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Hopper Unmanned Aircraft System: Applied Probability Analysis for Anti-Submarine Warfare

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Abstract: Hopper is a fixed-wing Uncrewed Aerial Vehicle (UAV) with solar recharge, vertical launch and take off capabilities from the water, and the ability to search for submarines through its use of a passive hydrophone (O'Donnell 2024). The Hopper UAV is part of the LOCUST (Low Cost UAV Swarming Technology) project from the Office of Naval Research. MITRE, which is a Federally Funded Research Development Center, has been tasked with the LOCUST project by the U.S. Navy and the Office of Naval Research; the U.S. Naval Academy midshipmen are working in sponsorship with MITRE in order to understand the operational challenges of deploying Hopper in tactical areas for detecting adversary submarines. We created an Excel-based decision analysis tool to calculate the probabilities of successfully deploying multiple Hopper UAVs to create an early warning barrier line to detect submarines. We applied our model to a scenario in the South China Sea to demonstrate the effectiveness of the model.

1. Introduction

In the anti-submarine warfare role, the goal of the Hopper platform is to reach a location and deploy a hydrophone to detect a submarine. Thus, we must evaluate the probability that this UAV can accomplish its goal. We created a decision aid tool for ONR that performs five distinct operations. First, it calculates the number of flights needed to reach its destination and the correlating number of days those flights will take based on given flight information, predicted weather and distance from launch site to the target. Second, it calculates the number of Hoppers that would be needed to create an anti-submarine barrier based on the listening range of the attached hydrophone. Third, it uses the predicted weather forecast to calculate an individual Hopper's probabilities of a successful launch, flight, recharging on water, and passively resting on water. The predicted weather is matched to extrapolated data from a weather forecast database (visualcrossing.com) in order to evaluate whether it is justifiable for the Hopper UAV to launch. This weather forecast database displays weather values for our target location. These weather values include precipitation, sea state, UV exposures, air temperature, wind speed, humidity, and conditions such as rainy or sunny. Fourth, it determines the probability of a single Hopper surviving each day, and the total probability of a single Hopper reaching its target after multiple flight days. Fifth, it calculates the expected number of Hoppers to launch to ensure that the number required to create a barrier patrol line at the target is achieved. The tool is user friendly, allowing the user to input known information about the Hopper, the target, and predicted weather conditions. Ultimately, the decision aid tool receives and outputs the probability of an individual Hopper successfully reaching its target.

2. Context Analysis

2.2 Hopper UAV

Hopper is an autonomous fixed wing drone that has the ability to take off and land on water without human intervention. Hopper has the ability to be launched off the side of a ship or from land. It is capable of flying, landing on the water, recharging, and then taking off again to continue towards the target. We consider the mission of Hopper is to reach a target area at sea, where it will land on water and then launch a hydrophone to listen for enemy submarines. This capability allows the surface fleet to launch a swarm of Hopper UAVs as an additional surveillance and reconnaissance tool. The Hopper UAV is also being researched as a low-cost alternative to traditional MH-60R or P-8 aircraft that require fuel and manpower to launch sonobuoys. The Hopper UAV is intended to be a long-range endurance platform that is cheaper and requires less human involvement than current methods of submarine detection. Our goal on this project is to determine the likelihood of Hopper successfully completing its mission and the number of Hoppers needed to ensure that the mission along the barrier patrol line can be accomplished.

2.3 Objectives

The objective of this project is to develop an Excel-based decision aid that enables the user to input information about the Hopper's capabilities and predicted weather conditions. Based on these inputs, the tool determines how many days it would take a Hopper to reach the target, the number of Hoppers needed to create an early warning barrier line, the probability that a Hopper survives each day, the probability of a Hopper successfully carrying out the mission and the overall probability that Hopper survives from launch to completion of mission. An early warning line is defined as an early notification of the launch for approach of unknown weapons (Office of Chairman of Joint Chiefs of Staff). For our situation, a single file line of Hoppers creates the "target" that the Hoppers are flying to. Once in line, the Hoppers use hydrophone capabilities to warn nearby ships when detecting enemy submarines. The early warning line is based on the length determined by the operator and the effective listening radius of the hydrophone. The tool also predicts the number of Hoppers that should be launched to ensure successful creation of early warning line. The tool utilizes an editable database that includes the probability of success based on weather inputs including, but not limited to: conditions, sea state, wind speed, air temperature, humidity, and precipitation. By evaluating the decision tool output, we can also determine if the Hopper platform is operationally feasible.

3. Model Data and Designs

3.1 Assumptions

The Hopper UAV is still in the testing and development phase, thus there is limited information on how well it performs in varying weather conditions. We made reasonable assumptions about Hopper's probability of survival in varying sea states, air temperatures, weather conditions, wind speed, and humidity based on the severity of these elements from research found in *Scientific Report, Vol 11* (Gao et al. 2011). We were able to calculate the probability of success, which tells us the chances that an individual Hopper successfully reaches its target. We also made assumptions about Hopper's capabilities based on information given to us from MITRE. The first was that the ability to recharge via solar power was based on solar energy output of the sun and assumed that the solar panels recharged at the rate advertised. For scheduling, we also assumed that the Hopper was able to recharge during all sunlight hours and was in a passive mode at night. Finally, we limited the scope of our tool to focus on the probability of an individual Hopper reaching its target. The model does not include the probability of the Hopper completing the mission or using the hydrophone to detect a submarine. We focused on the probability of the Hopper's survival in order to reach its target barrier line and intend to include the probability of Hopper successfully detecting a submarine in follow on work.

3.2 User Inputs

Our model requires the user to input the Hopper's expected flight speed, flight time, recharge time, exposure time (time spent resting on water when not recharging), average surface current and average surface wind. The user then inputs information about the operation box including the length or distance to the target, the width of the target and the radius of the hydrophone's listening capability. Finally, the user inputs the expected weather data for the next 15 days specific to the area of operation. This data can be found on Visual Weather Crossing website.

About Hopper:	
Flight Speed (km/hr)	75
Flight Time (hrs)	1.25
Recharge Time	4
Exposure duration (hrs)	21.5
Surface current (km/hr)	0.8
surface winds (km/hr)	26.15

About Ops Box:	
Length of Box (km)	535
Width of Box (km)	111
Radius of Hydrophone (km)	2

	Weather Information:		Based on Information from Visual Crossing		
Days	Weather From Last 15 Days	Max Temp	Wind Speed	Solar Energy	conditions
1	2/2/2024	87.3	20.1	22.1	Clear
2	2/3/2024	87.3	17	21.9	Clear
3	2/4/2024	88.2	19.9	22.2	Clear
4	2/5/2024	89.5	19.2	22.9	Clear
5	2/6/2024	87.2	15	23.1	Partially cloudy

humidity	precip	precipprob	precipcover	preciptype	sea state
67.4	0	3.2	0		3
69.5	0.004	9.7	4.17	rain	3
67.2	0	0	0		3
66.7	0	0	0		3
68.4	0	3.2	0		3

Figure 1. Hopper Decision Tool Input Screen

4. Probability Analysis

4.1 Basic Calculations

The model immediately returns the number of days it will take a single Hopper to reach its destination based on the distance it drifts, the flight range and the total distance traveled per day. The model also calculates the minimum and maximum number of Hoppers to cover the entire operation box. Finally, it calculates the number of Hoppers needed to create an early warning line to detect a submarine.

Basic Calculations:	
Distance of Drift (km)	17.6
Flight Range (km)	117.09
Distance Traveled in 24 hrs (km)	99.49

Determining Number of Hoppers	
Diameter of Hydrophone (km)	4
Area of Patrol Box (km)	59385
Area of Hopper (km)	8
Number of Picket Lines	134
Number of Hoppers on Line	28
Max Number of Hoppers	7423
Min Number of Hoppers	3712

Days Calculations	
Days to reach Picket Line	5.4
Launch Date	2/2/2024
End Date	2/8/2024

Figure 2. Hopper Decision Tool Preliminary Calculations

4.2 State Calculations

Hopper has 4 states to reach the early warning line, each with their own equation to calculate the probability of the Hopper surviving that state. The four states are the Hopper being launched, normal flight, passively floating on the water, and actively recharging on the water. The weather conditions that the user inputs have been pre-assigned a probability indicating the probability that Hopper survives in that given weather condition. Thus, the probability of surviving in a state is based on the following equations and calculates the probability of success in each weather condition. The specific weather conditions considered per day for each state can be found in Table 1. Each calculation below is specific to the weather for one day.

Table 1. Hopper State Equations

Probability of Success for a State	Weather Conditions Considered per State
P(Launch)	= .7(Conditions) x .3(Wind Speed)
P(Flight)	=.1(Air Temperature) + .5(Conditions) + .2(Windspeed) + .2(Humidity)
P(Passive Survival)	= .4(Conditions) + .2(Humidity) + .4(Sea State)
P(Recharge)	= .2(Solar Energy) + .3(Conditions) + .2(Humidity) + .3(Sea State)

Coefficient weights for each equation in Table 1 are determined using sensitivity analysis. A tornado diagram was conducted to determine which weather conditions have the most influence on an individual Hopper's success for one day. A tornado diagram is a sensitivity analysis tool to determine which variables impact the total outcome the most. The tornado diagram in Figure 3 was created when all other variables remain the same, changing one variable to its lowest and highest input value. The change in the probability of an individual Hopper having a successful flight on day 2 was then recorded. From Figure 3, we determined that the variables sea state and conditions have the greatest impact on the probability of a Hopper surviving one day, thus they were weighed heavier in creating the equations found in Table 1.

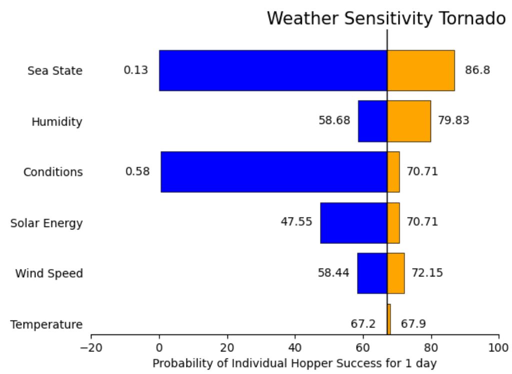

Figure 3. Weather Sensitivity Tornado Diagram

Figure 4 is an example of one of the state outputs in the tool. Using a scenario in the South China Sea, the image in Figure 4 shows the probabilities associated with each weather condition for two days. Figure 4 depicts the probability of an individual Hopper passively floating on the water. The totals columns are the total probability of survival for the Passive State for that specific day.

Probability of Successful Passive Rest Per Day

Days	conditions	prob	humidity	prob	sea state	prob		totals	ProbPassive = .4(conditions) +.2(humidity)+.4(seastate)
2/2/2024	Clear	1	67.4	0.98	3	0.95		0.976	
2/3/2024	Clear	1	67.4	0.98	3	0.95		0.976	

Figure 4. Hopper Decision Tool Weather Probability

4.3 Individual Hopper Daily Probability Calculations

In order to get the total probability of one Hopper UAV surviving for one day, each state for that day had to be calculated. Assume that each day, with the expectation of the initial launch day and the mission day, would be the exact same. Equation (1) is the calculation to predict the probability of daily survival for one Hopper UAV. As shown below, Equation 1 is squared because each state is encountered twice a day, as seen in Table 2.

Table 2. Individual Hopper Normal Flight Schedule Day

Time	State
0000-0800	Passive
0800-0900	Flight
0900-1400	Recharge
1400-1500	Flight
1500-1900	Recharge
1900-2359	Passive

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$$P(One\ Day\ Survival) = [P(Passive) * P(Flight) * P(Recharge)]^2 \quad (1)$$

4.4 Individual Mission and Swarm Mission Success Calculations

Finally, the total probability that the Hopper survives the entire mission is found by multiplying the probability of success for each day that it is on the mission. For example, if the Hopper is expected to take 3 days to reach a target location the total probability of reaching the target is found by multiplying the probability of Hopper's success from day 1, day 2 and day 3. The total probability of success represents the probability that one Hopper successfully reaches its target. To ensure that the mission can be accomplished, more Hoppers can be launched to account for those expected to fail. Thus, Equation (2) calculates the total number of Hoppers needed to be launched to ensure the number of Hoppers needed to create an early warning line to arrive on the target.

$$\text{Expected Number of Hoppers} = \frac{Number\ of\ Hoppers\ Required\ to\ form\ Barrier}{Probability\ of\ Individual\ Hopper\ Arrival\ at\ Barrier} \quad (2)$$

The expected number of Hoppers allows the user to know how many Hoppers to send in total to ensure the mission can be completed. For example, if the user needed 28 hoppers to form their early warning line, but the probability of an individual Hopper's success is only 56.40%, then the user would launch 50 Hoppers, anticipating that 22 will likely be lost.

Individual Hopper Probability of Success for Multiday Mission	
	0.5640
Expected number of hoppers	
	49.2

Total Proability Per Day			
Days	Dates	Probability Per Day	Product Per Day
Day 1	2/2/2024	0.9252	0.9252
Day 2	2/3/2024	0.9058	0.9058
Day 3	2/4/2024	0.9058	0.9058
Day 4	2/5/2024	0.9058	0.9058
Day 5	2/6/2024	0.9058	0.9058
Day 6	2/7/2024	0.9058	0.9058

Figure 5. Hopper Decision Tool Output

5. Scenario Application and Analysis

We use the negative binomial distribution to model the total number of Hoppers that are required to launch. Figure 6 is a cumulative distribution of the negative binomial distribution function showing the number of trials until 28 hoppers successfully reach the barrier patrol line. For an example scenario using predicted weather in the South China Sea, one Hopper UAV probability of arriving at the barrier patrol line is 56.4%. Because that scenario required 28 Hoppers to create the barrier patrol line, this individual probability requires the launching of 50 Hoppers total. Figure 7 is a sensitivity analysis that shows how the required number of Hoppers to launch changes as the probability of one Hopper reaching the barrier patrol line changes. The change in individual Hopper survival could occurs to variations in weather, sea state, solar power, as previously shown in the state equations. As expected, in better weather conditions, where an individual Hopper has a higher likelihood of survival, the number of Hoppers needed to reach the target decreases.

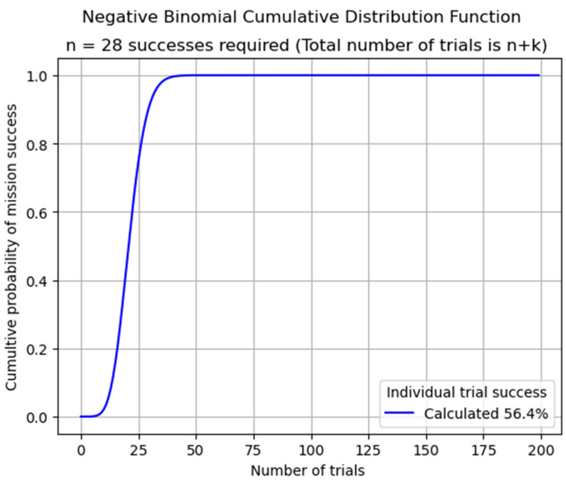

Figure 6. Graph of Negative Binomial CDF

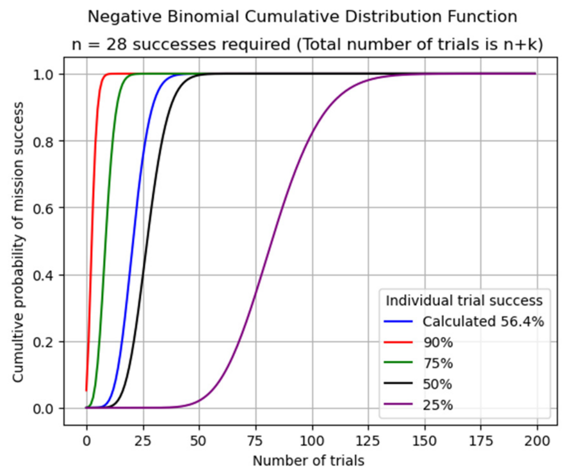

Figure 7. CDF Comparing Probabilities

6. Conclusion

In the anti-submarine warfare role, the Hopper UAV can perform multiple flights over water to reach a location and deploy a hydrophone to detect enemy submarines. However, multiple cycles of launches, flights, recharge and survival on water must be successful in order for a Hopper to perform a submarine detection mission. We created a decision analysis tool that would allow Hopper's operators to input up to date data about the mission parameter, and the tool would then be able to tell them the number of Hoppers that need to launch to have them successfully reach the target, the number needed to launch to maintain that number on target over several days and the probability of reaching the target.

7. Future Work

The Hopper UAV is still in the very early stages of testing and redesign. Because of this, much of the data we use in our example scenario for the Excel tool is notional. As MITRE gains more knowledge of Hopper's exact flight characteristics and survivability in varying weather and sea state conditions, they have the capability to change the numbers in our model and get a more accurate probability of Hopper's success. Our model is currently specific to the Hoppers likelihood of reaching the barrier patrol line. In future research, it would be valuable to involve analysis of the hydrophone detection probability. The probability of the Hopper detecting a submarine could prove to be vital information for the user to make command decisions such as what situation to use the Hopper, if Hopper is needed for quick responses at short ranges or if multiple Hoppers are more useful for long endurance missions.

8. References

Gao, M., Hugenholtz, C. H., Fox, T. A., Kucharczyk, M., Barchyn, T. E., & Nesbit, P. R. (2021). Weather constraints on global drone flyability. *Scientific Reports*, *11*(1), 12092. https://doi.org/10.1038/s41598-021-91325-w

Historical weather data for Manila | Visual Crossing. (Feb 2024). Www.visualcrossing.com. https://www.visualcrossing.com/weather-history/Manila

O'Donnell, P., & Schiavone, D. (2024, January 26). *Taking Flight: Hopper Drone Poised to Transform Maritime Missions*. MITRE; MITRE. https://www.mitre.org/news-insights/impact-story/taking-flight-hopper-drone-poised-transform-maritime-missions

Office of the Chairman of the Joint Chiefs of Staff, DOD Dictionary of Military and Associated Terms, (Washington DC: The Joint Staff, Nov 2021), page 69