ENS 491

Graduation Project Progress Report

Project Title:

Integrating Truck-Drone Systems for Enhanced Last-Mile Delivery in Logistics

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1. PROJECT SUMMARY

Abstract:

The objective of the proposed project is to transform the process of last-mile delivery by designing and implementing a hybrid logistics system that will make use of both traditional trucks and unmanned aerial vehicles (UAVs). This approach has been developed to offer solutions to some of the important logistical challenges posed by urban traffic congestion, increased operating costs, and delays associated with accessing remote or geographically challenging locations. The use of drones to perform the last-mile delivery process from vehicles strategically deployed along optimized routes is scalable and sustainable in dealing with growing e-commerce and fast-changing consumer expectations.

Trucks, defined by their ability to carry large amounts over long ranges, serve as moving bases for drones, which are characterized by agility and direct delivery capabilities. Through this symbiotic combination, the system avoids urban and suburban congestion while at the same time reducing greenhouse gas emissions and consumption of fossil fuels. Complex optimization algorithms are integrated into smoothly coordinating truck and drone operations to handle effectively constraints such as battery life, time windows, and payload.

The objective of the project is to prove that the system will offer faster, cheaper, and environmentally friendly delivery services, supported by simulation and empirical testing. This hybrid approach not only revolutionizes the future of last-mile logistics but also contributes to the greater goal of building more resilient and sustainable supply chains.

Gap in Literature and Existing Solutions:

While the application of drone technology in the logistics sector is rapidly developing and increasing in deployment, current solutions largely operate in isolation or demonstrate poor integration between trucks and drones. Whereas existing literature outlines the different benefits related to each delivery mode, there is an evident lack of detailed investigations exploring their coordinated collaboration. This lack of attention has resulted in disjointed and ineffective delivery systems where neither trucks nor drones work at their maximum capacity. Addressing this deficiency is quintessential to the creation of integrated systems that are capable of increasing the performance of delivery networks by the effective utilization of the distinct advantages of both vehicles and drones.

Motivation:

While considerable progress in drone technology and its application in logistics has been recorded, most of the existing solutions still operate autonomously or showcase a very small level of integration between trucks and drones. Even though the literature has clearly noted the special benefits of trucks, for their high carrying capacity, and drones, for their agility, a gap exists in research investigating coordinated collaboration between them. Current approaches fail to capitalize on the complementary nature of these two delivery modes, resulting in fragmented systems where efficiency is compromised and the full potential of neither trucks nor drones is realized. Synergy of truck and drone capabilities would create integrated systems to enhance the efficiency of deliveries, while optimizing operations in order to meet the ever-growing expectations of faster, more reliable, and sustainable logistics.

Objectives and Intended Results:

The project will focus on developing sophisticated mathematical models and optimization algorithms for synchronizing truck and drone operations. The key objectives are:

- Developing route optimization algorithms to coordinate drone deployment and truck navigation.
- Developing simulation models to evaluate the performance of systems under alternative scenarios.
- Setting constraints to ensure operational feasibility, including battery life, truck payload, and delivery time slots.
- Validating and verifying the model by case studies and simulation.

The expected results are the reduction in greenhouse gas emissions through optimized routes, decreased operational costs, and delivery speed. With this system, the intention is to create a new landmark in last-mile delivery by overcoming the logistical hurdles that impede efficient truck-drone collaboration and helping to build more sustainable and responsive supply chains.

The purpose of the project is to design a hybrid logistics model that includes both drones and trucks with an aim to improve the effectiveness of delivery, lessen the environmental impact, and ultimately promote sustainability. Our proposed framework will be outlined so that the operation costs will stay within acceptable ranges while reducing delivery times, and it is ensured that accessibility and feasibility are attested through the unique strengths in truck and drone transport.

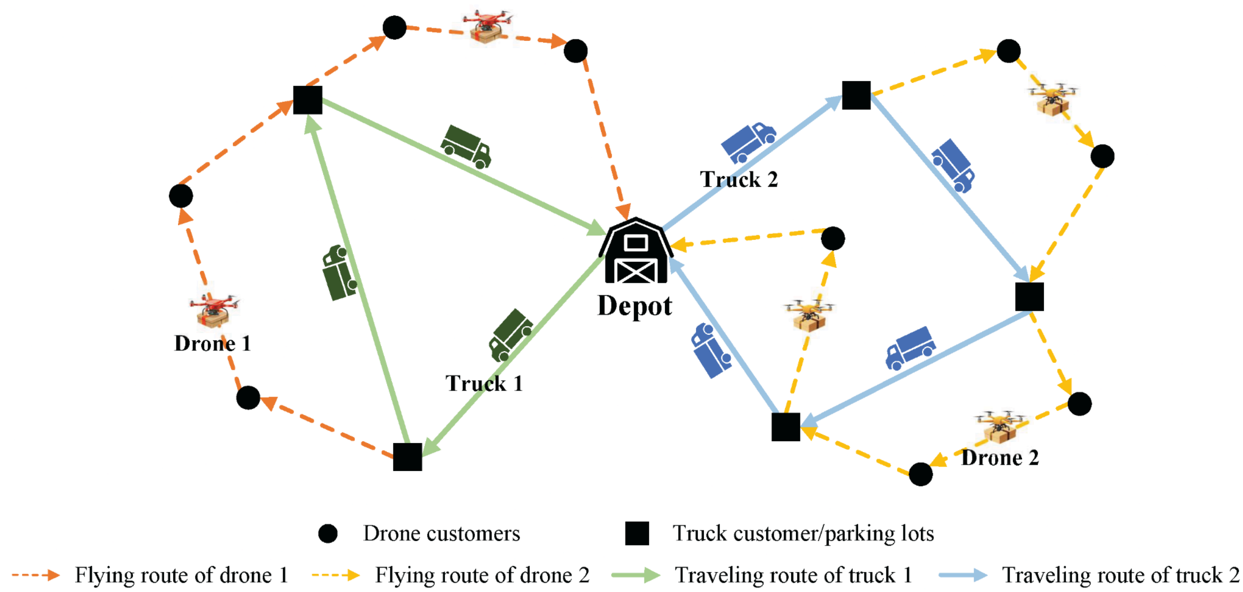
Compared with trucks, drones have a significantly higher efficiency in reaching specific locations due to their ability to operate independently of conventional road networks. This aspect facilitates penetration into difficult terrains that pose problems for larger vehicles, such as trailers, thus reducing the possibility of delays caused by vehicular traffic. Conversely, trucks are better placed in terms of covering greater distances and carrying much heavier loads. The proposed framework, therefore, aims at improving the adaptability and dependability of delivery networks by harnessing the synergistic strengths of the two modalities in question. Emphasis will be directed toward the creation of advanced mathematical models and optimization algorithms to achieve the ultimate goal of the project. These tools will enable truck-drone operation coordination by determining the best routes for trucks and the optimal time and place for drone deployment. Simulation models will be used in the development process to run many scenarios, which will enable the optimization of the system with respect to performance metrics such as cost efficiency, delivery speed, and resource utilization.

The probable results are diverse. On the environmental front, it can reduce greenhouse gas emissions by optimizing routes for transport and reducing the use of gasoline. In addition, the system is likely to increase the sustainability of the logistics networks since it significantly reduces inefficiencies and unnecessary travel. Economically, the hybrid system would probably reduce the costs of operations and hence benefit both businesses and consumers.

This project aims to set a new benchmark in last-mile delivery by integrating the use of vehicles and drones, enabled by advanced algorithms, while simultaneously looking at the impact on the environment, cost, and efficiency.

2. SCIENTIFIC/TECHNICAL DEVELOPMENTS

Recent development in hybrid logistics frameworks, combining the use of trucks and drones, has underlined the possibilities presented by advanced optimization methodologies and eco-friendly routing approaches. Kumar et al. (2024) proposed optimization algorithms driven by artificial intelligence to improve the integration of truck-drone operations, addressing key limitations such as battery duration and weight capacity. Their methodology uses advanced clustering methods to further improve delivery pathways, which markedly improves both the effectiveness and flexibility of last-mile distribution within metropolitan environments. Also, Wang and Zhao (2023) proposed energy-efficient routing algorithms to decrease environmental impacts while ensuring high delivery performance. The study has demonstrated the requirement for a balance between operational speed, energy consumption, and sustainability in order to develop greener and more economically feasible logistics networks. These developments align with the objectives of the project to improve truck-drone collaboration, reduce greenhouse gas emissions, and build sustainable supply chains.



Routing Problem for Cooperated Trucks and Drones (Adapted from Dang et al., 2024).

In what follows, we provide the MILP formulation of the problem. **Mathematical Notation** summarizes the mathematical notation

$$min \sum_{i,j,z} a_{ijz} x_{ijz} + \sum_{d,k} a_{dk} y_{dk} \tag{1}$$

subject to:

$$\sum_{i,j} d_i x_{ijz} \leq Q_{truck,z} \quad , \quad \forall z \in Z \tag{2}$$

$$\sum_{k} d_k y_{dk} \leq Q_{drone,,z} \quad , \quad \forall d \in D \tag{3}$$

$$e_i \leq b_{ijz} \leq l_i \quad , \quad \forall i, j \in I \ , \forall z \in Z \tag{4}$$

$$e_i \leq b_{dk} \leq l_i \quad , \quad \forall i \in I \ , \forall d \in D \tag{5}$$

$$\sum_{j} x_{0jz} = \sum_{i} x_{i0z} \quad , \quad \forall z \tag{6}$$

$$a_{ik} + a_{kj} \leq D_{max,d} \quad , \quad \forall d \tag{7}$$

$$\sum_{z}\sum_{j} x_{ijz} + \sum_{d} y_{di} = 1 , \forall i \in I \tag{8}$$

$$y_{dk} \leq \sum_{j} x_{ijz} \quad , \forall k \in K, \quad \forall d \in D, \forall z \in Z \tag{9}$$

$$\sum_{j} x_{kjz} = 0 \quad , \quad \forall k \in K, \quad \forall z \in Z \tag{10}$$

$$x_{ijz} \in \{0, 1\} \quad , \quad \forall i, j \in I \ , \forall z \in Z \tag{11}$$

$$y_{dk} \in \{0, 1\} \quad , \quad \forall k \in K \ , \forall d \in D \tag{12}$$

$$b_{ijz} \geq 0 \quad , \quad \forall i, j \in I \ , \forall z \in Z \tag{13}$$

$$b_{dk} \geq 0 \quad , \quad \forall k \in K \ , \forall d \in D \tag{14}$$

$$a_{ijz} \geq 0 \quad , \quad \forall i, j \in I \ , \forall z \in Z \tag{15}$$

$$a_{dk} \geq 0 \quad , \quad \forall k \in K \ , \forall d \in D \tag{16}$$

The objective function (1) minimizes the total distance. Constraints (2) and (3) enforce capacity limitations. Constraint (2) ensures that the total load carried by a truck does not exceed its capacity. Constraint (3) ensures that the total load carried by a drone does not exceed its capacity. Constraints (4) and (5) impose time window restrictions for both trucks and drones. Constraint (4) applies a time window to truck deliveries, ensuring the truck departs and arrives within the designated time window for each customer i. This guarantees that trucks respect the delivery schedule and avoid late arrivals. Constraint (5) enforces time windows specifically for drone deliveries, ensuring that drones complete their deliveries within the allowable time frame, aligning with customer availability and operational schedules.Constraint (6) ensures that trucks return to the depot after completing their deliveries. Constraint (7) limits the maximum operational flight range of drones. Constraint (8) enforces that each package is assigned either to a truck or a drone, ensuring that all deliveries are completed by the system. Constraint (9) enforces the coordination between trucks and drones by ensuring that a drone can deliver to a customer node k only if a truck has previously visited or is present at a nearby node j. Constraint (10) restricts trucks from visiting certain customer nodes that are designated as drone-only. Constraints (11)–(16) define the decision variables.

Mathematical Notation	
Sets	
I	Set of all customer nodes (both truck and drone accessible)
F	Set of depots
Z	Set of trucks
D	Set of drones
$K \subseteq I$	Subset of customer nodes only accessible by drones
Parameters	
t_{ijz}	Travel time for truck i to move from node i to node j
t_{dk}	Travel time for drone d to deliver to node k
d_i	Demand at customer i
d_k	Demand at customer k served by drones
$Q_{truck,z}$	Capacity of truck z
$Q_{drone,d}$	Capacity of drone d
$e_i,\ l_i$	Earliest and latest service times for customer i
$e_k,\ l_k$	Earliest and latest service times for customer k
$D_{max,d}$	Maximum operational flight range of drone d
$T_{max,z}$	Maximum operational time for truck z
$T_{max,d}$	Maximum operational time for drone d
Decision Variables	
a_{ijz}	Distance from node i to node j for truck z
a_{dk}	Distance to node k for drone d
x_{ijz}	1 if node j is visited following node i with truck z ; 0 otherwise

Mathematical Notation	
y_{dk}	1 if node k is visited with drone d; 0 otherwise
b_{ijz}	Service starting time at node i when serviced by truck z traveling from node i to node j.
b_{dk}	Service starting time at node k when serviced by drone d

Solution approach: To solve the aforementioned optimization problem, two phases are designed in the solu-tion approach. In the first phase, the customer points are clustered, and then an improved heuristics is proposed in the second phase.

3. ENCOUNTERED PROBLEMS

Challenges Faced During the Project:

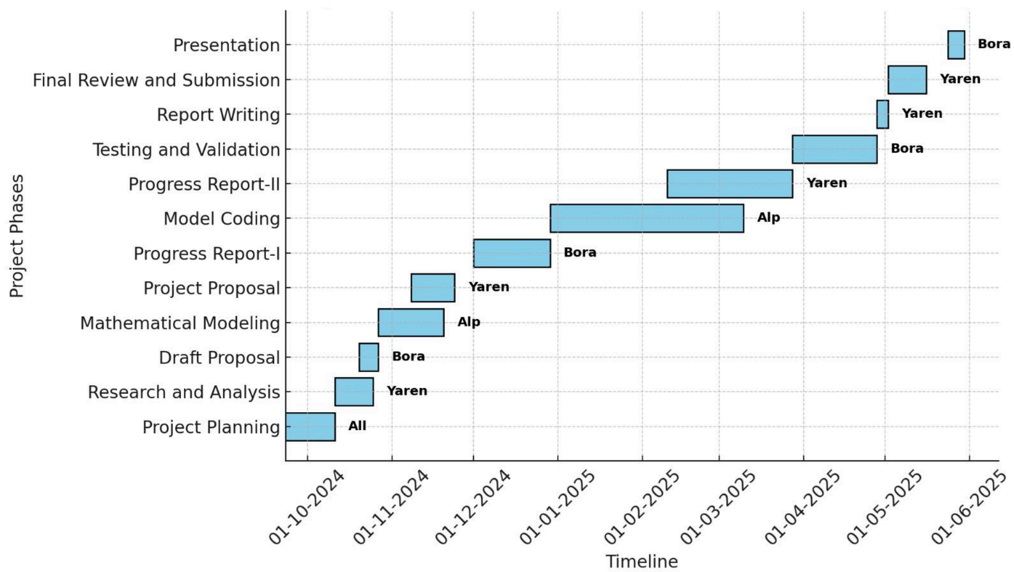
1. **Finding Resources:** During the first phases of the project, we did face some minor obstacles while trying to get hold of certain drone hardware and simulation tools. That indeed slowed down the development a little; however, we overcame that by focusing on mathematical modeling and conducting intensive literature studies. In the process, we had to make do with open-source software and publicly available simulation platforms that were available so as to not experience disruptions in our work.

2. **Knowledge Gaps:** During the mathematical model development, there were big gaps in knowledge on optimization algorithms and collaboration between trucks and drones. The team had to fill this gap by conducting extensive literature reviews and enrolling in online courses to improve their understanding. The team also reached out to academic mentors to clarify technical aspects, further solidifying the theoretical framework of the project.

3. **Development Time:** While the research and modeling phases progressed well, the lack of practical simulations did slightly delay the verification of results. In doing so, by concentrating on the optimization models and finishing the theoretical foundation, we kept the project on track with the original timeline, where simulations were planned for the later stages.

4. TASKS TO BE COMPLETED UNTIL PROGRESS REPORT II

1. Improve optimization models to allow for more efficient coordination between trucks and drones.
2. Conduct preliminary simulation tests to validate the system's performance under different scenarios.
3. Develop and explore constraints related to operational feasibility, including drone battery life and delivery time windows.
4. Develop a prototype model to validate theoretical results through case studies and controlled experiments.
5. Document findings and integrate results into the final design phase.



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