PFI-TT: Cloud-based Network-Aware Route Management Platform for Electric Truck and Drone Operations

1. Executive Summary

Societal Need and the Customer: There is a critical global need for governmental, non-profit, and commercial entities to address the growing strain on last-mile logistics, which is the most time-consuming, expensive and polluting segment of the delivery process. The global last-mile delivery market is projected to grow by 78% by 2030 [1]. Without intervention, such growth is expected to increase traffic congestion and greenhouse gas emissions by 30% by 2030. The last-mile delivery cost, which already accounts for 41% of the total supply chain cost [2], is also expected to increase. Moreover, in certain applications such as medical materials delivery (e.g., specimens, vaccines) and post-disaster relief distribution, it is critical to ensure timely deliveries. The efficient integration of emerging logistics technologies, namely unmanned aerial vehicles (UAVs or drones) and electric trucks (EV Trucks), could transform last-mile distribution to be *environmental-friendly, cost-effective, reliable and fast*.

Value Proposition: Existing technologies lack the capability to handle large-scale EV and UAV operations. This PFI-TT project will empower last-mile service providers to establish optimized routing plans for a scalable fleet involving EVs and UAVs. The service providers will be provided with an easy-to-use cloud-based platform, RoutePEARL (Route **P**lanner for **E**fficient **A**erial and **R**oad **L**ogistics), that generates routes by accounting for operational and communication networking decisions. This technology would be the first to generate safe and optimized EV and UAV route plans, while being able to quickly handle uncertainties that arise during deliveries. RoutePEARL will increase productivity, improve fleet utilization, reduce the distance traveled, lower carbon emissions, and decrease operational costs, while enhancing safety by minimizing operational risk and ensuring reliable network communication. Also, the platform will be implemented using cloud resources to facilitate scalable and reliable service for users.

Innovation: This project will advance the current state-of-the-art in last-mile logistics. It will enable optimized route management for EV trucks and drones by jointly considering operational and network communication decisions. It will also address existing market gaps through the development of novel modular mathematical models and artificial intelligence-enabled algorithms that can quickly generate optimized routes for different delivery methods (EV truck-only, direct drone or hybrid truck-drone). In addition, new dynamic models for real-time management of airspace and road networks, environmental factors, and communication networks will be developed for use in cloud-based applications. The proposed approaches will be validated using computational experiments and real-life piloting.

Partnership: The University of Missouri (MU) project team includes members with expertise in operations engineering, edge networking, machine learning, entrepreneurship, intellectual property and technology transfer. The MU team will be responsible for developing and evaluating the proposed technology through computational experiments and real-world testing. Workhorse, Transparent Sky, and Skylark Drones (see **Letters of Support**) will serve as the project's industrial partners. They will serve on the advisory board to: (1) facilitate piloting and field testing of the project outcomes, (2) help with assessing market potential, and (3) promote the proposed last-mile logistics management system to early adopters.

Training and Leadership Development in Innovation and Entrepreneurship: The graduate and undergraduate students will be trained through the following activities: (1) integration of entrepreneurial education into existing courses, (2) participation in the MU Entrepreneurship Alliance Program (an intensive 8-week program to train students in business aspects), (3) training on product discovery through industrial partnerships, (4) mentorship, pitch practice opportunities and real-world work experience through Center for Excellence in Logistics and Distribution (CELDi) industrial partners (e.g., Boeing, Schneider Electric) and through the resources of this graduated NSF I/UCRC Center at MU and other existing initiatives (e.g., NSF REU) for broadening participation within under-served/under-represented groups.

2. From NSF Basic Research to Addressing a Market Opportunity

2.1. NSF Lineage

This project has lineage from (1) PI Srinivas' customer discovery results from NSF award TIP-2240977 *I-Corps: A Scalable Cloud-based Route Optimization Software for Efficient Aerial and Road Logistics* and (2) Co-PI Calyam's NSF-supported research results from award CNS-1647182 *US Ignite: Resilient Virtual Path Management for Scalable Data-intensive Computing at Network-Edges*. **Fig. 1** shows how the NSF Lineage has shaped the proposed project.

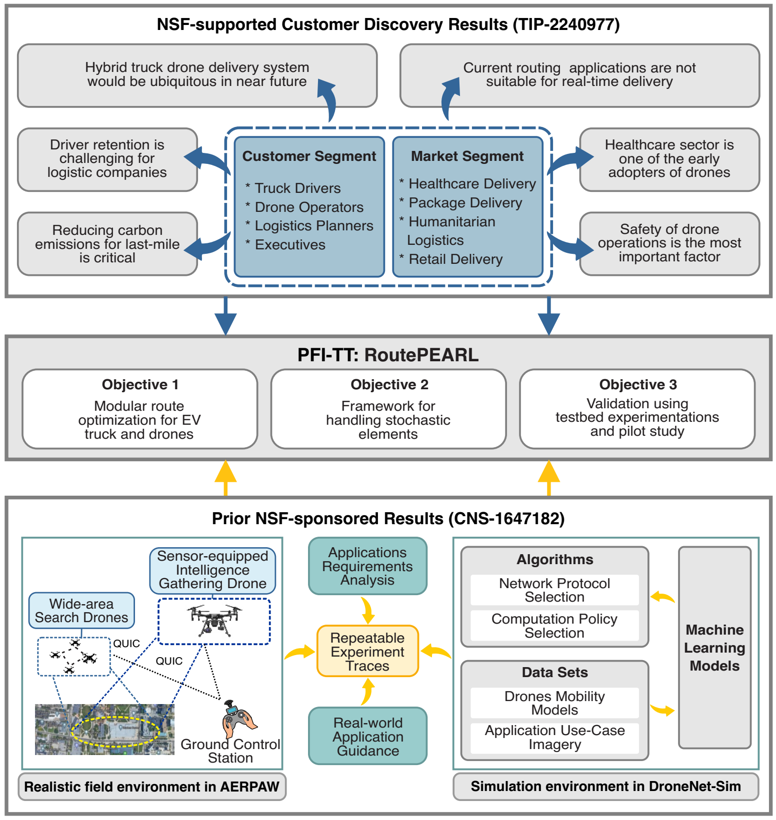


Fig. 1: *NSF Lineage for the proposed project*

Under the NSF-supported I-Corps award (TIP-2240977), PI Srinivas along with other team members (EL Alizadeh and IM Maland) conducted ***over 110 customer discovery interviews*** to understand the value proposition, pains and gains of different customer segments in last-mile logistics. The main findings are summarized in **Fig. 1**. A common challenge among all last-mile service providers is driver shortage and retention, as well as growing demand and high fuel costs. To address this, most have integrated or plan to integrate EV trucks and drones into the last-mile ecosystem. Also, real-time rerouting capabilities of existing platforms were found to be inefficient and often required manual intervention from planners. An interesting discovery regarding *EV delivery* is that existing route optimization platforms are not capable of generating reliable or cost-optimal routes for EV trucks. This is because they do not consider their unique characteristics, such as range and payload impact, for route planning. Regarding *drone operations*, the highest priority is the ability to generate route plans that: (1) reduce overlap over potential hazards (e.g., power lines, residential areas) and (2) ensure reliable network communication between drones and the ground station/truck. Specifically, for *combined truck-drone operations*, effective coordination is considered vital to achieving the highest safety and cost savings. In summary, our customer interviews led to the identification of several unmet needs and market opportunities.

Under the NSF-supported project (CNS-1647182), Co-PI Calyam is leading investigations around edge computing and networking for a variety of public safety and smart farming applications. The team has developed novel algorithms for *computation offloading* involving learning-based edge computation offloading strategies that use a function-centric computing paradigm [3] to decouple a video processing pipeline to perform optimal resource allocation. Decision making for dynamic offloading of compute functions is handled using a Markov Decision Process (MDP), wherein the aim is to minimize total computation costs and latency in edge/fog resources while reducing processing times to meet application requirements [4]. The team also developed novel algorithms for *control networking* involving resource-aware network protocols and video properties selection based on application requirements. The algorithms are capable of network protocol selection (i.e., UDP/RTP, QUIC) and adaptation of video properties during computation offloading procedures [5]. Thus, reliable video quality delivery is ensured in drone flight scenarios involving different mobility models (e.g., mission plan based) and with prediction on the trajectory of drones [6]. Further, the team created a novel AI-augmented geographic routing approach (AGRA) that uses physical obstacle information obtained from satellite imagery [7] to ensure reliable data transmission. **Fig. 1** shows a methodology for the integration of these algorithms with data analysis related to drone networks from field experiments in realistic testbeds (e.g., using AERPAW [8], an NSF-supported facility) to obtain repeatable experiment traces, and their use in scalable simulations using DroneNet-Sim [9].

2.2. Proposed Product: RoutePEARL Platform

The last-mile logistics transformation includes the use of EVs and UAVs in the following ways.

- **EV Truck-only Delivery:** This involves the use of a fleet of EV trucks for last-mile distribution. Although some aspects of route optimization are similar to traditional gas-powered vehicle routing, there are other unique characteristics, such as limited battery recharging windows and battery range that depend on several factors (e.g., payload, topography, and weather).
- **Direct Drone Delivery:** This last-mile system enables point-to-point package delivery using drones. This setting is suitable for delivery within a small radius. However, the efficiency depends on the distribution plan, such as sequencing launch/recovery of multiple drones and network communication reliability.
- **Hybrid Truck-Drone Delivery System:** In this setting, the truck and drones work in tandem to deliver packages. Such a system will have a mothership truck that transports drones and packages through the delivery network. To handle drone's limited payload capacity and battery range, the truck will be used as a *moving depot* while also being employed to make deliveries. Therefore, UAVs will be deployed at multiple truck stops for package delivery to nearby locations and later recovered at a rendezvous point.

Several companies have successfully used these aforementioned last-mile systems on a small scale. However, a large-scale delivery system that involves EV trucks and UAVs requires network-aware route planning for safe and efficient operations (see **Fig. 2**). The ground station or truck needs to communicate with the drones to: (1) guide them to different delivery locations, or (2) in exception cases, to update recovery location, adapt drones' delivery route to avoid crashes when facing obstacles (e.g., trees, buildings), or (3) for emergency landing in case there are issues with the drone to complete the delivery tasks as expected. The network links between the ground station and drones are also relevant for transmission of video or images to aid a remote operator who monitors drone operations to ensure safe and reliable delivery, as well as for supplementary services such as delivery confirmation, unmanned aircraft system traffic management (FAA R&D priority [10]) or documentation of unexpected events in course of the delivery.

Fig. 2: *Network communication illustration in drone routing*

To this end, we propose to develop and validate **RoutePEARL** (**R**oute **P**lanner for **E**fficient **A**erial and **R**oad **L**ogistics) - a web-based route management platform for large-scale use of EV trucks and drones in last-mile logistics. It will generate network-aware optimized delivery plans for EV trucks, UAVs, and hybrid truck-drone systems. It can also provide real-time adjustments of planned routes for handling uncertainties (e.g., drone failure). The platform will use cloud resources to handle the computationally intensive tasks of route planning and dynamic rerouting. **Fig. 3** illustrates the 3-tier architecture of RoutePEARL.

The **Intellectual Merit** of the proposed RoutePEARL platform lies in the holistic consideration of both operational and communication networking aspects in drone-based deliveries. Specifically, the proposed project innovates and advances the field through the development and validation of: (1) new optimization models and heuristic methods to efficiently solve the EV truck and UAV routing. Most importantly, the proposed solution approach will adopt a modular strategy, thereby allowing the route planning algorithm to be adaptive for three different delivery scenarios - EV truck-only routing, direct drone delivery, and hybrid truck-drone routing, (2) new dynamic routing models that integrate machine learning and optimization for handling stochastic elements, while accounting for airspace and road network management, environmental factors and network communications, and (3) network protocol design that features learning-based algorithms for UAV trajectory planning based on awareness of environmental conditions (e.g., obstacles caused due to heavy winds or trees) to guide multi-hop packet forwarding with sustained data throughput, and handle network partitions in long-distance truck-drone communications.

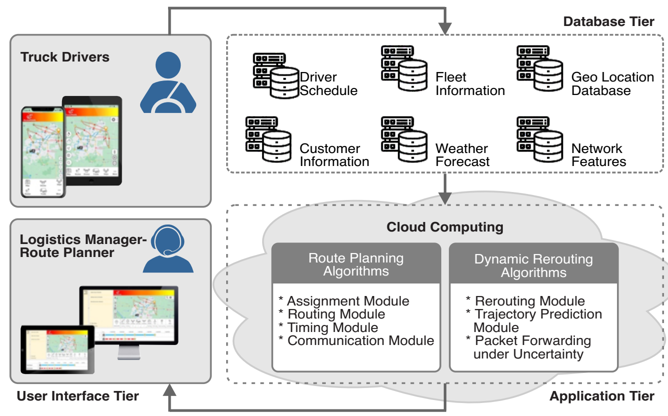


Fig. 3: *RoutePEARL's 3-tier architecture*

Broader Impacts: This research and its implementation will transform the logistics service to be faster, cost-effective and sustainable in many areas, such as medical delivery, humanitarian operations, emergency response, and last-mile delivery and therefore will have a positive impact on each individual. Besides, the knowledge from this research on how the use of EV trucks and UAVs impact carbon emissions and traffic congestion can allow policy makers to devise novel plans that incentivize sustainable development approaches. The proposed technology has the potential to revolutionize last-mile logistics and strengthen the economic competitiveness of the United States through safe and efficient use of EV trucks and UAVs. Most importantly, the proposed solution has promising commercial potential as it can alleviate the challenges and growing strain on the last-mile logistics sector, a multi-billion dollar global market.

2.3. Target Market

The global last-mile logistics market is expected to grow by $165 billion in the next 5 years [11]. During this period, the EV truck and drone delivery market is expected to reach $15.6 billion and $32 billion, respectively [12, 13]. Also, the market size of route optimization software is projected to grow from $3.2 billion to $12.4 billion by 2030 [14]. Given RoutePEARL's anticipated capabilities, there are many target markets with different value propositions as detailed in the following:

e-Commerce Market: Over 90% of the growth in last mile package delivery is attributed to the e-Commerce sector [11]. Our customer discovery results suggested it to be a *beachhead market* for hybrid truck-drone and electric truck-only deliveries. The proposed RoutePEARL platform can address the unmet market need by prioritizing safety in hybrid truck-drone route optimization.

Medical Delivery Market: It includes various segments such as prescription delivery, vaccine distribution to remote areas, and specimen (e.g. blood samples) transport. Our customer discovery results suggest that UAV-based delivery is ideal for this growing market, which is expected to exceed 93 billion dollars by 2027 [15]. Although companies such as Matternet and Zipline are using drones for medical deliveries [16, 17], the market is still in its infancy and requires optimized delivery planning to operate heterogeneous UAVs. Our RoutePEARL platform can address this unmet market need.

Disaster Relief Logistics Market: The distribution of critical relief supplies to affected areas is urgent and can be accomplished using hybrid truck-drone or direct drone deliveries. RoutePEARL will allow humanitarian coordinators to seamlessly generate the fastest plan for large-scale relief distribution using multiple heterogeneous UAVs and/or EV trucks.

Food Delivery Market: The US food delivery market has doubled in the last two years [18]. However, this sector has not been very profitable due to the high operating costs of these on-demand deliveries. Several meal delivery platforms (e.g., Uber Eats and Zomato) are investing in EVs and UAVs for meal delivery [19], and our technology can enable real-time delivery planning.

Defense Logistics Market: The timely and accurate delivery of ammunition, food, and medical supplies to inaccessible areas is crucial for battlefield logistics and includes several technological challenges. RoutePEARL can aid in effective tactical planning for such situations.

2.4. Existing Competitive Technologies

The competitive landscape for route management platforms is shown in **Fig. 4**. Currently, there are many technologies that optimize routes for gas-powered trucks (e.g., OptimoRoute, Route4Me). The capabilities of these platforms also vary widely. For example, Route4Me offers advanced machine learning-based real-time routing, unlike most other competitors. However, these platforms are not suitable for EV truck routing or hybrid truck-drone routing. Although there are a few platforms that facilitate EV route optimization (e.g., EVR) and drone delivery planning (e.g., flytzip), the proposed RoutePEARL platform has several competitive advantages. First, our platform will provide the unique ability to plan routes for various types of new last-mile technologies, giving us ***differentiation and first-mover advantages***. Second, RoutePEARL will have a ***technology-based advantage*** since it would be the first to: (1) leverage the state-of-the-art reinforcement learning approach to enable real-time route adjustments, (2) integrate network communications and operational decisions to enable safe and efficient drone deliveries, (3) employ a modular solution approach that would provide the flexibility to be scalable for any combination of vehicle types and delivery requirements. Notably, these competitive advantages are highly valued by customers, as evidenced by our NSF-supported customer discovery results.

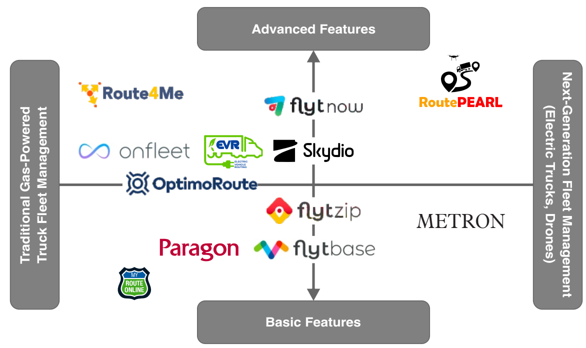


Fig. 4: *Overview of the competitive landscape*

2.5. IP Landscape

MU has a provisional patent application (US Patent Application Serial No. 63/375,442) directed to route planning for a hybrid truck-drone delivery system, and the technology transfer office intends to convert the application to a non-provisional. MU will also advance the intellectual property developed under this proposed project by licensing the copyright in the code and will keep the specific algorithms used to generate the routes as a trade secret. The patent landscape is crowded in the broad category of drone delivery, and companies with patents relevant to the patentability of the MU solution are Amazon, Route4Me and UPS. U.S. Patent No. 11,410,562, issued to Amazon, considers a host of inputs for route planning of drones. However, the patent does not employ the hybrid truck-drone model. Route4Me provides route planning software for last mile delivery and has 25 issued patents and applications in this space. However, only a few of those contemplate the use of drones and none of those consider network communication capabilities, as envisioned in RoutePEARL, for safe and efficient operations. US Patent No. 11,435,744 issued to UPS covers the route of an autonomous drone from a manual delivery truck, but does not consider network communication capabilities. Despite these existing patents, there is potential to patent the processes involved in static and dynamic routing of a hybrid truck-drone delivery system that jointly consider both operational and networking issues.

3. Technical Challenges and Applied Research Plan

3.1. Current Advancements and Technical Challenges

Regulations and Industry Use: The Federal Aviation Administration (FAA) is establishing regulatory pathways to embrace and integrate drones safely in low-altitude airspace [27]. The FAA has granted waivers for beyond visual line of sight (BVLOS) drone operations to more than 100 companies to date. Companies such as Google (Wing Aviation), Amazon (Prime Air), and UPS (Flight Forward) are employing drones for last-mile delivery in several US cities (e.g., Raleigh and Lockeford [20]). In addition, companies around the world (e.g., DHL, Zomato) have adopted electric vehicles for last-mile logistics, and some companies like Workhorse (our **industrial partner**) are piloting the hybrid truck-drone delivery system. However, safe and efficient use of drones for last-mile delivery is a topical issue in practice and requires advanced methods to manage it, which this research aims to achieve.

Overview of Current Research: The *hybrid truck-drone delivery system* is based on conventional routing problems, such as the traveling salesman problem (TSP) and the vehicle routing problem (VRP). Recently, several variants of truck-drone route planning have been investigated using optimization and approximation algorithms, such as single truck multi-drone delivery [21–23], simultaneous pickup and delivery [21], and capacitated truck-drone delivery [24]. However, none of the existing approaches considers critical practical constraints (e.g., minimizing operational risk) and communication reliability. With regard to *direct drone deliveries*, existing research has proposed planning algorithms for applications such as meal delivery [25], humanitarian logistics [26], and medical delivery [27], but does not consider operational and networking decisions together. Research on *EV truck route optimization* has extended TSP by incorporating battery and payload capacities as new constraints [28, 29]. Nevertheless, they do not consider real-world constraints, such as limited recharging windows and disruptions. Therefore, there are critical knowledge gaps for the large-scale adoption of EV trucks and UAVs in the last-mile ecosystem.

Knowledge Gaps and Technical Barriers: The **first critical challenge** is to consider operational and network communication decisions to establish route plans. This requires answers to key: i) *operational-level questions*, such as: Which customers must be served by which vehicle type? Where and in what sequence should a mothership van deploy its UAVs for hybrid truck-drone delivery? Which paths to avoid (e.g., no-fly zones)?, and ii) *networking-level questions*, such as: how to set up network properties (e.g., communication channel, data transport protocols) for data transmission? How to optimize the vehicle's trace to provide a relay for reliable communication? The **second key challenge** is to be able to handle uncertainties and real-time coordination, and requires answers to: i) *operational-level questions* such as: what is the best strategy to re-route under disruptions? as well as, ii) *networking-level questions* such as: how to assign a dynamic delivery request and update the end-to-end communication network link connections to foster delivery success? How to ensure sustained network connections for data/video communications when facing hazards (e.g., buildings)? In summary, to ensure safe and reliable delivery operations, it is vital to consider independent and cross-linked issues related to operational and network communications planning. Yet, existing approaches have not addressed them in a joint context. Such challenges impede the effective use of these technologies on a large-scale, and therefore must be tackled.

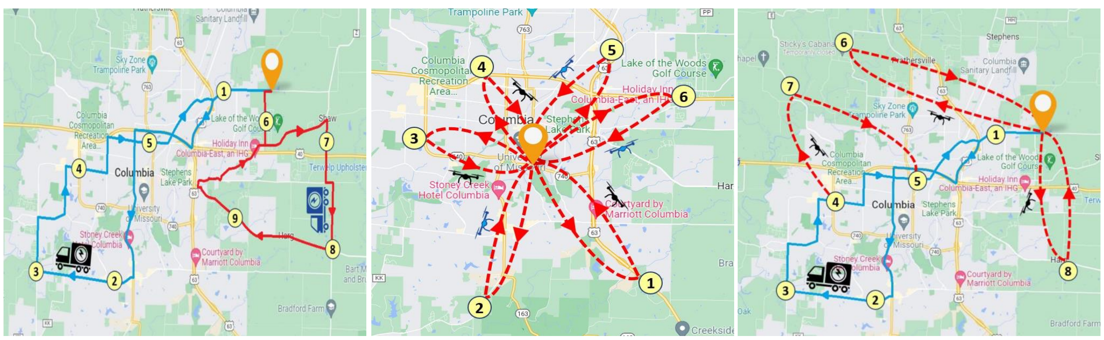
3.2. Applied Research Plan

Objective R1: Modular Route Optimization Approach for EV Trucks and Drones. The last-mile logistics problem deals with routing a fleet of vehicles to serve a set of customer locations $\mathcal{L} = \{l_1, ..., l_N\}$ within region $\mathcal{R}$ in a 2D Euclidean plane. The goal is to start from the depot(s), visit each location exactly once by one of the vehicles, and return to the depot so that a specific objective (e.g., operational cost) is optimized. In the case of a hybrid truck-drone delivery system with T trucks that carry D drones, a fully defined solution to the problem consists of four types of decisions:

- **Assignment Decisions**: Which vehicle type should be used to serve each delivery location? Which locations must be served by drone from each truck stop?

- **Routing Decisions**: How do we route the truck via a set of assigned locations? How to route the drones at each truck stop?
- **Sequencing/Timing Decisions**: At what time should the truck start at each stop? At what time should the drones be launched/recovered at each truck stop?
- **Communication Decisions**: How to route UAVs within a communication range for a given operation? How to assign relay nodes for long distance communications?

The route plan must also account for vehicle-specific operational constraints (e.g., drone and EV travel range, truck capacity, communication range) as well as other temporal (e.g., time-of-day operating restrictions), spatial (e.g., geofenced areas), logistical (e.g., customer time windows) and network communication-related (e.g., obstacles such as trees and wind) constraints. Note that the EV truck-only routing and direct drone delivery problems are a subset of the hybrid truck-drone delivery system. For **EV-truck only routing**, all decisions except network communication are required for route planning. On the other hand, **direct drone delivery** with multiple UAVs encompasses assignment, sequencing, and communication decisions. Thus, we will develop a **modular solution approach** that accounts for all four decisions and can be adapted for the three types of delivery methods illustrated in **Fig. 5**.



a) Electric truck-only delivery *b) Direct drone delivery* *c) Hybrid truck-drone delivery*

Fig. 5: *Route planning capabilities of RoutePEARL*

Preliminary Work: PI Srinivas has developed optimization and approximation algorithms to obtain hybrid truck-drone route plans [22, 30, 31]. His research was among the first to optimize UAV launch/recovery locations [30], and consider assignment, routing, and sequencing decisions [22, 31]. Co-PI Calyam investigated techniques based on Kalman Filtering and machine learning models for trajectory optimization, which enable drones to follow intelligent paths and establish optimal trajectories [32]. We will extend this preliminary work by: (1) considering four key decisions, (2) incorporating real-world constraints gathered from NSF-supported customer discovery, and (3) developing a modular solution approach.

Task R1.1: Formulate optimization models. A mixed integer linear programming model (MILP) to establish a baseline for routing EV trucks and UAVs will be formulated to optimize the aforementioned key decisions. To accelerate the model's convergence, valid inequalities will be introduced and warm-start strategies will be explored. The valid inequalities will bound several decisions, such as the total travel time of vehicle $v \in \mathcal{V}$, feasible operations, communication range, and precedence relationships. A potential warm-start strategy is to leverage the spatial distribution of $\mathcal{L}$ locations to establish non-overlapping clusters, where the truck will serve the location closest to the cluster centroid, and the UAVs will be dispatched to the locations within that cluster. The clusters will be established using an *unsupervised machine learning* technique, such as k-means or density-based spatial clustering. The MILP model will be solved to obtain optimal solutions for small instances and to understand their properties. Subsequently, these insights will be used to develop approaches for solving large instances.

Deliverable: New modular MILP models for optimizing EV truck and UAV route plans. **Assessment**: Ability to get optimal plan in ≤ 5 minutes for instances with up to 15 nodes.

Task R1.2: Algorithms for large-scale EV and UAV route planning. To overcome the intractability of MILP models, we will develop **iterative heuristic algorithms** to solve large instances. The proposed approach is to decompose the problem into manageable subproblems and solve them sequentially to obtain a good solution. An overview of the planned approach is given in **Algorithm 1**, which aims to hybridize stochastic local search and optimization methods to solve large-scale instances. The planned approach is to use a neighborhood search to vary the solution to Subproblem 1 at each iteration. Besides traditional search operators (e.g., insertion, swapping), problem-specific intelligent operators will also be developed. To solve Subproblem 2, a rule-based heuristic approach will be developed to assign the remaining locations to the UAVs and determine their sortie plans. The plan is to develop heuristic rules that aim to reduce the truck wait time at each stop along its route. The complexity associated with Subproblem 3 is lower since the assignment and routing decisions are already fixed (by Subproblems 1 and 2), and therefore an exact method will be developed to solve it. To solve Subproblem 4, a direct network connection will be selected when feasible (typically for short UAV sorties). Otherwise, a multi-hop geographic packet forwarding approach will be used that involves a state-of-the-art information routing protocol that we have developed viz., SPIDER [33]. It also ensures sustained data throughput performance and learning-based delay-tolerant network routing protocol strategies, viz., LADTR [34]. The iterative search continues until a termination criterion is met (e.g., time limit, no improvement for X iterations).

Algorithm 1 Pseudocode for the Modular Route Planning Algorithm

Inputs: $\mathcal{R}, \mathcal{V}$, and $\mathcal{L}$, spatial parameters, temporal factors and cost data
Obtain a feasible initial solution using a constructive heuristic (s_0)
Initialize current solution ($s = s_0$) and current objective value ($f(s) = f(s_0)$)
Set best solution ($s^B = s$) and best objective value ($f(s^B) = f(s)$)
while termination criterion is not met **do**
    repeat
        Subproblem 1: Assign a subset of locations to trucks and determine the route plan
        Subproblem 2: Assign and route the UAVs and SADRs to the remaining locations
        Subproblem 3: Sequence the vehicles given their routes and stops
        Subproblem 4: Assign direct connections and multi-hop relay nodes
    until $\mathcal{N}$ feasible neighborhood solutions to s are obtained
    Compute $f(s'_n), \forall\, n \in \mathcal{N}$ and determine best neighborhood solution $f^*(s')$
    Decide whether to accept or reject $f^*(s')$ based on acceptance criterion
    if accepted **then** $s = s'$, $f(s) = f^*(s')$
    if $f(s)$ is better than $f(s^B)$ **then** $s^B = s$, $f(s^B) = f(s)$
return s^B and $f(s^B)$

Fig. 6: *Modular approach for route planning*

The solution approach will provide the customer with the flexibility to optimize different minimization objectives, namely, delivery completion time, operating cost, carbon emissions, or weighted sum of multiple criteria. Based on customer discovery insights, we will also integrate the objective of **minimizing operational risk** for route planning. The planned approach is to use geospatial data (i.e., integration of buildings, vegetation and street data) and weather forecast to locate potential hazards (e.g., buildings, powerlines, residential area and densely populated regions) and establish drone route plans to minimize operations overlap over such locations. This is an important criterion in practice for safe and non-intrusive drone operations, but, to the best of our knowledge, *none of the existing technologies* considers it during route planning.
Deliverable: New large-scale route planning algorithm. **Assessment**: Numerical experiments for validation and performance benchmarking (e.g., $\leq$1% optimality gap).

3.3. Objective R2: Approaches for Real-Time Route Management under Uncertainty.

The execution of planned routes may require real-time readjustments to handle unexpected events. For example, a UAV operational disruption (due to obstacle or component failures) makes it unusable for the remainder of the planned route. Also, a new service request can arrive dynamically and require re-routing. This objective aims to develop new approaches to efficiently handle such situations.

Preliminary Work: Our prior work on obstacle awareness [7, 35] considered network routing strategies involving smart devices with naive mobility models. Also, a trajectory prediction algorithm for drone swarm systems [36] was developed, where an MDP framework was used to generate dynamic decisions in a large-scale environment. We will extend these works to handle uncertainties such as new requests, communication blockage, and weather or traffic intrusion.

Task R2.1: Drone Trajectory Prediction (DTP) to Handle Uncertainties. A DTP algorithm will provide the relative future position for each UAV, which as a result could process decisions in advance for potential uncertainties (e.g., obstacles such as buildings, traffic congestion). As a result, the re-routing of UAVs can be handled quickly and efficiently. To this end, we will develop a DTP algorithm based on the theory of partially observable Markov decision process (POMDP) [37], defined by the following components - state space ($\mathcal{S}$), action set ($\mathcal{A}$), transition probabilities ($\mathcal{P}$), reward function ($\mathcal{R}$), observations ($\mathcal{O}$) and probability distribution function for observed states ($\mathcal{Z}$). $M_{traj} = (\mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \mathcal{O}, \mathcal{Z})$ where, the POMDP aims to maximize the cumulative rewards that are received by the drones along their trajectories during the operation. We expect the POMDP model to: i) detect deviation from the planned path ahead of time, and ii) predict the trajectory of the drone for the next T seconds. For a learning environment involving a drone and truck setup, the current state can be defined as $s_t = (P_{D_{(n)}}, P_{T_{(n)}}, \phi_t, E_{t_n}, F_{t_{(n)}}, L_{d_{(n)}})$ representing drone's position, truck's location, vehicle's heading, vehicle's total time capacity, truck's remaining range and delivery location, respectively. Then, we can provide different action choices for the drone. For example, a drone in operation can perform the following actions: $a_t \in A$, (i) $a_{(C)}$ - *'changing the 2D coordination T_k'*, (ii) $a_{(S)}$ - *'changing the speed'*, and (iii) a_H - *'changing the altitude'*. Moreover, the rewards r_t are defined as follows: $+\alpha$: flying or moving toward $L_{d_{(n)}}$; $-\alpha$: flying or moving away from $L_{d_{(n)}}$; $-\theta$: failed delivery (e.g., returns to the truck or emergency landing site). In general, such a PODMP problem can be solved using an off-policy actor-critic network that uses reinforcement learning algorithms such as Q-Learning or deep deterministic policy gradient (DDPG) algorithm [32, 38]. **Deliverable**: UAV trajectory prediction model for awareness and re-routing decisions. **Assessment**: Ability to achieve at least 90% accuracy for UAV trajectory prediction.

Task R2.2: Obstacle-aware Online Packet Forwarding under Uncertainty: When encountering obstacles, such as high winds, buildings, or trees, the stability of the UAV network connection can be affected. In such situations, it is vital to quickly re-establish network communication to ensure safe operations. To this end, we will design a policy-based algorithm that uses a stateless network routing protocol (to reduce the overhead of maintaining routing tables) to setup on-demand communication when requested. We will model the obstacle factors by considering a node n that forwards a packet p to a destination d to re-establish communication on air-to-air (A2A) links between drones, and air-to-ground (A2G) links between drones and truck/ground server. The node n has to decide which neighbor must receive packet p to progress toward d. Such a decision needs to also balance between the neighbor's residual energy and the total throughput of p, and should minimize $f(n, d, \theta) = \theta \cdot \tau(n, d) + (1 - \theta) \cdot \epsilon$ where, $\tau(n, d)$ is the normalized updated shortest path approximation time [39] with respect to obstacle blockage, ϵ is the average residual energy at node n, and $\theta \in [0, 1]$ is the balancing parameter. The goal is to find the best θ value that gives the minimum energy consumption from node n, and keeps the network connection continuous and stable by calculating the path. Once n is aware of its propagation Fresnel zone radius and the i^{th} obstacle's center C_i, it computes $\tau(n, d)$ as$\tau(n, d) = \sum_{i=1}^{M} \frac{O_i - 1/\sqrt[\delta]{\|n-d\|}}{\|n-C_i\|^{\delta}}$, where $\|\cdot\|$ represents the Euclidean distance, δ is the attenuation order of obstacles' potential field, M is the number of obstacles, and O_i is the intensity of i^{th} obstacle induced by the destination node d, calculated as:$O_i = \frac{F_i^{\delta}}{\delta(\|d-C_i\| + F_i)^2}$ where F_i represents the i^{th} Fresnel zone in 3D. We suppose that two nodes on A2A or A2G links can communicate if the blockage is up to 20% of the Fresnel zone [40]. Otherwise, communication is obstructed.

Deliverable: Online packet forwarding algorithm for data transmission with sustained throughput. **Assessment**: Ability to detect network partitions and re-establish multi-hop connections in real-time.

Task R2.3: Dynamic Rerouting Algorithm for EV Trucks and UAVs. Given a new event (i.e., new request, drone failure), it is necessary to establish a revised route plan quickly for the unserved locations. To efficiently tackle this computational challenge, we will explore the following approaches: (1) periodic reoptimization, where methods proposed in Task 1.2, will be adopted to solve the problem every time a new event occurs, and (2) use of heuristic search algorithms and rules that identify a new route plan. based on a pool of pre-processed feasible routes or new insertion schemes. These approaches would involve handling uncertainty by assigning a truck or UAV to the new request and updating the routes of all vehicles. Therefore, the route plan evolves from the arrival of a new event to the post-decision state (e.g., see **Fig. 7**).

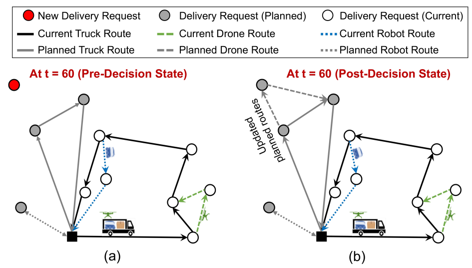


Fig. 7: *Illustration of dynamic re-routing*

Deliverable: New dynamic routing model for EVs and UAVs. **Assessment:** Ability to establish updated routes within 1 minute for at least 80% of uncertainties.

3.4. Objective R3: Validation using Testbed Experimentation and Pilot Study

To evaluate the proposed algorithms, we will: (i) perform field experimentation using the NSF-supported AERPAW [8] platform, which is a main facility to configure cloud-based drone experimentation testbeds, and (2) pilot test a minimum viable product (MVP) in collaboration with our industrial partner.

Preliminary Work: We will leverage testbed setups from our preliminary experiments and deploy field experiments for different drone and ground node configurations. **Fig. 8** shows an AERPAW exemplar experiment with a drone and ground server setup using a 4G/LTE signal. This field experiment involves the emulation of adapting a drone's flight path with various mobility models and using network measurements.

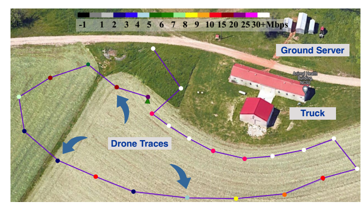


Fig. 8: *Field experiments at Test Site*

Task 3.1 Field Experiments. As shown in **Fig. 9**, we will configure AERPAW testbeds along with DroneNet-Sim (prior work of Co-PI Calyam [41]) to implement, test, and validate repeatable configurations developed in **Objectives R1** and **R2**. To support the experimental setup, edge devices with GPU resources (e.g., Nvidia Jetson Nano) in AERPAW will be used to analyze the operation guidance information as well as obtain updates of the delivery tasks. We will effectively leverage simulations using DroneNet-Sim to train our models and validate results. Specifically, our experiments will validate how routing at operational and network levels, and our environment-aware approach applied in hybrid truck-drone operation will benefit different application cases, and further help us obtain model-driven insights.

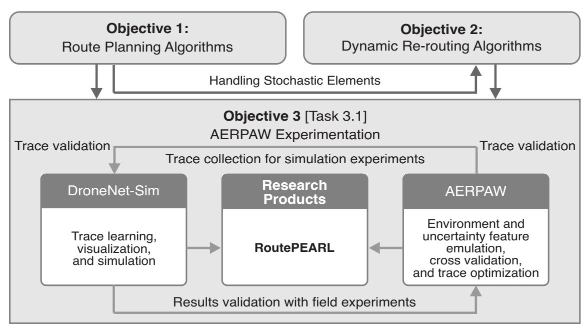


Fig. 9: *Field experimentation integration steps with RoutePEARL in AERPAW combined with simulation*

Deliverable: Validation of proposed models using realistic testbed experiments. **Assessment**: Ability to execute planned routes and information exchange successfully, and reroute in the presence of uncertainty.

Task 3.2: Pilot Testing a Minimum Viable Product (MVP). Upon successful testbed experimentation (Task 3.1), we will develop a MVP (i.e., a functional RoutePEARL platform with essential core features). The investigators have experience developing interactive software platforms in prior sponsored projects [42, 43], and will use this knowledge to develop the pilot application. For agile development and cloud integration of the RoutePEARL MVP, we will use DevOps tools, such as the Apache Maven [44] build management tool and Jenkins [45], to manage dependencies and versions, compile source code, run tests, package code into deployment-ready file formats, and deploy a final production code instance using Docker containers [46]. The user interface design will be developed using QGroundControl [47]. The route management algorithms will be coded in Python and solved using cloud/edge GPU platforms for faster computing, e.g., NVidia Jetson Series devices, AWS-hosted Kubernetes clusters, and MU's Lewis cluster (see **Facilities, Equipment & Other Resources**). The routes generated by the MVP will be evaluated by the industrial partners based on the following criteria: (1) operational risk (i.e., does the plan avoid no-fly zones and reduce flying over hazardous areas?), (2) efficiency (i.e., does the route provide value in terms of key measures such as cost and time?), and (3) appropriateness of the relay nodes assigned for network communication? To test real-time adjustment of planned routes and network communication, the project team will work with Workhorse to pilot EV truck and UAV operations for various route plans under different environmental conditions (e.g., weather, geography, congestion). The project team will solicit feedback on platform usability and route management capabilities at various stages and address potential issues at each iteration. The timeline of the proposed research activities is presented in **Fig. 10**.

Deliverable: Validation of MVP performance and usability. **Assessment**: Ability to achieve $\geq$ 25% efficiency improvement over current practice and $\geq$ 95% communication availability.

Objectives	Responsible	Milestone	Year 1				Year 2	
			Q1	Q2	Q3	Q4	Q1	Q2
Objective 1: Modular Route Optimization Approach for EV Trucks and Drone								
Task 1.1: Create Optimization Models Routing Vehicles	PI Srinivas and Co-PI Rjendran co-lead, Co-PI Calyam assists, WH validates route plans	Ability to get optmal routes in less than 5 minutes for 15 nodes						
Task 1.2: Develop Efficient Methods for Large Scale Problem		Numerical experiments for validation and get optimality gap less than 1%						
Objective 2: Approaches for Real-Time Route Management Under Uncertainty								
Task 2.1: Develop Trajectory Prediction Models	Co-PI Calyam leads, PI Srinivas and Co-PI Rajendran assists, SD provides data, TS evaluate communication protocols	Ability to achieve >90% accuracy for UAV trajectory prediction						
Task 2.2: Create Obstacle-Aware Stochastic Models		Ability to re-establish network communication in real time						
Task 2.3: Develop dynamic re-routing algorithm	PI Srinivas leads, Co-PI Calyam assists, WH validates solution	Ability to re-route within 1 minute for 80% of uncertainty occurences						
Objective 3: Validation using Testbed Experimentation and Pilot Study								
Task 3.1: Experimentation using AERPAW	Co-PI Calyam leads, Co-PIs assist, TS assists with experimental scenarios	Ability to execute planned route and re-route in presence of uncertainty						
Task 3.2: Pilot Testing of Minimum Viable Product	PI and Co-PIs lead, WH facilitates pilot test, TS assists with interface design	>25% improvement over current practice and >95% communication availability						

Fig. 10: *Project timeline and milestones*

3.5. Potential Risks and Mitigation Strategies

The potential risks in this plan are uncertainty related to market growth and regulatory restrictions on autonomous technologies. For instance, modeling the routing operations involves assumptions on the capabilities of drones (e.g., autonomous sensing systems, traffic laws). To mitigate these risks, we will evaluate the operational efficiency of the hybrid delivery system for numerous scenarios to avoid overly optimistic results, and develop a modular solution framework to allow easy incorporation of changes to the problem characteristics. Another potential risk includes uncertainty related to the fast-paced evolution of network connectivity and data transmission technologies. For example, the state-of-the-art communication protocol, QUIC [4], is still under active development, although it is expected to be a main baseline in the future. To mitigate such risks, we will utilize the most recent radio, network, and communication technologies and explore the potential of applying a generic framework featuring a catalog of communication protocols that can be adapted to the problem characteristics related to a given application context.

4. Achieving Societal Impact through the Realization of Commercial Potential

4.1. Societal Impact

The efficient utilization of vehicle fleet and optimized routes is crucial to achieve a faster, cheaper, and sustainable last-mile distribution. RoutePEARL will achieve these pivotal requirements and enable last-mile service providers to fully reap the benefits of using EVs and UAVs. The coordinated truck-drone route plans generated by the proposed technology allow easy access to difficult to reach geographical locations, improve driver productivity, reduce deadhead miles, energy consumption, and carbon emissions.

RoutePEARL also has other practical applications and societal impacts. It can: (1) generate optimized EV and UAV route plan for post-disaster humanitarian relief distribution (e.g., hygiene kits and food to affected areas) in a safe and timely manner, (2) enable efficient planning of the transport of essential medical supplies, and (3) help in public safety by generating patrol routes for police vans and drone mission plans to relay videos of affected regions (e.g., fire accidents) to first responders.

4.2. Commercialization Strategy

Commercialization Potential: The opportunity for the commercialization of RoutePEARL is substantial. The global volume of parcels shipped was over 130 billion in 2020 and is projected to double in the next 5 years [48], thereby creating a critical need to transform the traditional way of delivering goods. According to a survey of 200 logistics providers in North America and Europe, 36% of the companies plan to invest in emerging technologies (such as electric trucks) within the next 6-12 months, and 90% of the companies will implement automated routing software within 2 years [49]. Our innovative technology platform will meet the needs of this emerging market and empower service providers.

Commercialization Strategy: Our strategy is to offer RoutePEARL as a cloud-based application by adopting the software-as-a-service (SaaS) distribution model with a subscription pricing model. A cloud-based RoutePEARL platform will provide better flexibility and functionality to route planners (e.g., logistics managers) because they can use any device (computer, mobile phones, tablets) to quickly generate route plans. We plan to provide three main subscription plans: **Basic (freemium)** plan allows route planning for up to 10 stops every day. The **standard version** will include EV and UAV route planning with up to 100 stops. It will also enable the user to input driver schedules, customer availability, package pickup, and optimization criteria (time, cost, carbon emission). In addition to these features, the **premium version** will include dynamic re-routing capabilities, planning with up to 500 stops, analytics capabilities, and a dispatcher web application. We expect to charge $30/vehicle/month and $50/vehicle/month for standard and premium versions, respectively, as it will be competitive with existing platforms.

Marketing Plan and Sales Strategy: Through our NSF-supported customer discovery activities, we understood that logistics service providers learn about new technology platforms through trade shows, word of mouth, direct marketing, and online search. We will use these insights to prioritize our marketing efforts. We will demonstrate and market RoutePEARL at trade shows such as the Last Mile Delivery Conference and Final Mile Forum and Expo. We will also leverage our industrial partners, CELDi connections, and MCTI network to market the platform. We plan to do door-to-door marketing since it allows the team to demonstrate the platform and address customer questions. We will also offer a 1-year free premium subscription to influencers (e.g., logistic managers in e-commerce, healthcare and humanitarian sectors). Finally, we will advertise online via Google's search and display campaign to secure sales leads. The **sales strategy** involves: (1) Direct B2B Sales where a team with expertise in sales and last-mile market will promote it to logistics service providers, follow-up on leads and convert it into platform subscription, (2) Online Sales where a website highlighting RoutePEARL's value proposition and features will be used to acquire new customers, and (3) Channel sales where the team will partner with EV and UAV manufacturers and offer RoutePEARL to their customers at a subsidized cost for the first year.

Financing Plan: Using the PFI-TT funding, we will develop RoutePEARL's MVP and beta test the product with multiple partners. We then plan to seek SBIR/STTR funding to update and scale the platform. Subsequently, we will seek private capital to increase the customer base and grow the company.

4.3. New Patents

This project is the first to propose the integration of operational and network communication layers for the planning of a hybrid truck-drone system, and we believe that the development of new functionality and processes to be patentable. Our innovations are expected to focus on the following ideas: (1) a routing component that generates an optimized route for the truck-drone system while ensuring reliable information exchange between drone and truck throughout the delivery process, (2) a data processing system that generates routes by considering collision-avoiding sequences for multiple drone operations, and (3) a processor that controls the actions of a drone and EV truck in real-time. The PI and Co-PIs will closely work with Senior Personnel Maland (Technology Transfer Officer) to patent and protect the proposed platform.

4.4. Assessment

The success of our strategy will be assessed based on the following outcomes: (1) File $\geq$2 new patents to protect the proposed innovation, (2) Direct Marketing to $\geq$100 customers, (3) Secure 20+ clients within 6 months of establishing RoutePEARL, and (4) Provide 100 free premium subscriptions to influencers.

5. Project Team

The project team is multidisciplinary and includes the following members.

- **Dr. Sharan Srinivas (PI)** conceptualized the RoutePEARL platform. He has over 10 years of academic and industry experience, and has successfully completed several translational projects [50–54]. He has led several industry-sponsored projects, and solved many complex, large-scale problems in the service industry (logistics, finance) using innovative approaches involving optimization models, decomposition techniques, and approximation algorithms, as substantiated by his publication record [55–62]. He has authored over 75 journal articles and conference presentations. His work on optimizing last-mile logistics using truck and drones serves as a foundation for this project [22, 31, 56].
- **Dr. Prasad Caylam (Co-PI)** is an expert in cloud computing and system/network performance monitoring [63–69]. He has published over 195 peer-reviewed papers, commercialized his research as "Narada Metrics" through multiple DOE SBIR/STTR funded projects, and has led several NSF-funded efforts on testbed research infrastructures involving NSF Cloud platforms relating to application domains such as public safety, neural engineering, and special education. He has developed novel approaches for cross-validation between drone-network simulation results at large scale with his DroneNet-Sim [41], coupled with field experiments using testbed resources at NSF-supported AERPAW [8]. Also, his expertise in developing network protocols for systems will be leveraged for the success of the proposed project activities.
- **Dr. Suchithra Rajendran (Co-PI)** has expertise in optimization, data analytics, simulation modeling, and pilot testing of software applications. She has over 5 years of experience working in the logistics sector and has developed, piloted, and successfully implemented optimization-based decision support tools for several companies (e.g., Case New Holland, Chennai Port Trust). She has also served as an investigator on various industry projects, and published more than 40 peer-reviewed articles (15 journal publications pertaining to emerging transportation/logistics network design and operations).
- **Mr. Brett Maland (Senior Personnel)** is a technology transfer expert and patent attorney at MU and has his own private law practice. He has worked with many startups, including software companies. His previous work in the industry and extensive experience in translating technologies to market, combined with the many industry connections, will be invaluable for transferring the proposed technology.
- **GRA Qualification:** One of PI's GRA, Arash Alizadeh, is a Ph.D. student and has experience developing algorithms for route optimization. He was the *Entrepreneurial Lead* for the NSF I-Corps Teams program and will be the GRA for this PFI-TT project. He has extensive industry experience as a logistics consultant, and has published over 10 peer-reviewed journal articles. **Selection of Additional GRA and UGRAs:** We will recruit an additional GRA and two undergraduate research assistants (UGRA). The ***selection process*** involves resume screening, review of recommendation letters, and interviews.

Team Member's Role and Collaboration Plan: The MU team is well suited to achieve the project goals for the following reasons: (1) complementary experience and expertise of the team members, (2) promising preliminary works and prior synergistic collaborations among investigators, (3) better understanding of customer pains and gains through participation in the NSF I-Corps Teams program, and (4) prior translational research experience and successful industry collaboration. The PI and Co-PIs will work with the student assistants to develop and validate the models proposed in the research plan. Senior Personnel Maland will assist with IP protection, patenting of the proposed innovation, and training students on technology transfer. The industrial partners will provide entrepreneurship expertise to establish a robust commercialization, marketing and sales pathway for RoutePEARL and will also train the students.

6. Partnerships

The MU team will partner with the following three companies to accelerate RoutePEARL technology toward commercialization and train next-generation entrepreneurs (see **Letters of Support**).

- **Workhorse (WH)**, established in 2007, is an original equipment manufacturer of EV trucks and UAVs and telematics software developer for last-mile delivery. It is **one of the first companies** in the US to perform hybrid electric truck-drone deliveries using their Horsefly drones (4-rotor custom-built autonomous UAV that meets FAA guidelines) and C1000 EV truck (equipped with a control center and auto-landing drone platform). They have also partnered with UPS to pilot the hybrid truck-drone system in US cities.
- **Transparent Sky, LLC (TS)** is a technology company that develops sensors and software applications for UAV-based aerial imaging and surveillance. TS has expertise in conducting multiple drone operations for military and commercial use. They also have the resources to facilitate rapid prototyping and testing of advanced network communication technologies.
- **Skylark Drones (SD)**, founded in 2015, is a technology company that empowers other enterprises with drone analytics and execution of drone operations. Their software platform allows users to plan and execute drone missions, and their customers include several Fortune 500 companies.

The MU team will lead the development of the RoutePEARL platform. WH, TS and SD will facilitate business leadership by providing the necessary resources to validate the technology and develop an MVP. WH will guide in defining key features (e.g., customer requirements, real-life constraints), validating generated route plans, and piloting MVP. Besides, WH is interested in subscribing to the RoutePEARL platform and will also promote it to early adopters. TS will assist the project team with various tasks, including but not limited to assessing the communication reliability of planned paths and software usability. SD will provide data from their 100,000+ drone missions, technical expertise on developing a planning software platform, and assessing market potential outside the US. The project team will work closely with WH, TS and SD to validate the proposed technology and develop an MVP through an iterative process. The industrial partners will also contribute to educational goals by advising students on the technology validation process and helping them address critical questions about RoutePEARL commercialization. The **success of the partnership** will be assessed based on the completion of following activities: (1) three site visits for student learning, (2) inputs for inclusion of at least three new critical features, (3) development of RoutePEARL's MVP, and (4) securing ≥ 2 companies who are interested in being early adopters.

7. Training Future Leaders in Innovation and Entrepreneurship

The **entrepreneurship education goal** of this project is to engender next-generation of entrepreneurs who will have the necessary principles and practices to innovate and lead. The following four learning tasks are planned to achieve the education goal and enhance the knowledge as well as the readiness of the student researchers for innovation and technology commercialization beyond the usual research experience.

Task L1: Fostering Entrepreneurship through Existing Courses: We will integrate entrepreneurship into at least two courses (IMSE 4410/7410 Predictive Modeling and CMP_SC 4530/7530 Cloud Computing) through the following activities: (1) Relate techniques taught in the course to core technology for existing businesses, (2) Integrating outcomes of **Objectives 1 and 2** to illustrate the idea of commercializing applied research, and (3) Introducing the business model canvas with illustrative examples.
Expected Outcomes: (1) Foster entrepreneurial mindset in students, (2) Pursue entrepreneurship minor.
Assessment: Performance on assignments, and survey evaluating entrepreneurship interest.

Task L2: Participation in Entrepreneurship Alliance (EA) Program. The PFI students will participate in the EA Program offered by the Center for Entrepreneurship and Innovation (CEI) at MU (see **Letter of Collaboration**). It is an intensive 8-week program that trains students in various business aspects such as financial models, legal structure, MVP development, and marketing. The program will provide opportunities to network with founders, receive funding, and engage with the local entrepreneurship community. **Expected Outcomes:** (1) Understanding entrepreneurial process, (2) EA alumni network access, (3) MVP development. **Assessment:** EA program completion and instructor feedback.

Task L3: Product Discovery Training. The PFI students will visit WH and TS to learn how they refine ideas and technology to meet user needs. Students will then identify potentially critical and desirable features for RoutePEARL through these interactions. The MU team will advise students during this process. **Expected Outcomes:** (1) Understanding route planning challenges, (2) Conception of new product features. **Assessment:** (1) ≥ 3 site visits, (2) Quality of feature recommendations.

Task L4: Practical Leadership Training and Mentorship. We will leverage MU CELDi's industry connections to identify mentors with expertise in innovation, leadership, and technology transfer. They will mentor and train students to become next-generation entrepreneurs. Also, qualified students involved in this PFI-TT project will receive summer internship opportunities through industry partners to gain hands-on experience in technology and innovation (see **Letters of Support**).
Expected Outcomes: (1) Leadership skills, (2) Experience in creating proprietary technology. **Assessment:** (1) Pre/post-surveys to evaluate skills acquired, (2) Mentor's evaluation of student performance.

8. Broadening Participation

The project team will leverage the resources at MU to recruit underrepresented minorities (URM) and students with disabilities (SWD). The team will work with the MU Women in Engineering (WIE) group, National Society of Black Engineers, Disability Center, and Inclusivity Center to encourage the participation of URMs and SWDs. The prospect of receiving training in a multidisciplinary approach (theory and methods pertaining to operations research, computer science, and aerospace engineering) to address emerging global supply chain issues is a unique advantage of this project and, therefore, will attract students from different backgrounds. The PI and Co-PIs have involved and trained a total of 76 graduate and 85 undergraduate students (including 36 women, 11 African Americans, 5 Hispanic, and 4 SWDs) in prior research projects. Building upon the project team's established URM mentoring record, we will work with the Undergraduate Research Mentorship Program (URMP), STRIVE Program (for employment readiness of SWDs), and McNair Scholar programs at MU to organize outreach talks that disseminate project outcomes, excite URM and SWD students, and also recruit them in this project. We will also collaborate with the REU Site on Consumer Networking Technologies at MU (active program for over 15 years; 52 URMs have been trained), which is led by Co-PI Calyam, to engage URMs on the topic of network-aware route optimization using EV trucks and drones. The project team will leverage REU and other partnerships to educate, and prepare women and URMs to pursue careers in science innovation.

9. Broader Impacts

The Broader Impacts of this proposed PFI project are detailed in prior sections of the Project Description.

10. Results from Prior NSF Support

PI Srinivas is supported by "*I-Corps: A Scalable Cloud-based Route Optimization Software for Efficient Aerial and Road Logistics*", (TIP-2240977, \$50,000, 9/22 – 8/23). **Intellectual Merit:** Resulted in understanding the technical challenges and unmet needs of last-mile logistics sector through 110+ customer-discovery interviews. ***Broader Impacts:*** Led to identification of the market potential and societal benefits of EV truck and UAV routing. Graduate student training on entrepreneurship and customer-discovery.
Co-PI Calyam has been supported by "*US Ignite: Resilient Virtual Path Management for Scalable Data-intensive Computing at Network-Edges*", (CNS-1647182, \$750,053, 1/17 – 12/19). ***Intellectual Merit:*** Resulted in 5 journal and 6 conference papers addressing issues of mobile edge computing and networking for video analytics applications [7, 64, 65, 70–77]. ***Broader Impacts:*** Open-source software and datasets have been disseminated via Github. 7 graduate, including 2 female students, have been trained.