Cooperative Localization with Symbiotic Planetary Rovers

Carnegie Mellon University

Ananya Kumar, Sunny Nahar – Advisor: Red Whittaker

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Introduction

The **Moon** and **Mars** are rife with uncharted features of immense scientific value:

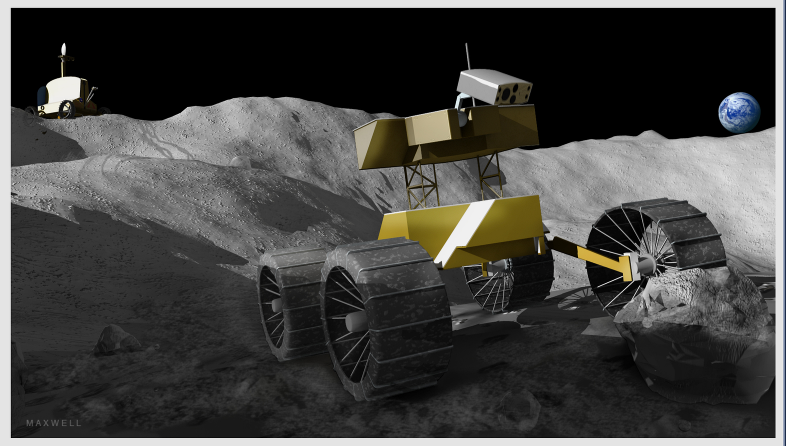
- **Caves** are prime prospects for water and life.
- **Pits** are a safe haven from radiation, meteorites, and temperature variations.

These features are **too risky** for the primary rover to explore.

Research Question

A **symbiotic multi-rover system** is a possible solution:

- Large sophisticated **parent rover.**
- Smaller, inexpensive, and **expendable child rovers**.



Issue of **Localization** for child rovers:

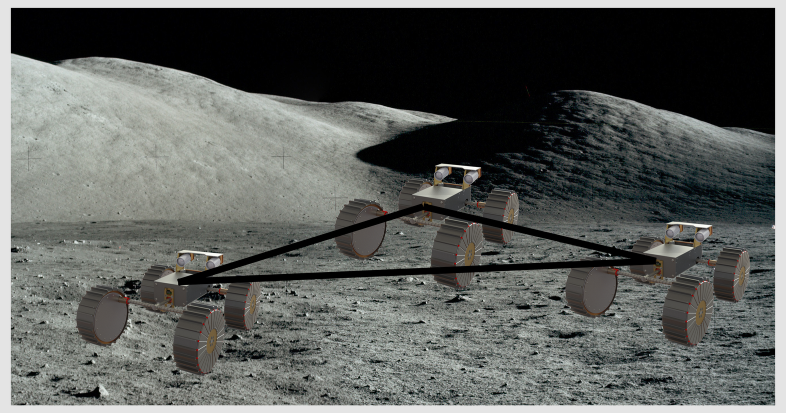
- **Lack hardware** to localize well.
- Need to **accurately** navigate and explore.
- Need to return to the parent to **recharge battery**.

This research uses **cooperative localization** to improve position estimates.

Past Research and Current Approach

Past research on **cooperative localization:**

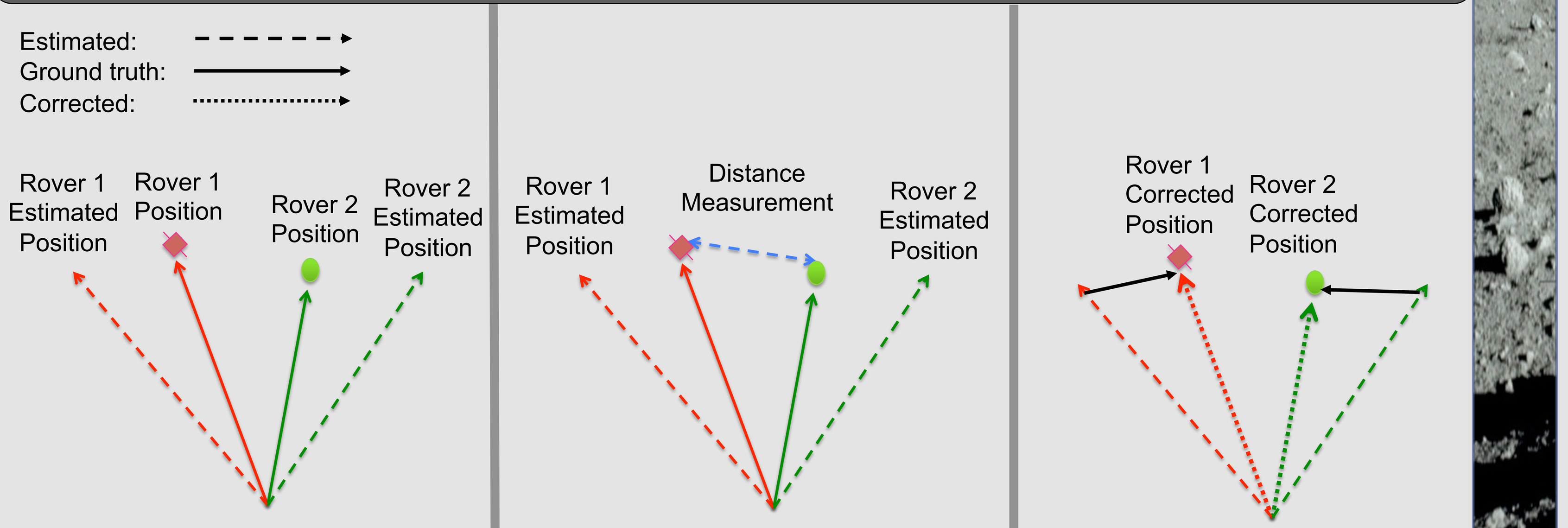
- Some rovers are stationary (e.g. Leapfrogging).
- Rovers move in fixed formations.
- Landmarks are used to localize.
- Rovers are identically modeled.



Current approach:

- Motion is **not constrained.**
- Sensor models are based on **planetary** analogs**.**
- **Parent – child** rover model is used.
- One rover's starting location might not be known.

Method

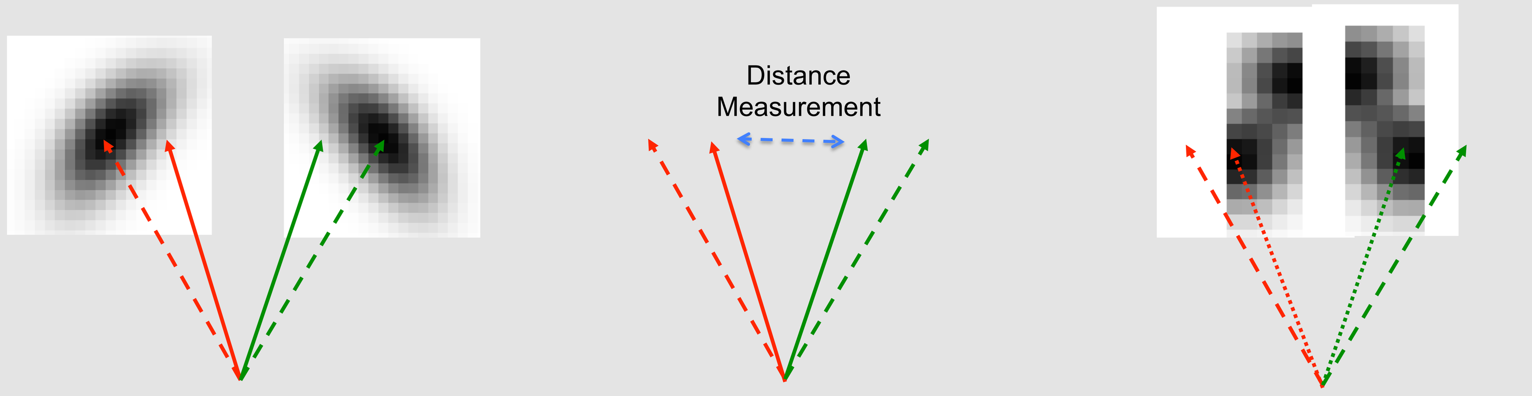


Step 1: Rovers move, incorrectly estimate pose.

Step 2: Rovers measure distance to each other.

Step 3: Rovers correct pose estimate.

Grid Filter



Step 1: Both rovers have incorrect pose estimates.

Step 2: Distance measurement updates grid.

Step 3: Filter improves pose estimate for both rovers.

- Each rover stores a **moving grid** of possible locations of its position.
- For each grid cell, the rover stores the **probability** that it is in the grid cell.
- The grid is updated when rovers move and take distance measurements.
- The **maximum likelihood** estimate is used for corrected position.

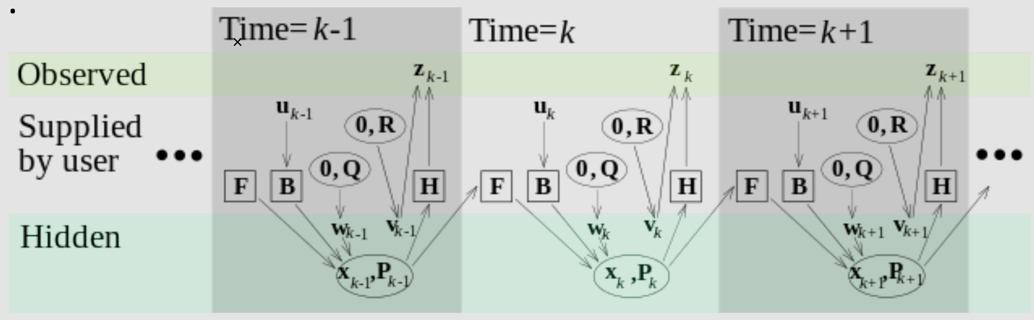
Extended Kalman Filter

State estimator combining prediction and measurement data:

- Learns a continuous space **Hidden Markov Model**.
- Extended Kalman is **non-linear** version of Kalman filter.
- Optimal for Gaussian error.

Model:

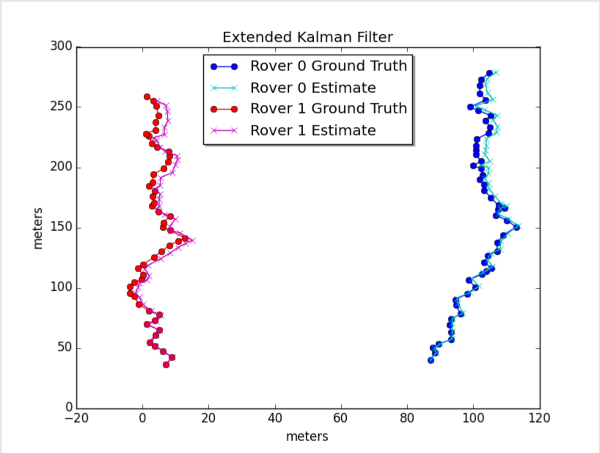
- x_k = Rover (x, y) state
- P_k = Rover (x, y) covariance
- u_{k-1} = Rover (distance, heading)
- z_k = Rover (pairwise distance)
- w_k, v_k = Process / Measurement noise
- F = State transition
- H = Observation transition



Test Scenarios

The Extended Kalman and Grid filter were tested using simulations (300 simulations/scenario):

- Rovers take a pseudo-random path.
- Algorithms observe sensor readings with noise.
- Algorithm position estimates are compared with ground truth.

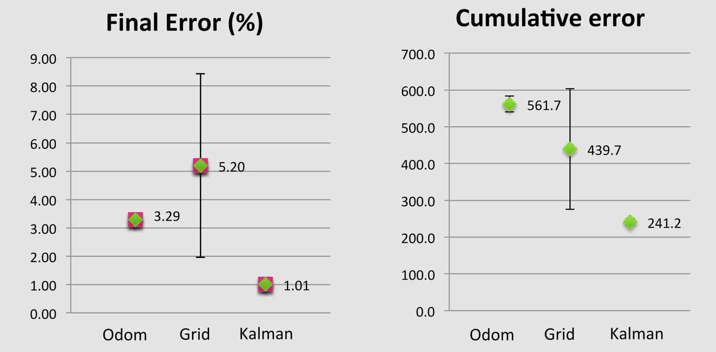


Scenarios:

- **Twin rovers**: Both have moderately accurate sensors.
- **Parent-child rovers**: Parent has accurate sensors; child is less accurate.
- **Camera**: One rover can also get the direction to other rover.
- **Sensor error model**: Gaussian or Uniform.
- **Biased sensors**: Sensors have biases.
- **Standard start**: Both rovers start at the origin.
- **Lost child problem:** Initialize with child rover position unknown and parent known.

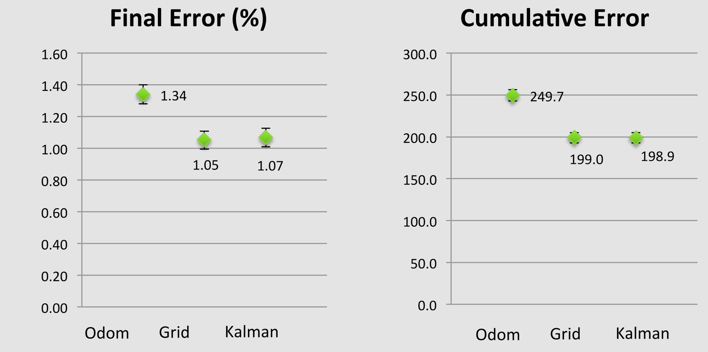
Results

Parent-child, 500m trek



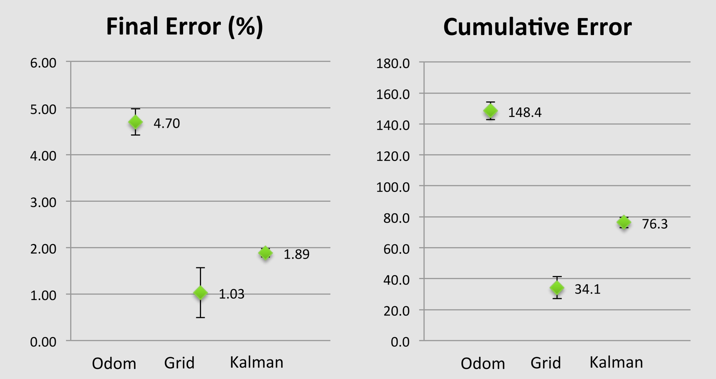
Kalman had **2.3 times lower error**, and did better than dead reckoning in 294/300 runs.

Twin rovers, 500m trek



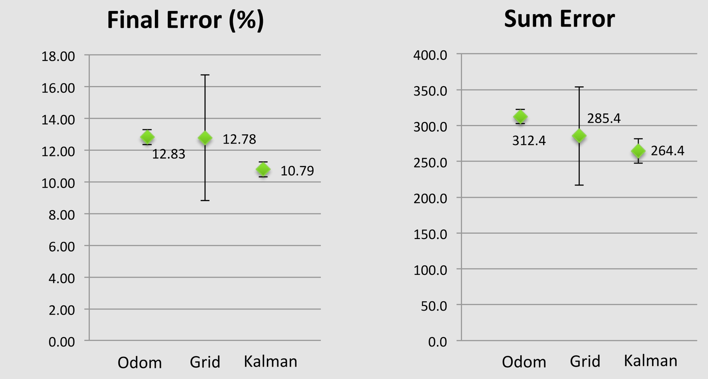
Grid had **1.25 times lower error**, and did better than dead reckoning in 291/300 runs.

Parent-child, 100m trek with camera



Grid had **4.3 times lower error**, and did better than dead reckoning in 299/300 runs.

Parent-child, 100m trek with bias



Kalman had **1.17 times lower error**, and did better than dead reckoning in 237/300 runs.

Parent-child, lost child, 100m trek

Method	Error (%)	2 × Standard Error
Odom (both rover positions known)	2.70	0.15
Kalman (child lost)	4.10	0.56

Kalman got **only 4.10% error** although location of child rover was initially unknown.

Twin rovers, lost twin, 100m trek

Method	Error (%)	2 × Standard Error
Odom (both rover positions known)	0.69	0.04
Kalman (child lost)	5.31	0.69

Kalman got **only 5.31% error** although location of child rover was initially unknown.

Conclusion, Impact, and Future Work

By incorporating **pairwise distance** between rovers, our algorithms **significantly improved localization accuracy** relative to dead reckoning by the same rovers if acting alone:

- **Parent – child:** Kalman did 2.3 times better.
- **Twin rovers:** Grid based method did 1.3 times better.
- **Camera:** Grid based method did 4.3 times better.
- **Sensor bias:** Kalman did 1.17 times better.
- **Random reboot:** Kalman had 95% accuracy.

This research shows **cooperative localization** for planetary exploration is feasible:

- Algorithms work well in a variety of situations and realistic scenarios.
- Algorithms establish a **lower bound** for what is possible.
- Large scope for potential research.

Future Work:

- Implementing our methodologies on real rovers.
- Experiment with other algorithms (unscented Kalman filter, particle filter).

Acknowledgements

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