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Design of an In-Flight Drone Range Monitoring System

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Abstract: The Federal Aviation Administration has approved 250 beyond visual line of sight (BVLOS) drone operations, notably for drone delivery. BVLOS missions face the challenge of navigating unpredictable wind. Furthermore, low-altitude weather forecasts are unavailable away from airports; thus, drone operators are left without a reliable means to plan for the enroute wind. Unpredictable wind means that the drone's battery may deplete faster than expected, resulting in complete battery depletion before completing the BVLOS mission. To counter wind unpredictability resulting in complete battery depletion, the Drone Range Dynamic System (DRDS) provides drone operators with real-time in-flight data, alerts, and courses of action, including mission analytics and most importantly, range. Simulations between Onancock, VA and Tangier Island, VA demonstrated DRDS effectiveness, increasing successful flights from 74% to 95% with deterministic wind and from 73% to 90% with stochastic wind. The DRDS enhances safety in BVLOS operations amidst wind unpredictability.

Keywords: Beyond Visual Line of Sight, Drone Delivery, Simulation, Model-Based Systems Engineering, Cameo Systems Modeler, Cameo Simulation Toolkit

1. Context & Ecosystem Analysis

Drone delivery is an industry that is continuing to gain momentum as drones become more lightweight, reliable, and cost-effective. It is projected that 100,000 drone related jobs will be created within the next 2 years as a result of drone delivery adoption by big technology corporations such as Amazon, Wing, and Zipline (Peek, 2024). Drone delivery provides a faster, cheaper, and more convenient way to transport goods for a variety of purposes. For instance, residents of Tangier Island, located on the Chesapeake Bay, have limited access to medical supplies on the island (VISA, 2023). They rely on deliveries from Riverside Shore Memorial Hospital located on the eastern shore of Virginia. DroneUp, a drone delivery startup based in Virginia Beach, has partnered with Riverside Shore Memorial Hospital to implement drone delivery of medical supplies.

This specific drone mission poses a unique set of challenges since the 15 nautical mile flight takes place across the Chesapeake Bay over land and water. The change in geography results in shifting wind magnitude and direction that can impact the drone's flight. Drone operators gather and utilize low-altitude wind for their flight planning, but the meteorological aerodrome reports (METAR) are only available at airports. Often times, these airports are nowhere near the planned route, making the forecasted wind even more unpredictable. An analysis of the winds from the two closest airports Melfa/Accomack Airport (MFV) (Windfinder, 2024a) and Tangier Island Airport (TGI) (Windfinder 2024b) in 2023 is shown in Figure 1. Calm along-track wind (from 270° at 3 knots or less) at MFV occurred 60.4% of the time, while at TGI occurred 38.6% of the time. These results show that while METAR data is helpful to make assumptions about the wind patterns, they do not provide forecasts of unexpected changes in wind direction enroute.

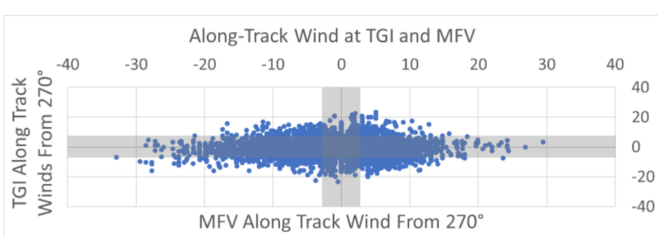


Figure 1. Scatterplot of the 2023 Historical Winds at MFV and TGI Airports

Drone operators face the challenge of navigating unforeseen low-altitude winds during in-flight operations of the drone package delivery. Unforeseen low-altitude wind forces the drone operator to increase thrust to maintain the desired groundspeed. Doing so causes the battery to deplete faster than expected; thus, jeopardizing the safety of the drone and completion of the mission. Drone operators need a system that offers support in navigating unforeseen low-altitude wind during in-flight operations of drone package delivery. Furthermore, drone operators need a system that proactively estimates the range remaining.

2. Concept of Operations

The DRDS serves as a decision support tool to help the drone operator make time-critical actions. Consider a scenario where a drone must fly from point A to point B. The drone departs point A and the DRDS estimates the range to extend just beyond point B. However, if unexpected headwinds arise during the flight, the estimated range may shorten, potentially falling before point B. In such cases, the DRDS issues an alert and recommends a course of action to the drone operator. The aforementioned scenario provides a high-level overview of the to-be process.

The DRDS interfaces with a remote control to access real-time telemetry data from the drone. This data includes flight plan information (waypoints of the flights and desired groundspeed), current position, and battery level, which is affected by environmental factors like wind. The remote control continuously updates the DRDS with telemetry data.

The DRDS also provides operators with essential mission analytics. Utilizing the drone operator's flight plan and existing drone control software, it displays waypoints on a map to outline the flight path. Information such as total distance of the flight, current distance flown, endurance, battery remaining, GPS coordinates, remaining distance to the destination, and live headwind components is displayed. Waypoints and the drone's current position are highlighted on the map, with lines connecting waypoints changing color to indicate progress. The most important feature is the range shown in bold on the primary display, which updates in real-time during the flight.

3. Requirements

A robust set of requirements were developed, but the mission, system, and functional requirements shown in Table 1 highlight the key objectives and goals of the DRDS.

Table 1. Sample Mission, System, and Functional Requirements

Requirement ID	Description
MR.1	The system shall provide operational support to the drone operator during the in-flight stage of the drone delivery by:
SR.1	Interfacing with the Remote Control: The system shall interface with the drone's remote control to receive real-time flight parameters, including current location, groundspeed, and battery level (or battery drawn).
SR.2	Providing Real-Time Flight Parameters: The system shall provide real-time flight parameters on a display.
FR.2.1	The system shall calculate along-track range remaining at a 10 second update rate.
FR.2.2	The system shall compare along-track range remaining to the along-track distance to the destination plus an additional threshold distance.
SR.3	Generating Alerts: The system shall generate alerts for the drone operator in the event the estimated range falls short of a threshold (or the destination).
FR.3.1	The system shall provide an alert to the drone operator when the along-track range remaining is less than the along-track distance to the destination plus an additional threshold distance.
SR.4	Recommending Courses of Action: The system shall recommend a course of action to the drone operator in the event of an alert.
FR.4.1	The system shall alert the operator with a "CONTINUE FLIGHT," "RETURN HOME," or "DITCH" annunciation.

4. DRDS Design

To perform the functionality as described in the requirements above, the DRDS accepts input from three separate sources: (1) The drone's onboard battery sensor which provides *Current battery level*, (2) The drone's onboard global positioning system (GPS) module which provides *Current Position* and *Current groundspeed*, and (3) The flight plan created by the drone operator which provides the *Waypoints* and *Full mission distance*. These inputs can be seen entering the *Drone Range Dynamic System* in Figure 2 below.

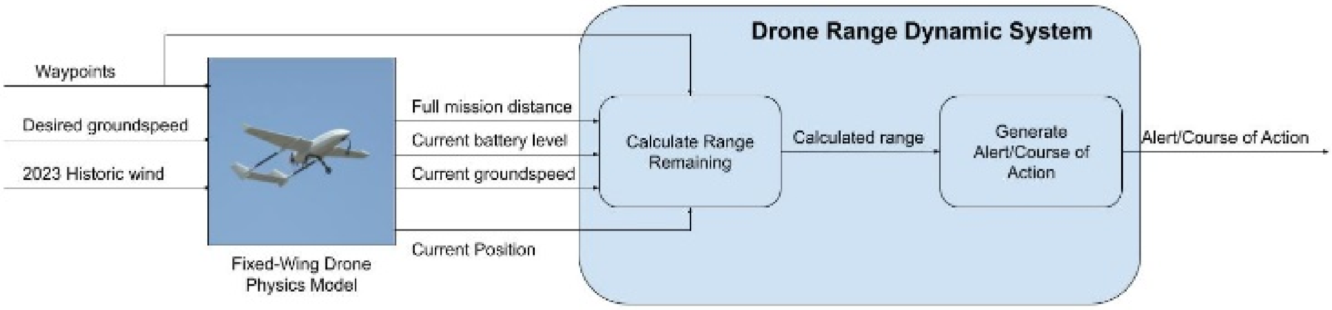


Figure 2. DRDS High-Level Design with Inputs and Outputs

Taking a deeper look at how the DRDS works, the drone's battery sensor must provide battery information such as the battery level at the time of the battery reading. After the DRDS receives three battery level readings, the average depletion rate (ADR) can then be calculated and used along with the battery level to calculate the endurance (E) of the drone as a unit of flight time remaining in minutes. While the DRDS can technically operate with only one battery level reading, a case exists where there may be an extremely strong headwind at the start of the flight causing a premature alert and the drone operator to turn the drone around unnecessarily. Thus, the average of the three battery level readings provide a stronger case as to when an alert should trigger. Additionally, the ADR is a moving average, meaning the three battery level readings are always being cycled in a list of length three. The idea is that when a new battery level reading is sensed, the oldest battery level reading in the list is removed, all the other battery level readings shift down one index with the newest battery level reading at the first index, and the new ADR is calculated.

While the flight plan of the drone operator can be used for other purposes outside of the scope of the system, the DRDS only needs information such as future along-track groundspeed (FATGS), the departure point (DepP), and the destination point (DestP). The FATGS and E are both used to calculate the estimated range (R), which is now a unit of distance extending outward from the drone in nautical miles.

The drone's GPS module must provide information such as its current position (CP). The DRDS is mission focused, so the CP of the drone as GPS coordinates are converted to a relative scale, indicating the number of nautical miles the drone is away from the DepP and DestP.

An alert is generated when the drone's CP added to the R falls before the DestP. In this case, if the DRDS estimates the drone can return home using the exact same R but in the backwards direction, the "return to home" course of action is issued. Otherwise, the drone operator should continue the flight in hopes the drone experiences unexpected tailwinds that reduce the thrust required to maintain the desired groundspeed.

To test the DRDS, a simulated drone, flight plan, and environment must be created. The *Fixed-Wing Drone Physics Model* is designed to provide the required data for the DRDS to operate. The *Fixed-Wing Drone Physics Model* translates the thrust required to maintain the desired groundspeed to the amount of battery drawn from the total battery capacity over a finite period of time. Additional parameters such as the fixed-wing drone's coefficient of drag, wing reference area, battery voltage, and battery efficiency were incorporated into the simulated drone. A simulated environment is also modeled and can be seen as an input to the *Fixed-Wing Drone Physics Model*. Specifically, wind is generated from 2023 historic data from TGI and MFV.

5. DRDS Implementation

A model-based systems engineering (MBSE) approach was used to provide a simulation testbed for how the system will perform in its intended environment via Cameo Systems Modeler (CSM) paired with Cameo Simulation Toolkit (CST). First, the system structure and system boundary were defined by using a system context which only contains the components that the DRDS is comprised of. There is then a simulation context which simulates the flight aerodynamics of the drone and feeds its telemetry into the DRDS. This is evident through the unidirectional reference association indicated in Figure 3. Note that the DRDS can only access the simulation context and not the other way around.

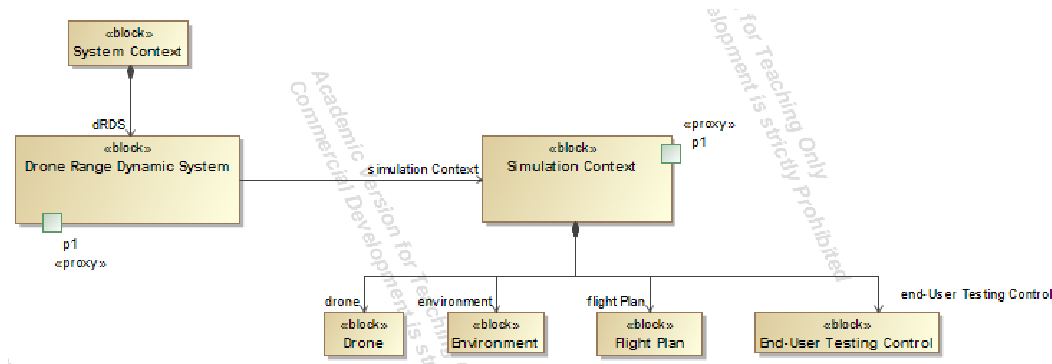


Figure 3. Block Definition Diagram of System Testbed

Both the *Drone Range Dynamic System* and *Simulation Context* blocks contain behaviors which then correspond to the activities that they perform. Within the *Simulation Context* block, a continuous loop occurs where the new wind data received from the *Environment* block affects the required thrust needed to maintain the desired groundspeed of the *Drone* block. Thrust affects power and power affects the amount of charge being drawn from the battery. These battery levels along with the groundspeed are then sent to the DRDS after every loop to calculate the range.

The range of the drone is calculated by averaging the three most recent battery readings that were received. The calculated range is then evaluated against the distance already traveled and distance remaining for the flight. Only when the specific conditions stated in the design section are true, an alert will be prompted.

Upon running the simulation within CSM, the graphical user interface shown on Figure 4 is generated. Across the top of the left-half of Figure 4, flight information such as current distance, range, total distance, estimated time of arrival, endurance, battery remaining, and course of action are shown. Below the flight information is a graph that shows the dynamic values of current distance (yellow) and range (red), along with the total flight distance (blue) to reach the destination. The Y-axis indicates distance in nautical miles, and the X-axis indicates time. The assumption is that each time step is exactly 1 minute to represent the time between which the DRDS is fed new drone telemetry data, hence the name of the system, the drone range *dynamic* system. The newest values are plotted on the right of the graph, while the older values are shifted to the left. The graph is read by adding the y-values of the yellow line and red line and comparing the sum of the two with the y-value of the blue line. Figure 4 indicates a flight where the total distance to the destination from the origin is 15.5158 nm. The drone is at a current distance of 6.6667 nm with a range of 8.3806 nm from the drone's current position. The right-half of Figure 4 illustrates the current position of the drone on a map. Purple indicates the active flight leg, red indicates the flight leg that has already been flown, and black indicates the flight leg(s) that remain. MATLAB is used to plot the current position of the drone on a map, but due to software limitations, range and the point of no-return for the drone are not plotted. The drone operator should instead divert their attention to the left-half of Figure 4 where the range and current position are also plotted on the dynamic graph. More specifically, the operator should keep their attention on the "Course of Action" section towards the top of the screen which will update based on the conditions stated in the design section. The operator can expect the output to change from "Continue", to "Turn Around" to "CRASH IMMINENT" depending on the projected range.

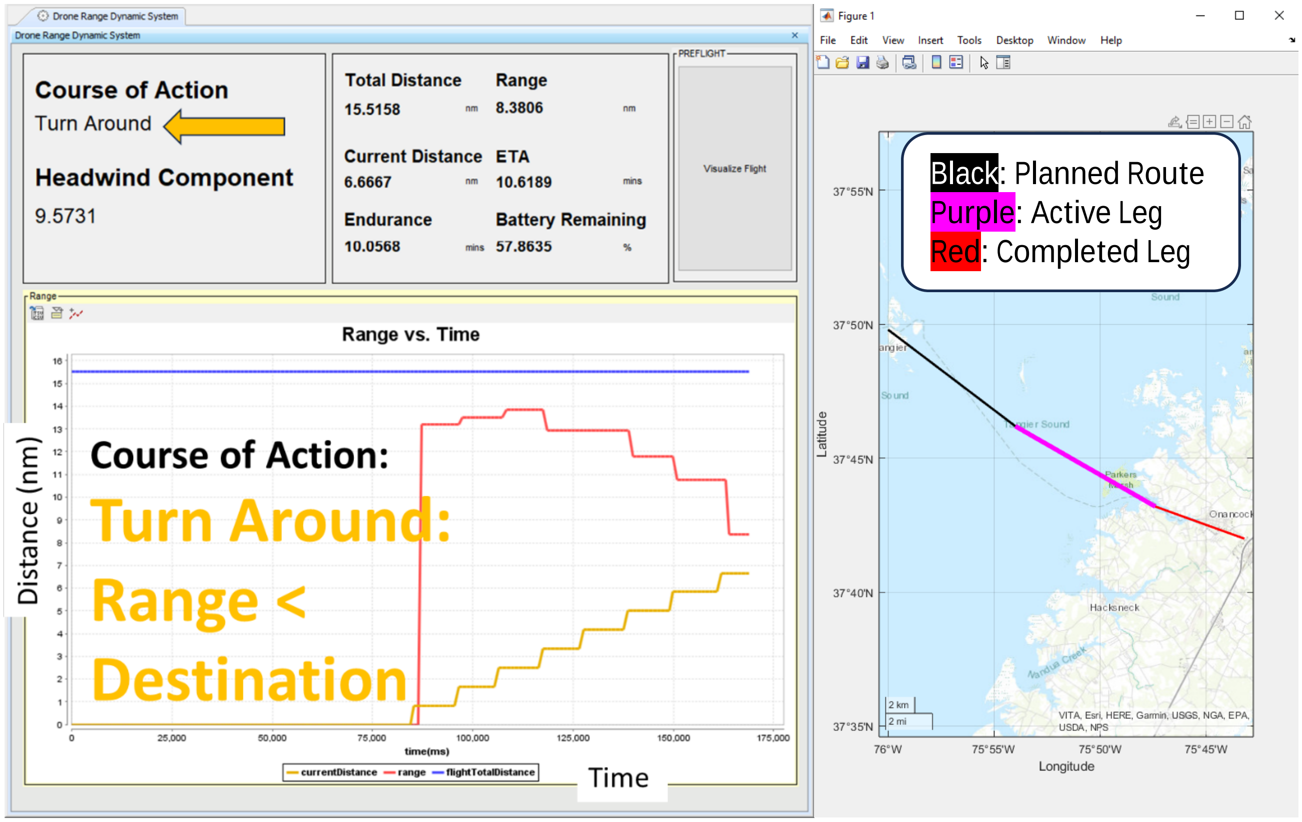


Figure 4. Battery Depletion, Range, and Map Graphical User Interface of the DRDS

6. DRDS Verification

Verification of the system was performed which tested how accurate the mathematical equations were implemented in the code. This test was conducted via a deterministic simulation using controlled environment parameters/conditions among all verification tests. 10 tests were performed using different combinations of the *desired groundspeed* and *environement wind speed* parameters of the simulation, starting with the case of 10 knots of headwind and 50 knots desired groundspeed for the entire route. All tests consisted of a hand-simulation first performed in Microsoft Excel to obtain a baseline of output battery values. Once the numbers in Excel were recorded, the simulation was recreated in the DRDS implementation within CSM to ensure that the system architecture operates per spec of the requirements. This was evaluated by comparing the output values in Excel and ensuring they were equivalent to the output values in the DRDS. The compared results of both simulations were seen to be equivalent which provided confirmation that the system operates as designed.

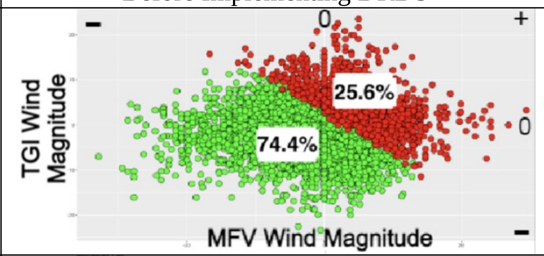
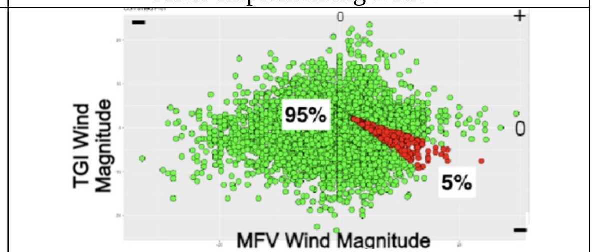
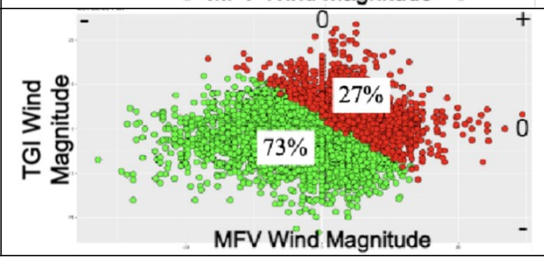
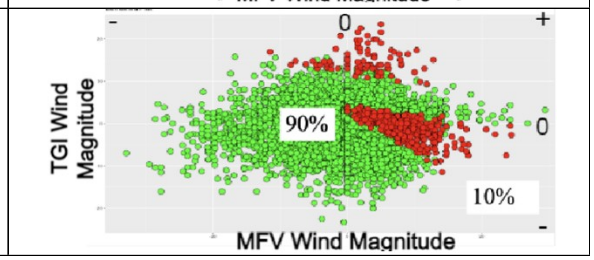
7. DRDS Concept of Operations Validation

Validation of the concept of operations was performed by developing a Monte Carlo simulation that tests effectiveness of the DRDS in the operating environment. Effectiveness in this case means an increase in the number of safe flights, where safe is defined as flights that end with a positive battery level. Four cases were tested and are described as follows: (1) Deterministic Winds without DRDS, (2) Stochastic Winds without DRDS, (3) Deterministic Winds with DRDS, and (4) Stochastic Winds with DRDS. For each test, the following assumptions were made: The drone flies at a constant 50-knot groundspeed the duration of the flight for as long as the drone can fly using the Fixed-Wing Drone Physics Model as described in Figure 2. The flight path is a straight line from origin to destination, resulting in a total flight distance of 15.833 nautical miles. The wind used in each case originate from 2023 historical wind readings from TGI and MFV. For each replication in a deterministic case, the wind follows a linear growth/decay pattern between origin and destination along the flight path. For each replication in a stochastic case, the wind also follows a linear growth/decay pattern between origin and destination;

however, the winds are given a slight perturbation from a Random Variable defined by a uniform distribution with the range of [-3,3]. As soon as the condition for an alert is met, a return to home decision is made by the drone operator and the drone immediately begins the return to home journey.

Results of the simulation are shown in Table 2. Green dots represent flights which ended with a positive battery level, while red dots represent flights which ended with a negative battery level. All in all, the DRDS raised the number of safe flights 21% for the deterministic winds and 17% for the stochastic winds

Table 2. Visualized Concept of Operations Validation

	Before Implementing DRDS	After Implementing DRDS
Deterministic Wind		
Stochastic Wind		

8. Conclusion

Following the systems engineering V-model, the DRDS decision support tool helps monitor the drone in-flight and supports the drone operators' decision-making. The tool can help decide if the drone should continue the flight or turn around and return home due to the unforeseen low-altitude winds. Next steps would entail utilizing a real fixed-wing drone over the Chesapeake Bay to collect live data to further test the implementation of the DRDS. Doing so will remove the need for the *Fixed-Wing Drone Physics Model* since an actual drone will be used.

9. References

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