Collaborative Research: NRI: Dispersed Autonomy for Marsupial Aerial Robot Teams

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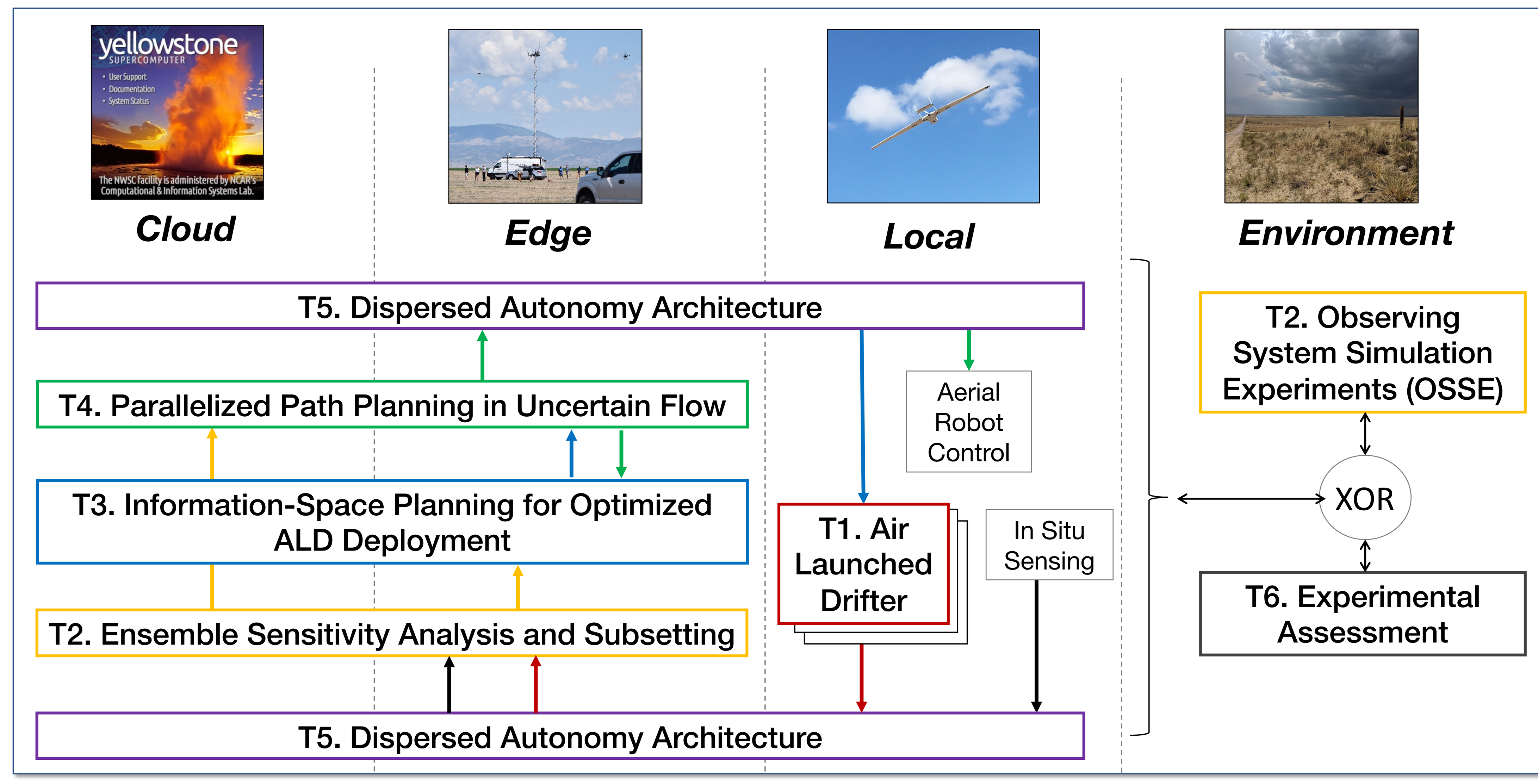
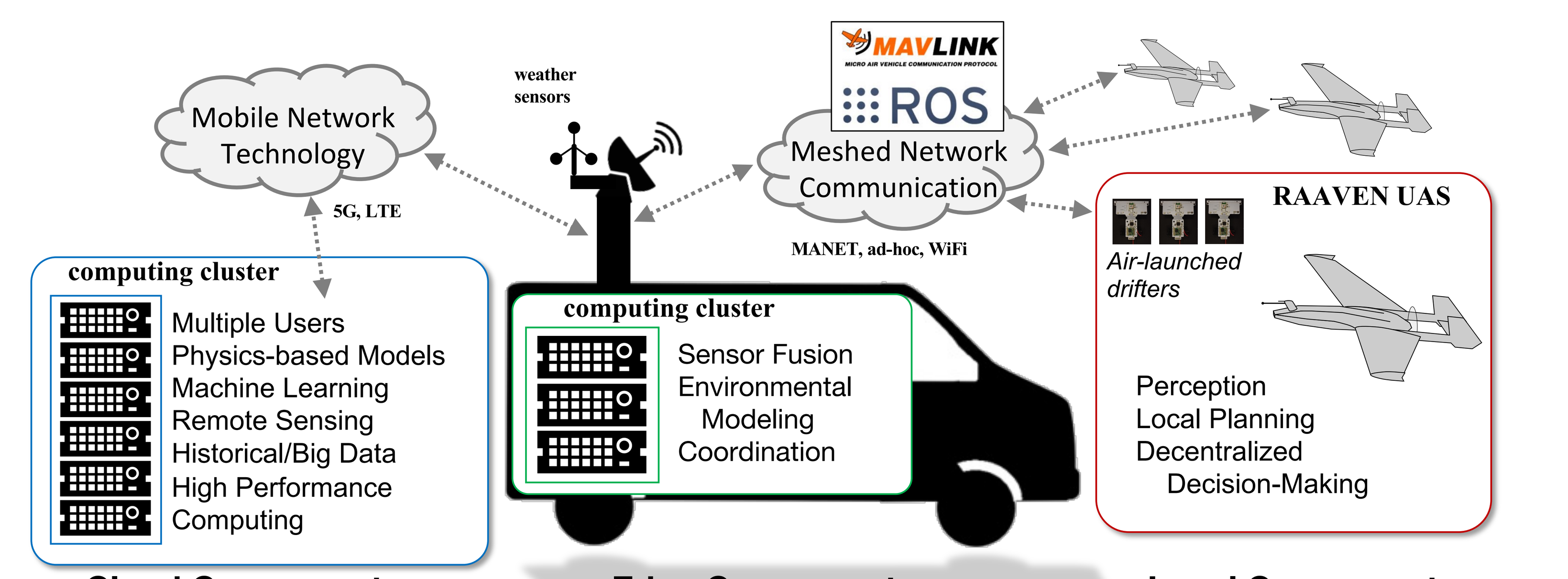
This project advances current practices through new devices and algorithms integrated, deployed, and evaluated on **marsupial aerial robot teams (MARTs)** whereby small uninhabited aircraft systems (SUAS) provide in-situ observations of the atmosphere through on-board sensors and air-launched pseudo-Lagrangian drifters. The project culminates in experimental assessment through a field campaign in complex weather conditions



Key Problem

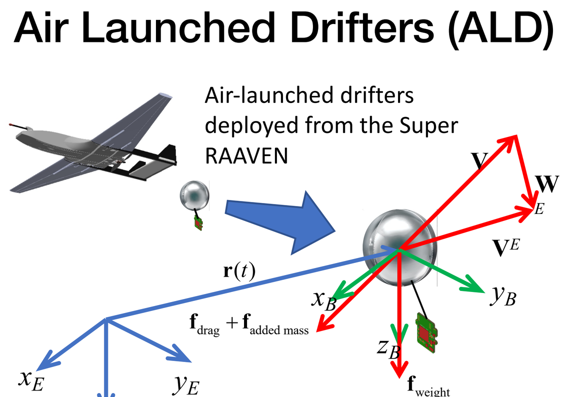
- Aerial robots are fundamentally limited by size, power, and weight constraints.
- By leveraging computing dispersed across different robots, located in ground control stations in the field, or housed in high-performance computing centers, significantly more complex prediction, learning, and planning algorithms can be run compared to what could be implemented locally onboard.
- This work will realize the vision of an *autonomous airborne meteorologist* that performs online targeted observation and forecasting of complex weather.

Innovative Integration: Dispersed Autonomy



Technical Accomplishments

Air Launched Drifters (ALD)

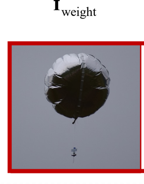


Equations of motion numerically integrated for simulated trajectories through supercell wind field from nature run

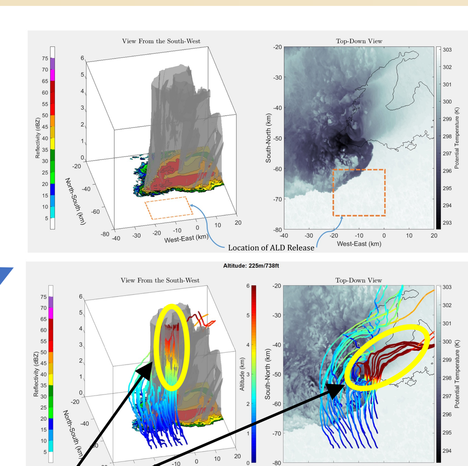
$$m_b \frac{du}{dt} = \sum f_{ext} = \underbrace{m_b g}_{\text{weight}} + \underbrace{m_f g}_{\text{buoyancy}} + f_{\text{added mass}} + f_{\text{drag}}$$

$$B = \frac{m_f - m_b}{m_b + \frac{1}{2} m_f} \qquad K = \frac{\frac{1}{2}\rho_f c_d A}{m_b + \frac{1}{2} m_f}.$$

$$\frac{du}{dt} = K|\boldsymbol{u}_{rel}|(u_w - u) \qquad \frac{dv}{dt} = K|\boldsymbol{u}_{rel}|(v_w - v) \qquad \frac{dw}{dt} = B + K|\boldsymbol{u}_{rel}|(w_w - w)$$

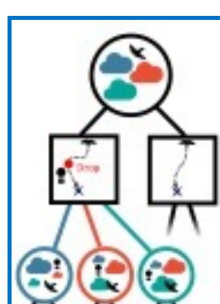


The goal of this research task is the design and integration of an air-launched drifter (ALD) based on a demonstrated prototype microsonde sensor.



Ellipses show simulated trajectories entrained into the updraft; others successfully entrained altitudes of interest

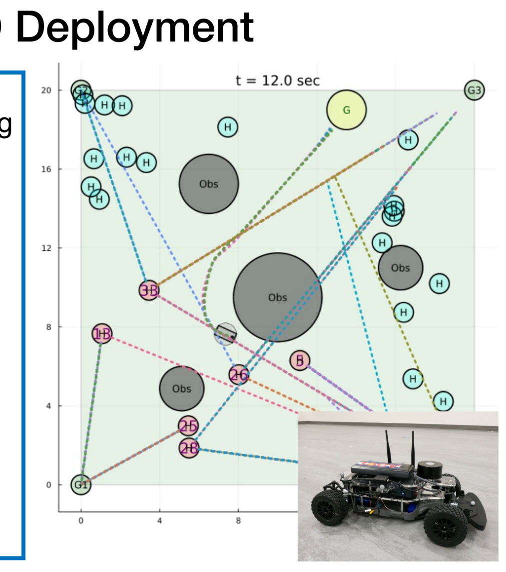
Information-Space Planning for ALD Deployment



The primary objective of the planning effort in MART is to find regions in the environment to go and deploy ALDs to gather useful weather observations. This problem is formulated as an information-gathering POMDP (belief MDP).

$$Q(b,a) = \rho(b,a) + \gamma \mathop{\mathbb{E}}_{o \sim Z(b,a)}\left[V(\tau(b,a,o))\right]$$

$$V(b) = \max_{a \in A} Q(b,a)$$



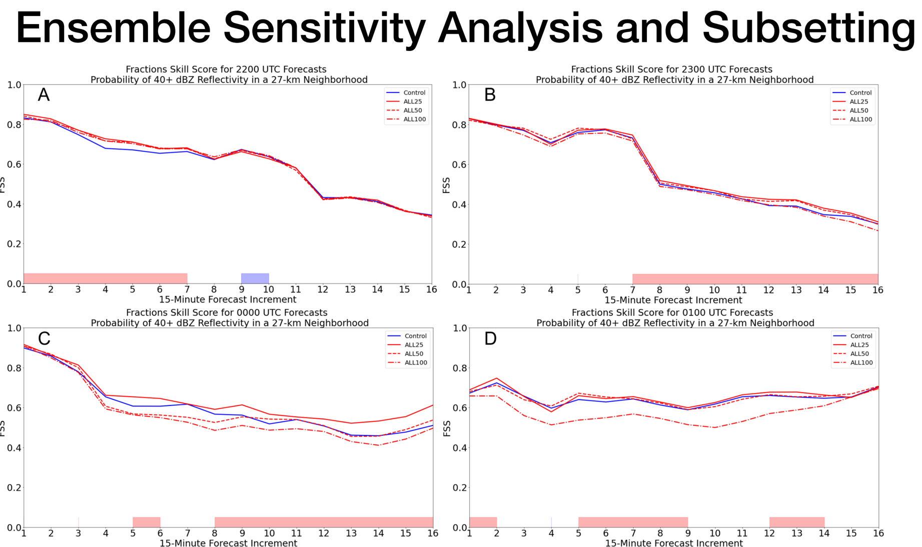
To simplify testing, we first implemented POMDP planning for an RC car navigating between pedestrians.

- The action space was multidimensional, similar to MART.
- The POMDP was solved online using state of the art algorithm planned for use in MART, **DESPOT**.
- The tree search was guided using multi-query path planning techniques.
- The approach runs in real time on a non-holonomic vehicle (see Figure).

An interface has been implemented to extract and use weather forecast ensemble data for POMDP planning.

Julia code has been developed to simulate aircraft dynamics and control algorithms.

Ensemble Sensitivity Analysis and Subsetting



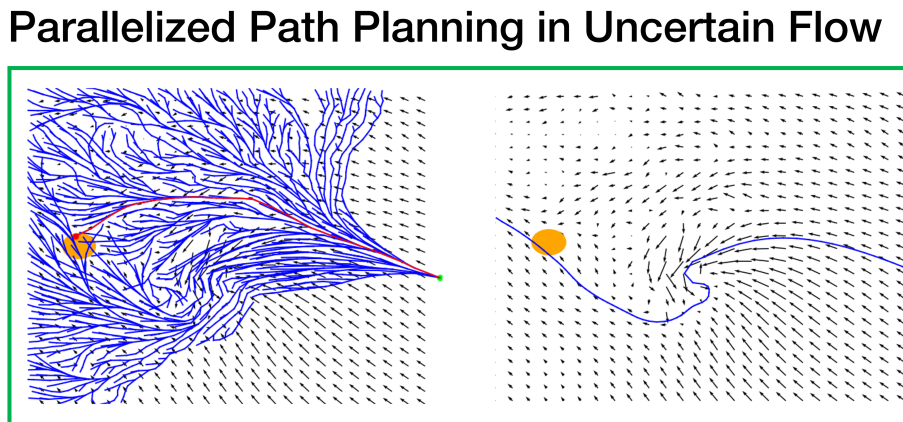
Designed a data assimilation system for UAS and conducting observing system experiments (OSEs) that, unlike OSSEs, use actual observations to assess the impact of new observing systems on forecast skill.

Progress has included

1. Refining the radar data assimilation in all experiments,
2. Adding special observation types to the Data Assimilation Research Testbed (DART) to assimilate UAS and mobile mesonet data,
3. Examining the impact of different error characteristics on the assimilation of TORUS observations
4. Running initial data denial experiments to examine the impact of each TORUS data subset (see Figure)

Fractions Skill Score (FSS) time series for CNTRL, ALL25, ALL50, and ALL100 time series for 27 km neighborhood exceedance probabilities of 40 dB composite reflectivity for ensembles forecasts initialized from a) 2200 UTC b) 2300 UTC, c) 0000 UTC and d) 0100 UTC analyses. Red shading at the bottom of the plot indicates where the ALL25 experiment FSS exceeds that of the control experiment by at least 0.01, and blue shading indicates where the FSS of the CNTRL experiment exceeds the ALL25 FSS by at least 0.01.

Parallelized Path Planning in Uncertain Flow



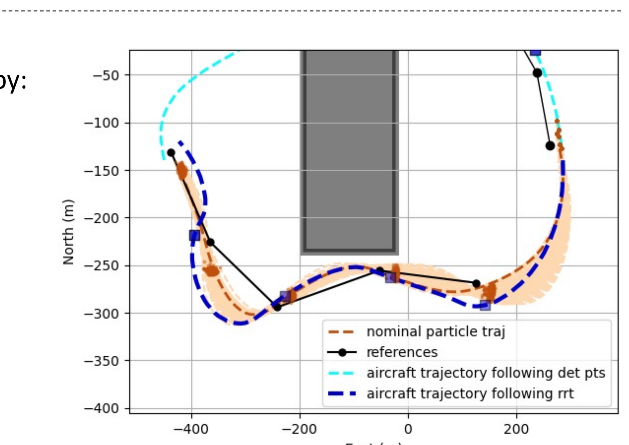
Sample based motion planners that treat complex dynamics as black box are being developed to reason over complex, uncertain flow field

Parallelization achieved by:

1. Multiple planner threads
2. Particle-based assessment of uncertainty

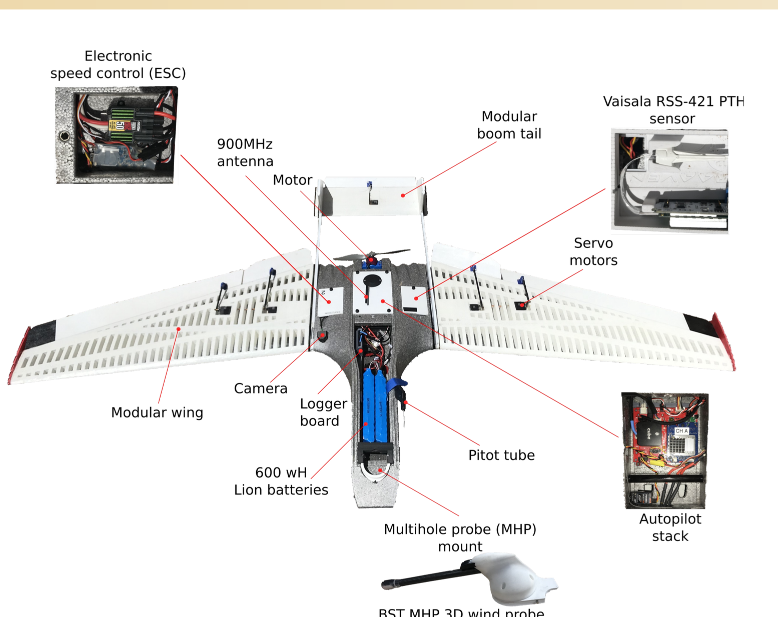
Black-box treatment of dynamics:

1. Avoids solving boundary value problem
2. Generalizes method to aircraft and ALD paths



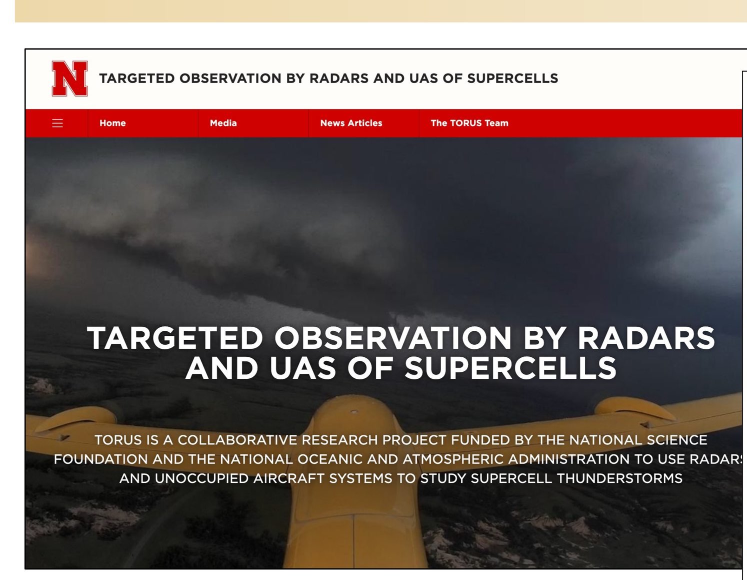
Katherine Glasheen, John J. Bird, and Eric W. Frew. "Experimental Assessment of Chance-Constrained Motion Planning Leveraging Dispersed Computing for Small Uncrewed Aircraft." *Field Robotics*. April 2023.

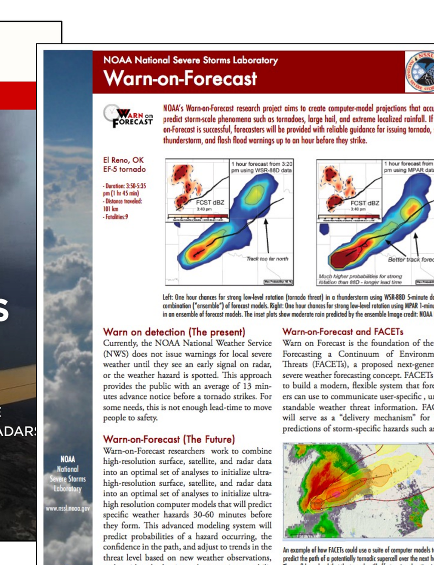
Aerial Robotic System



The CU Robust Autonomous Aerial Vehicle - Endurant and Nimble (**RAAVEN**) UAS were designed at the University of Colorado for nomadic, mobile field deployment.

Broader Impact





Collaborations with the National Severe Storms Lab (NSSL), the National Oceanic and Atmospheric Administration (NOAA), and other meteorologists and atmospheric scientists insure dissemination to stakeholder communities