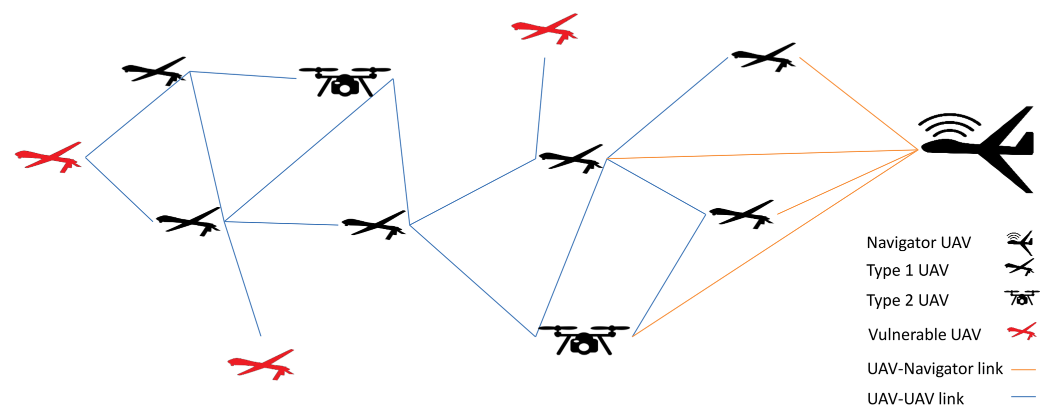
Safety Analysis for UAV Networks

A H M Jakaria and Mohammad Ashiqur Rahman, Dept. of Computer Science, Tennessee Tech University

Research Problem

- Collaborative operations of a network of Unmanned Aerial Vehicles (UAVs) to achieve a common objective is a recent research trend [1].
- However, as these smart devices are targets of adversaries, they need to maintain safe communication with each other while avoiding fuel outage and mid-air collisions, as well as reducing possibilities of being compromised [2].
- We present the model and implementation of a formal verification tool that takes different UAV parameters, safety requirements, and resource constraints as input and verifies the safety of the network.



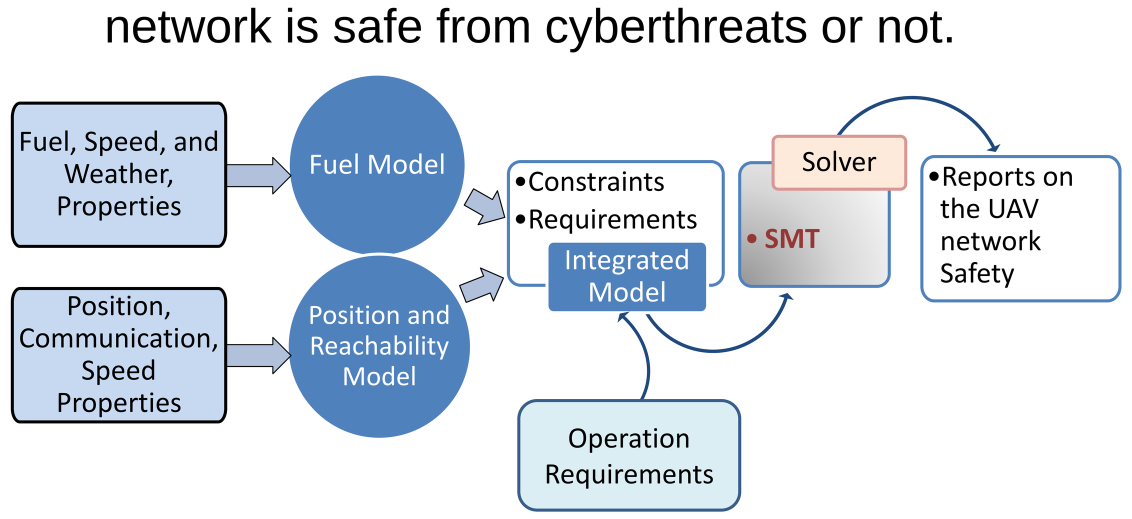
UAVs can be vulnerable because of having inadequate fuel, being too close to neighbors, or too few neighbors to communicate with.

Challenge and Objective

- Any vulnerable UAV needs to be instructed immediately to return to a safe territory.
- Satisfying all the requirements of the mission and constraints of the resources, given the UAV properties of a large network is a multi-objective combinatorially hard problem.
- As no other work in the literature solve the same kind of problem, to the best of our knowledge, we propose a formal method-based framework.

Framework

- The framework formally models the UAV parameters such as remaining fuel, current position, their velocity and direction, communication ranges, and weather conditions.
- The framework can solve the model and provide a solution that denotes whether a network is safe from cyberthreats or not.



Fuel Model

- Remaining flying time of a UAV depends on the remaining fuel, and the resultant velocity of the speed of the UAV itself and the wind speed along with their directions.
- A UAV has adequate remaining fuel if the remaining flying time is greater than or equal to a certain threshold.

$$RemTime_{v,t} = \frac{\alpha \times RemFuel_{v,t}}{|\beta \times \vec{S}_{v,t} + \gamma \times \vec{W}_t|}$$

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}}\ SafeRemFuel_{v,t} \rightarrow RemTime_{v,t} \geq T_{th}$$

Position Model

- Any two UAVs should always maintain a safe distance to avoid mid-air collision.
- The distance, namely, *Isolation*, is calculated as a triangle formed by the paths after a pre-specified time from the current instance, according to the velocity of the UAVs, and their current positions.

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}}\ SafeDist_{v,t} \ \rightarrow\ \neg\exists_{v'\in\mathbb{V},v\neq v'}\ Iso_{v,v',t} < I_{th}$$

$$Iso_{v,v',t} = \left|\frac{v_{x,t}(v'_{y,t} - \hat{v}_{y,\hat{t}}) + v'_{x,t}(\hat{v}_{y,\hat{t}} - v_{y,t}) + \hat{v}_{x,t}(v_{y,t} - v'_{y,\hat{t}})}{2}\right|$$

- One UAV is considered to be in range if it has some neighbors within its specified range.
- Two communicating UAVs should be within a safe range so that seamless communication is possible.

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}}\ InRange_{v,t} \ \rightarrow \ \exists_{v'\in\mathbb{V},v\neq v'}\ (Dist_{v,v',t} \leq Range_v) \ \land\ (\sum_{v'} v' \geq N_{th})$$

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}}\exists_{v'\in\mathbb{V},v\neq v'}\ InRelRange_{v,v',t} \ \rightarrow\ InRange_{v,t} \land InRange_{v',t} \ \land\ (Dist_{v,v',t} \leq min(Range_v, Range_{v'}))$$

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}}\ SafePos_{v,t} \ \rightarrow\ SafeDist_{v,t} \land InRange_{v,t}$$

Reachability Model

- All the UAVs should have multiple paths to communicate with the navigator, maintaining low latency [3].

$$\forall_{t\in\mathbb{T}}\forall_{v\in\mathbb{V}},\exists_{\hat{v}\notin\mathbb{V}}\ Reachable_{v,\hat{v},t} \rightarrow \exists_p\forall_{l\in P_{v,\hat{v},p}}\ i,j \in l \ \land Uav_{i,t} \land Uav_{j,t} \ \land InRelRange_{i,j,t} \land (\sum_{l} l \leq Hop_{th})$$

Overall Constraints and Requirements Model

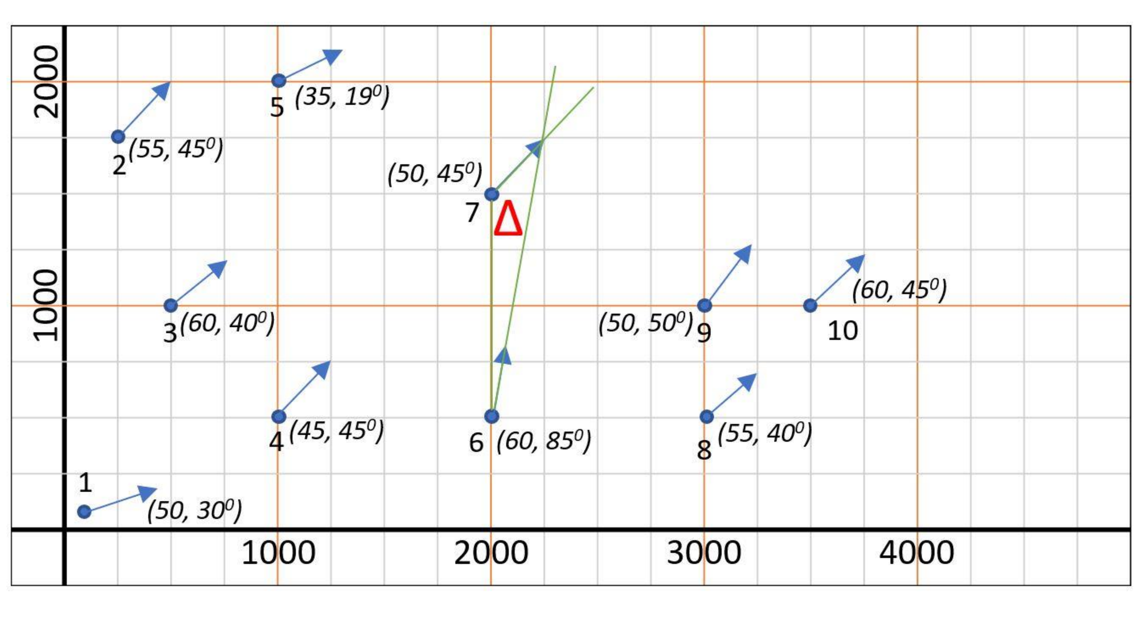
- The system is not safe if at any time, there exists at least one UAV that, although being alive, does not have safe remaining fuel to return to a refueling station, or does not maintain a safe position with respect to others, or cannot reach the navigator successfully.
- We model our solution as an assertion of non-safety of a UAV network.

$$\exists_{t\in\mathbb{T}}\exists_{v\in(\mathbb{V}),\hat{v}\notin\mathbb{V},Uav_{v,t}}\ \neg Safety_t \ \rightarrow\ \neg SafeRemFuel_v \ \lor\ \neg SafePos_{v,t} \ \lor\ \neg Reachable_{v,\hat{v},t}$$

Prototype Implementation

- We encode the model in Satisfiability Modulo Theory (SMT) logic.
- We use z3, an efficient SMT solver for the implementation.
- The solver returns an *unsatisfiable* result if there is no threat (no vulnerable UAVs) to the network.
- The solver provides a *satisfiable* result if the network is not safe in terms of all the requirements and constraints.
- The solver tells the user which UAV is vulnerable, *i.e.*, is not safe in terms of remaining fuel, position, or reachability to the navigator.

A Synthetic Case Study

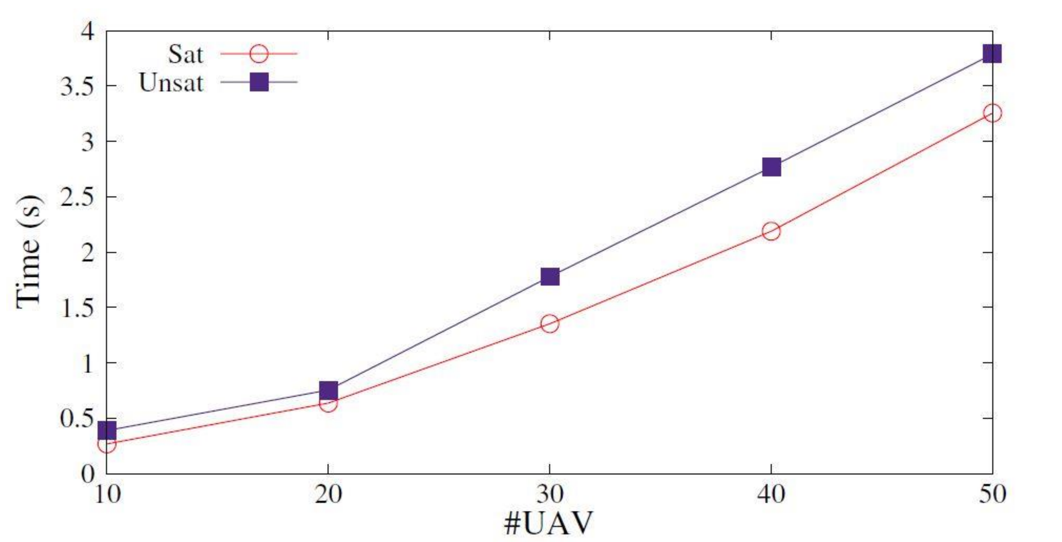


- Position and direction of 10 UAVs plotted on a Cartesian plane.
- According to the position, velocity, direction, wind velocity, remaining fuel, range, connectivity, and other information provided from an input file, the tool returns a *satisfiable* result for this network.
  - This means that the network is not safe.
  - The tool also informs that UAV 6 and 7 are not in safe distance, and there is a possibility of mid-air collision within the verification time specified by the user.
- This can be avoided by instructing UAV 6 to change its position to coordinate (2000, 250).

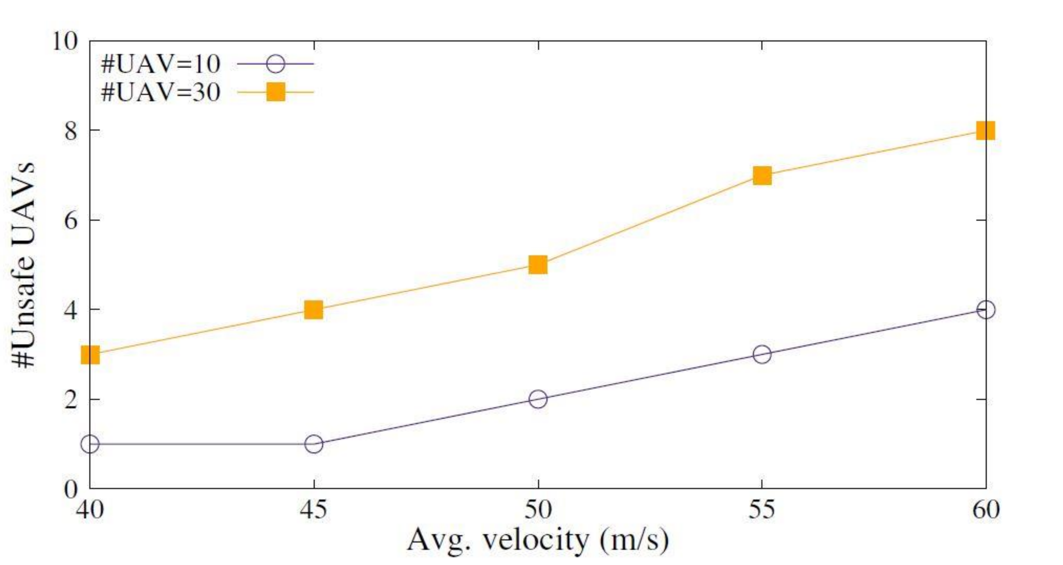
Input File for Case Study

```
# Number of UAVs
10
# UAV x-coordinates
100 250 500 1000 1000 2000 2000 3000 3000 3500
# UAV y-coordinates
100 1750 1000 500 2000 500 1500 500 1000 1000
# UAV velocities (m/s)
50 55 60 45 55 60 50 55 50 60
# UAV angles (degree with x-axis)
30 45 40 45 35 85 45 40 50 45
# UAV ranges (m)
2000 1200 1500 3500 2500 2000 1800 2400 1100 1100
# Remaining fuel (l)
50 35 35 40 30 25 30 30 25 20
# Wind speed (m/s)
20
# Wind direction (degree with x-axis)
20
# Verification period (s)
30
```

Results



Verification time increases almost linearly with the increment of number of UAVs, proving the scalability of the tool.



With the increment of avg. velocity of the UAVs the number of unsafe ones also increases. All these results are from satisfiable solutions of the model.

References

[1] Gupta et al., "Survey of important issues in UAV communication networks," IEEE Comm Surveys & Tutorials, vol. 18, no. 2, pp. 1123–1152, 2016.

[2] Borges et al., "A local comm model for improving stealth in uav net." *Anais do Comp on the Beach*, pp. 249–258, 2017.

[3] "Pentagon calls for drones," https://defensesystems.com/articles/2015/01/22/darpa-drones-pack-of-wolves-autonomy.aspx.