Lastly, Table 2 presents the standard deviations for the time required to track and trigger reroutes. Insufficient data exists to calculate standard deviations for the 60 m cruise altitude condition.

Figure 9 presents the re-route altitude as a function of cruise altitude. Figure 10 presents the time between the first observation of the R/C car in the camera's FOV until a re-route was triggered. Figure 11 presents the altitude lost during approach to the primary ditch site before a re-route was triggered. Minimizing altitude lost during an approach to an unusable ditch site is critical since that could affect the vehicle's capability to re-route to another location.

As can be seen from Table 2, the VAL system was able to detect the presence of the car within approximately 1 to 2 seconds for both the 60 m (197 ft) and 120 m (394 ft) cruise altitudes. This result indicates that the camera resolution (800x600@30 fps) in a fixed-mounted orientation is adequate to detect and track targets within a very short amount time from representative altitudes.

At the cruise altitudes of 60 m (197 ft), and 120 m (394ft), the FOV of the camera was able to view approximately 46m (150 ft), and 91 m (299 ft), of ground respectively. The approximate width of a pixel would then be 0.058 m (0.190 ft), and 0.115 m (0.377 ft) respectively, for the 60 m (197ft) and 120 m (393 ft) cruise conditions. This analysis reveals that at the 120 m cruise condition, the camera was able to put approximately 8 pixels onto the ~1m (3 ft) long R/C car. For the 60 m cruise altitude, the number of pixels on the car increased to approximately 16.

In addition, Table 2 also reveals that while the detection time of the motion in the ditch site was considered adequate, the time to trigger a re-route sometimes took much longer. Higher re-route altitudes results in more desirable overall system performance as the vehicle can proceed to an alternate location higher and sooner and preserve potentially precious flight time. For the 60 m cruise condition, S2D selected a re-route within an average of 11 seconds from the time the target was within the camera's FOV and within the ditch site. For the 120 m cruise condition, the average time for re-route increased to 40 seconds with a 23.5 second standard deviation. The difference between the detection time and the time to re-route involves the ability of the S2D system, combined with the vehicle's sensors, to geolocate the detected target with the ditch site.

It should be noted that one run for the 120 m cruise altitude condition contained prolonged out-of-bounds driving of the R/C car as the flight vehicle approached the TOD waypoint that could have adversely impacted the results for that run. However, when the car re-entered the ditch site approximately 20 seconds later, the vehicle did not immediately trigger a re-route. That run is considered valid data, yet needs to be acknowledge as a potential outlier. Results for this run are illustrated in Figures 9, 10, and 11 as the outlying data point for the 120 m cruise condition.

For these flight tests, the size of the ditch sites were 60ft (18.3m) diameter circles. The R/C car was randomly driven through the ditch sites. The VAL reported all moving objects within the camera's FOV, and then the reported locations of the motion objects were evaluated to determine if they were located within the ditch site boundaries. When true, a re-route was triggered. Review of the resulting video, combined with the data from Table 2 and Figures 9, 10, and 11, indicates that some type of angular error was likely present within the geolocation system because apparent geolocated position error varied with altitude and range to the vehicle. These errors could be due to compass sensor errors, errors or latency in the reported vehicle states by the autopilot, or errors in the axial transformations to resolve the camera FOV to the north-east-down axis. Identification of this error source is on-going.

While specific requirements for time to re-route have not been established, minimization of wasted time in descent to an unusable ditch site is considered critical. The longer the vehicle spends imaging an unusable the ditch site the less time available for re-route to an alternate.

The re-route altitudes ranged from a maximum of 103m (338ft) to a minimum 31m (102ft). These results are considered effective and verify the feasibility for a prototype S2D system for this type of vehicle.

Table 2. Time to detect and track target, and subsequent re-route.

Variable	Cruise alt (m)	Average (s)	Standard Deviation (s)
ΔT track	60	1.3	-
ΔT track	120	1.5	0.6
ΔT re-route	60	11	-
ΔT re-route	120	40	23.5

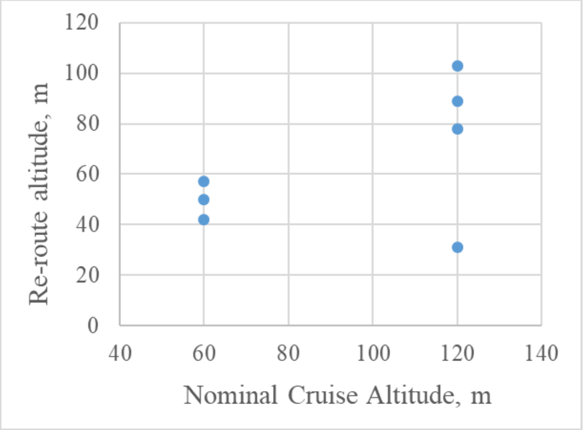

Figure 9 - Re-route altitude as a function of cruise altitude.

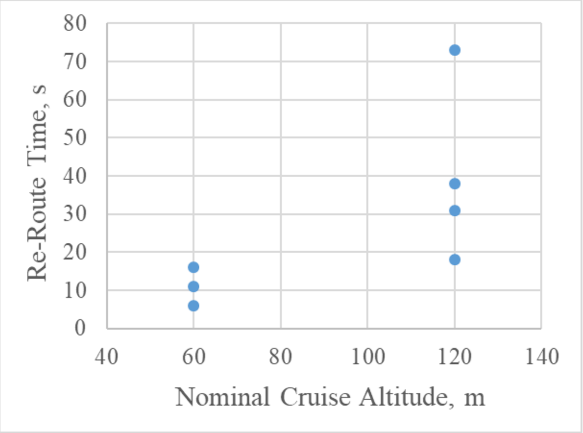

Figure 10 - Re-route time as a function of cruise altitude.

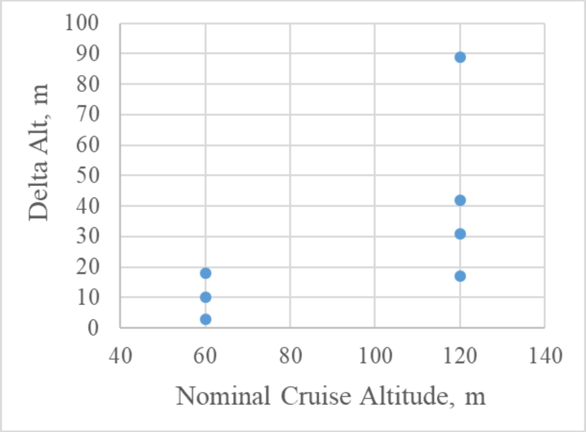

Figure 11 - Altitude lost during S2D descent as a function of cruise altitude.

Summary

Test of a prototype S2D system was performed at NASA LaRC during the late spring, 2018. The objectives of the testing were to: 1) Demonstrate the feasibility of S2D system on a representative sUAS, 2) Evaluate the performance of a prototype LSS, and 3) Evaluate the integration of S2D elements along with a representative autopilot.

Results from testing described previously indicate the feasibility of the S2D system to function adequately on a representative sUAS. This is supported by the prototype S2D systems' ability to select the best ditch site, create a route to that ditch site, support real-time imaging and landing site verification, and to effectively re-route when required due to sensed motion in the ditch site.

A prototype Vision Assisted Landing (VAL) system was developed and evaluated over realistic emergency scenarios. Results indicate that adequate performance was achieved along with areas defined to improve performance (geolocation). Required altitude to re-route ranged from as high as 103m (338ft) to as low as 31m (102ft), which is considered acceptable for this type of vehicle.

Results from the integration of a prototype S2D system with a representative sUAS revealed that even very small and minimal sUAS could host an S2D system. In addition, it is to be expected that as micro-computers become more powerful and cameras decrease in size/weight, that a fully-functional S2D system, including landing site verification, is feasible for virtually all sUAS capable of beyond visual line of sight (BVLOS) operations.

Future work

Future work includes an analysis of the vehicle sensors and axial transformation algorithms to identify the sources of the geolocation errors for the motion objects. If accuracy of the sensors is found to be a driving factor, analysis will establish the geolocation error as a function of range and altitude to the ditch site to baseline system performance requirements for an S2D application. Future work also includes a dynamic steer-to-clear control mode that will tactically maneuver the flight vehicle to avoid detected motion in the ditch site as a last resort if an alternate ditch site was not available. In addition, integration of real-time risk assessment (RTRA) tools (such as described in Reference 12) is planned to dynamically categorize the risk of specific ditch sites as well as help to potentially shape or constrain the routes used to access them. Similarly, track data from the S2D VAL system can be provided to the RTRA system to update and verify its predictions. Finally, integration of S2D within an advanced UAS control system architecture, such as described in Reference 13, is planned to ensure that S2D re-routes remain within cleared airspace when possible.

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14. ABSTRACT

Small unmanned aerial systems (sUAS) have potential for a large array of highly-beneficial applications. Typically sUAS vehicles weigh less than 55 lbs and will be performing flight operations in the National Air Space (NAS). Certain sUAS applications, such as package delivery, will include operations in the close proximity of the general public. The full benefit from sUAS is contingent upon the resolution of several technological areas in order to provide an acceptable level of risk from widespread sUAS operations. Operations of sUAS vehicles pose risks to people and property on the ground as well as manned aviation. While several technological areas need to be addressed and advanced to enable wide-spread sUAS operations, contingency or emergency systems can greatly contribute to sUAS risk mitigations to manage situations where the vehicle is in distress. The Safe2Ditch (S2D) system is an autonomous crash management system for sUAS. Its function is to enable sUAS to execute emergency landings and avoid injuring people on the ground, damaging property, and lastly preserving the sUAS and payload. A sUAS flight test effort was performed to test the integration of sub-elements of the S2D system with a representative sUAS multi-rotor.

15. SUBJECT TERMS
Autonomous Crash Management; BVLOS; National Airspace System; S2D; Safe2Ditch; sUAS

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