

Evaluating Faulty State Occurrence in Wildfire UAS Missions Using Markov Chains

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AIAA Aviation, July 29th-August 2nd 2024

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Motivation

- UAS are increasingly used in **novel operations**, including wildfire response [1]
- New UAS use-cases must have **equal to or lesser risk** than manned operations [2]
- Risk is currently managed using **safety management systems**, which must adapt into a **continuous, data-driven** architecture to ensure safety of future operations [3,4]



NASA ACERO/Joel Kowsky: <https://www.nasa.gov/image-detail/nasa-takes-wildfires-with-flight-demonstration-2/>

Contribution

- We provide a **data-driven** probabilistic **risk assessment** style analysis of a UAS wildfire mapping mission, including:
 - Hazard identification
 - Fault Tree Analysis
 - Event Tree Analysis
 - Markov Chain analysis

Safety Management Systems

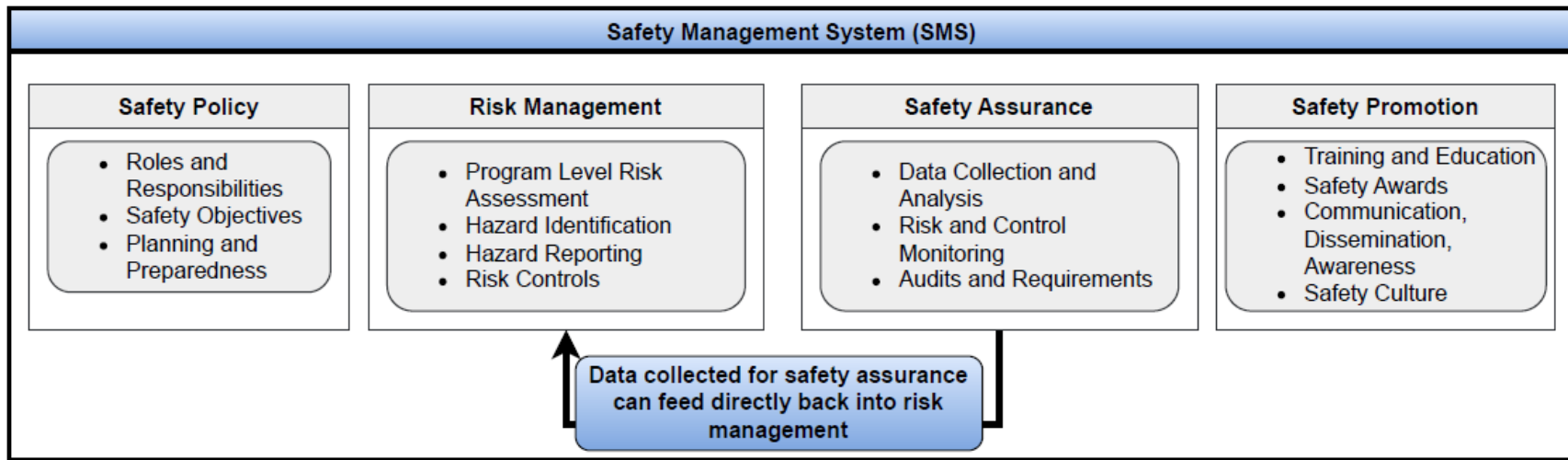
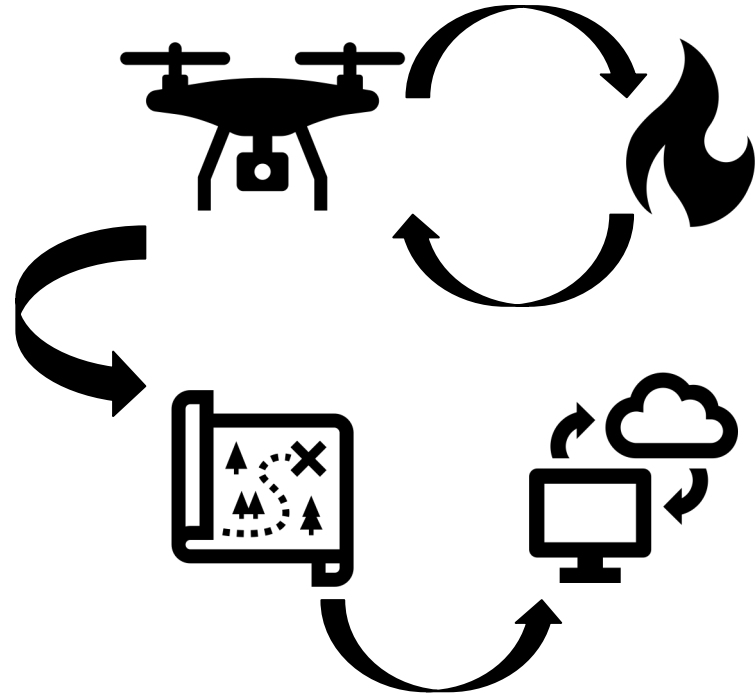


Fig. 1 The Traditional “Four Pillars” of a Safety Management System with emphasis on connecting Safety Assurance and Risk Management

Scenario Case Study

- Small UAS flying a mission over a wildfire, generates a map of the fire to publish in tracking system
- Data from SAFECOM mishap reporting system [5]
 - 63 reports from 2015-2022
- Analyze hazards from reports using initiating event, failure category, and top event strategy



Method

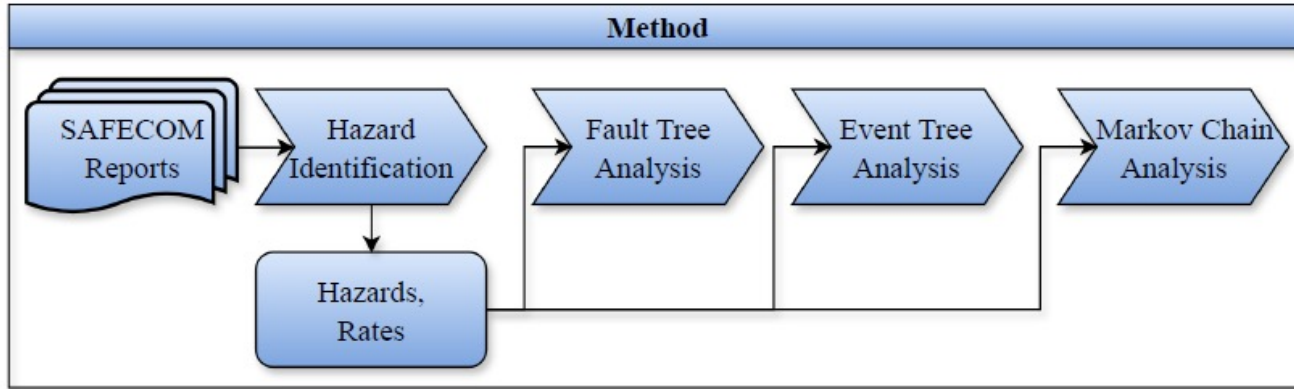


Fig. 2 Method flowchart showing the use of historical documents for hazard identification and further analyses.

Results: Hazard Identification

- Wildfire UAS mapping missions represent approximately 6.3% of flights[5]
- The number of fire related UAS mishap reports is increases
- UAS mapping missions represent a large proportion of mishaps
- Number of events per year is increasing, though the rate of occurrence is decreasing due to more flights overall

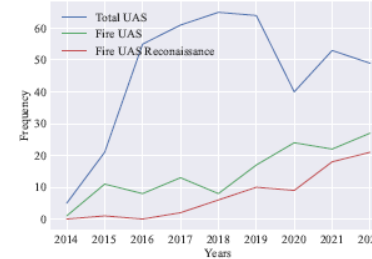


Fig. 3 UAS SAFECOM reports per year, indicating increasing reports over time.

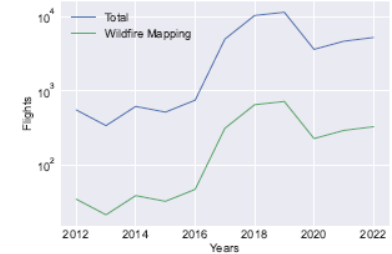


Fig. 4 UAS flights and estimated UAS wildfire mapping mission flights over time.

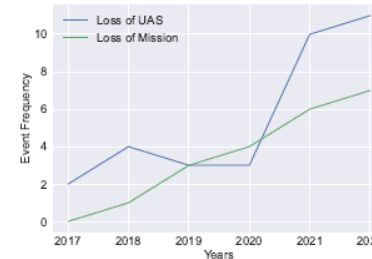


Fig. 5 UAS top events per year, indicating increasing events over time.



Fig. 6 Number of flights until top event per year.

Results: Hazard Identification

Table 1 Granular initiating failure events associated with failure categories and frequencies.

Failure Categories	Failure Mode	Frequency
Airspace	Manned Aircraft Intrusion	6
	Airspace Conflict	4
Equipment Failure	Propeller Arm Disconnection	1
	Motor Failure	2
	Motor Mount Failure	1
	Parachute Landing Failure	1
	Battery	4
	Landing Gear Failure	1
	Casing Dislodged	3
	Fasteners Dislodged	2
	Engine Failure	1
	Autonomous Malfunction	2
Human Factors	Miscommunication	1
	Pilot Error	9
	Procedural Error	1
	Inappropriate Landing Site	3
Loss of Control	Control Surface Damage	1
	Loss of GCS	1
	Loss of GPS	4
	Loss of Link	4
	Uncontrolled Flight	12
	High Wind	1
Total		65

- 4 total failure categories
- 22 initiating events
- Incidents can have one or more initiating event
- Uncontrolled flight is the most common event, followed by pilot error and intrusions
- Many events were only reported once or twice

Results: Hazard Identification

Table 2 Top event definitions and frequencies.

Top Event	Description	Frequency
Loss of Mission	Any outcome or failure mode effect that results in the termination of a current mission or the termination of remaining missions in the day.	21
Loss of UAS	Any outcome or failure mode effect resulting in substantial damage to the UAS requiring off-site repair or complete loss of vehicle.	33
None	Reports that detail no negative outcome with failure mode effects mitigated prior to events occurring.	9
Total		63

Two top events were detected:

1. Loss of Mission
2. Loss of UAS

- Some reports did not result in a top event
- Loss of UAS was slightly more common

Results: Fault Tree Analysis

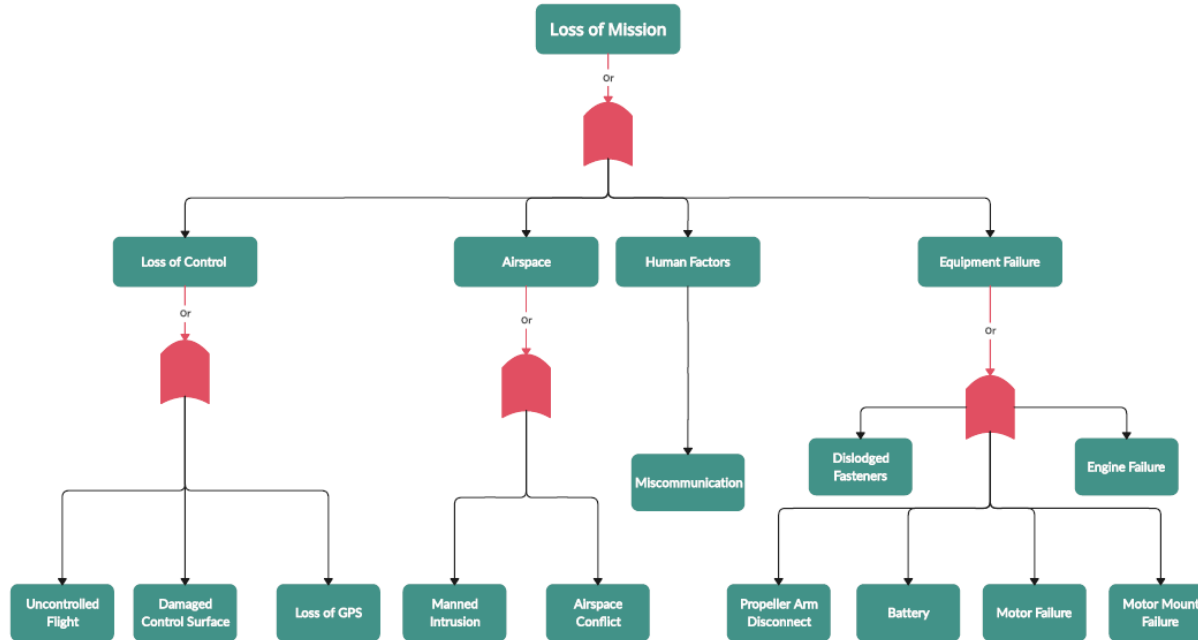


Fig. 7 Loss of Mission Fault Tree.

Results: Fault Tree Analysis

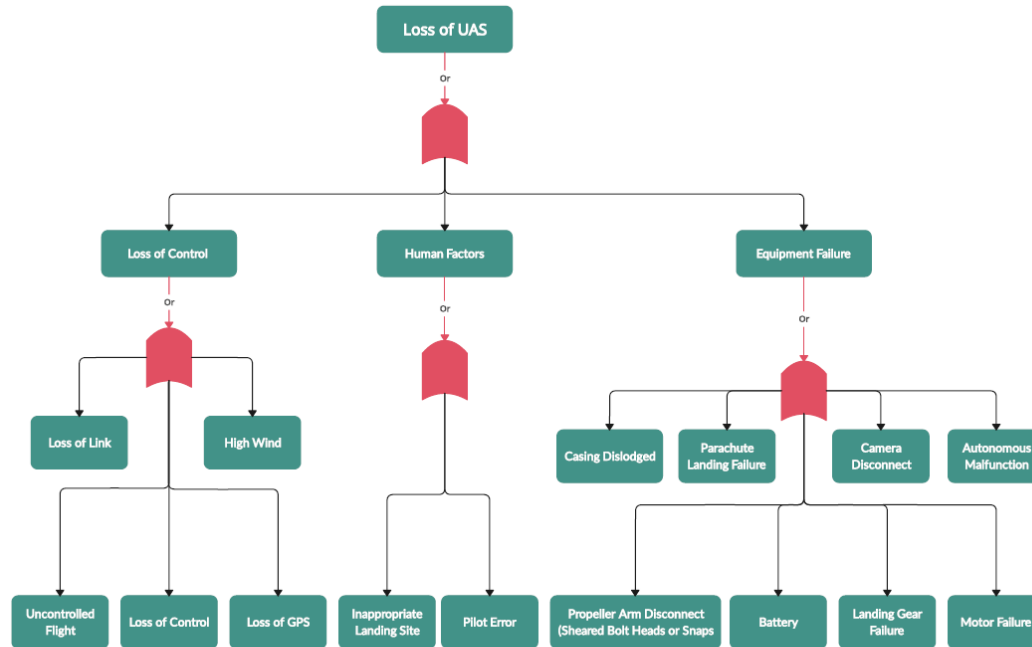


Fig. 8 Loss of UAS Fault Tree.

Results: Event Tree Analysis

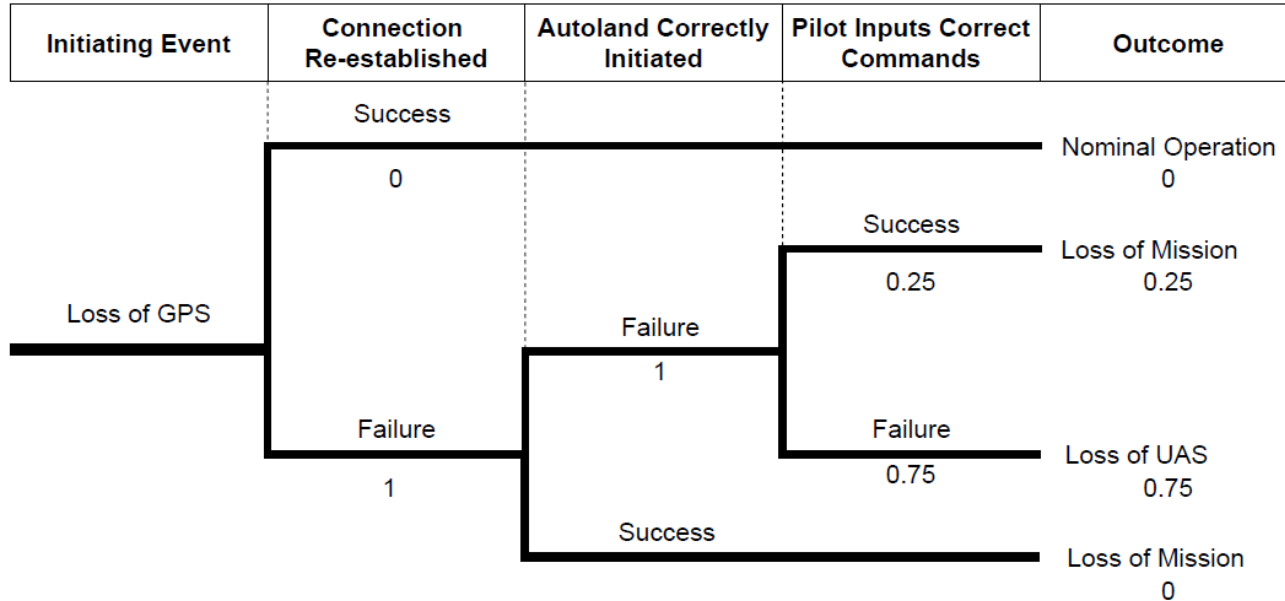


Fig. 9 Loss of GPS event tree.

Results: Markov Chain Analysis

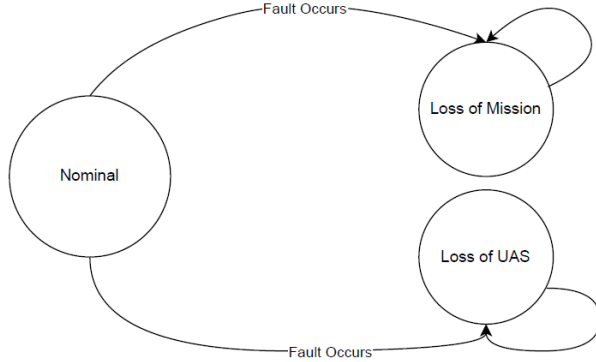


Fig. 10 Markov Chain representation of the system with two top event states.

$$P = \begin{matrix} & \begin{matrix} \text{Nominal} & \text{Loss of UAS} & \text{Loss of Mission} \end{matrix} \\ \begin{matrix} \text{Nominal} \\ \text{Loss of UAS} \\ \text{Loss of Mission} \end{matrix} & \begin{pmatrix} 0.986 & 0.009 & 0.005 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

- Consider system as a 3-state Markov Chain: nominal, loss of mission, loss of UAS
- Probability of a state on the next flight, $t+1$, is given by:

$$P(X_{t+1} = x | X_t = x_t, X_{t-1} = x_{t-1}, \dots, X_0 = x_0) = P(X_{t+1} = x | X_t = x_t)$$

- Modelled using a probability transition matrix to the left

Results: Markov Chain Analysis

- Time until failure is modeled by exponential distribution:

$$f(x, \lambda) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

- Estimate λ from data, with distributions to the right – this provides the probabilities in the transition matrix:
 - Loss of UAS: [58.659, 179.332]
 - Loss of Mission: [49.799, 448.394]
- Estimated number of flights until failure is 71, with 95% confidence interval [27, 125]

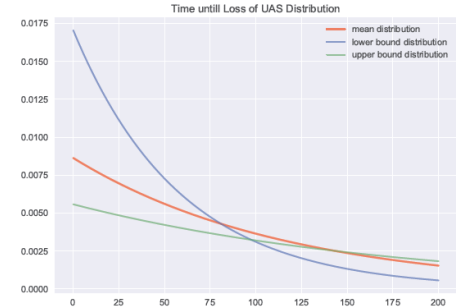


Fig. 11 Time until failure distributions for loss of UAS.

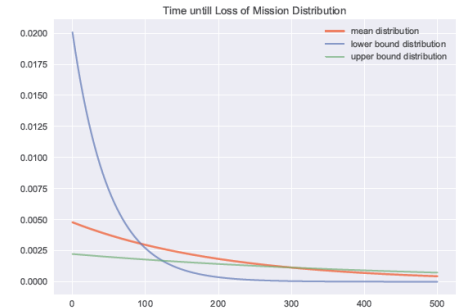


Fig. 12 Time until failure distributions for loss of mission.

Discussion

- A key contribution of this study is moving towards a dynamic risk analysis
- As more flights take place and new reports come in, new initiating and top events can be annotated, and the following analyses can be updated
- This process could be considered a capability of an In-Time Safety Management System
- The analyses are limited by the completeness of the reports and thus are likely underestimations of true failure rates
- Flight data is limited prior to 2022
- Failure rate changes from year to year and different time frames should be considered

Conclusions and Future Work

- We moved towards a **dynamic, data-driven**, risk assessment of a UAS wildfire mapping mission, including:
 - Hazard identification
 - Fault Tree Analysis
 - Event Tree Analysis
 - Markov Chain analysis
- Future extensions will:
 - Use Natural Language Processing to assist in the hazard identification step [6,7]
 - Perform Markov Chain analysis for other components of the system, including chains of events in event trees
 - Provide programming capabilities for fault tree checking from raw data

References

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➤ Additional Resources:

- Robust Software Engineering:
<https://ti.arc.nasa.gov/tech/rse/>



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