Autonomous Uncrewed Aircraft for Mobile Operations in Severe Weather

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Abstract. The 2023 TORUS-LItE campaign simultaneously deployed three uncrewed aircraft into 14 severe thunderstorms while contextualizing the aircraft measurements with remote sensing and ground-based instruments. The rapid formation and evolution of severe storms demanded a data-driven approach to planning and obtaining observations. Launch points and times, flight paths, and coordination between the aircraft was all driven by human and instrument observations in the field. While humans formed a key part of the perception and decision chain in TORUS-LItE, several areas were identified where autonomy could enhance observational effectiveness. The functions performed by humans also identify key capabilities which need to be developed to enable future advanced autonomous observing systems.

Keywords: UAS · Severe weather · Autonomy · DDDAS · Dynamic Data Driven Applications Systems · InfoSymbiotic Systems

1 Introduction

Autonomous small uncrewed aircraft systems (SUAS) have become an important tool in atmospheric science and weather forecasting [5]. As this technology develops, swarms are beginning to be employed[1] and adaptive observation replacing pre-defined sampling plans, allowing dynamic environments such as wildfires[2] and cumulus clouds[6] to be observed. Severe local storms are especially challenging to sample because the storms form quickly, move rapidly, and can produce heavy precipitation and strong winds. Recent advances have enabled mobile operations of teams of fixed-wing uncrewed aircraft to sample these storms [3, 4].

The Targeted Observation by Radars and UAS of Supercells - Left-flank Intensive Experiment (TORUS-LItE)[3] project carried out a nomadic, mobile field campaign during the 2023 spring storm season. The TORUS-LItE campaign had the objective of gathering in situ dynamic and thermodynamic observations of boundary structure and surface vorticity currents in the vicinity of supercell

[3] https://data.eol.ucar.edu/project/TORUS-LItE

thunderstorms. These observations were to be coordinated with remote sensing observations of the storm as well as in situ and remote observations of the environment surrounding the storm. The project's primary observing targets were small-scale features thought to be involved in tornadogenesis which are located at altitudes between 200 m and 2000 m above ground level, and within 10 km of the storm mesocyclone. These features are thus not accessible to in situ observation except by aircraft, but access by piloted aircraft is far too hazardous. Small, fixed-wing UAS were thus used as observing platforms.

To resolve the vertical structure of these boundaries, a new feature of TORUS-LItE compared to prior campaigns was coordinated observation using two UAS in a "stacked" flight configuration in the left flank of the storm (a third aircraft observed the environment immediately surrounding, but outside the storm). The stacked aircraft flew with a target vertical spacing and as close as practicable to directly one-above-the-other and above a CoMeT ground vehicle [3]. This provided three points of vertical structure information on the storm – the two aircraft, with the CoMeT as the base of a virtual meteorological tower.

The TORUS-LItE campaign had multiple unique features compared to previous SUAS weather campaigns that included: i.) operation in highly dynamic environments in storms evolved on scales of minutes and moved with speeds on the order of 10–20 m s^{-1}; ii.) in situ (UAS-based) sensing had to be coordinated with multiple mobile ground instruments; iii.) loose formations of UAS were coordinated to measure atmospheric structure and fluxes; iv.) sampling plans had to evolve in response to UAS observations; v.) and humans in the loop as observers and decision-makers.

This paper describes how the TORUS-LItE campaign employed the dynamic data driven applications systems (DDDAS) paradigm to obtain coordinated, targeted observation and the use of assisted-autonomy. Information and decision flow in an assisted-autonomy data-driven application is described, where key model and decision components were provided by human experts. Key roles for autonomy in current and future elements of targeted oservations solution are identified through results from the TORUS-LItE campaign.

2 Severe Storms UAS Observation as a DDIP Problem

The TORUS-LItE team operated as a distributed estimation and planning system (Figure 1). During "intensive observing periods" (IOPs) the chief meteorologist acted as a field-deployed model for the environment and as a decision-making agent for targeting observations. Observing locations were tasked to the UAS, and an internet application distributed the UAS observing location to other sensing systems in an "armada" which independently targeted on the UAS observing locations. The UAS and "armada" in turn fed observations to the meteorologist who ingested this information and their own visual observations to produce subsequent observation targets. In this way a direct (meteorologist-UAS) and indirect (meteorologist-UAS-armada) DDDAS loop operated to gather coordinated, informed observations.

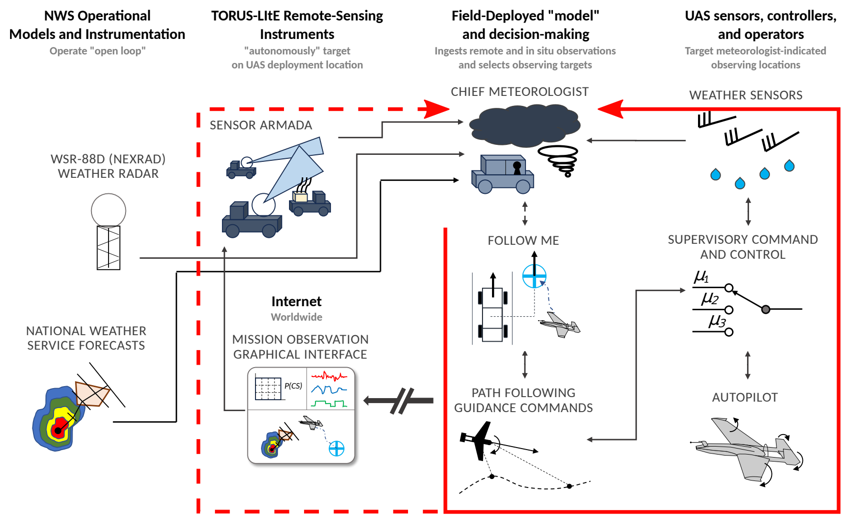

Fig. 1: Autonomy architecture for mobile sensing of severe weather by teams of small uncrewed aircraft. Direct and indirect model-control-observation loops are indicated by red solid and dashed arrows respectively.

Human experts operated in modeling, data assimilation, and control functions. Thus, the representations and "computations" are different than would be performed by an autonomous observing system. Many of the functions are similar however, and can shed light on the capabilities needed by fully autonomous systems performing similarly complex tasks in very dynamic environments.

2.1 TORUS-LItE Team Information Flow

To function as a distributed estimation system the TORUS-LItE team obtained observations from the team's instrumentation and from National Weather Service (NWS) operational observing systems, distributed via voice and data channels. A networked desktop application allowed display of NWS radar, a subset of the team's in situ observations, and for the team to exchange text messages.

These data would be "assimilated" by experts throughout the observing team to provide an estimate of the current and future state of the environment. These states were further discussed via voice and data channels so that the team arrived at an ensemble prediction of the state and evolution of a target storm. These estimates typically focused on dynamic features (e.g. a mesocyclone) and gross evolution (e.g. translation east at 20 knots while strengthening) readily understood by team members. While this is a relatively imprecise description of the environmental state, it is compact to communicate and conveys both state and an appropriate dynamical model. The precision of this description was also fairly well matched to the complexity and uncertainty of the environment, and sufficient to enable coordinated targeting of storms.

2.2 Decision-Making for Targeted Observation

Prior to an IOP deployment, the field coordinator monitored information from the NWS and TORUS-LItE team, providing waypoints to the team. The objective was to position the team in front of a developing storm cell so that each instrument could reach suitable deployment and simultaneously observe a mature storm cell. Once the decision to deploy on a cell was made by the field coordinator it was distributed to the team via voice radio and an annotated map on the desktop application, accompanied by an IOP start time. Figure 2 shows a screenshot of the tool following the deployment in western Oklahoma on 2023-06-15. The tool was also used to communicate to the team when and where UAS operations could be conducted.

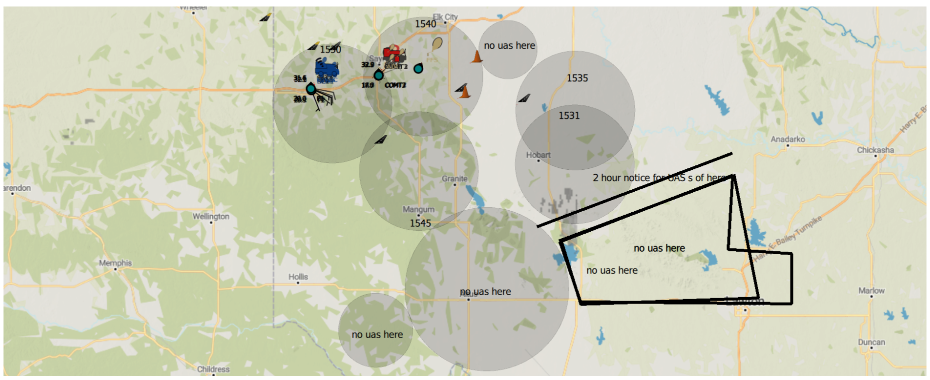

Fig. 2: A screenshot from the Situational Awareness for Severe Storm Intercept (SASSI) tool immediately following the observing period on 2023-06-15.

The deploy call triggered several consensus decision processes in the team. The left flank lead, UAS airboss, and left flank UAS flight crew would locate a suitable road for intercepting the storm, confirm airspace availability, and identify launch and recovery site options. Occasionally these constraints forced a launch location or time away from the primary sampling region and the aircraft were then ferried into the observing region while airborne.

Teams with radar, a profiling UAS, and ground instrumentation engaged in similar observation planning exercises once an observing region and time was available. Each team would identify observing locations suited to their instrument characteristics and scientific role, as well as suitable roads for egress as the storm developed and moved.

2.3 Deployed UAS Operations

During each IOP the UAS team used observations from crew members, TORUS-LItE surface instrumentation, and the UAS-carried sensors to target the UAS observations. A second networked application was used by the UAS team to monitor airspace approvals, aircraft locations, and to share text communication and map annotations specific to flight operations. This information was used to support a number of observation and safety critical decisions:

– Where to intercept a storm
– How far into the storm to progress
– When to discontinue scientific operations
– Where to travel for storm egress

The decision of where to intercept the storm was typically informed by road network constraints and visual observations made by the lead meteorologist in the left flank team. The decision of how far to progress into the storm and when to egress required processing aircraft data in real time – to detect thermodynamic boundaries and identify when safety dictated recovering the aircraft.

To improve situational awareness, aircraft observations were distributed via mobile internet. A decision support tool was created which received these observations and displayed them to the UAS airboss and left flank lead meteorologist. The tool provided time histories of sensor data, allowing airmass boundaries to be identified in real time. It also processed aircraft reported winds and inertial information to display the inertial velocity which can be achieved as a function of track direction at both the current airspeed and at the maximum possible speed. Figure 3 illustrates the display provided by this tool during the sampling flight on 2023-05-24. Dashed circles show the possible inertial velocity at the present airspeed, solid circles the maximum achievable inertial velocity.

This real-time processing assisted both in targeting scientific observations, and in making the decision to cease operations and egress from a storm. Of particular concern were extreme winds encountered by the team in previous storm deployments[3] which severely restricted the speed at which the team could move while maintaining the UAS stack and visual contact with the aircraft. The in situ observations provided direct feedback about the possible directions of motion and achievable speeds, supporting egress planning.

3 Flight Results and Decision Case Studies

The UAS were deployed on 12 days, including 10 days where the LF stack was able to conduct coordinated operations. Deployments took place in four states between 2023-05-26 and 2023-06-15 during which the UAS accrued more than 27 hours of flight time and covered more than 1,600 km of distance while airborne.

During the project several events highlighted capabilities needed for future autonomous observing systems operating in highly dynamic environments.

3.1 Environmental Prediction and Satisficing

On 2023-05-27 the team had completed scientific observations on a storm near the New Mexico / Texas border and begun storm egress when visual observations and ground instrumentation indicated a surge in the storm's Rear Flank

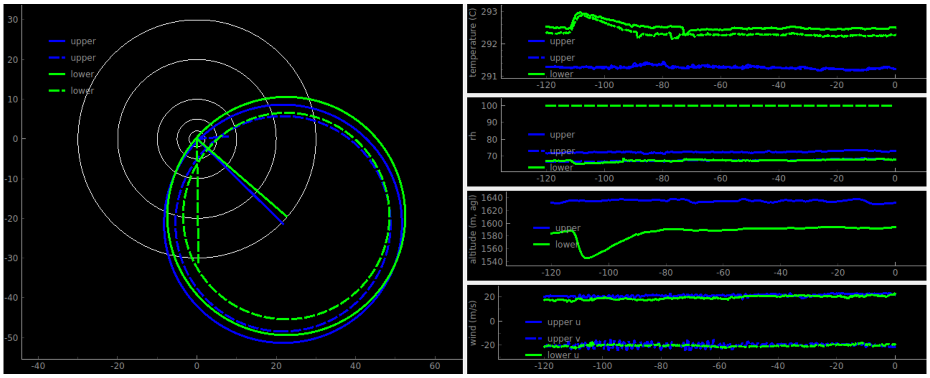

Fig. 3: Visualization of mission data used for monitoring instrument function and aircraft storm egress capability. Data shown here is post-processed from the flight on 2023-05-24. Wind speeds during this deployment were so strong that observations were stopped and the aircraft recovered.

Downdraft (RFD), associated with extreme winds and precipitation (Figure 4). Evaluating the trajectory of the RFD and the aircraft's present location, the team determined that continued egress would fly directly through the RFD. In response, the team elected to hold position within the storm but outside the RFD. The aircraft were brought to a lower altitude and physically separated to maintain visual contact and separation. After some moderate precipitation, including small hail, passed the aircraft were successfully recovered.

This successful response was possible because critical features of the environment were correctly classified and associated with key dynamics (the hazard posed by and where the RFD would reach), and a decision was made which would expose the aircraft to less severe conditions. The ability to synthesize distributed observations and forecast the storm evolution at a very qualitative level was essential to safely recovering the aircraft.

3.2 Correlating Vehicle, Sensor, and Environmental Dynamics

While sampling a storm on 2023-06-12, the stack encountered sudden, extremely heavy precipitation and reversed course. Shortly after reaching clear air both aircraft showed rapidly decreasing altitude. Initially the improbably high descent rate appeared to be a result of inaccurate air data associated with water contaminated instruments. However, the inertial speeds remained consistent with the air speed and approximate wind speed. The air temperature sensors also showed warming consistent with the reported altitude change.

While the aircraft were descending at a rate which was concerning from an operational perspective, dynamically consistent observations at least indicated that the air data systems were functional so autopilot-guided flight (and thus egress) could continue. Shortly afterward the aircraft rapidly climbed, achieving

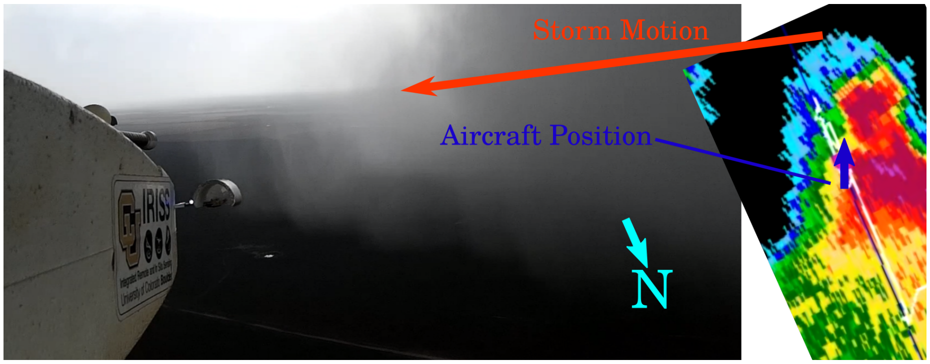

Fig. 4: Onboard and radar views of the approaching RFD

a vertical rate beyond their physical capability. Post-processing reveals that the aircraft flew through a very strong vertical velocity couplet, possibly associated with a streamwise vorticity current (SVC).

4 Discussion

The information gathering, coordination, control, and field experience from TORUS-LItE reveals several opportunities and challenges for deploying coordinated autonomous systems in very dynamic environments. Broadly speaking there are three categories of difficulty in implementing greater autonomy in targeted severe storms observation.

When information is readily available and errors are not immediately hazardous, implementing greater autonomy is principally a matter of information sharing. Such functions include managing aircraft spacing, monitoring the function of sensors, and the egress speed prediction developed during TORUS-LItE. The most obvious candidate is controlling inter-UAS spacing which required visual monitoring, control station interaction, and radio communication as no direct data links between aircraft existed during TORUS-LItE. Adopting a mobile ad hoc network architecture would allow direct data links between UAS, and thus for formation control algorithms to be employed.

A more challenging set of functions to provide autonomously includes aircraft recovery, sensor failover, and airspace management. These functions require broader perception and reasoning about the past and future states of systems. In the case of airspace reservation, the future evolution of the storm system and flight paths of the aircraft must be anticipated in order to ensure airspace is active prior to the aircraft reaching an area. Often contingency reservations had to be made, guarding against multiple possibilities for storm track and evolution. In the case of sensor failure, the totality of sensors as well as the environmental conditions must be considered as seen in the vertical gust encounter.

The most challenging set of functions to automate are those focused on big-picture safety and mission decision-making. This includes making the decision of when to egress from a storm or end a deployment and where to target a storm for sampling. The factors determining these decisions are complex to perceive (often visual) and are processed through a mental model of the evolution of the aircraft and environmental state. For instance, the decision to wait out the RFD surge required identifying a storm feature in order to assign the correct dynamics (both severity of the feature and rapidity of evolution). In the absence of this recognition, the decision to fly through moderate rain and light hail is unlikely to be made. To make these decisions a new approach to understanding and forecasting the environment state may be required, one which provides a classifying function similar to the qualitative "forecasts" made by the TORUS-LItE crew. Such forecasts may capture the effects of the environmental evolution without quantitatively describing exactly what the state will be.

5 Conclusion

This paper described recent results deploying a team of autonomous fixed-wing uncrewed aircraft to sample supercell thunderstorms to study tornadogensis. The DDDAS paradigm was deployed with human elements helping closing the loop on the dynamic environmental processes. Current and future work is expanding the autonomous capabilities of this system. The paper identified key areas of near- and mid-term improvements needed to move toward the end goal of autonomous targeted observation.

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