Drones, Delivery Robots, Driverless Cars, and Intelligent Curbs for Increasing Energy Productivity of First/Last Mile Goods Movement

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Carnegie Mellon University
Civil & Environmental Engineering

Overview

Overall Goal:
- Demonstrate an improvement of at least 20% in energy productivity of goods delivery using drones, ground delivery robots and automated vehicles, compared to a baseline network

Timeline:
- Start: Jan 1, 2019
- End: Dec 31, 2021
- 40% complete

Budget:
- Total: $1,878,290
- DOE share: $1,502,632
- Cost share: $375,658
- Budget Period 1: $721,726
- Budget Period 2: $585,203
- Budget Period 3: $571,361

Barriers addressed:
- Vehicle energy use data is uncertain because of very limited empirical data exists for drones and delivery robots
- System-wide impacts of drones, delivery robots and driverless vehicles uncertain due to lack of holistic systems models
- Mobility energy productivity improvement uncertain with automated air and ground vehicles and intelligently managed curbspaces

Partners:
- **Lead**: Carnegie Mellon University (CMU)
- Pittsburgh Region Clean Cities (PRCC)
- Amazon
- The City of Pittsburgh

Project Objectives

Objectives

- Use empirical testing, life cycle assessment, and systems analysis to research and demonstrate an improvement of at least 20%, compared to a baseline network, in energy productivity of goods delivery using drones, ground delivery robots and automated vehicles.
- Develop proof-of-concept testing, a model, and simulation for a smart curb space as an intelligently-managed urban delivery zone, with a goal of demonstrating at least an additional 10% improvement in energy productivity (BP 3).

VTO TI goals

- National Security: improve fuel diversity and alternative fuel use
- Economic growth: enable new modes of goods delivery and new business models
- Affordability for business and consumers: reduce delivery costs and times for consumers and businesses
- Reliability/resiliency: provide methods for contactless automated deliveries during pandemics, disasters, and disruptions

Impacts

- Generation of novel, open data set of high resolution energy use from package delivery drones and delivery robots generated from empirical testing in the field can inform DOE's other modeling efforts and technical targets
- Provide an understanding of the system-wide energy use implications of drones, delivery robots, and driverless delivery vehicles to inform policies, benefits assessment, and technology development
- Provide an understanding of the energy benefits of intelligently-managed curbspaces in an urban delivery zone to inform policies, benefits assessment, and technology integration

Project Approach: Budget Period 1

- **Hypothesis:** both an urban flight environment and on-board autonomous capabilities affect the energy use of delivery drones across a range of vehicle types and payloads, and this needs to be considered and optimized.

- **Hypothesis:** ground delivery robots will navigate urban conditions with collision avoidance sensing, computer vision, and on-board autonomous software—changing transport patterns and energy requirements. Energy use per package delivered increases non-linearly as a function of payload and additional people and obstacles these vehicles have to navigate on urban sidewalks. Thus, there is a tradeoff between vehicle size, payload mass, battery size, delivery range, and energy use, all of which affect energy productivity estimates.

- **Hypothesis:** wind speed and direction can affect the energy use and optimal routing of delivery drones, but little data exist about wind speeds and drone energy use.

Project Approach: Budget Period 1

- **Task – Design an experimental protocol for air and ground drone testing**: The team has designed and executed an experimental protocol to empirically measure the energy use of drones of various designs and sizes, carrying a range of payloads through various campaigns and altitudes.
- **Task – Empirically measure the energy use of air and ground drones:** Measure the energy use of air and ground drones of various designs and sizes, carrying a range of payloads through various campaigns, with and without autonomous capabilities
- **Task – Construct a model of drone and vehicle efficiency and simulate energy use of a range of driverless delivery vehicles:** Simulate energy use of a range of driverless delivery vehicles, carrying a range of payloads through various campaigns, with and without autonomous capabilities.
- **Task – Collect traffic and delivery data for test site:** Collect existing traffic data and validate existing commercial vehicles arrivals data at test site data using sensors, cameras, and existing data sets, and initiate network model development.

Project Approach: Budget Period 2

- **<u>Hypothesis:</u>** drones, delivery robots, and driverless delivery vehicles can improve energy productivity of delivery in a region by 20%

- **Task – Develop a goods delivery network model to simulate and optimize energy productivity of goods delivery using the data collected**
- **Task – Develop a standardized life cycle inventory of materials and components for the range of vehicles**
- **Task – Revised campaign to empirically measure the energy use of air and ground drones**
- **Task – Test and simulate improvements to drone energy productivity with automating scheduling and optimized routing, including maximizing tailwinds and minimizing headwinds**

Project Approach: Budget Period 3

- **Hypothesis:** when coupled with an intelligent curbspace, drones, delivery robots, and driverless delivery vehicles can improve energy productivity of delivery in a region by an additional 10%

- **Task – Develop simulation for intelligent curbspace as a managed urban delivery zone for Pittsburgh test site**
- **Task – Empirically test and simulate potential energy productivity of intelligent curbspace for existing and potential vehicles at test site**
- **Task – Implement commercialization plan and identify potential customer testbeds**
- **Task – Publish findings, release all datasets, and disseminate the research**

Project Approach

- Overall contributions
  - Publicly available real-world data on drone and driverless delivery robot energy use is extremely limited, and the team generated novel vehicle energy use data for use across DOE and its partners
  - Unique blend of empirical testing and modeling and simulation of emerging transportation technologies can inform technology integration, benefits assessment, and R&D planning across DOE

Milestones Budget Period 1

Milestone	Type	Description	Status
Design an experimental protocol	Technical	Design of experimental protocol complete	Complete
Conduct flight and mobility tests	Technical	Flight and mobility tests of air and ground drones complete	Complete
Develop simulation architecture and energy modeling for driverless vehicles	Technical	Simulation architecture and energy modeling complete	Complete
Collect traffic and delivery data for test site and network model plan complete	Technical	Data collection complete	Complete
Empirical Measurements acceptable	Go/No Go	90% of empirical measurements are within theoretical limits and expected values	Complete

Milestones Budget Period 2

Milestone	Type	Description	Status
Build model of existing energy productivity of goods delivery for Pittsburgh test site	Technical	Model of existing energy productivity of goods delivery for Pittsburgh test site complete.	In-Progress
Standardized life cycle inventory of materials and components for the range of vehicles examined.	Technical	Inventory complete and results compared to GREET model.	In-Progress
Develop an energy productivity model that incorporates automated scheduling and optimized routing with combinations of vehicles	Technical	Estimation of range of drone energy productivity improvements with automated scheduling and routing and vehicle combinations complete.	In-Progress
Investigate other sites for replication and analysis	Technical	Estimation of energy productivity improvements for drone package delivery in one other location with wind maximization algorithms complete.	In-Progress
Energy improvement verification	Go/No Go	Verify an improvement in energy productivity of approximately 20 percent	In-Progress

Milestones Budget Period 3

Milestone	Type	Description
Develop simulation for smart curbspace as a managed urban delivery zone for Pittsburgh test site	Technical	Model of smart curbspace developed for Pittsburgh test site complete.
Empirically test vehicles and evaluate energy productivity with a smart curbspace concept	Technical	Testing and reporting of energy productivity results complete.
Simulate optimized scheduling, routing, and urban ground delivery network configuration on energy productivity	Technical	Energy productivity improvement of optimized vehicle network is complete.
Implement commercialization plan	Technical	Commercialization plan implementation complete.

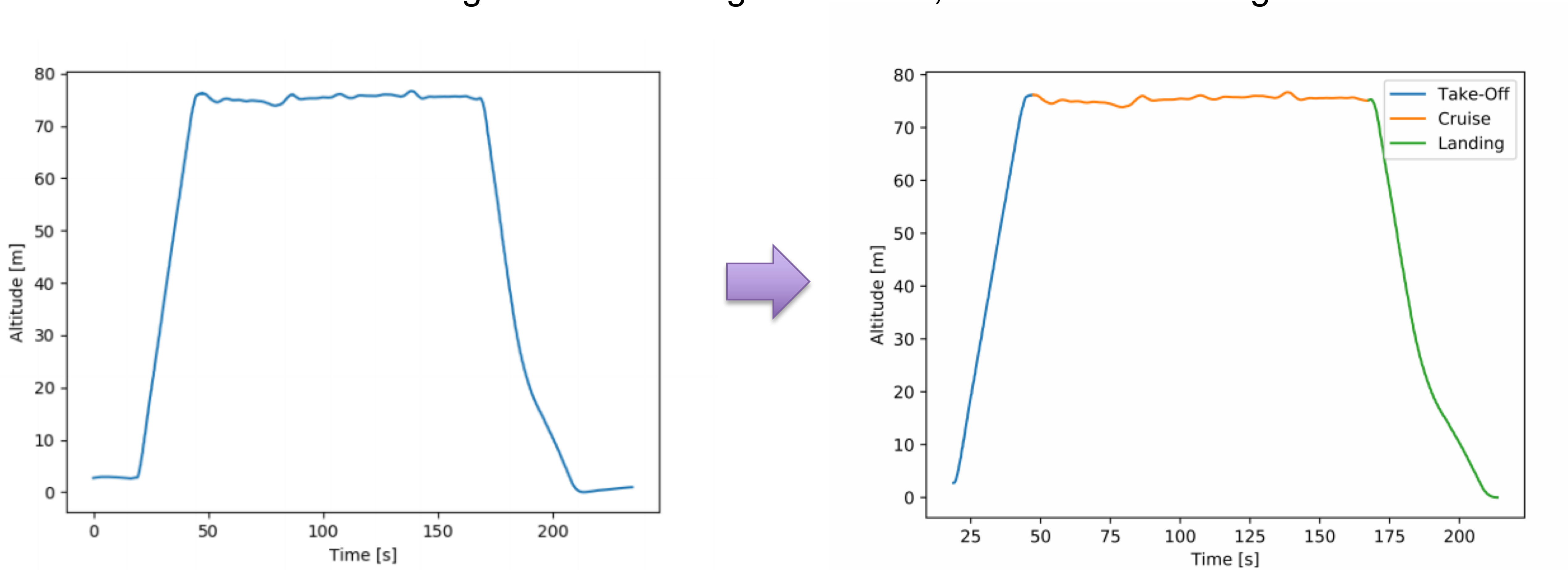
Project Accomplishments and Progress

- The team recorded testing environment conditions of wind speed, temperature, and other factors, and on-board sensors recorded voltage and current, GPS location, speed, wind speed, and drone movement characteristics for each flight. This enabled the team to estimate the energy used for each flight at a high resolution.
- The team has designed and executed an experimental protocol to empirically measure the energy use of ground delivery robots carrying a range of payloads through various campaigns
- The team also estimated the theoretical propulsion energy use of an electric, rubber-tired delivery vehicles of various masses and assessed the energy tradeoffs between vehicle, battery, and payload mass across a range of existing and potential battery specific energy values.

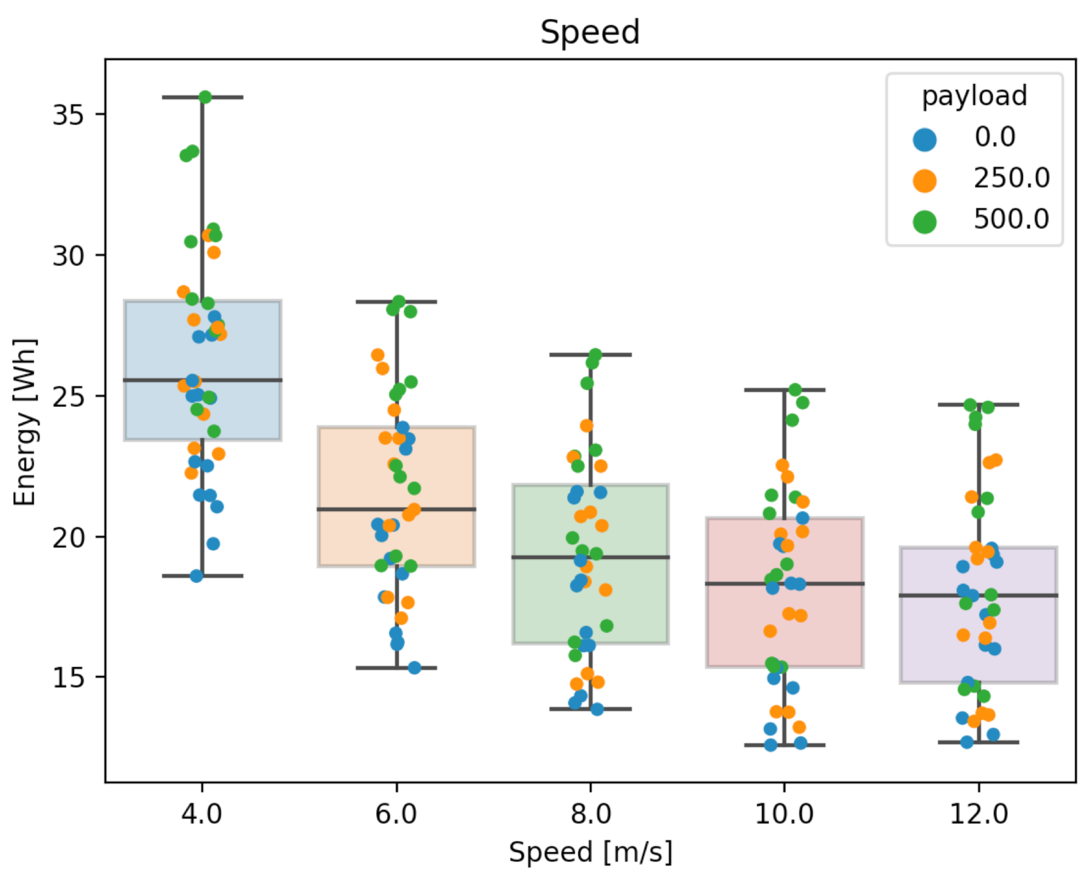
Project Accomplishments: More Than 200 Package Drone Test Flights Completed

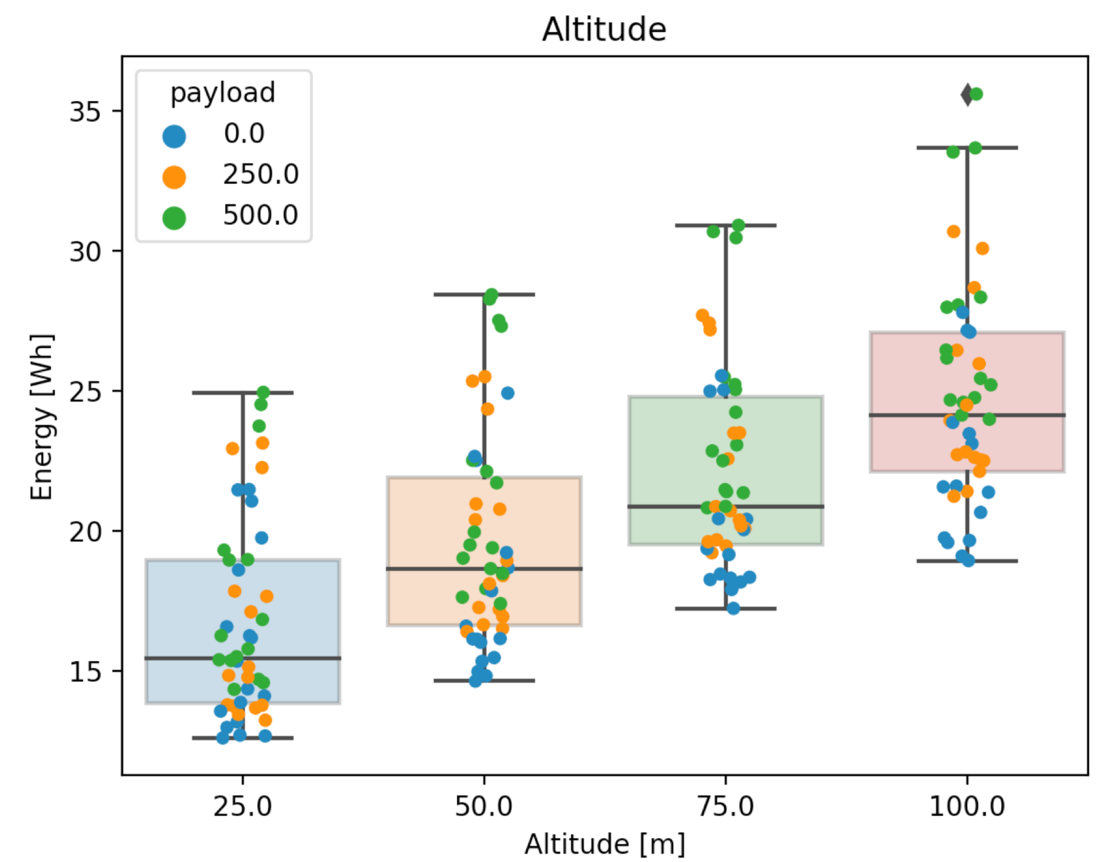
Project Accomplishments: Machine Learning Algorithm Developed to Classify Flight Regimes

Algorithm created to divide the regimes of each flight: Take Off, Cruise and Landing.



Project Accomplishments: Package Drone Energy Use Measured Across Altitude, Payload, Speed





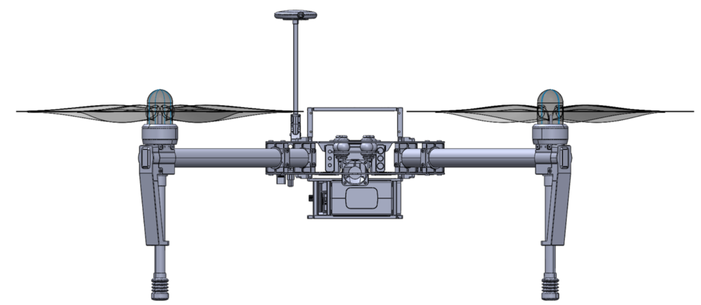
Higher altitudes during cruise and heavier payloads increase total energy consumption for a fixed route.

Higher cruise speed values reduce total energy consumption for a fixed route → Reduced time in air.

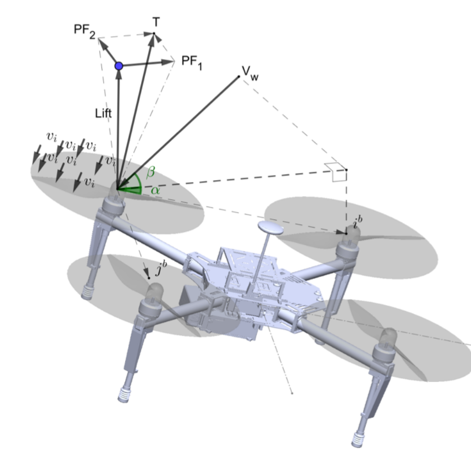
Project Accomplishments: Two Novel Energy Models Developed For Package Delivery Drones

Model 1: Energy estimation based on the induced power at a hover-no-wind condition

$$E = \sum (b_1 P_i + b_0) t$$



Model 2: Energy estimation based on sum of four different forms of power consumption

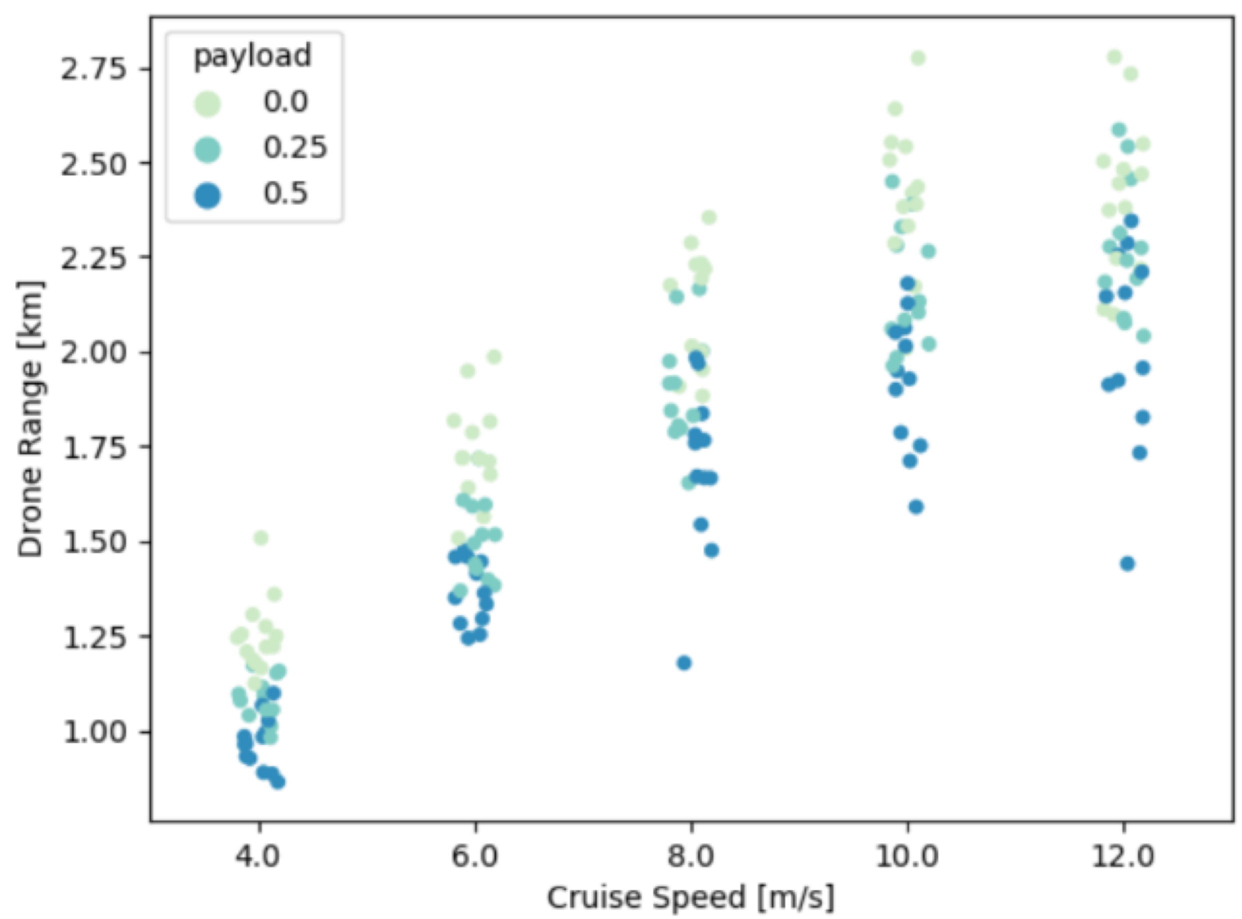


$$E = P\ t$$

$$P = \sum (P_i + P_p + P_d + P_a)$$

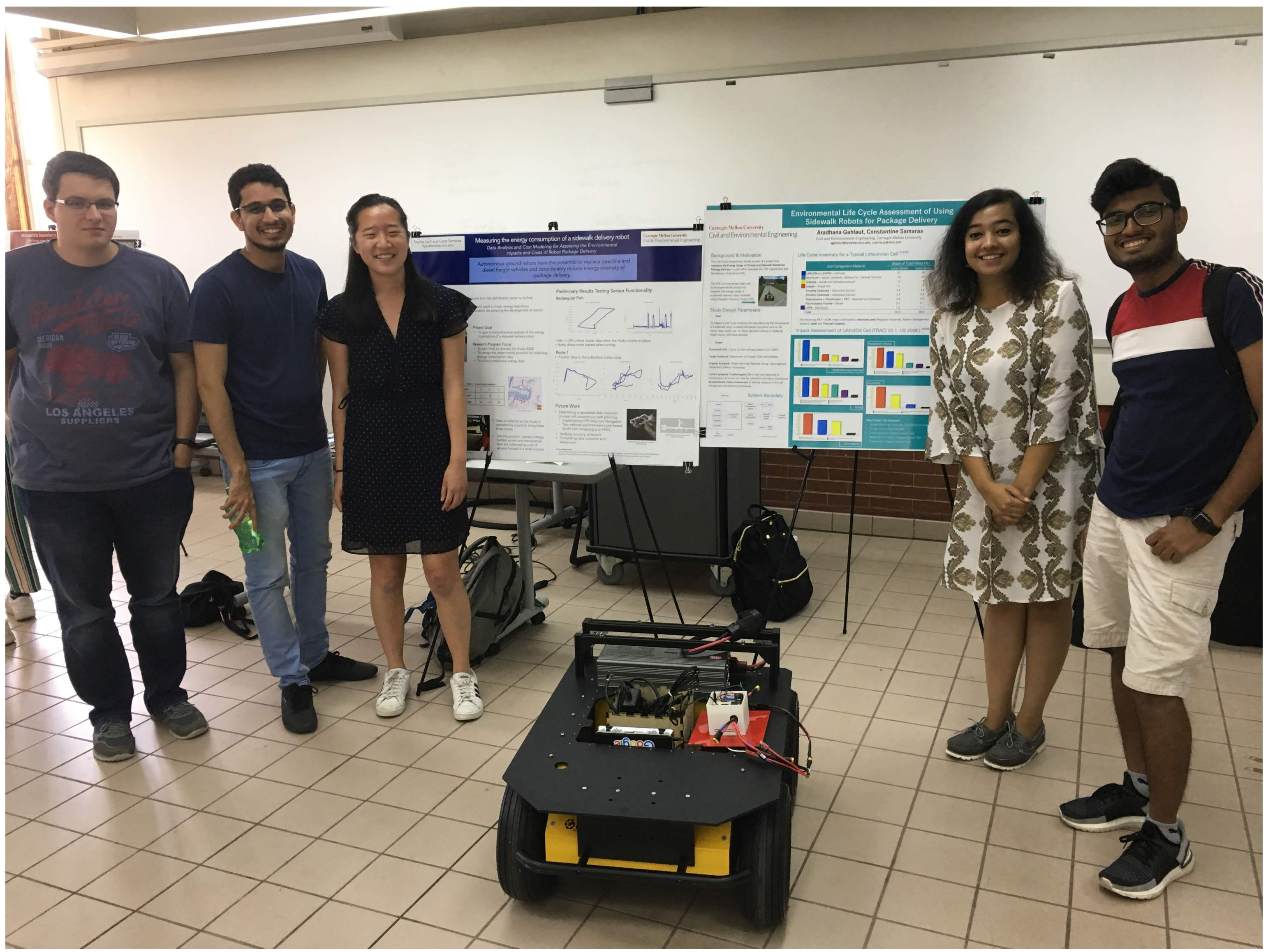
$$P = \sum (B_1 + c_1 B_2 + c_2 B_3 + c_3 B4 + c_4 B_5 + c_5 B_6 + c_6)$$

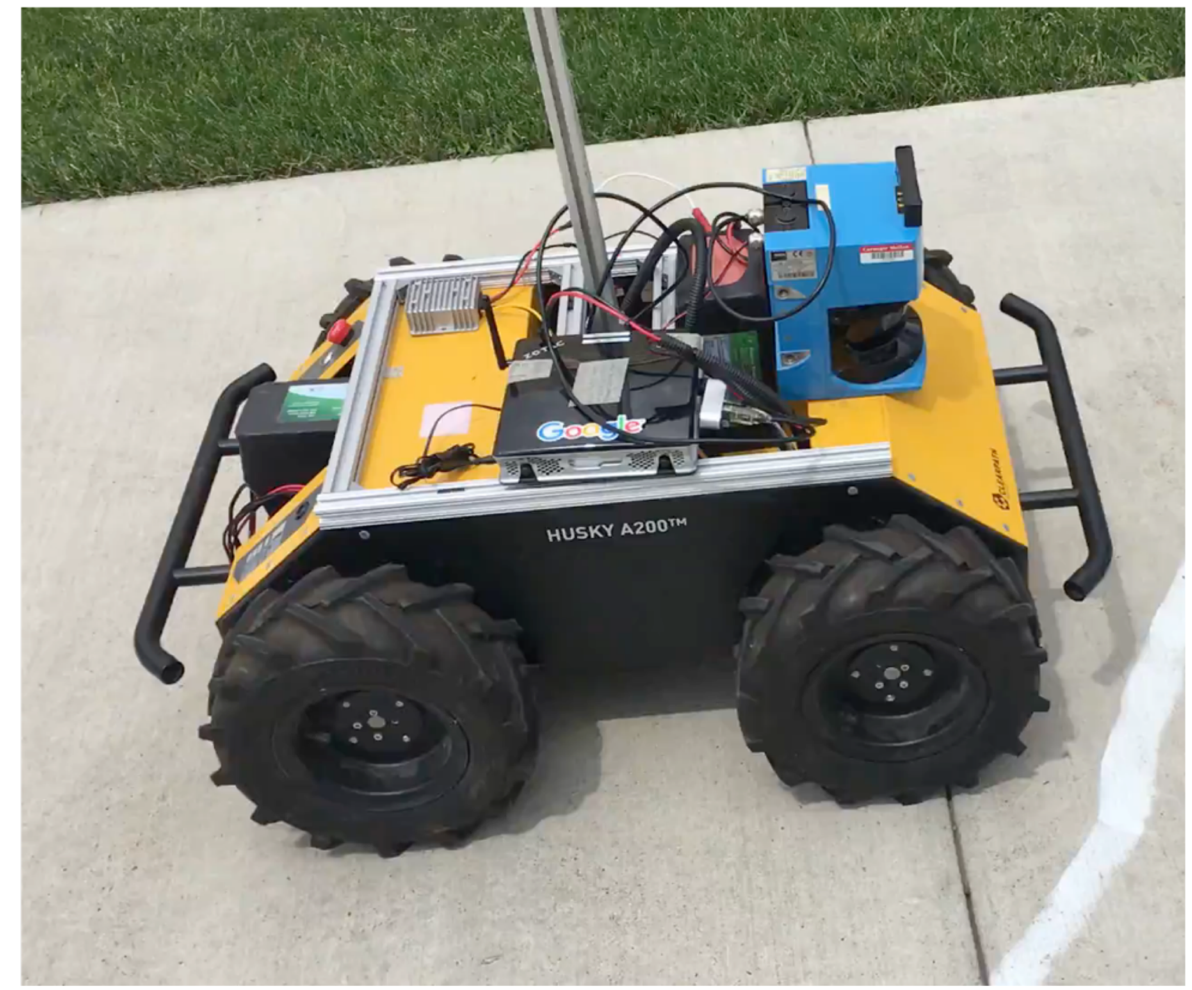
Project Accomplishments: Optimum Package Drone Energy Use Estimated as 0.16 MJ/km



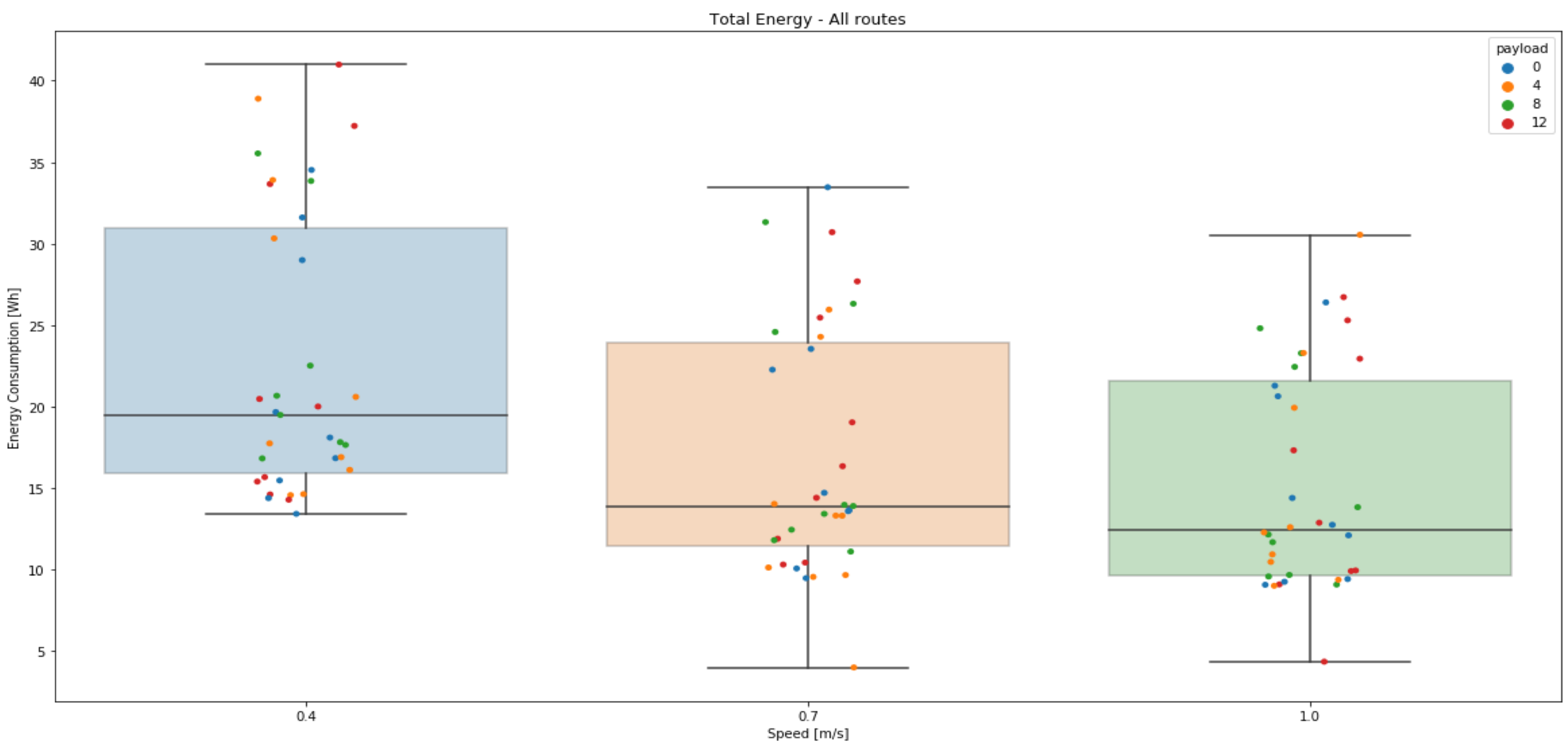
Increased drone speed can increase range because with the same flight time and energy use range is increased

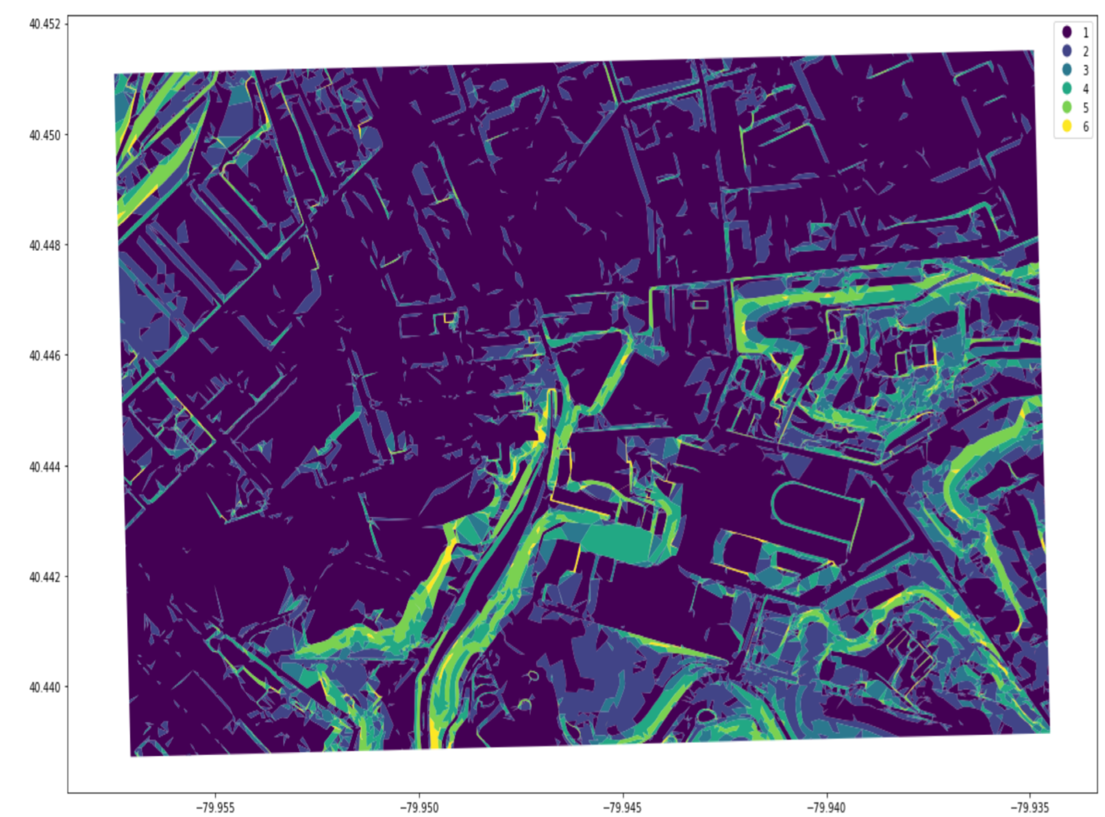
Project Accomplishments: More than 100 driverless delivery robot test campaigns completed





Project Accomplishments: More than 100 driverless delivery robot test campaigns completed across routes with varying slopes





Data from:
http://www.pasda.psu.edu/uci/FullMetadataDisplay.aspx?file=AlleghenyCounty_Slopes201001.xml

Project Accomplishments: Traffic speed and count data collected for Pittsburgh, PA region

Collaboration and Coordination

- Interdisciplinary team of roboticists, engineers, and economists
- Biweekly meetings
- Cloud fileshare
- Team Slack Workspace
- Quarterly progress reports
- Project partner briefings and feedback
- Briefings to DOE

Sponsor: DOE VTO

Performer: Carnegie Mellon University (CMU)

Dr. Costa Samaras, PI, energy modeling and systems analysis
Dr. Sean Qian, traffic modeling and data
Dr. Sebastian Scherer, automated robot design and algorithms
Dr. H. Scott Matthews, data assessment and economics
Dr. Jeremy Michalek, optimization and data analysis
2 graduate students in engineering
1 graduate student in robotics
1 staff engineer in robotics

Partners:
- Pittsburgh Region Clean Cities (PRCC)
- Amazon
- The City of Pittsburgh

Overall Impact

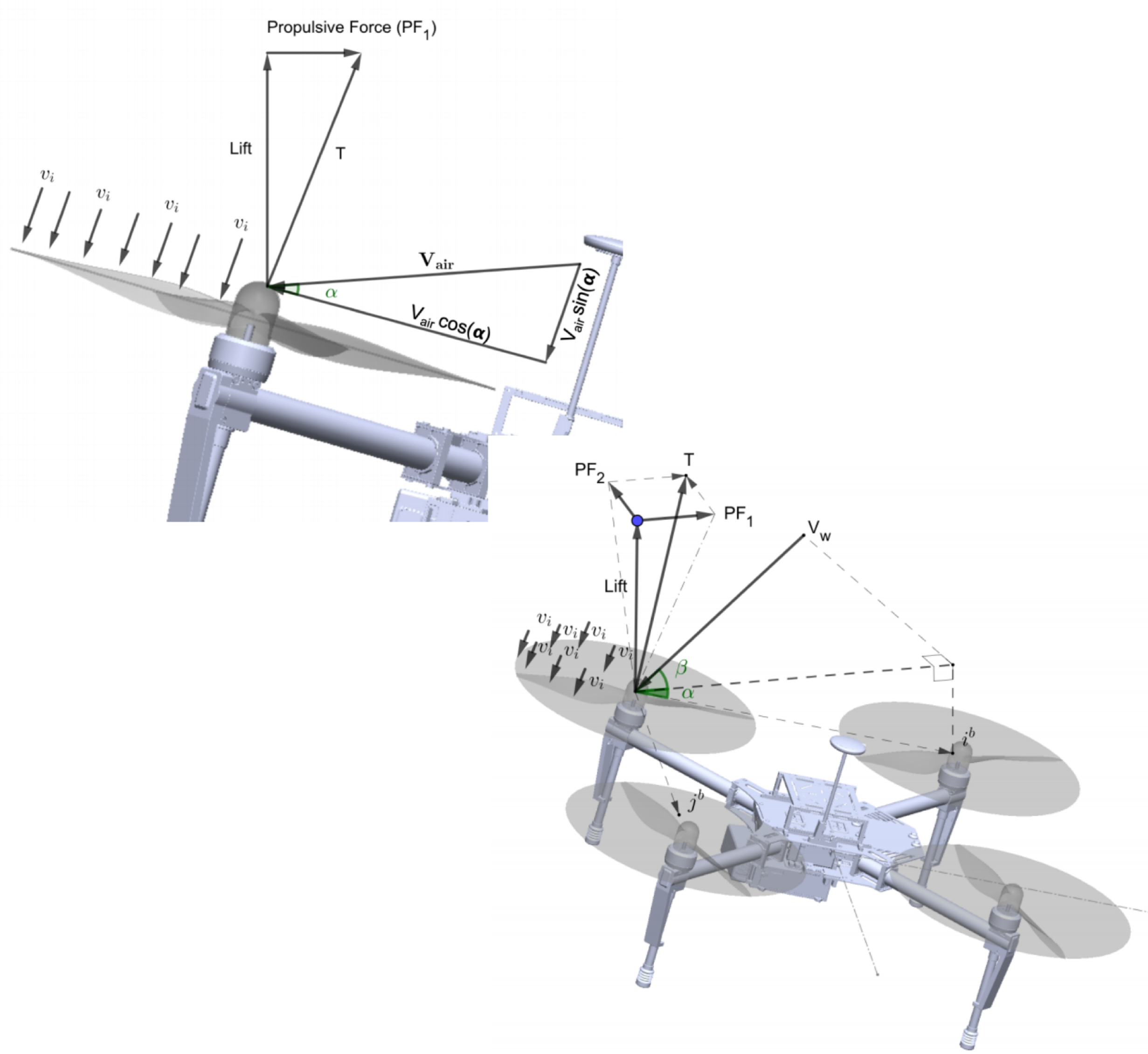
- Novel empirical energy use data generated for package delivery drone and driverless delivery robot
- Novel and replicable drone energy use model developed
- Publication: “A Path Forward For Smart Cities and IoT Devices”. *IEEE Internet of Things Magazine* (2019).
- Publication: “Real-time Motion Planning of Curvature Continuous Trajectories for Urban UAV Operations in Wind”, International Conference on Unmanned Aircraft Systems, (2020).
- Patent filed in Q3 2019: “System, Method, and Computer Program Product for Transporting an Unmanned Vehicle”
- Invention disclosure filed in Q3 2019: “Risk-aware Wind Planning for Last Mile Delivery”

Summary

- The team made substantial progress on the project and the results from the initial year align with achieving the project objectives.
- Publicly available real-world data on drone energy use is extremely limited, and the team generated novel vehicle energy use data and delivered it to DOE.
- The team is continuing vehicle testing and simulation of the pathways to improve the energy productivity of delivery with several variants and scenarios, which will provide insights to entrepreneurs, researchers, designers, and decision-makers.
- Two publications, one patent application, one invention disclosure, several conference presentations, and media mentions resulted from the project in the initial year, and the team is finalizing several more research publications for submittal to peer-reviewed journals.

TECHNICAL BACK-UP SLIDES

First Principle Analysis



A first principle analysis was conducted to determine the theoretical power consumption of a UAV

Power as result of:

- Induced Power (to fight gravity)
- Profile (drag on the blades)
- Parasitic (drag on the body)
- Ancillary (run the system)

Experimental Protocol

An experimental protocol was created and followed to ensure a reliable approach for data acquisition.

- DJI® quad-copter Matrice 100 (M100)
- Data on **wind speed and direction**, **battery current** and **voltage**, and **GPS position**, **orientation**, **velocity** and **acceleration**.
- 211 flights performed varying altitude, speed, payload, route.

Flights were grouped by similar attribute (altitude, speed and payload) and data was assessed

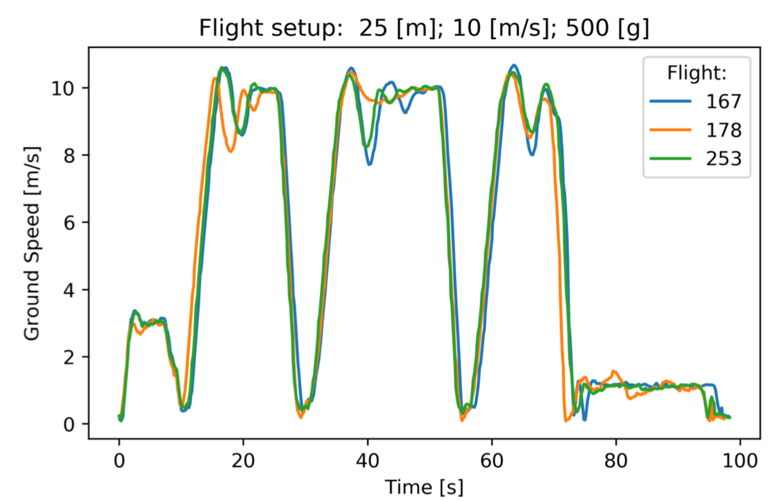


Figure 133: Ground Speed for flights 167, 178 and 253

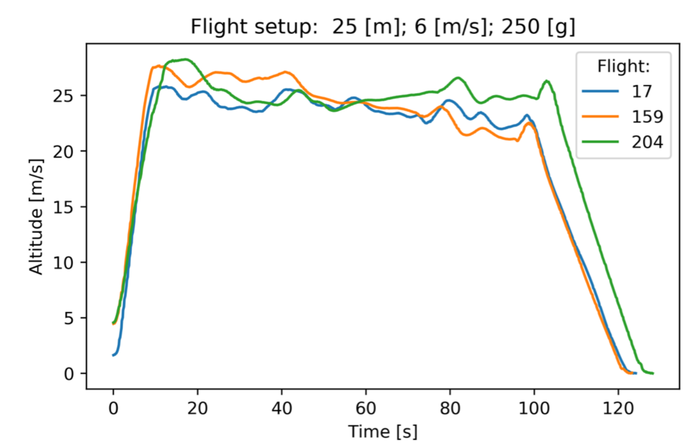


Figure 6: Altitude for flights 17, 159 and 204

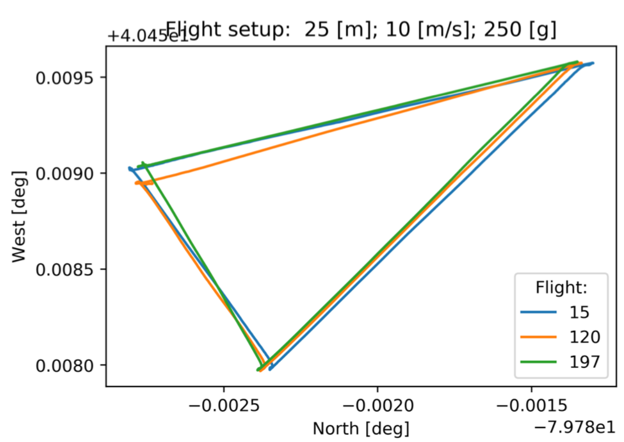


Figure 72: Latitude and Longitude for flights 15, 120 and 197

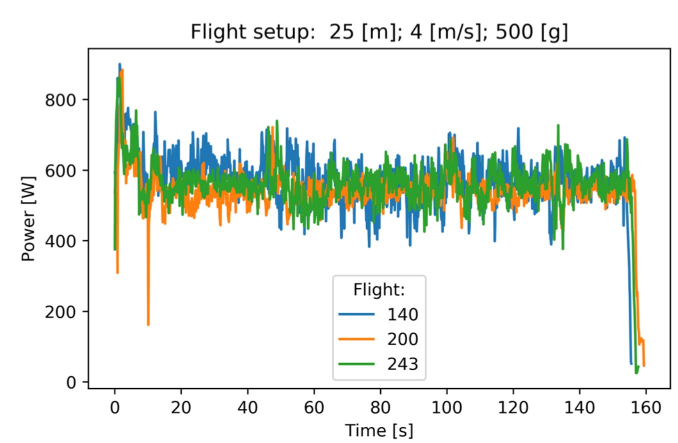


Figure 244: Power for flights 140, 200 and 243

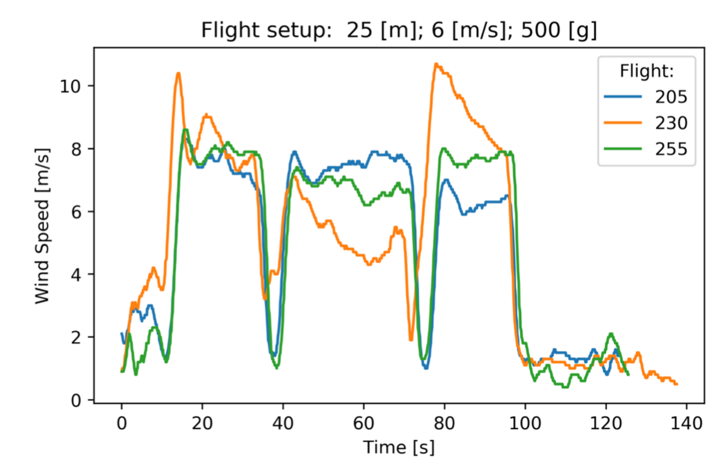


Figure 187: Wind Speed for flights 205, 230 and 255

Data Collection With Delivery Robot

Summary of data collection

- Total missions with all data completed: 130
- Missions with data with all fields of useable data: 113
- Tests from a subset of combinatorial combinations of the following control variables

Husky Speed (in m/s)	0.4	0.7	1	
Payload (in kg)	0	4	8	12
Routes	A	B	C	D

Data collection with Delivery Robot

- 3D printed sensor box with the main components as follows:
  - Power sensor: Mauch PL-200 units for taking voltage and current measurements
  - IMU+GNSS unit: Microstrain 3DM-GX5-45 units for measuring the acceleration, angular rate, and orientation of a body as well as location on earth
    - IMU: Inertial Measurement Unit
    - GNSS: Global Navigation Satellite System
  - Environment sensor: Bosch BME-280 unit for measuring temperature, pressure, relative humidity
  - Microcontroller: Raspberry Pi 0 for collecting and collating the data

REVIEWER-ONLY SLIDES

Publications and Presentations

- Bergés, M., Samaras, C. (2019). "A Path Forward For Smart Cities and IoT Devices". *IEEE Internet of Things Magazine.*
- Patrikar, J. et al. Real-time Motion Planning of Curvature Continuous Trajectories for Urban UAV Operations in Wind", International Conference on Unmanned Aircraft Systems, (2020).
- Samaras, C. (2020). Transportation Energy Use Under Automation Uncertainty, SAE Government and Industry Forum, Washington, D.C., January 23, 2020
- Samaras, C. (2019). Improving Energy Productivity of Mobility, SAE Government and Industry Forum, Washington, D.C., April 3, 2019.
- Samaras, C. (2019). The Impact of Automated Vehicles on Cities. National Renewable Energy Laboratory, Washington, D.C., (Governmental Briefing), May 23, 2019.
- Samaras, C. (2019). Robust Pathways For Light Duty Vehicle Deep Decarbonization. Department of Energy Resources Engineering, Stanford University, December 11, 2019.