# VICTOR-CPR Energy Logistics, Corridor Coverage Academic Scenario

Version 1.0


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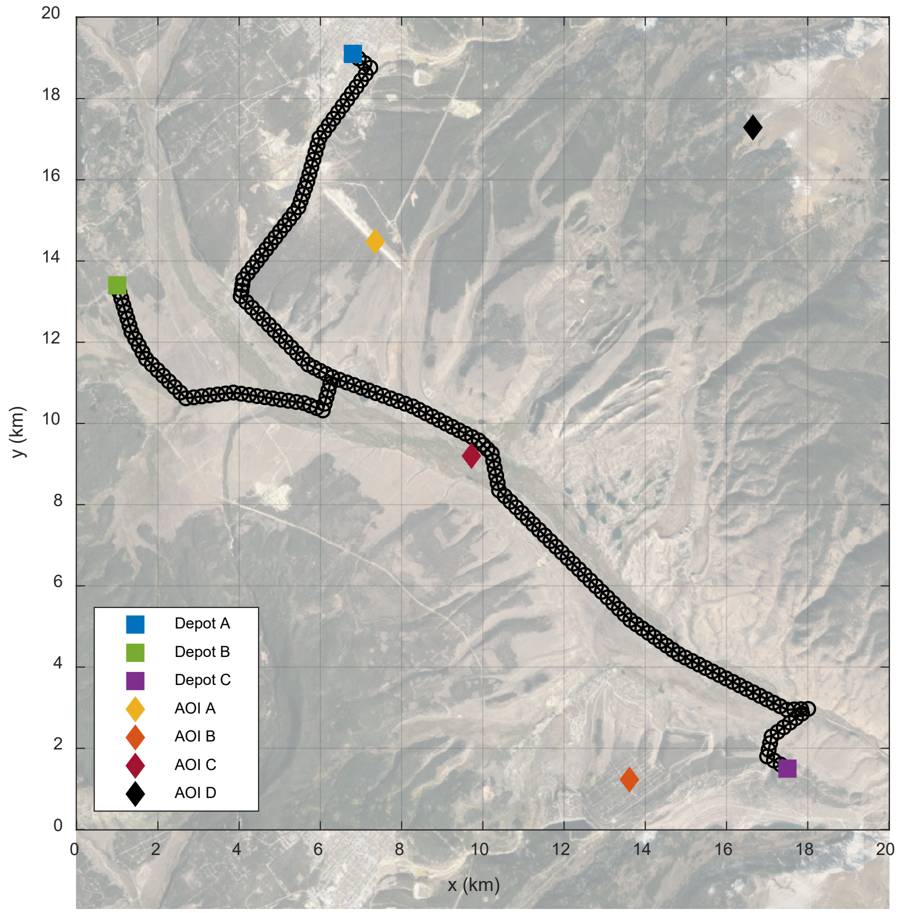


## Scenario Specifications

This document describes an academic scenario provided to scope some of the autonomous decision making capabilities to a scale that is pertinent to the energy-constrained logistics challenges being addressed by VICTOR-CPR. The scenario takes place over a 20 km x 20 km area as shown in Figure 1. There are three depots, termed A, B, and C, and a route that connects them.

Over a 72 hour period there will be three distinct mission types that will occur at predetermined times. Each mission type will have a running total score, with the global objective being to minimize that score.

Mission 1: Persistent ISR

Every node along each path needs to be routinely visited. The visit entails a simple fly by, with no perching or wait time. Each time a node is visited, an associated timer will be reset. The total score for this mission will be related to the intervals at which each node is visited. Every time a node is visited, the time (in minutes) between visits is weighted according to the following function:

$$S_1 = \frac{t^2}{30^2}$$

This weighting will penalize 30 minutes intervals by 1, and 60 minute intervals by 4.

Mission 2: Convoy Support

Three times a day, at known times and locations, a convoy will depart from one depot, heading towards another travelling at 15 m/s. This is a routine, scheduled mission. As the convoy moves, the autonomous team must visit each node along its route between 15 minutes and 1 minute ahead of the convoy's arrival at that node. These missions follow the following schedule:

| Time | Start | End |
|---|---|---|
| 0600 | Depot A | Depot A |
| 1400 | Depot B | Depot B |
| 2200 | Depot C | Depot C |

For each node that is not visited within this time window, 10 points are added to the Mission 2 score. These visits also count towards completion of Mission 1 goals.

Mission 3: Area of Interest

Occasionally, at unknown times and locations, a high priority task is added to the mission area. These tasks conform to the following schedule, which are only made known to the system as they need to be addressed.

| Time | Task | AOI |
|---|---|---|
| 1800, day 1 | Loiter | D |
| 0600, day 2 | Perch | C |
| 1800, day 2 | High Cost | B |
| 2200, day 2 | Loiter | D |
| 0600, day 3 | High Cost | A |
| 1000, day 3 | Perch | C |
| 1800, day 3 | High Cost | B |
| 2200, day 3 | Perch | A |

The energy and time costs of each task are given in the following table. Both UAS and UGV can perform any of these tasks. They can also be performed by the UGV while a UAS is charging. These time and energy costs are paid in addition to the compute cost for the stationary UAS/UGV, as well as costs of landing/taking off or hovering as applicable to the UAS.

| Task Name | Loiter | Perch | High Cost |
|---|---|---|---|
| Time Cost (min) | 0.5 | 60 | 8 |
| Energy Cost (kJoules) | 6 | 0 | 100 |
| Representative Mission | Quick search | Thorough surveillance | Donate Power/ Carry Payload |
| Requirements | none | UAS must land and takeoff | UAS must land and takeoff |

These tasks follow a similar score criteria as Mission 1, but with greater weighting. The time (t) is based on the duration for which the mission was available to be performed, before a UAS or UGV began acting on it.

$$S_3 = 10\frac{t^2}{30^2}$$

*Team Composition*

The baseline autonomous team consists of 3 UAS and 1 UGV. All UAS and UGV are capable of visiting targets. The specifications and capabilities of each unmanned system are described in subsequent sections. After initial tests with 3 UAS and 1 UGV have been performed, additional combinations of UAS and UGV can be evaluated.

*Communication*

Communication between air and ground vehicles is assumed to only occur during the charging process, meaning that computationally routing the vehicles and setting rendezvous locations must conclude before the UAS is fully recharged. Once it takes off, the UAS has no knowledge of any other vehicle's positions, nor does the UGV know of the UAS location or progress on its task list. History of each trip information is given to the UGV upon landing. If multiple UGV exist, they can share knowledge, and UGVs can share knowledge with fixed recharging stations.

The UAS is capable of making logical decisions, such as evaluating its current energy levels and pruning future visits from its task list if deemed impossible. It can perform a landing maneuver at any point to perch and reduce its power requirement to 13 watts (but it must subsequently perform a takeoff maneuver). It can also loiter to wait in place without landing.

*Sensing*

From 0600 to 1800, the sensor range is greater than 300m, allowing every visit to also count as a visit at the two or three adjacent route coordinates. From 1800 to 0600, the darker conditions prevent sensor range from exceeding 150m, requiring the UAS to visit each coordinate.

## UAS Specifications

*Power and Velocity Profile*

The UAS is a custom quadrotor with a 4000mAh, 22.2 V battery (319.7 kJoules). Of the 319.7 kJ available in the battery, let us assume that 10% will not be used to account for battery voltage droop and other inefficiencies, leaving 287.7 kJ of usable energy.

The ideal power curve follows the following equation, where velocity is given in meters per second and power is given in Watts.

$$P = 0.0461V^3 - 0.5834V^2 - 1.8761V + 229.6$$

Of this, 13 Watts is avionics and compute power, which will be consumed whether it is flying or perched (but not while recharging). The specific design speeds of interest are given below, where velocity of best endurance maximizes time in the air, and velocity of best range maximizes distance flown per unity energy. To account for wind gusts, perturbation rejection, and obstacle avoidance we will add a 5% margin to each value.

| | Perched | Hovering | Best Endurance | Best Range |
|---|---|---|---|---|
| Velocity (m/s) | 0 | 0 | 9.8 | 16.0 |
| Ideal Power Requirement (Watts) | 13 | 229.6 | 198.6 | 239.1 |
| Expected Power Requirement (Watts) | 13 | 241.1 | 208.5 | 251.1 |

For perception requirements, the UAS will not exceed 16 m/s.

This gives an expected maximum range of 18.32 km (11.4 mi) with 19.1 minutes of flight, or a maximum endurance of 23.0 minutes of flight, covering 13.52 km (8.4 mi).

*Landing and Take-off*

The process of landing and taking off from the ground or a landing pad on a UGV has a time and energy cost given in the following table.

| Maneuver | Landing | Takeoff |
|---|---|---|
| Time Cost (min) | 0.5 | 0.1 |
| Energy Cost (kJoules) | 7.2 | 4 |

## UGV Specifications

The UGV is a Clearpath Warthog with a 19.01 MJ battery for transport, plus 8.78 MJ of battery for autonomy compute. We will assume a net 27.79 MJ of total available energy on board. As with the UAS, 10% of the total energy is withheld to account for inefficiencies and voltage droop, leaving 25.01 MJ of usable energy.

The ideal power curve follows the following equation, where velocity is given in meters per second and power is given in watts.

$$P = 464.8V + 356.3$$

Of this, 200 Watts is the cost of running the autonomy stack and additional compute power. When the UGV is stationary, the power requirement will drop to 200 Watts. To account for additional computation needs, terrain, and obstacle avoidance, add a 5% energy margin.

The maximum velocity of the UGV is 4.5 m/s.

At 4.5 m/s, the range of the UGV is 48.65 km (30.2 mi).

## Wireless Power Transfer

Wireless power transfer requires the UAS to land on the UGV. The UGV must be moving 1 m/s or slower for the UAS to land on it. While landed it cannot exceed 3 m/s to ensure proper power transfer.

The power transfer uses constant current until 94% battery capacity, with a 3.5C charge rate. From 0% capacity to 94% capacity, the 3.5C charge rate corresponds to 14A. After 94% capacity, it switches to a constant voltage charge. A first order approximation of the battery recharge rate is given below:

$$P = \begin{cases} 310.8; & E \leq 270.4kJ \\ 17.965 \cdot (287.7 - E); & 270.4kJ < E \leq 287.7kJ \end{cases}$$

For every Joule of energy that is transferred to the UAS, an extra 10% (total 1.1 J) is subtracted from the UGV power to represent transferred power plus losses.

Extra energy available upon landing is not lost and can reduce the total recharge time. The UAS also does not need to fully recharge. Only one UAS can be in the process of landing or taking off at a time to ensure adequate airspace traffic management, but up to two UAS can be charging concurrently at any given time.

## Depot Power Transfer

Depot B also contains the necessary hardware and landing pad to wirelessly recharge the air vehicles, as well as the capacity to recharge the UGV. Recharging the UGV is a battery swap that takes a flat 5 minutes. Recharging the UAS at Depot B follows the same dynamics as wireless recharging on the UGV, and has three available landing pads.

## Metrics

Metrics to keep track of during simulation and evaluation

1. A histogram of time between visits for all nodes along the routes (as given in Mission 1).
2. Percentage of dropped visits as defined for Mission 2.
3. A histogram of time before visit for all Mission 3 items.
4. Percentage of time spent on mission for each UAS and UGV, and for the entire system. This includes time spent at an individual marker for Mission 3, as well as time spent moving between road nodes for Missions 1 and 2. This does not include time spent flying to and from Depot B or the UGV for purposes of recharging. It also does not include time spent moving between mission targets (i.e. moving from a road coordinate to AOI B, or from addressing Mission 1 to Mission 2).
5. Percentage of energy spent on mission for each UAS and UGV. This follows similar rules as the prior metric.

## References

Hurwitz, A., Dotterweich, J., and Rocks, T., "Mobile Robot Battery Life Estimation: Battery Energy Use of an Unmanned Ground Vehicle," Proc. SPIE Defense & Commercial Sensing, April 2021.