Resilient UAVs Traffic Operation Using Fluid Queueing Models

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November 8, 2019

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Background and Motivation

- Background
  - Increasing amount of activities of UAVs in the civil aviation domain.
    - ★ Over one million UAVs have been registered.
    - ★ 7 million UAVs will be registered as estimated and 2 million for commercial use.
  - Large companies have initiated projects on UAVs delivery and transportation service.
    - ★ Amazon: Prime Air
    - ★ Uber: Uber Elevate

Figure: Prime Air

Figure: Uber Elevate

Motivations

- Motivation
  - Recent transportation research has been focused on UAVs assisted traffic, but UAVs themselves can cause traffic congestions with increasing volume.
  - UAVs are sensitive to weather uncertainty. Congestion control under weather uncertainty brings more challenges.
  - Models that capture the characteristics of UAVs traffic is needed. Tools need to be developed to analyze the congestion of the UAVs traffic under uncertainties.

Goals

- Develop realistic and tractable models for UAV traffic under weather uncertainty
  - the system level model of UAV traffic: aggregated flow
  - the change of the weather conditions
  - the impact of weather change
- Analyze the system level of performance of UAV traffic in the merits of resilience
  - define resilience for UAV traffic
  - derive conditions for the UAV traffic to be resilient
  - improve the traffic efficiency

Simple Model

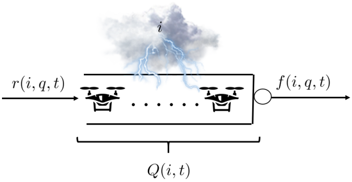

Figure: Single Fluid Queuing Model

Fluid Queueing model for UAV traffic:

$$\dot{Q}(i, q, t) = r(i, q, t) - f(i, q, t),$$
$$f(i, q, t) = \min\left(s\left(i, q, t\right), c_i\right).$$

States:
Q: stochastic queue length,
q: realization of queue length,
I: stochastic mode,
i: realization of mode,
r: receiving flow
s: sending flow
f: outflow
c_i: saturation rate(capacity)

Weather Uncertainty:
Continuous Markov Process with governing transition matrix: Λ
Assume: process is irreducible and ergodic:
steady state distribution: $p\Lambda = 0$, $|p| = 1$

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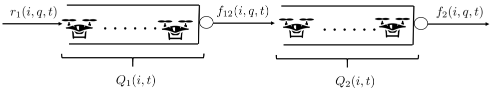

Figure: Tandem Fluid Queuing Model

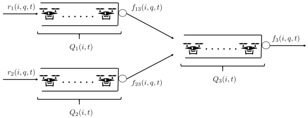

Figure: Merge Fluid Queuing Model

$$
\begin{aligned}
r_1 &= a,\\
s_1(i,q) &= \min(vq_1, c_{1i}),\\
r_2(q) &= w(\theta - q_2),\\
f_{12}(i,q) &= \min(s_1, r_2),\\
f_2(i,q) &= \min(vq_2, c_{2i}).
\end{aligned}
$$

Observation(fundamental diagram):

- More traffic flow can be sent to downstream if there is more traffic in upstream.
- Less traffic flow can be sent to downstream if there is more traffic in downstream.
- No flow can be sent to downstream if downstream is congested.

$$
\begin{aligned}
r_1 &= a_1,\\
r_2 &= a_2,\\
s_{13}(i,q) &= \min\{vq_1, c_{1i}\},\\
r_{13}(i,q) &= \frac{q_1}{q_1+q_2} w(\theta - q_3),\\
f_{13}(iq) &= \min\{s_{13}, r_{13}\},\\
s_{23}(i,q) &= \min\{vq_2, c_{2i}\},\\
r_{23}(i,q) &= \frac{q_2}{q_1+q_2} w(\theta - q_3),\\
f_{23}(iq) &= \min\{s_{23}, r_{23}\}\\
f_3(i,q) &= \min\{vq_3, c_{3i}\}.
\end{aligned}
$$

Resilience Definition

- Quantity of Interest
  - Stability: the long run boundedness of the queueing system
    - Mathematical Definition:

$$\limsup_{t\to\infty} \frac{1}{t} \int_0^t \mathbb{E}[\exp(|Q(\tau)|)] d\tau \leq C. \tag{1}$$

  - Efficiency: maximum throughput of the queueing system
    -

$$\begin{aligned} \underset{a}{\text{maximize}} \quad & |a|, \\ \text{subject to} \quad & (1). \end{aligned} \tag{2}$$

Results

- Some intuitive results:
  If the tandem queue is stable, then $a \leq \sum_{i=1}^{m} c_{ji} p_i, \; j = 1, 2.$
  If the merge queue is stable, then $a_j \leq \sum_{i=1}^{m} c_{ji} p_i$*, for* $j = 1, 2$*, and* $a_1 + a_2 \leq \sum_{i=1}^{m} c_{3i} p_i$*.*
- Some not so intuitive result:
  If there exist positive constants $\alpha_1, \alpha_2 \dots \alpha_m$ *and* β *such that:*

$$\forall i \in \mathcal{I}, \alpha_i \beta (2a_1 + 2a_2 - \tilde{F}_m(i)) + \sum_{j \in \mathcal{I}} \lambda_{ij} (\alpha_j - \alpha_i) \leq -1$$

  merge queue system is stable.[1]

[1] See details at: *"Resilient UAV Traffic Congestion Control using Fluid Queuing Models"* (Under Review)

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Numerical Experiments

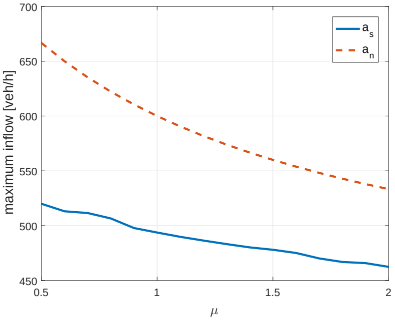

Figure: Effect of Transitional Intensity

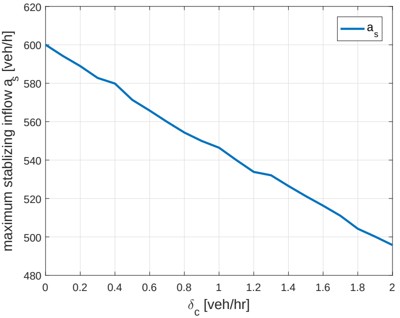

Figure: Effect of Capacity Fluctuation

Discussion

- Stochastic fluid queueing models can also be applied to other types of traffic.
- Discrete version of the results can also be derived.
- Feedback control policies can be developed for more models.