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Design and Validation of a System for Targeted Observations of Tornadic Supercells Using Unmanned Aircraft

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Abstract— **This paper presents an aerial robot system designed to perform *in situ* sampling of supercell thunderstorms, including those that produce tornadoes. A description of the system architecture and concept of operations is given, along with a brief discussion of the evolution of critical system components. Results are given from two field campaigns, an airmass boundary intercept in Northern Colorado during the spring of 2009, and two supercell transects during the Spring 2010 campaign of the VORTEX2 project. The 2010 results represent the first aloft sampling of the rear-flank downdraft in a tornadic supercelluar storm.**

I. INTRODUCTION

Over the past three years, researchers at the University of Colorado and the University of Nebraska have been collaborating to create an unmanned aircrat system (UAS) for *in situ* atmospheric sampling of severe storms[1], [2]. Lessons learned from preliminary operations during the Collaborative Colorado - Nebraska Unmanned Aircraft System Experiment (CoCoNUE) [1], [2] have informed the design of a UAS for operation during the VORTEX2 field campaign [3], a fully nomadic multi-agency field program of 100 scientists and over 40 science and support vehicles studying tornado formation in the United States Great Plains region. This paper describes the unmanned aircraft system designed to participate in VORTEX2.

The unmanned aircraft system described here is based upon the need to understand the thermodynamic nature of the airmass boundaries in thunderstorms with a persistent and deep mesocyclone (vertically-oriented storm-scale vortex), also known as a supercell[4]. It was refined by realistic expectations determined by a two year pilot program, and further restricted to meet FAA regulatory requirements[5].

To optimize science returns, two sampling scenarios were developed for conducting targeted observations of tornadic storms. In the first scenario, the unmanned aircraft (UA) is used to provide samples at a defined altitude approximately 20 km to either side of and perpendicular to an airmass boundary preceding the storm. In the second scenario (Fig. 1), the UA is used to fly transects out to 5km of the boundary of the rear-flank downdraft (RFD)[6] at different altitudes for each pass. These operations are not necessarily intended to be conducted on the same storm, but if the team arrives far enough ahead of an approaching storm, it is possible to run both scenarios.

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II. CONCEPT OF OPERATIONS

The concept of operations for UAS observation of tornadic supercells is driven by two primary factors: the rapid evolution of the storm and Federal Aviation Administration (FAA) regulations. Supercell thunderstorms are the most dynamic class of severe convective storms. Therefore the entire system, including all ground support, must be mobile and the aircraft must be launched from a previously undetermined position in as little as five minutes. FAA regulations [5] require an observer within visual line of sight of the aircraft at all times, which in our case was defined to be less than 1/2 mile horizontally and 1000’ vertically. As a result, during flight operations the aircraft is commanded to orbit around a ground vehicle which then drives the aircraft to the sampling location. The total system is comprised of four main elements: i.) the unmanned aircraft; ii.) a mobile ground control station used to command the UA; iii.) a ground tracker vehicle that is followed by the aircraft; iv.) and a scout vehicle outfitted with a mobile mesonet[8] sensor suite in order to provide ground based data to validate with the aircraft. Each vehicle has a meteorologist with a laptop running the SASSI tool for severe weather situational awareness [7].

A mobile ground control station (GCS) is used to support the deployment of the UAS by providing the necessary tools for operation and maintenance of the system. In its nominal state, the GCS provides the space to transport two full airframes, their support systems, and the crew needed to launch and operate the UAS. This crew consists of a driver, meteorologist, UAS manual pilot (who can control the UA through joystick commands from a conventional radio-control handset), UAS operator, and pilot in command (PIC). Typically the tasks associated with PIC and UAS manual pilot are performed by the same person. During transport, the meteorologist uses WAN access and VHF voice communications to determine the status of the rest of the research group and the current storm situation.

Despite limiting the flight speeds and directions of the UA, orbiting the tracker vehicle is vital to satisfying the requirements of the FAA to operate the UA in the national airspace system (NAS). An observer inside the tracker provides constant “see and avoid” capabilities for the UA by remaining within visual range during the flight and scanning for other air traffic. Should any traffic enter the UA airspace,

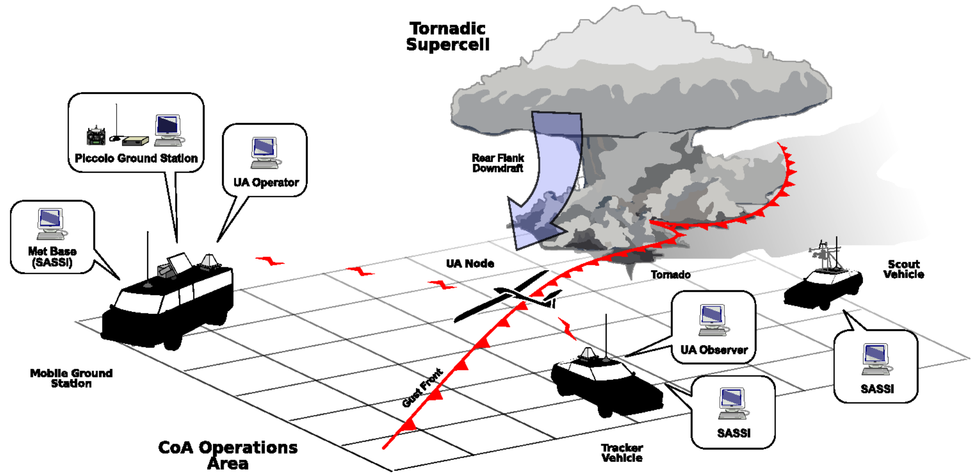

Fig. 1. VORTEX2 concept of operations for the sampling of the RFD. Each vehicle has a meteorologist with a laptop running a tool for severe weather situational awareness called SASSI[7].

the spotter coordinates with the UA operator over VHF voice communications to perform avoidance maneuvers. The tracker vehicle carries a driver, secondary meteorologist, the observer, and an assistant to the observer. The secondary meteorologist provides the primarily meteorologist (in the GCS) with field observations of the storm, and looks for visual cues to indicate the UA's position relative to the storm. The assistant observer maintains an interface to the UA, providing telemetry to augment the observer's situational awareness, and a secondary command and control link for emergency situations.

A standard deployment scenario is coordinated by meteorology and UAS team leads. During the targeting phase of a mission the meteorologist examines Doppler radar products and devises a flight plan for the UA. Upon reaching the deployment location, the GCS is parked and remains stationary for the UA operation unless it is determined that the safety of the crew is threatened. Once the GCS is positioned, the driver and UA pilot assemble the UA outside of the GCS while the UA operator performs final checks and establishes a takeoff flight pattern. During launch and climb-out the UA is controlled by the UA pilot using a handset. Following verification that all systems are functioning appropriately, the UA is switched to autopilot control and tasked to orbit the tracker ground vehicle. To perform boundary sampling the meteorologist indirectly moves the UA by issuing driving directions to the tracker vehicle. During the sampling, the UA operator monitors the status of the UA from the GCS, and performs altitude changes as directed by the meteorologist. When it is determined that the sampling operation has finished, the tracker is instructed to return. As soon as the UA enters visual range of the GCS, it is commanded into a holding pattern from which the UAS manual pilot takes control and lands the aircraft. Following landing, the expended propulsion battery pack is "hot swapped" with fresh pack for a second flight, or the UA is disassembled and loaded into the GCS van where it is prepped en route to another deployment.

III. Vehicle Design

A. Aircraft

Two key considerations for the design of the UA were the ability to launch within five minutes of establishing the location for the GCS, and the desire to maximize sampling time while retaining the ability to combat a range of atmospheric conditions. Given these constraints, the UA must fit into a trailer or van, but be large enough to fly in the down drafts anticipated in the vicinity of a severe convective storm. A compromise between these two constraints was met by the use of removable wings that can be quickly attached to the fuselage. Propulsion is provided by an electric motor which compared to gas engines best addresses the balance between the instantaneous power requirements for maneuvers, the total energy requirement for endurance, and the portability and reliability requirements for rapid deployments. Quick, repeatable launches from previously undetermined sites is achieved through rail or hand launching.

The airframe chosen to conduct testing during the CoCoNUE project was the NexSTAR Almost-Ready-to-Fly (ARF) aircraft manufactured by Hobbico, Inc., modified to operate autonomously[9]. Measures taken to ensure the reliability of the platform and feasibility of deployment include: strengthening to allow for rail launch, conversion to electric propulsion, addition and tuning of an autopilot system, addition of single-board computer for flight management and communication through an ad hoc network, and the integration of a meteorological sonde for airborne measurements of pressure, temperature, and humidity.

For the VORTEX2 project, it was clear the NexSTAR airframe did not meet all the design requirements for severe storm sampling, specifically its inability to operate in high humidity and precipitation, its use of landing gear which restricts landings to improved surfaces, its relatively inefficient airframe, and its inability to handle strong aerodynamic forces. To accommodate these shortcomings, a new airframe was selected that combined the aerodynamic efficiency of a high-aspect-ratio wing (evident in Figure 2) and the structural efficiency of the materials used in high-performance gliders to meet the airframe requirements for endurance and gust survivability. To reduce development time and to take advantage of the materials and techniques used in the manufacture of competition sailplanes, the Tempest airframe is based on a modified consumer off-the-shelf (COTS) sailplane design.

Fig. 2. The Tempest UA pictured ready for deployment into the tornadic supercell pictured in the background. Photo taken during the Spring 2010 campaign of the VORTEX2 experiment.

The Tempest UA[10] was designed to be the first generation low-cost unmanned aircraft for collecting in situ data in supercell thunderstorms. The fuselage of the Tempest airframe (Figure 2) is primarily fiberglass with a wing set based on a design used in competition remote-control dynamic soaring where aircraft routinely obtain high air speeds and accelerations. The detachable wings have a full span of 10.5 ft with a maximum gross takeoff weight of 15 lbs. The Tempest is easily hand launched, rail launched, or launched using a bungee-cord “high start” launcher. Smooth under surface and a folding propeller enables landing in grassy fields and road surfaces. The electric motor is powered by a high-capacity battery. These features enable quick deployments, with rapid turn-around, while providing 45 minutes of endurance. The UA is flown semi-autonomously with a Piccolo SL autopilot, manufactured by Cloud Cap Technologies, and in situ meteorological data is collected with a Vaisala RS-92 sonde.

B. Mobile Ground Control Station

The mobile GCS (Figure 3(a)) is a 15-passenger van modified to support the Tempest UAS. The van contains several after-market systems that facilitate quick deployment and streamline field operations. First, voice communications radios have been installed in a console and combined with an intercom system that allows occupants to speak to each other clearly through headsets and to use a VHF radio to communicate with the tracker vehicle, the scout vehicle, and the team lead. Furthermore, a hand-held VHF radio is maintained by the PIC and is tuned to the frequencies of nearby airports before operations commence. This enables quick communications with local air traffic should the need arise.

UAS communication, command, and control is provided in the GCS by two computer systems and a wide area network (WAN) interface that accommodates two types of cellular connections (Figure 3(b)). This provides an interface to the Internet, and the systems are used by the meteorologist for radar data and communications with others in the research group, and the UA operator for dynamic map requests and the real-time publication of UA location and meteorological measurements. A small linux single-board computer (SBC) is also connected to the LAN and provides GPS and magnetometer readings. Through these measurements, the UA operator and meteorologist are able to know their exact position and heading relative to the UA, tracker vehicle, and target storm.

Two tracking antennas, a mechanical system with a 900MHz antenna, and a phased array for directed 802.11 communications are positioned on the roof of the GCS. The Linux SBC automatically points the antennas using GPS feeds from the GCS and the UA in conjunction with local magnetometer readings. This helps to ensure continuous communications over the range of operations, and enables the GCS to be moved during the UA flight in the case of an emergency while maintaining communications with the UA.

The UA are stored on wall-mounted racks in the rear of the van to enable the subsystems to be powered during transport to the deployment site. This allows for the UA operator to perform system initialization and operational verification before arrival. By removing these vital steps from the list of tasks to be performed after parking the GCS, deployment in under five minutes can be realized.

C. Tracker Vehicle

The ability of the UA to follow the tracker vehicle and ability of the observers within the tracker vehicle to maintain sight of the UA and the surrounding airspace is critical to maintaining safe operation. The vehicle contains two systems that allow for this task to be accomplished with a high level of autonomy, freeing the tracker vehicle occupants to focus on other critical issues. The first system is a small Linux SBC designed to participate on an ad hoc network, and provide the GPS location of the tracker vehicle to the UA. By allowing the flight computer to subscribe to this GPS location, a controller on the UA can track and orbit the tracker vehicle. This provides two advantages: the aircraft remains within the required distance of the tracker vehicle, and the sampling of the storm can be conducted by directing the driver of the tracker using voice commands over a VHF radio. The second system is a laptop computer running the networking software and a limited-functionality graphical user interface. This interface provides status of the system and position of the aircraft at all times, allowing personnel in the tracker to provide an offset to the orbit of the aircraft. This tracker-relative orbit location is chosen to allow for easy, full-time observation by one of the designated UA observers through a side window or sunroof.

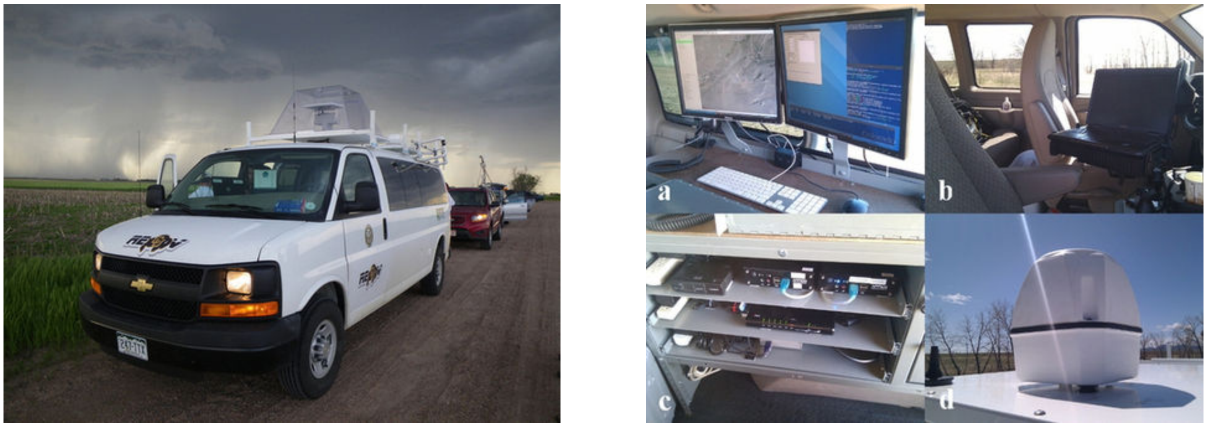

Fig. 3. 1) The mobile GCS, shown during the 2010 VORTEX2 campaign. 2) A few of the components of the mobile GCS, a) the UAS operator station b) the meteorologist station c) the electronics racks, containing the Linux SBC for controlling the tracking antenna, two computers for interfacing with the autopilot ground station, and equipment for WAN access.

IV. Communications and Control

A. Communications Architecture

Communications between all vehicles is critical to mission safety and success. The system's core communications, command, and control is supported by the NetUAS software[11]. This software provides mechanisms for service discovery across the network and the ability to easily add interfaces to new transport media, sensors, or other physical devices.

The concept of operations for sampling severe storms required the addition of several new software interfaces to the NetUAS suite. Functionality was added to accommodate control of two tracking antennas on the mobile GCS using a Linux SBC, use of the 900 MHz autopilot link as a backup to the ad hoc data network, the addition of two graphical user interfaces (GUIs) for use by the PIC and meteorologist, and an WAN interface to a server at the Severe Storms Lab for providing UA telemetry and meteorological data to all VORTEX2 participants[7].

The concept of operations dictate that communications must reliably support flights up to 10km from the GCS. This was a significant increase from previous operations that rarely exceeded 2km from the GCS. Also of paramount importance to the project is the ability to create ad hoc networks. Without this ability, all nodes in the system would have to retain a static set of routes between each other. Should one participant leave the network, it could result in a loss of data for many of the other participants. Since the CONOPS for storm sensing requires several vehicle configurations, it is possible that the GCS would need to communicate directly with the tracker vehicle or use the UA as a relay. For this reason COTS 802.11 cards were used to create the communication, command and control backbone, and a reactive routing protocol was used.

Following the recommendations presented in [12], the implementation of the B.A.T.M.A.N. (Better Approach To Mobile Ad hoc Networking) protocol[13] was chosen over AODV (which presented problems in initial test flights). In several experiments conducted in both the laboratory, and in the field using mobile and stationary nodes, the functionality of B.A.T.M.A.N. was verified for identifying and properly selecting routes. However, use of amplifiers with the stock 802.11 cards, along with a few factors including antenna placement continued to cause small problems throughout the deployment. A more intensive investigation of these artifacts is left to future work. For the VORTEX2 deployments, the base system defined in this paper provided enough up time (approximately 10% packet loss during a 1 hour experiment) to successfully complete the experiments.

B. Graphical User Interface Enhancements

The NetUAS GUI was originally created to manage all nodes and links participating in a networked UAS. Given that each node communicates with its neighbors periodically in order to provide a routing table, by building the GUI on top of the network, the system can provide the users with statistics on a per node basis. A list of the connected nodes, along with their associated services (telemetry, link statistics, etc.) is contained in a panel on the left. The majority of the GUI is used to display several layers of geo-referenced data. The lowest layer contains one of several selectable forms of maps: satellite imagery, road network, topographical, and aviation charts. The upper layers contain node icons and contextual information (node name, altitude, current target waypoint), flight plans, established network links. From this, the operator can quickly deduce the number of nodes connected on the network, their current location, node type (fixed, mobile, UA), and some simple node context information.

For the CoCoNUE and VORTEX2 projects, the NetUAS GUI was enhanced to satisfy the needs of the atmospheric sampling mission. This was done by adding several new layers and functionality. The new layers include real-time WSR-88D weather radar data, National Weather Service warnings, flight region boundaries, VORTEX2 vehicle locations (available through SASSI[7]), and real-time UA wind measurements. The functionality enhancements include support for geo-coded searching, quick flight plan generation, and

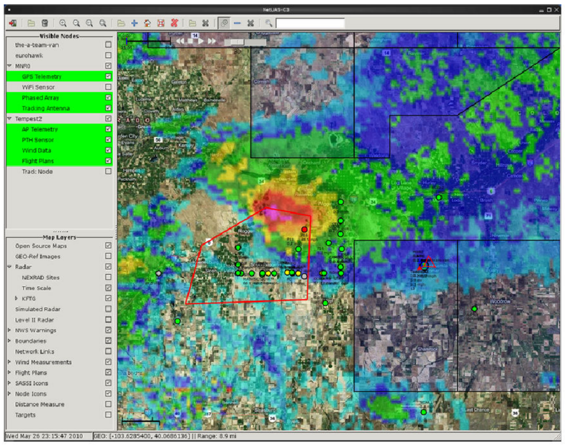

Fig. 4. NetUAS GUI screenshot taken during 26 May 2010 operations. The left panel contains a list of connected nodes and their respective services, along with a list of displayable layers. The right panel shows the overlay of WSR-88D image of the supercell, COA boundaries, and locations of other deployed VORTEX2 vehicles.

the ability to send waypoint plans to all vehicles (including ground vehicles). Geo-coded searches were added to center the map on a search string, enhancing the ability to follow travel instructions from the VORTEX2 field commander, which were commonly given as small town names. Quick flight take-off and landing plan generation was added to reduce setup time, and to accommodate occasions where the UA must be landed quickly, or out of sight of the ground station. The ability to send waypoints to ground vehicles was added to address the issue that giving directions to the tracker vehicle using only voice commands over the VHF link is tedious (especially when road names don't exist). Figure 4 is a screenshot of the GUI during the 26 May 2010 operations.

V. Regulatory Issues

All aircraft, including UAS operated by public institutions in the NAS is regulated by the FAA. Permission to fly in specific parcels of airspace is obtained through achieving the equivalent level of safety of manned regulations defined by a certificate of authorization or waiver (COA)[5]. This document defines operational requirements, emergency procedures, airworthiness requirements, and a specific area of operations. The size of this area can be quite large, but the FAA requires that during flight operations, the UA position is known with some degree of precision. This can be satisfied either by specifying a flight plan 72 hours in advance of a flight, or restricting the size of the COA region.

Given the dynamic nature of the CONOPS required for supercell intercepts, it is nearly impossible to define flight plans 72 hours in advance; therefore, the size of the COA areas used for this experiment was limited to 20x20 miles. By observing flight limitations over populated areas, airports, and into particular classes of airspace, an area located around the Colorado, Kansas, and Nebraska border was divided into 61 operational areas. Each of these areas can be "activated" for flights with a two hour advance warning in the form of a notice-to-airmen (NOTAM). In our particular case, only four of these regions could be "active" at one time.

VI. Field Results

A. *CoCoNUE Results*

Three sets of experiments were run for the CoCoNUE project. A functional test of the complete UAS and ground-vehicle system was completed 1 March, 2009[1]. There were two successful flights of NexSTAR-3 with a sonde mounted on the wing. The second flight also ended with successful automatic landing. The second set was conducted on 24 September, 2009, and was the first attempt to perform an atmospheric airmass boundary intercept. Four successful flights of NexSTAR-2 were conducted, three of which were used to test various aspects of the VORTEX2 deployment strategy and equipment, and the final test was used to gather RSSI data from the 802.11b link. The final set was conducted on September 30th, 2009 and resulted in successful boundary intercepts[14], thus verifying the UAS concept of operations. For all the CoCoNUE flights, real-time feeds from the Pawnee and CHILL Doppler radars were used for boundary identification and UA navigation. The radar products were also recorded and used for post flight analysis of meteorological products from the UAS.

B. *VORTEX2 Deployment*

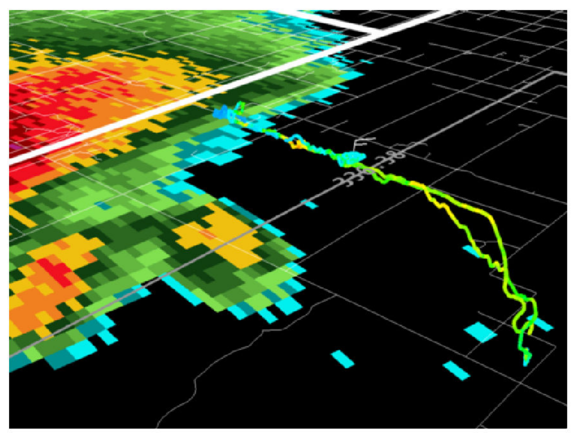

Fig. 5. 10 June 2010 flight path and corresponding radar data. Note the white COA boundary just North of the end of the flight path. This boundary restricted flight closer to the storm.

The VORTEX2 deployment saw two boundary intercepts and one supercell intercept, the more notable being on a tornadic supercell on 10 June, 2010 (Fig. 5). Verification of the intercept at a specified altitude can be seen in Figure 6. Intercept of the boundary was also confirmed through visual cues sighted by the secondary meteorologist in the tracker vehicle.

Verification of the CONOPS during the VORTEX2 campaign was accomplished through the achievement of several engineering and science objectives. On both the 9 June and 10 June 2010 experiments, which were the only deployments with supercells passing close enough to COA regions to

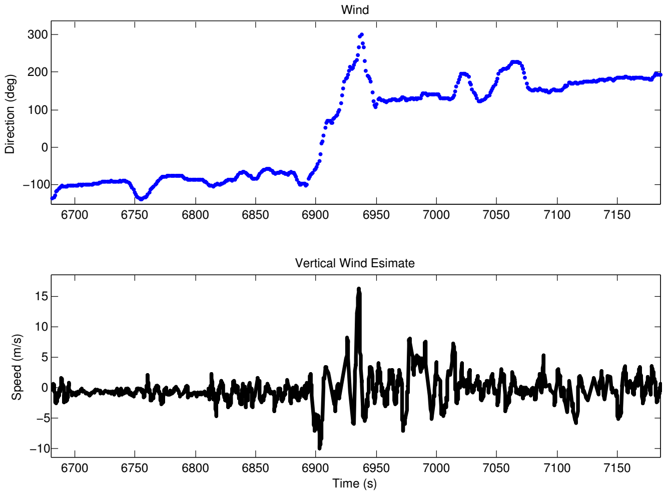

Fig. 6. Wind data recorded during 10 June, 2010 deployment. The top plot shows wind direction, which clearly indicates a shift at around 01:46 UTC. The bottom plot shows the vertical wind estimate, and demonstrates an updraft associated with highly variable winds following the shift in wind direction.

sample primary storm features, the UA was able to intercept the gust front of the RFD at a specified altitude and successfully return the data. In total 21 missions were flown in Colorado, Nebraska, and Kansas, from 5 May to 15 June 2010, without incident despite being flown near severe storms and through light precipitation. In all cases where an intercept was attempted, the GCS was positioned and the UAS was set up with plenty of advance time to intercept the feature of interest. Having the UA orbiting the tracker vehicle, combined with situational awareness through the observer laptop, and the ability to move the orbit center point, the observer had relatively little difficulty keeping eyes on the aircraft. Furthermore, enough time was left for the UA to return, even given varying wind conditions, and the UA was never forced to land away from the GCS.

Given these successes, the difficulties of reaching supercells for intercept resulted not from system design, but rather from dealing with regulation and policy. Figure 5 demonstrates that during the intercept on June 10th, the UA was unable to proceed closer to the storm due to the limitations of the COA boundaries. Figure 4 shows how the UAS team (shown as the red triangle shape icon) was forced to wait east of the approaching storm inside a COA boundary, while the rest of the VORTEX2 team (pictured as red, yellow, and green circles) was already performing sampling of the storm. The UA was not allowed to fly over population dense areas (towns, interstate highways, etc.), or into specific classes of airspace. Given these restrictions, the probability of a supercell crossing a box in such a way that the UA could be flown into the RFD during an interesting portion of the storm's lifespan was small.

VII. Conclusion

Through a short timespan of slightly over two years, a system was developed from scratch to accommodate *in situ* measurements of tornadic supercells. This system and its concept of operation were incrementally verified through a series of experiments beginning with the CoCoNUE project and culminating with the Spring 2010 deployment with the VORTEX2 project. Following the VORTEX2 project, it became apparent that frequent sampling of supercells using a UAS is mostly limited by policy and regulation, not technology.

Future work will examine how the effectiveness of the sampling scenario could be increased by allowing more time on station. This can be performed by adding further propulsion batteries, or by allowing the UA to continue to fly without requesting a return to the GCS. In this manner, the UA can continue to sample up to a distance of 20 miles from the GCS before being forced to perform an autonomous landing.

VIII. Acknowledgments

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