A micro-UAS to Start Prescribed Fires

Evan Beachly[1], James Higgins[1], Christian Laney[1], Sebastian Elbaum[1], Carrick Detweiler[1], Craig Allen[2], and Dirac Twidwell[3]

[1] Computer Science and Engineering Department, University of Nebraska, Lincoln
[2] U.S. Geological Survey - Nebraska Cooperative Fish and Wildlife Unit, Lincoln
[3] Department of Agronomy and Horticulture, University of Nebraska, Lincoln

Abstract. Prescribed fires have many benefits, but existing ignition methods are dangerous, costly, or inefficient. This paper presents the design and evaluation of a micro-UAS that can start a prescribed fire from the air, while being operated from a safe distance and without the costs associated with aerial ignition from a manned aircraft. We evaluate the performance of the system in extensive controlled tests indoors. We verify the capabilities of the system to perform interior ignitions, a normally dangerous task, through the ignition of two prescribed fires alongside wildland firefighters.

Keywords: micro unmanned aerial system; UAS; UAV; drone; prescribed burn; interior fire ignition

1 Introduction

Prescribed fires can reduce wildfire severity [6, 11, 7], control invasive species [10, 2, 20], and improve rangelands for livestock and grazing [15]. However, conducting prescribed fires also puts ground crews at risk of injury or death. Firefighters igniting the interior of an area are surrounded by unburned fuel, and the tool of choice for interior ignition, the drip torch, puts the fire dangerously close to the crew. Changes in wind can smother the personnel in smoke and transform a slow backburn into a fast-moving blaze, leaving firefighters little time to escape or deploy a fire shelter [1]. Burning large acreages introduces additional difficulties, as the fire line may be kilometers long with ravines, dense vegetation, or other difficult-to-escape terrain.

Aerial ignition removes the need to have personnel inside the burn area, but existing helicopter-mounted ignition systems [13] are too expensive for most private landowners [21] and introduces the risk of crashing [14]. Firefighters need new tools for interior ignition that reduce risk, yet are low cost and easy to operate, to make them available to the majority of prescribed fire users.

In this paper we present an Unmanned Aerial System (UAS) for fire prescription, called the UAS-Rx. The UAS-Rx transforms UASs from those that only remotely measure and monitor fires to a system that can actively manipulate the shape and trajectory of the fire to achieve the desired environmental management goals. Figure 1 shows the results of the UAS-Rx igniting a prescription by dropping delayed aerial ignition spheres onto the invasive Cedar trees in the targetted area.

Fig. 1. The prototype UAS-Rx returning after starting a prescribed fire with the Loess Canyon Rangeland Alliance [3].

Our vision is that the UAS-Rx would be used at prescribed burns that cannot afford aerial ignition from a manned aircraft. The lightweight UAS could be carried on the back of a firefighter to the burn site, and then be deployed to ignite terrain that is unsafe to enter and ignite by hand. Another advantage of using a UAS for prescribed fires is that it offers an aerial platform for cameras and sensors, allowing the firefighters to maintain situation awareness. Indeed, UASs are increasingly used for remote fire measurement and monitoring [4, 16, 17], including simulations on how to track fire and optimize flight paths in these conditions [8, 19]. Dropping the ignition spheres is similar to dropping wireless sensor nodes, which has been performed using autonomous helicopters [9, 5], and fixed-wing UAS's [18], but we must also deal with the harsh fire environment. To the best of our knowledge, this is the first autonomous robotic system that has been designed for and used to start prescribed fires.

2 Requirements

For the UAS-Rx to be successful, the technical capabilities need to be contextualized in the fire-ignition domain. This context is defined by target areas covering hundreds to thousands of acres, teams of firefighters performing different roles and operating a variety of vehicles, all working under a burn plan and a set of regulations and common practices, and operating in specific ignition situations that make firefighters especially vulnerable. This context and our early studies with fire ecologists, land managers, and firefighters defined an initial set of parameters that have influenced the design of the UAS-Rx:

- Must be small and light enough to be carried by a single firefighter.
- Must be easily deployable and operable in a hostile environment (e.g. wind gusts, smoke, hot temperatures) and terrain (e.g. canyons, trees, gullies).
- Must not increase the potential for uncontrolled fires.
- Must align with large body of practices and regulations on how such fires must be conducted.

These requirements lead to the design of a UAS-Rx prototype built on a micro-UAS platform, that can be operated from a small laptop (in its current form), that can navigate and drop a fire payload with enough precision to remain within specified regions, and that replicates an accepted form of fire-ignition delivery in a miniaturized and automated fashion. The next section covers key technical elements underlying these themes.

3 Technical Approach

3.1 Design Overview

We have developed a prototype UAS-Rx, shown in Figure 2. It consists of three main parts: a hexacopter (commercially available, Ascending Technologies Firefly UAS), a chute that contains ignition spheres, and a "Dropper" attached underneath the hexacopter. Our design of the UAS-Rx has gone through several revisions that explored different sensing and payload tradeoffs. We present the latest here, for details on prior revisions see [12]. The UAS-Rx is 39 cm tall, 65 cm wide, and has a mass of 1.9 kg at takeoff.

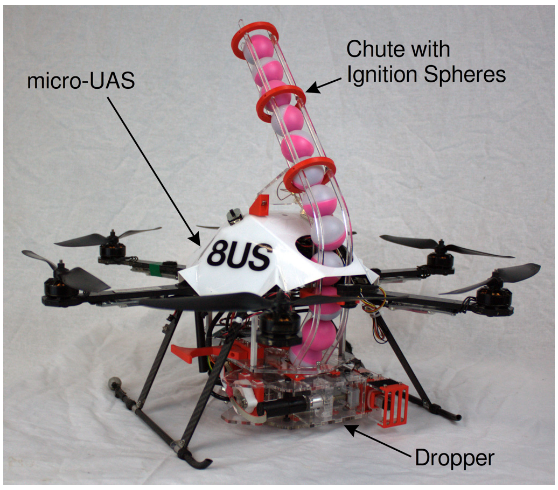

Fig. 2. Unmanned Aerial System for Fire Prescription (UAS-Rx).

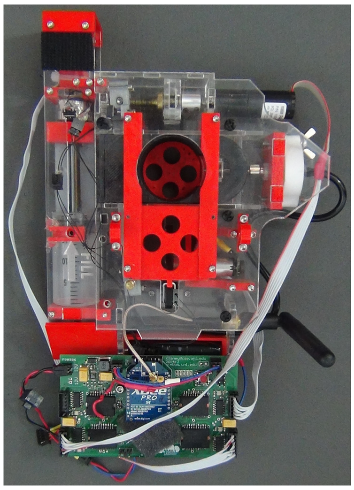

Fig. 3. Dropper Top View.

The chute on the UAS-Rx carries 12 delayed aerial ignition spheres, which are used to start the fire. Ignition spheres are a commercially available product designed to be used for aerial ignition from helicopters. The brand used in this work is the Premo Fireball. Each ignition sphere is a 32 mm diameter hollow plastic sphere containing 3 grams of Potassium Permanganate. When an ignition sphere is injected with 1 ml of common automotive antifreeze, the Ethelyne Glycol in the antifreeze will start an exothermic chemical reaction with the Potassium Permanganate. The ignition sphere will burst into flame 20 to 60 seconds after injection, depending on the ambient temperature. The use of ignition spheres that were already widley used by the fire community has significantly aided the acceptance of the UAS-Rx.

The device for injecting and dropping the ignition spheres, the Dropper, (shown in Figure 3) is attached underneath the hexacopter by a manual quick-release mechanism. The ignition spheres are gravity-fed to the Dropper by a chute that wraps around the front. The total mass of the ignition spheres and dropper is 782 grams. On the Firefly, this payload constrains the maximum flight time to 10-12 minutes. The system, however, is designed to be self-contained with its own battery, processing, and communication, so that it can be carried by larger multi-rotor or fixed wing UASs with correspondingly longer flight times.

3.2 Dropper Mechanical Design

The dropper is responsible for loading, piercing, injecting, and releasing the ignition spheres, and accomplishes this using three motors. The structural components of the Dropper were rapidly prototyped from 3-D printed thermoplastics and laser cut acrylic. Figure 4 shows the loading and release system, a pair of sliding hatches controlled by a single motor.

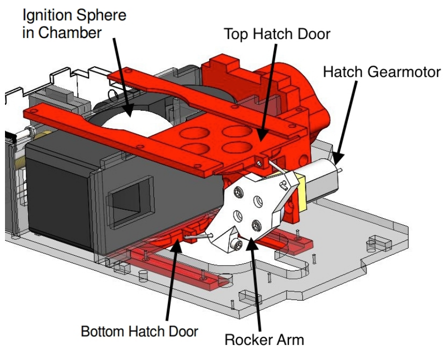

Fig. 4. Loading and Releasing System.

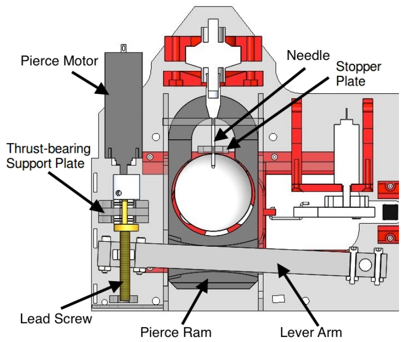

Fig. 5. Piercing System.

Once an ignition sphere has fallen into the chamber, the pierce motor (see Figure 5) pulls on the lever arm and drives the ignition sphere onto a 16 Gauge stainless-steel needle. Puncturing the ignition sphere with the needle normally requires approximately 50N of force. However, the shell of the ignition sphere has ribs and a seam of thicker plastic that can require up to 100N of force to pierce. The combination of the piercing motor, lead screw, and lever arm can produce an estimated piercing force of 130N, assuming 80% loss caused by the lead screw and friction between moving components.

As the pierce ram pushes on the ignition sphere, the curved surface on the interior of the chamber centers the ignition sphere onto the needle. This ensures that the needle does not get deflected and bent by an oblique strike on the curvature of the ignition sphere.

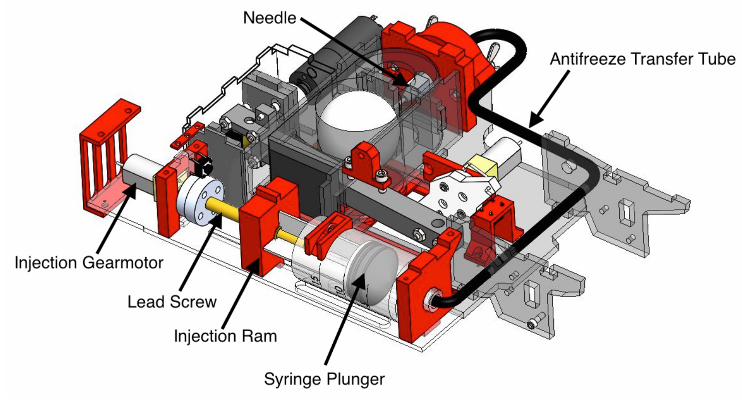

Fig. 6. Injection System

Figure 6 shows the system that injects the ignition sphere with antifreeze after it has been pierced. Antifreeze is carried in the syringe, which gets compressed by the injection motor. After compression, the antifreeze travels through the antifreeze transfer tube and out the needle.

When the ignition sphere is pulled off the needle, there is 2mm of clearance between the needle tip and the sphere. This is more than enough to ensure that it will not remain stuck on the needle tip when it needs to be dropped, and account for any variability in the shape of the ignition sphere.

3.3 Dropper Embedded System Design

The embedded system was designed to reduce the risk of an ignition within the dropper. This is accomplished by closely monitoring the motors to detect any failures, taking precautions before injecting the ignition sphere, and making the sequence of operations required to inject and drop an ignition sphere an atomic operation from the user's perspective.

The Dropper is controlled by an ATMega2560 microcontroller on a custom-designed printed circuit board. Each motor is controlled by a motor driver with built-in current sensing and over-current protection. A quadtrature counter chips track the position of magnetic encoders on each motor. We placed pushbutton switchs at the limit of each actuator's range of motion to calibrate the positions on startup. The processor communicates to the ground station using a 2.4 GHz XBee radio module that has a range of 1 km.

While operating a motor, the processor monitors the current draw and position in a 500Hz control loop. The processor uses the counter to track the actuator's position, and stop it at the correct place. If the counter stops incrementing or decrementing while the motor is being powered, or if the motor is drawing a large amount of current, the motor is assumed to have stalled, and is stopped to prevent damage. As a failsafe, each operation has a configurable timeout that limits how long the motor will run before the processor considers its next action.

Status messages are transmitted from the dropper automatically at a rate of 5 Hz, and inform the operator about what the dropper is trying to do, its state, and any failures that have occurred. Figure 7 shows the details of the procedure that the processor follows to inject and drop an ignition sphere.

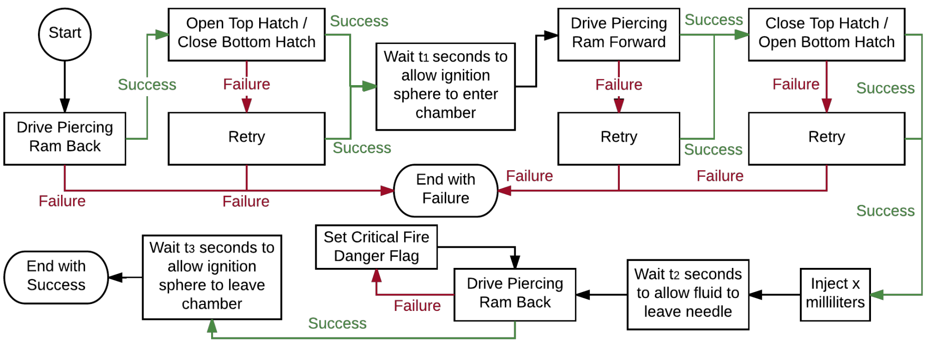

Fig. 7. Procedure to inject and drop an ignition sphere. Wait times and the injection amount can be customized over the radio link, but default to 1 s and 1 ml.

The worst case scenario is for an ignition sphere to be injected, but unable to be released. The procedure in Figure 7 helps reduce the probability that a mechanical failure will lead to this situation by only injecting if the bottom hatch was successfully opened, and if the piercing ram is functional. In the event that the piercing ram is unable to drive back after injection and drop the ignition sphere, the operator is alerted by the critical fire danger flag in the periodic status messages transmitted by the Dropper's processor.

The operator has limited control over the actuators in the dropper. This is to prevent unintentionally injecting an ignition sphere without dropping it. A single command starts the entire inject and drop process.

3.4 User Interface

Prescribed burns are highly dynamic, and changes in wind or the progress of the fire may require adjusting the burn plan. The operator needs a clear understanding of the UAS-Rx's situation in order to react to these changes. To facilitate this, we render a top-down view of the area centered on the UAS-Rx's takeoff point (which is presumed to be near the operator). The rendered view has icons for the UAS-Rx, the path it has recently traveled, and the current waypoint. This interface could be extended to overlay this information onto pre-downloaded satellite imagery of the area. In addition to this rendered view, the UAS-RX has a downward-facing video camera and analog video transmitter to allow the operator to see where the ignition spheres are landing.

The operator is able to place GPS waypoints that the UAS-Rx autonomously flies to using a PID controller, and can also customize the travel speed. To drop ignition spheres, the operator can either press a button to drop a single ignition sphere at the UAS-Rx's current location, or can specify a customized sequence of periodic drops.

4 Experiments and Results

We tested the UAS-Rx both in-lab and at two actual prescribed burns. In-lab tests were conducted mainly to quantify the reliability of the dropper in a controlled setting. The purpose of the prescribed fire tests was to gain information about the kind of missions the UAS-Rx is expected to be able to complete, the fire environment, and to identify ways to further improve it for use at prescribed burns.

4.1 In-lab tests

The UAS-Rx was extensively tested in our lab and also in an indoor arena where we could test ignitions in a controlled environment. Encoder and motor failures were simulated in order to validate that the software can detect the failures and respond correctly. Communication tests showed that 96% of status messages are received when the UAS-Rx was 200 meters away. Over 120 water injection tests indicated that approximately 90% of the ignition spheres will be injected with enough antifreeze to ignite. The other 10% were punctured at a thick part of the shell, and the plastic partially obstructed the needle during injection. During these tests, the needle never became dull, bent, or plugged with plastic, and no sphere became jammed in the system or had difficulty leaving the dropper after injection.

4.2 Loess Canyon Rangeland Alliance Prescribed Burn

The first UAS-Rx prescribed burn was conducted with the Loess Canyon Rangeland Alliance [3] in south-western Nebraska. It required coordination with the fire council of the area (which includes the land owners) and the Federal Aviation Administration. Under the guidance of the burn boss, we targeted an area of approximately 40 acres (0.16 km^2), within a larger effort to ignite over 2000 acres (8 km^2), and involved about 60 fire-fighters for a full day. We performed 5 flights over 3 gullies that were overgrown with Eastern Red-Cedar (an invasive evergreen tree species).

Our ignition plan was to hover about 10 meters over the cedar trees and drop multiple ignition spheres in each spot to ensure ignition. However, we learned that due to the flammability of the cedar trees, a single ignition sphere was sufficient to ignite a large portion of the gully. The left side of Figure 8 shows the paths of the five flights we performed and the spots where the UAS-Rx dropped ignition spheres. Note that the UAS-Rx is able to ignite locations within or behind thickly vegetated terrain that a human would have a difficult time accessing (see flight paths 1 and 2, at the top). All five flights successfully ignited their targets. The delay on the ignition spheres ensured that the fire started after the UAS-Rx had left the area.

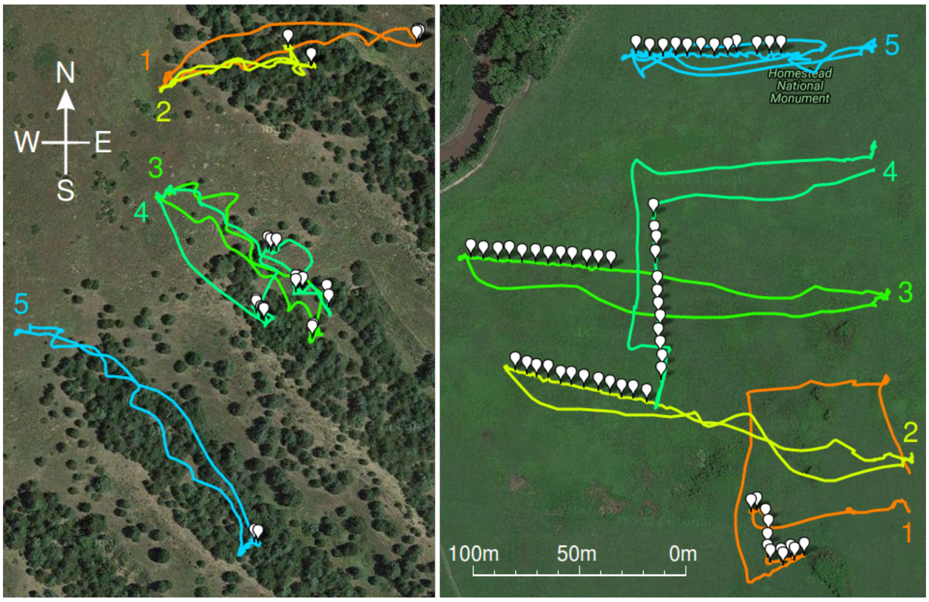

Fig. 8. Flight paths and ignition sphere drop locations (white markers) at prescribed burn tests. Left: Loess Canyon Rangeland Alliance (LCRA), Right: Homestead National Monument (HNM). Both images are at the same scale. Map Data ©Google, Imagery ©DigitalGlobe, Map created at GPSVisualizer.com

This exploratory test was conducted with an earlier version of the UAS-Rx that could hold 30 ignition spheres in an agitated hopper (see the cylindrical container on the UAS-Rx in Figure 1). Since a single ignition sphere can ignite a large area, we redesigned the UAS-Rx to use a gravity-fed chute, which holds fewer ignition spheres, but is lighter and provides a smoother ball flow. The dropper was redesigned to be able to apply more force, making it more reliable. In regards to the interface, we attached a downward-facing camera to the UAS-Rx so the operator can see if the UAS-Rx is above the target, and also see where the ignition spheres land.

4.3 Homestead National Monument Prescribed Burn

The prescribed burn at Homestead National Monument of America tested the latest design of the dropper. It required cooperation with professional fire-fighters and numerous government organizations (FAA, National Parks, Department of the Interior, and others), including needing special permission to fly a UAS at a national monument. This prescribed burn involved 22 firefighters, and burned 23 acres (0.09km^2) in 2 hours. During this prescribed burn, firefighters with drip torches ignited the perimeter, while the UAS-Rx ignited the interior. Interior ignition is typically conducted by igniting a line of ground perpendicular to the wind. The downwind side of the line is quickly burned, and the fire runs out of fuel when it reaches the previously burned area. When that happens, another line is ignited. The UAS-Rx flights at this test sought to replicate this strategy.

The right side of Figure 8 depicts the Homestead National Monument burn area. The wind is blowing towards the South. Firefighters ignited a perimeter along the East, South, and West sides of the image. A typical flight proceeded as follows: we set up behind the East perimeter, launched the UAS-Rx to a height of about 15m, and flew over the perimeter and 200m into the interior. We then directed the UAS-Rx to fly back to us at a speed of 0.5 meters per second while dropping one ignition sphere every 8 seconds (one every 4 meters). After it had dropped all 12 ignition spheres, we directed it to return to us and land. The total flight lasts approximately 5 minutes, giving us over 5 minutes of reserve flight time. The right side of Figure 8 shows the flight paths of the 5 tests conducted at Homestead National Monument. Table 1 lists information about each of the 10 prescribed burn test flights.

Table 1. Prescribed Burn Flight Data

Flight	Flight Time	Round Trip Distance	Max Range	Battery Voltage before landing	# of Drops	Avg Dropping Altitude AGL
LCRA 1	4.62 min	270.79 m	122.82 m	10.784 V	4	16.38 m
LCRA 2	6.02 min	169.24 m	73.53 m	10.673 V	5	12.17 m
LCRA 3	4.52 min	257.31 m	100.76 m	10.821 V	2	14.66 m
LCRA 4	5.67 min	310.97 m	99.49 m	10.777 V	14	13.19 m
LCRA 5	4.47 min	346.90 m	151.46 m	10.764 V	2	20.42 m
HNM 1	5.67 min	373.73 m	96.06 m	10.830 V	12	11.05 m
HNM 2	5.53 min	429.34 m	195.56 m	10.535 V	12	17.49 m
HNM 3	4.73 min	420.40 m	200.86 m	10.946 V	12	20.39 m
HNM 4	4.88 min	466.42 m	157.37 m	10.988 V	12	17.23 m
HNM 5	6.32 min	456.07 m	116.60 m	10.691 V	12	16.11 m

The average dropping altitude was between 11 and 21 meters above the ground. This height was high enough prevent the line of sight from being blocked by terrain or vegetation, and provided at least 7 meters of clearance over trees, bushes, and fire. Flying any higher would only increase the distance the ignition spheres could be carried by the wind as they fall.

The longest flight was HNM 5, which lasted 6.32 minutes. For this flight, we were sufficiently far enough ahead of the fire line that we had time to fly back over the locations we dropped ignition spheres and collect footage with the downward-facing camera mounted on the UAS-Rx. Figure 9 shows several frames of this footage.

Of the 12 ignition spheres that were dropped as part of flight HNM 5, only the tenth did not ignite. This ignition sphere took 15% more time to puncture than normal, indicating that the needle struck a thick spot on the shell of the ignition sphere, such as the seam or a rib, which may have obstructed flow of antifreeze into the ignition sphere. This ignition success rate closely corresponds to the 90% ignition rate found by the in-lab tests. After examining the logs during the

Fig. 9. Video frames from a flyover of the ignition spheres dropped during the fifth flight at Homestead National Monument. Arrows point to locations ignition spheres were dropped.

other 4 Homestead flights, we inferred that 6 of the 48 ignition spheres were unlikely to ignite, based on the time it took to puncture and inject each sphere.

Despite the fact that some ignitions spheres failed to ignite, we did not discover any unburnt patches of land after the fire, as the fire from each ignition sphere was able to spread to cover the gap. Notice in Figure 9 that the fire from ignition spheres 1 and 2 have joined together. It is probable that the ignition spheres could be spaced further apart than the 4 meters we programmed and still yield a connected line of fire. This would allow the current prototype of the UAS-Rx to ignite longer fire lines.

In addition to the downward-facing camera, we also attached a temperature sensor to the UAS-Rx. However, it didn't measure any abnormally high temperatures. It measured an average temperature of 24 C while the UAS-Rx was on the ground, and 17 C while the UAS-Rx was flying 15 meters in the air.

The average preparation time between flights at the Homestead National Monument was 5 minutes, which we would like to reduce further. We have some ideas on how to reduce the time needed to reload the UAS-Rx, such as adding a tube so that antifreeze can be refilled without removing the dropper or lifting the UAS-Rx.

During these tests, we observed that the fire fighters' attention is heavily demanded by observing how the fire is progressing, and communicating over their hand-held radios. Manually directing the UAS-Rx requires the operator's continual focus, therefore more extensive autonomous flight planning would be beneficial. For example, the fire-fighter could draw the perimeter of the area that needs to be burned, and the UAS-Rx could autonomously plan the ignition lines and drop locations, take off, and complete the mission.

5 Conclusion and Future Work

Fire-fighters need new tools for interior ignition that are safe and cost-effective. This paper described the design and evaluation of an unmanned aerial system to start prescribed fires from a distance. This unmanned aerial igniter (UAS-Rx), was designed to safely and reliably puncture, inject, and drop ignition spheres, a commercial product designed for aerial ignition from manned aircraft. The UAS-Rx's mechanical and system design detect and help prevent failures, and reduce the severity of their consequences. The UAS-Rx has demonstrated reliability, with a 90% ignition rate and no mechanical or system failures occurring in hundreds of test injections, and it has demonstrated effectiveness, by successfully igniting the interior areas at two prescribed fires. The prescribed burn tests gave valuable insight into ways to improve the usability of the UAS-Rx, such as adding a downward-facing camera, reducing preparation time, and increasing autonomy.

Our work demonstrates a great potential of unmanned aerial systems as an ignition tool. Although the UAS-Rx prototype presented in this paper has a limited flight time and ignition sphere capacity, the modularity of our Dropper allows us to easily continue our work on a larger UAS in the future. The mechanical design of the dropper can be further refined to be stronger, more light-weight, and easier to resupply. Furthermore, we would like to make the UAS-Rx capable of autonomously planning and flying missions. These improvements should make the UAS-Rx a valuable tool for conducting prescribed burns safely and easily in the future.

Acknowledgments. This work was supported in part by NSF-1638099, NSF-1217400, and NRI-USDA-2013-67021-20947. We are thankful to the National Parks Service, the Department of the Interior, the Federal Aviation Administration, and other government agencies that made these tests possible. We especially appreciate the efforts of Loess Canyons Rangeland Alliance, Homestead National Monument, and all of the firefighters for letting us learn and participate in their efforts, and for their willingness to assess new technology. We would also like to thank Becca Horzewski for designing the temperature sensor and Dr. Brittany Duncan for her assistance with field experiments. The Nebraska Cooperative Fish and Wildlife Research Unit is jointly supported by a cooperative agreement between the U.S. Geological Survey, the Nebraska Game and Parks Commission, the University of Nebraska–Lincoln, the U.S. Fish and Wildlife Service and the Wildlife Management Institute. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

1. Rock Creek Rx Entrapment Facilitated Learning Analysis (Nov 2011), `http://www.wildfirelessons.net/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=9c200d99-b54e-46ea-84ab-370ff5444176`
2. Allen, E.A., Chambers, J.C., Nowak, R.S.: Effects of a spring prescribed burn on the soil seed bank in sagebrush steppe exhibiting pinyon-juniper expansion. Western North American Naturalist 68(3), 265–277 (2008)
3. Alliance, L.C.R.: Loess canyons rangeland alliance (2016), `http://www.loesscanyonsburngroup.com/`
4. Ambrosia, V., Wegener, S., Zajkowski, T., Sullivan, D., Buechel, S., Enomoto, F., Lobitz, B., Johan, S., Brass, J., Hinkley, E.: The ikhana unmanned airborne system (uas) western states fire imaging missions: From concept to reality (2006–2010). Geocarto International 26(2), 85–101 (2011)

5. Anthony, D., Basha, E., Ostdiek, J., Ore, J.P., Detweiler, C.: Surface classification for sensor deployment from uav landings. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA) (2015)
6. Baeza, M., De Luıs, M., Raventós, J., Escarré, A.: Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. Journal of Environmental Management 65(2), 199–208 (2002)
7. Boer, M.M., Sadler, R.J., Wittkuhn, R.S., McCaw, L., Grierson, P.F.: Long-term impacts of prescribed burning on regional extent and incidence of wildfiresevidence from 50 years of active fire management in sw australian forests. Forest Ecology and Management 259(1), 132–142 (2009)
8. Casbeer, D.W., Beard, R.W., McLain, T.W., Li, S.M., Mehra, R.K.: Forest fire monitoring with multiple small UAVs. In: American Control Conference, 2005. Proceedings of the 2005. vol. 5, pp. 3530–3535 (Jun 2005)
9. Corke, P., Hrabar, S., Peterson, R., Rus, D., Saripalli, S., Sukhatme, G.: Autonomous deployment and repair of a sensor network using an unmanned aerial vehicle. In: Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on. vol. 4, pp. 3602–3608 Vol.4 (April 2004)
10. DiTomaso, J.M., Brooks, M.L., Allen, E.B., Minnich, R., Rice, P.M., Kyser, G.B.: Control of invasive weeds with prescribed burning 1. Weed technology 20(2), 535–548 (2006)
11. Finney, M.A., McHugh, C.W., Grenfell, I.C.: Stand-and landscape-level effects of prescribed burning on two arizona wildfires. Canadian Journal of Forest Research 35(7), 1714–1722 (2005)
12. Higgins, J.: Design, Testing, and Evaluation of Robotic Mechanisms and Systems for Environmental Monitoring and Interaction. Master's thesis, Department of Materials and Mechanical Engineering, University of Nebraska-Lincoln (2016)
13. Hodgson, A., Cheney, N.P.: Aerial ignition for backburning. Australian Forestry 33(4), 268–274 (1969)
14. Ippolito, G., Murray, E.: Two U.S Forest Service Employees & Pilot Die in Helicopter Crash (Mar 2005)
15. Keeley, J.E.: Fire management impacts on invasive plants in the western united states. Conservation Biology 20(2), 375–384 (2006), `http://dx.doi.org/10.1111/j.1523-1739.2006.00339.x`
16. Merino, L., Caballero, F., Martínez-de Dios, J.R., Maza, I., Ollero, A.: An unmanned aircraft system for automatic forest fire monitoring and measurement. Journal of Intelligent & Robotic Systems 65(1-4), 533–548 (2012)
17. Merino, L., Martínez-de Dios, J.R., Ollero, A.: Handbook of Unmanned Aerial Vehicles, chap. Cooperative Unmanned Aerial Systems for Fire Detection, Monitoring, and Extinguishing, pp. 2693–2722. Springer Netherlands, Dordrecht (2015)
18. Pister, K.S.: Tracking vehicles with a uav-delivered sensor network (2001), `http://robotics.eecs.berkeley.edu/~pister/29Palms0103/`
19. Skeele, R.C., Hollinger, G.A.: Aerial Vehicle Path Planning for Monitoring Wildfire Frontiers. In: Wettergreen, D.S., Barfoot, T.D. (eds.) Field and Service Robotics, pp. 455–467. Springer Tracts in Advanced Robotics, Springer International Publishing (2016)
20. Stritzke, J.F., Bidwell, T.G.: Eastern redcedar and its control. Weeds Today 15(3), 7–8 (1984)
21. Wade, D.: Ignition devices for prescribed burning (Mar 2013), `http://southernfireexchange.org/SFE_Publications/factsheets/2013_3.pdf`