Drone-Truck Cooperated Delivery Under Time Varying Dynamics

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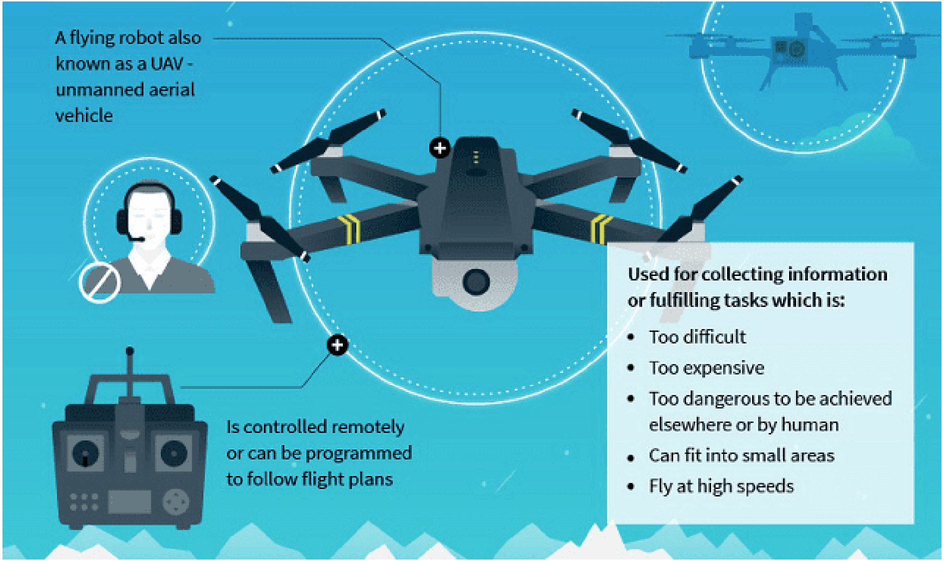
What is a Drone?



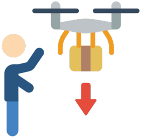
Drones in the global COVID response

- Chilean community is using drones to deliver medicine to the elderly
- Hutchinson (Kan.) Regional Medical Center is collaborating with Wingcopter to pilot a drone-powered delivery network: The aircraft will deliver healthcare resources, such as medicine, lab samples and vaccines
- MAKASSAR, Indonesia; A group of drone enthusiasts are using their aerial skills to help during the pandemic by providing a contactless medicine and food delivery service to COVID-19 patients isolating at home
- UPS Flight Forward is now making COVID-19 vaccine deliveries via drone for Atrium Health Wake Forest Baptist in Winston-Salem, North Carolina, using new cold chain packaging developed specifically for drones

Delivery

With the introduction of UAVs, the delivery systems of online goods can be more practical, effective, and efficient.

- They can deliver products quickly
- Easy to traverse difficult terrain
- Shorter routes

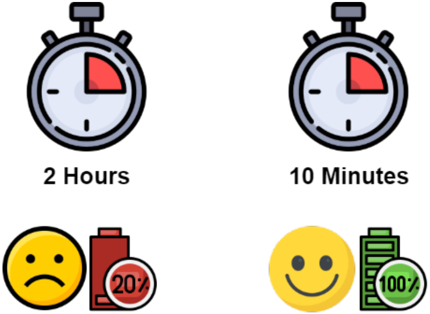


Challenges

- Energy depends on many factor
- Can transport only one package at a time (planning!)
- Location of the warehouses they are launched from
- Security: could potentially be hacked

Static Parameter:

- Flight Length



The UAV: a Energy Constrained Technology

Static Parameter:

- Flight Length
- Speed

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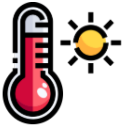
Dynamic Parameter:

- Temperature

Cold



Warm

The UAV: a Energy Constrained Technology

Static Parameter:

- Flight Length
- Speed
- Payload Weight

Dynamic Parameter:

- Temperature
- Wind Speed and Direction

Strong

Weak

The UAV: a Energy Constrained Technology

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Dynamic Parameter:

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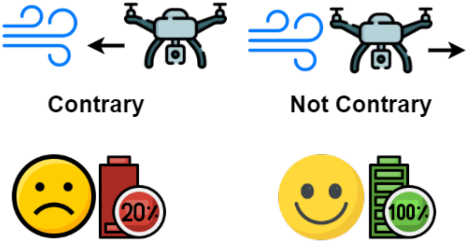
- Wind Speed and Direction



The UAV: a Energy Constrained Technology

Static Parameter:

- Flight Length
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Dynamic Parameter:

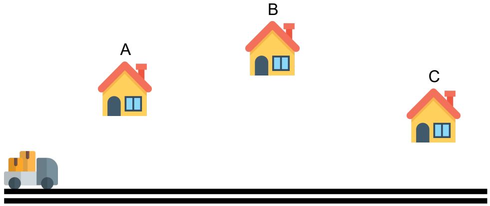
- Temperature
- Wind Speed and Direction

- The BIGGEST culprit of them all is **the wind**, so...

$\Rightarrow$ It is crucial consider the wind, because the drone **may dynamically decide** to take different routes taking advantage of the wind changes

The Problem[1]

- **Scenario:** A transportation company has to execute several deliveries to customers inside a city



[1] F. Betti Sorbelli, F. Corò, S.K. Das, L. Palazzetti, and C.M. Pinotti. "Greedy Algorithms for Scheduling Package Delivery with Multiple Drones", ICDCN 2022.

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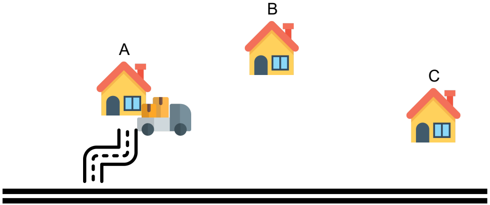

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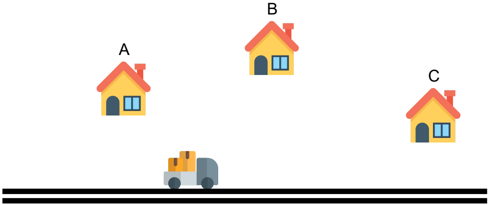

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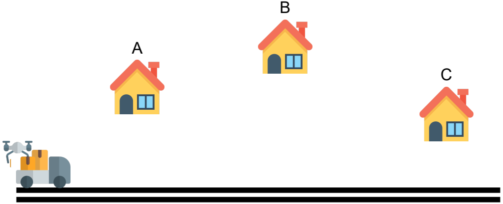
- **Idea:** Cooperation between a ground wheeled vehicle and drones in a last-mile delivery scenario



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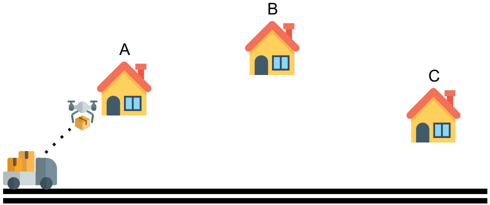
  - drone takes off (from the truck) with a package, visits the customer, and rendezvouses with the truck



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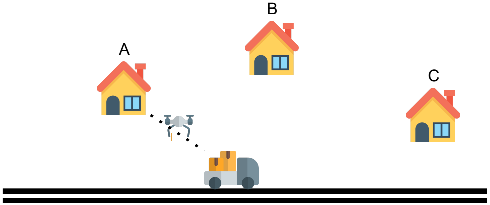

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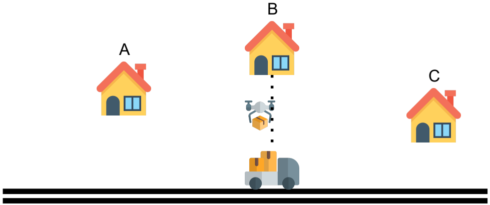

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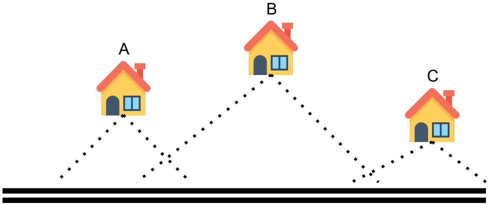

- **Constraints:**
  - each drone can execute *a single delivery at a time*
  - battery constraints
  - not all deliveries can be done
- **Objective:** The company has to schedule flying sub-routes for the drones to maximize its revenue

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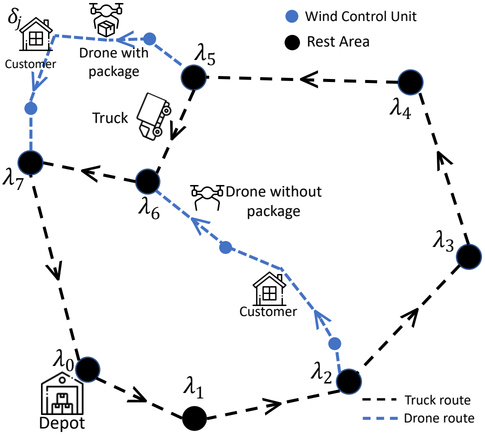
The model

- Fixed route for truck with designated rest areas
- Drones start delivery from a rest area and return to the truck at a (possibly different) rest area
- Truck stays at a rest area for a time to send/collect drones
- Truck works as mobile charging station for drones
- Orders and customer locations are known in advance
- A drone serves a single customer at a time



Time-varying Dynamics

- Speed and direction of wind can affect energy consumption and delivery time of a drone[2]
  - Tail-wind decreases energy usage
  - Head-wind increases energy usage
- Road traffic can affect the speed of a truck

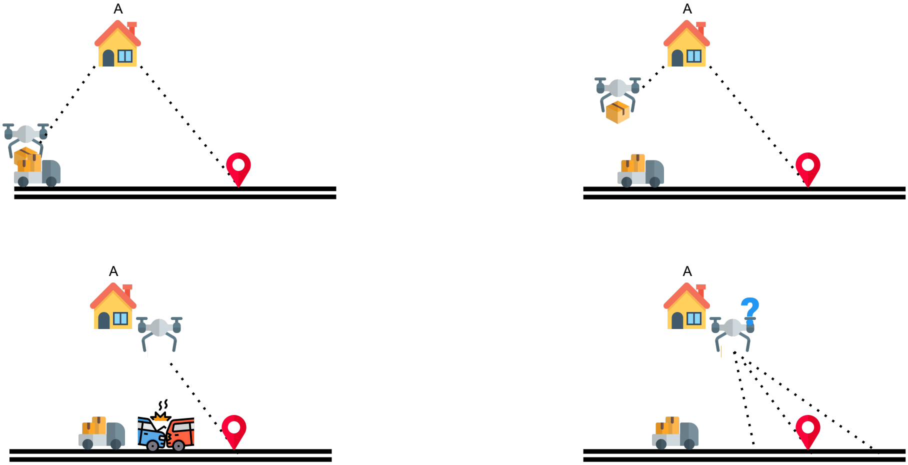
Challenges

- Travel time becomes unpredictable
- Energy efficient route selection for drones becomes complex[3]

[3] F. B. Sorbelli, F. Corò, S. K. Das, and C. M. Pinotti. "Energy-constrained delivery of goods with drones under varying wind conditions." IEEE Transactions on Intelligent Transportation Systems 2020

[3] A. Khanda, F. Corò, F. B. Sorbelli, C. M. Pinotti and S. K. Das, "Efficient Route Selection for Drone-based Delivery Under Time-varying Dynamics," MASS 2021

Example: Dynamic rendezvous point



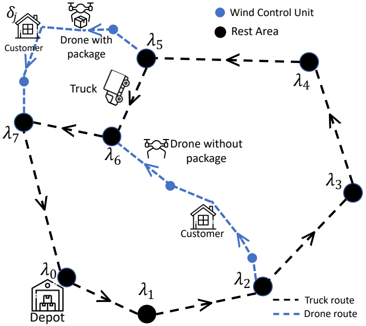
Objective

Primary:

- Minimize total delivery time (includes wait time)
- As road traffic is uncertain, our first objective is to minimize the waiting time at each rest area.

Secondary:

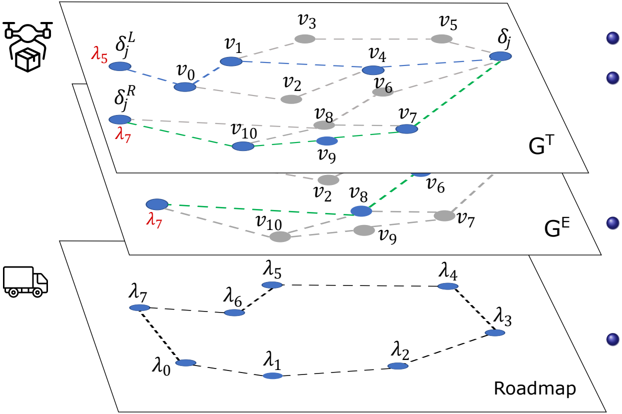
- Minimize the energy consumption of the drones without increasing the total delivery time



Our Contributions

- A **distributed delivery setup**, where:
  - each drone updates their route independently
  - synchronization between any drone and the truck is formulated by message passing

Drone Truck Cooperated Delivery System (DTCDS)



- Truck uses a fixed roadmap
- Drones use two delivery graphs
  - G^T: edge weight is time to travel
  - G^E: edge weight is energy requirement
  - both have same vertices and edges
- An energy efficient route to customer's location is the shortest path from drone's location to in G^E
- The time efficient route is the shortest path in G^T

Pre-processing

Algorithm 2: PreProcess $(G^{T*}, G^E, D, \mathcal{T})$

for $i \in 1 \ldots n$ **do**
- Compute SSSP on G^{T*} to find δ_i^L (Let λ_u) and shortest route distance d^f from λ_u to δ_i.
- Compute shortest path distances d_y^b from δ_i to all rest area λ_y such that $u \leq y \leq r+1$.
- $v \leftarrow argmin_y(|\tau_y - (\tau_u + d^f + d_y^b)|)$
- $\delta_i^R \leftarrow \lambda_v$
- $t_i^T \leftarrow \tau_u + d^f + d_v^b$
- **if** $t_i^T > \tau_v$ **then**
  - $\tau_v \leftarrow t_i^T$
- Compute t_i^E by finding shortest path from λ_u to δ_i, and shortest path from δ_i to λ_v on G^E.
- **if** $t_i^E < \tau_v$ **then**
  - $\delta_i.mode \leftarrow E$ `// Energy efficient`
- **else**
  - $\delta_i.mode \leftarrow T$ `// Time efficient`

Steps:

1. For a delivery find the launching point and rendezvous point by finding shortest paths from rest areas to the delivery location in G^T
2. Compute energy efficient path by finding shortest path in G^E
3. If the energy efficient path does not increase the waiting time for the truck, use Energy efficient route.
4. Else use the Time efficient route and update Truck's start time from the rendezvous point

Note: Shortest path may change due to varying wind condition

Algorithm 3: DynamicDroneRoute($\Delta_{all}, G^T, G^E, \delta_x$)

/* Drone's current location loc, assigned delivery δ_x, and current time t_{now} */

if *new* Δ_{all} *received* **then**
- $route^E \leftarrow$ RouteUpdate ($loc, \delta_x^R, G^E, \Delta^E$)
- $route^T \leftarrow$ RouteUpdate ($loc, \delta_x^R, G^T, \Delta^T$)
- $t_x^E \leftarrow t_{now} +$ time to travel $route^E$
- $t_x^T \leftarrow t_{now} +$ time to travel $route^T$

/* Let $\delta_x^R = \lambda_v$ */

if $t_x^E > \tau_v$ **then**
- **if** $t_x^T \leq \tau_v$ **then**
  - $\delta_x.mode \leftarrow T$ // Time efficient
- **else**
  - Send (λ_v, t_x^T) to the Truck

Steps:

1. For any change in edge weight, Update shortest route in G^E, G^T
2. If energy efficient route increases the waiting time for the truck use time efficient route.
3. If Time efficient route increases the waiting time for the truck, Truck's start time from the rendezvous point should be updated
   $\rightarrow$ **Send new rendezvous time to truck**

Truck under Time Varying Dynamics

Algorithm 4: ComputeAtTruck($\mathcal{T}, \Lambda$)

/* Truck's current location *loc*, and current time t_{now} */

if *loc lies on* ρ_j *and* $t_{now} > \tau_{j+1}$ **then**

  Estimate τ_{j+1} using traffic movement and road distance to cover.

  Update all τ_x for $j < x < r+1$ in $\mathcal{T}$.

  Broadcast $\mathcal{T}$ to all drones.

if *a message* (λ_j, t) *received from a drone* **then**

  if $\tau_j < t$ **then**

    $\tau_j \leftarrow t$

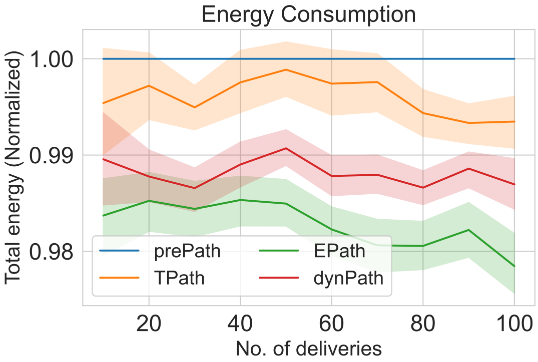
    Update all τ_x for $j < x < r+1$ in $\mathcal{T}$.

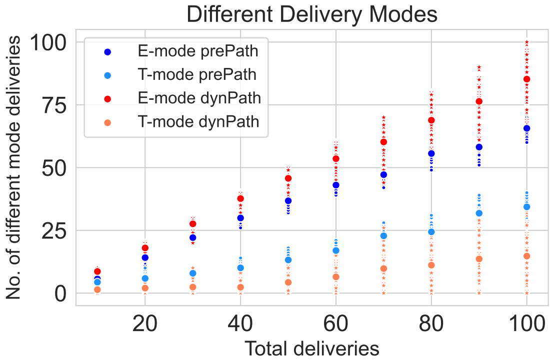
    Broadcast $\mathcal{T}$ to all drones.

Steps:

1. **Case 1 (Varying Road Traffic):**
   - If the truck fails to reach next rest area on time, it estimates the reaching time and broadcasts the new times to all the drones
2. **Case 2 (Varying Wind):**
   - If a drone informs the truck about a new rendezvous time, the truck checks if the new time affects $\mathcal{T}$
   - If $\mathcal{T}$ changes, the truck broadcasts $\mathcal{T}$ to all the drones

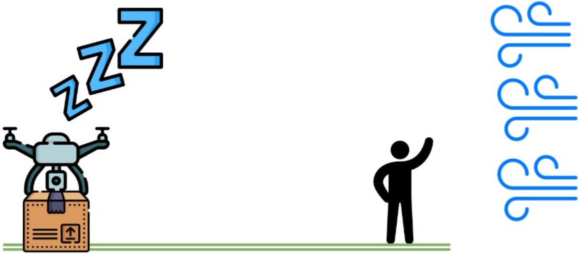
Experimental Evaluation





Future Works

- Improve the problem setting by taking into account the *fuel consumption of the truck*
- What about if we allow the possibility for the drone to attend better wind conditions?
- *Adaptive stochastic* optimization problem
- Investigate a *multiple-package* delivery approach

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Hybrid Electric Vehicle