Collaborative Autonomous Ground Vehicles Achieving Energy Independence

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Opportunity for Greater Autonomous System Performance

In Autonomous Systems:

- Many new energy intensive missions and payloads are emerging.
- Energy storage capacity is limited unless the system harvests energy.
- Hard to optimize for energy *and* mission.

Problem: Performance (endurance, range, speed, etc.) is energy limited.

Underwater Vehicles

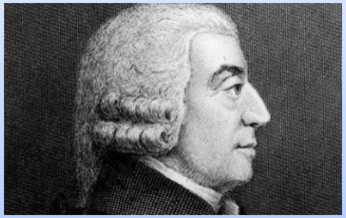
Air Vehicles

Ground Vehicles

In Human Societies:

- Individuals collaborate to raise productivity and/or achieve otherwise infeasible objectives
- Specialization and trading resources make groups more effective

Solution: Autonomous vehicles that collaborate to harvest, store, share, and consume energy.



Adam Smith: Specialization

Project Concept: Overview

Goal: Demonstrate that autonomous systems can overcome energy limitations by collaborating to harvest and share energy.

Status Quo

- No autonomy – human remote control
- No energy harvesting or collaboration
- Limited mission endurance; must return for human to replace/recharge batteries

PackBot 510

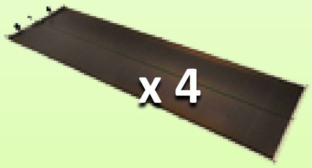
BB2590 Batteries: 432 Wh

New Approach

- Provide vehicles with autonomy (computers with AI software) so they can collaborate
- One “Farmer” robot harvests and stores solar energy
- Two “Worker” robots carry out a mission and then recharge from farmer
- Vehicles share energy information to maximize energy harvesting and minimize consumption

Farmer

Battery Pack 1728 Wh total



Rollable Solar Panels 240 W nominal total

Energy →

← Information →

Workers

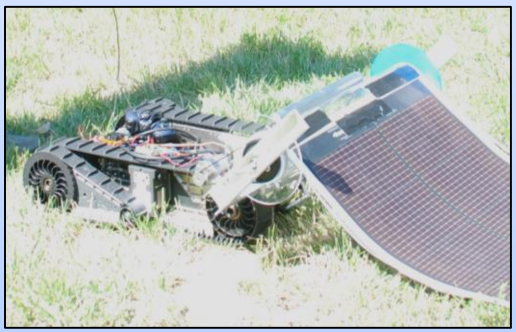
Battery Pack 864 Wh total

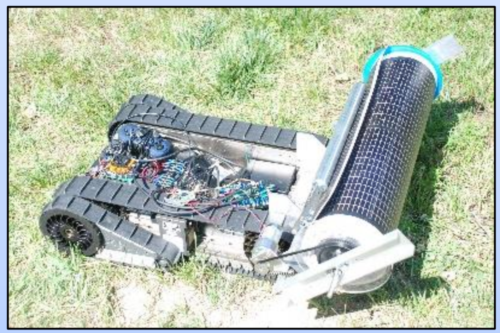
Autonomous Hexcopters

Project Concept: Notional Mission

Notional Mission for the Group: Long-endurance, forward deployed, unattended sensing/reconnaissance operations

<u>Farmer Mission</u>: Maximize harvested and stored energy; support worker operations


Deploy Panel & Charge Batteries


Stow Panel & Seek Better Location

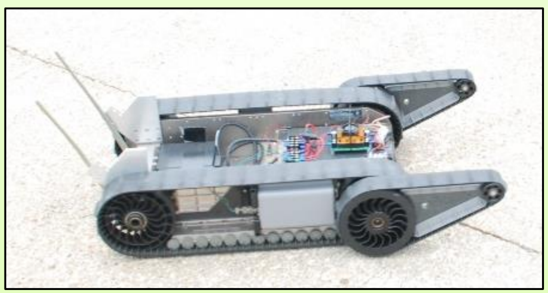
<u>Farmer Design Goals</u>

- ***Gather and store ≥ 1728 Wh/day in AM1.5 conditions (capacity of two Workers)***
- ***Solar panel survives collisions & drive over; expandable capacity, COTS, inexpensive, and autonomously deployed***
- ***Two charging ports (one for each Worker)***

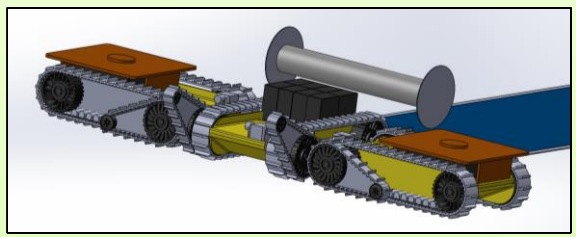
Project Concept: Notional Mission

Notional Mission for the Group: Long-endurance, forward deployed, unattended sensing/reconnaissance operations

Worker Mission: Execute sensing mission; launch hexcopter to sense in inaccessible regions



Deploy Panel & Charge Batteries



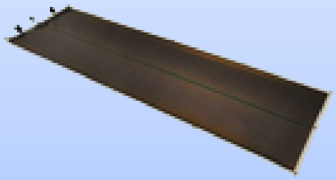
Stow Panel & Seek Better Location

Worker Design Goals

- ***Carry stock Packbot energy (432 Wh) + two hexcopter recharges (~432 Wh).***
- ***Maintain stock maneuverability & efficiency***
- ***Robust charging ports for farmer and hexcopter interfaces; ability to find farmer and connect***

Farmer Energy Harvesting Hardware

Solar Panel Assembly



60 W nominal PowerFilm
Amorphous Si rollable solar panel

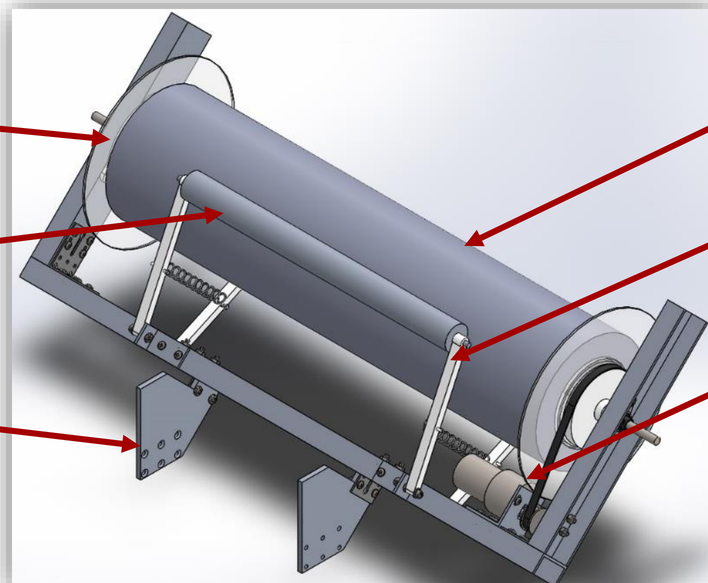
Panels are sewn into a single
strip and then wired

Solar panel is stowed on rotating drum

Slip rings transfer power from rotating drum to fixed frame

Two spring-loaded rollers keep solar panel tightly wound on drum

Mounting brackets



Rolled solar panel

An optical limit switch informs controller of panel position

A motor and belt assembly rotates the drum to deploy & stow the panel

Farmer Energy Harvesting Hardware

Energy Storage and Electronics

- Commercial maximum power point trackers (MPPTs) from Genasun
- Custom power distribution, tracking, and protection board
  - Switch battery strings in/out
  - Tracks charge and string voltages for SOC estimation
  - Switchable outputs
- BB2590s offer many safety features

Genasun MPPT

Power distribution board

BB2590 Battery

Energy Transfer Ports

- Farmer shares location over network or with a beacon
- Port are concave oblate cones with spring contacts
- Workers use machine vision to locate ports labeled by AprilTags
- Robots communicate over network to coordinate connection process

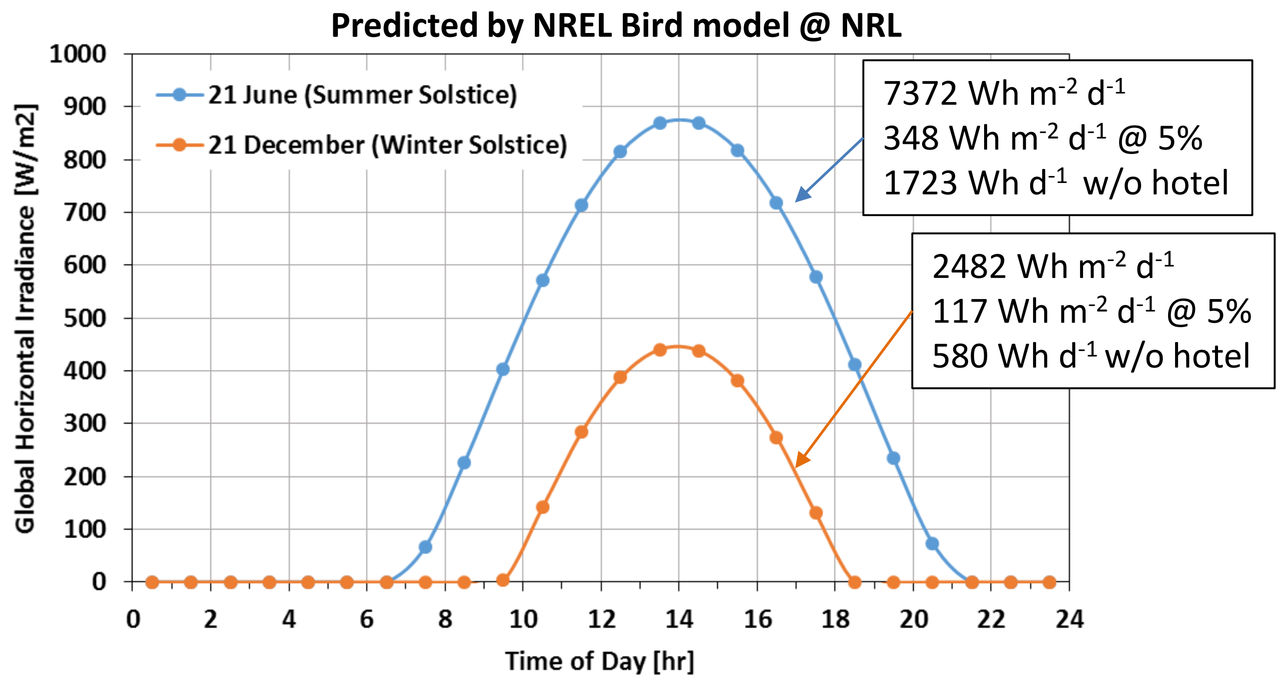
AprilTag

Energy Transfer Ports

Farmer Performance Estimates

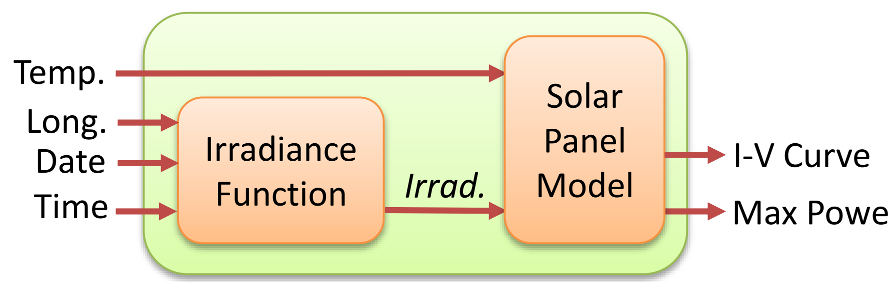
Solar Irradiance

- Estimated using NREL atmospheric (Bird, et al.) model
- Gross estimates and hourly estimates to inform group planning
- Upper and lower bounds for clear weather at NRL in Washington, DC



Solar Panel Model

- Measured PF R28 panel voltage and current as functions of irradiance and temperature; built look-up table to capture relationship
- Extrapolates power density to larger PF R60 panel area

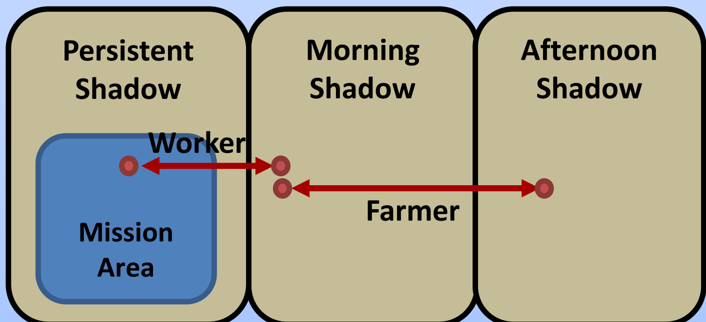


Harvested Power Estimation

Conceptual Implementation: Energy "Optimization"

Maximize Energy Harvesting

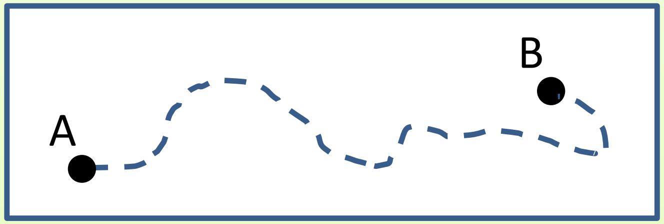
- *Use solar power model to choose best (least opportunity cost) transit distance and time*
- *Use radiometer to measure solar flux; when it decreases suddenly, move to avoid shadow*
- *Workers also carry radiometers; over many trips, they can map shadows vs. location & time and share map with Farmer*
- *Use arm-mounted imager to identify "sunny" regions with greater harvesting opportunity*



Coordinating Packbot activities to maximize harvesting

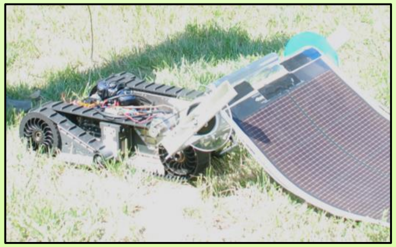
Minimize Energy Consumption

- *Largest energy costs are transit and hotel power*
- *Identify minimum energy cost trajectory from present location to new location*



Efficient Packbot trajectory from point A to point B

- *Actively manage hotel loads to keep systems "off" or in "standby" as much as possible.*



Choose low power state when Packbot is stationary

Minimizing Transit Energy Consumption

Transit Energy Cost

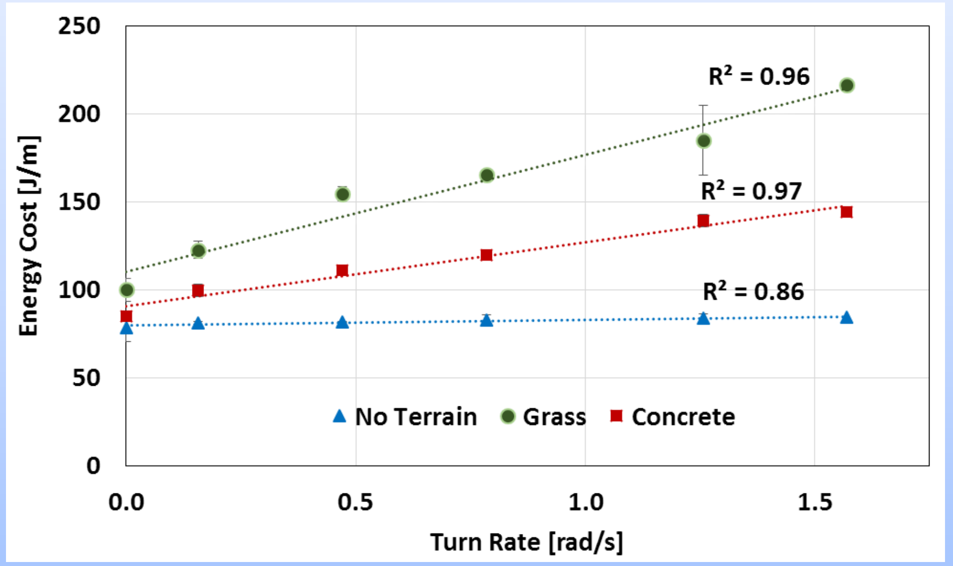
- Total energy per meter (J/m) can be broken into contributions by:

terrain, turn rate, elevation change

$$E_c = E_{ter} + E_{turn} + E_{elev}$$

- Can measure E_{ter} & E_{turn} to correlate them with terrain and turn rate.
- Can estimate $E_{elev} \approx m_{pb} g \Delta h$

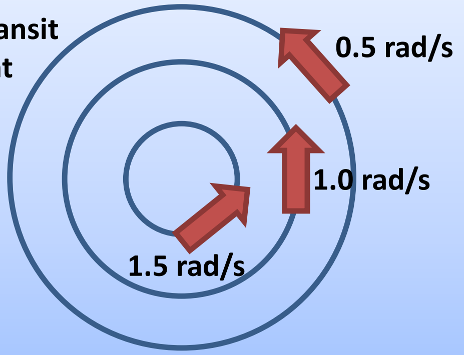
Measured Packbot Transit Energy Cost @ 0.5 m/s



Measurement Methods

- Use iRobot/NRL programming interface to transit with constant speed and turn rate
- Data logger records power consumption
- Average over many experiments on each terrain type

PackBot Paths for Transit Energy Measurement

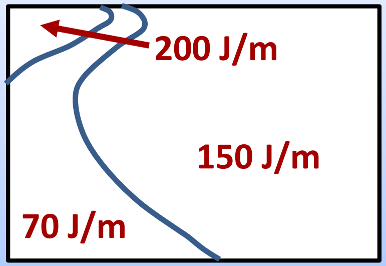


Minimizing Transit Energy Consumption

Terrain Identification –> Energy Cost Map

- Visual/IR images → terrain type
- LIDAR → terrain elevation
- Terrain type & elevation maps correlated with energy cost data yield an energy cost map

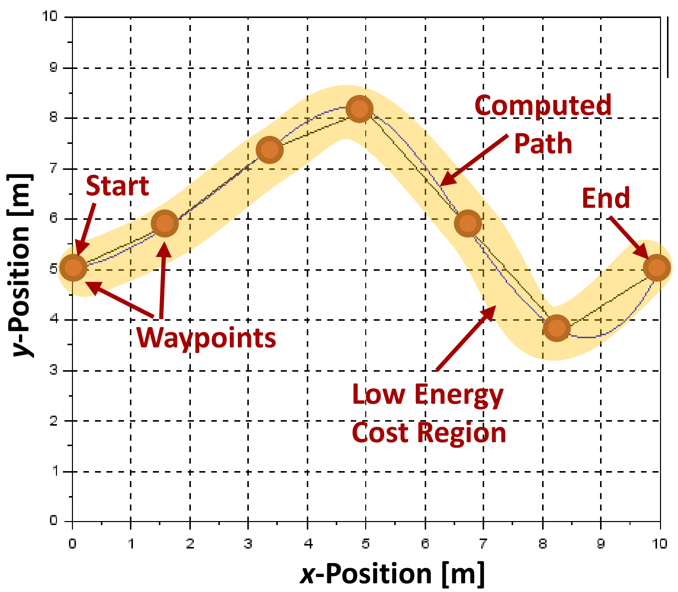
Image with terrain ID



Map with traversal cost(s)

Computing Minimum Energy Cost Path

1. Assign arbitrary waypoint locations
2. Calculate path as spline fit to waypoints
3. Calculate energy cost of path
4. Adjust waypoint locations (Newton solver) to decrease energy cost
5. Repeat 2-4 until energy cost ceases to decrease.



Minimizing Transit Energy Consumption

Strengths of this Approach

- Accommodates sparse and/or discontinuous data
- Computationally inexpensive
- Simple integration with existing obstacle avoidance codes
- Measured power consumption can be used to update cost correlations and the cost map ("learn")
- Can apply same approach to other vehicles (esp. tracked vehicles)
- Can be extended to minimize energy consumption of a group

Weaknesses of this Approach

- Initially, only useful for known regions and terrain types
- Does not guarantee *global* minimum energy consumption
- Cost map(s) can become obsolete quickly (in rain, dirt → mud)

Influence of Hotel Power Consumption

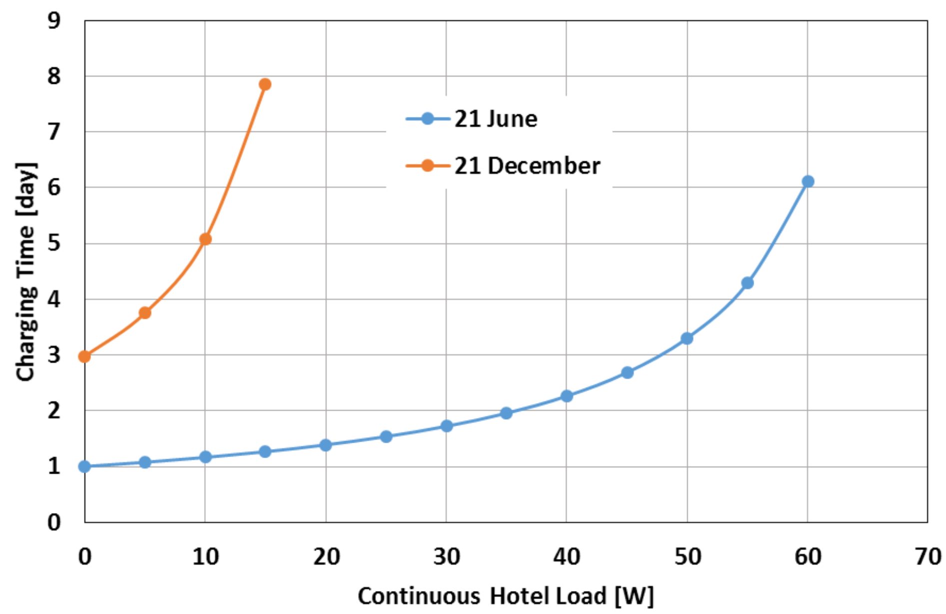
Energy Harvesting Time

- With 10 W hotel, charge time: 1 – 5 d
- With 20 W hotel, charge time: 1.5 – 17 d
- Hotel load is significant! Penalty is paid *at all times*.
- Operational Frequency: 1 mission/week
- System appropriate for LONG missions

Hotel Power Reduction

- Low power (Intel NUC) computer for autonomy
- Shut down all systems except watchdog electronics; wake on timer or WAN signal from Worker
- Packbot shutdown whenever stationary
- Low power energy management board electronics

Predicted Farmer Packbot Charge Time, 0% → 100% SOC



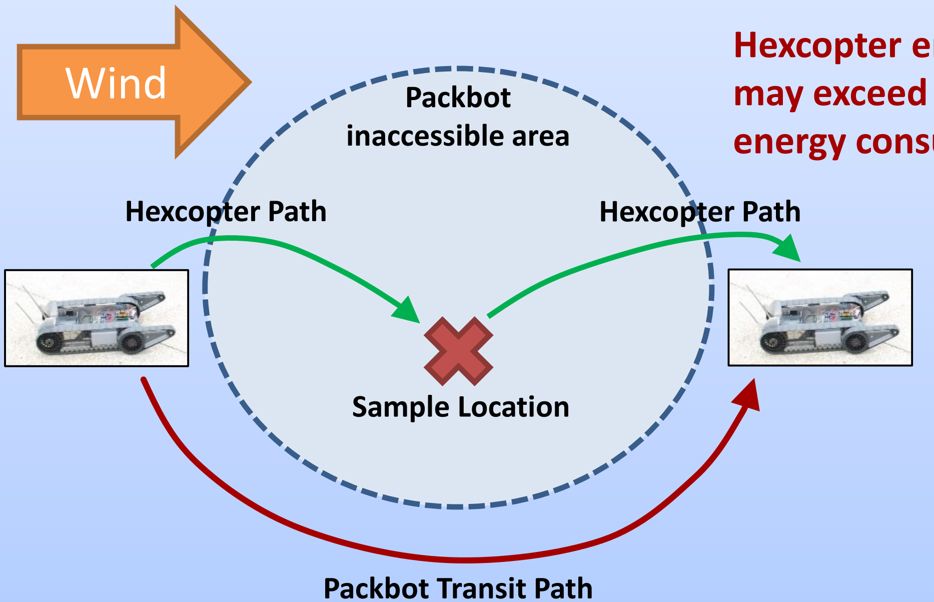
Time of year is significant away from equator due to hotel loads…

Charge times could be much shorter (~ 4x) with expensive custom InGaAs solar panels…

Other Major Energy Consumers (Opportunities!)

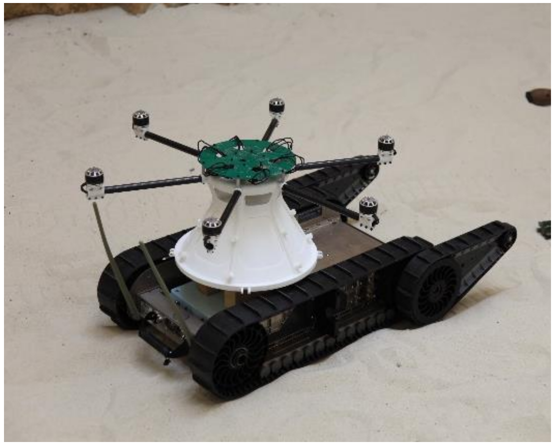
Collaboration with Hexcopter

- Asymmetric capabilities and cost introduce new optimization opportunities into the energy problem. Example scenario:

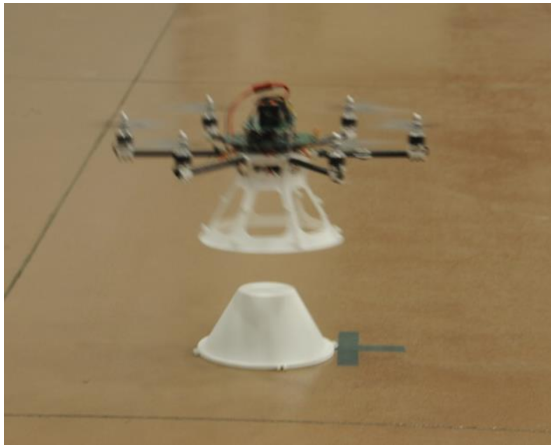


Hexcopter energy saved may exceed extra packbot energy consumed!

- Hexcopter can image operating area to augment maps of packbot energy harvesting opportunity and transit energy cost.



NRL-designed hexcopter on Packbot with capture device & recharging port



Early hexcopter test flight

Status; Where do we go from here?

Status

- Prototype solar panel mechanism and electronics demonstrated
- Energy management boards complete and demonstrated
- Minimum energy cost path code and measurements complete
- Energy transfer port design and fabrication underway

Near-Term (2015) Tests/Demonstrations

- Fully autonomous solar panel deployment/stowage
- Autonomous packbot-packbot docking and energy transfer
- Minimum energy cost path selection and execution; possibly validation

Long-Term (2016/17) Demonstration

- Fully autonomous harvesting (site selection, etc.) and energy transfer
- Minimum energy cost map generation from sensor data; integration with autonomy software
- Demonstrate sensing mission with all vehicles (three packbots & two hexcopters)

Acknowledgements

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