In-pipe Robot Localization with Reciprocal Sensor Fusion

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Background

Manual measurement of U-235 deposits in pipes is a costly, time consuming, and labor-intensive process that is subject to many errors. Autonomous, robotic innovation enabled by this research is revolutionizing the measurement speed, quality and safety of this important operation. The huge advantage is the robot's ability to measure from inside the pipes. The upside is sensing the geometry, appearance and radiometry directly. The downside is the **inability to know precise, absolute position** of the measurements in very long pipe runs.

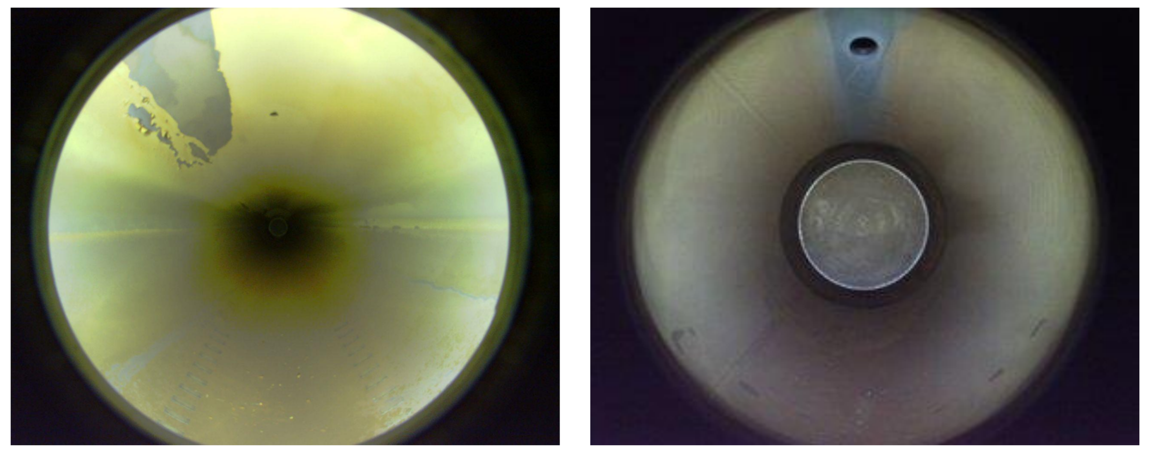

Fig. 1: Pipe interior surface and U-235 holdup

The RadPiper is a battery-powered and tether-less robot which self-steers using two tracks. A detector assembly is mounted on the front to acquire radiometric data. The robot is recovered from the same pipe opening from which it is launched, hence it drives the same distance out and back, measuring the same deposits twice. This achieves redundant radiometric and odometric measurements which adds further to statistical significance.

For this in-pipe radiation measuring robot, localization is essential, because it is required to report the precise location of each radiation source measured. Since the robot will measure the same deposit twice running forward and reverse , the locations of the two measurements must match up with each other precisely.

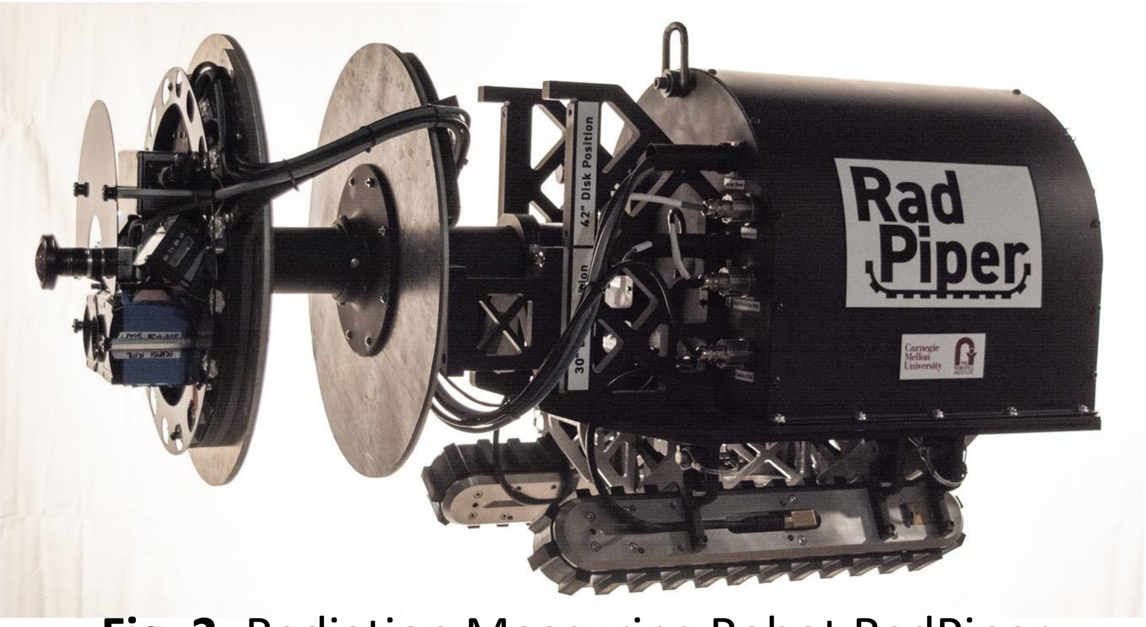

Fig. 2: Radiation Measuring Robot RadPiper

How Localization works

Odometry based on **track encoding** alone drifts unacceptably due to non-linearity. The three innovations that achieve requisite position and certainty are:

- Additional laser **rangefinder** for acquiring intermittent **absolute position** data;
- **Reciprocal preprocess of** sensor data: rangefinder filter & encoder counts calibration;
- Sensor fusion and trajectory optimization with **factor graph (GTSAM)**;

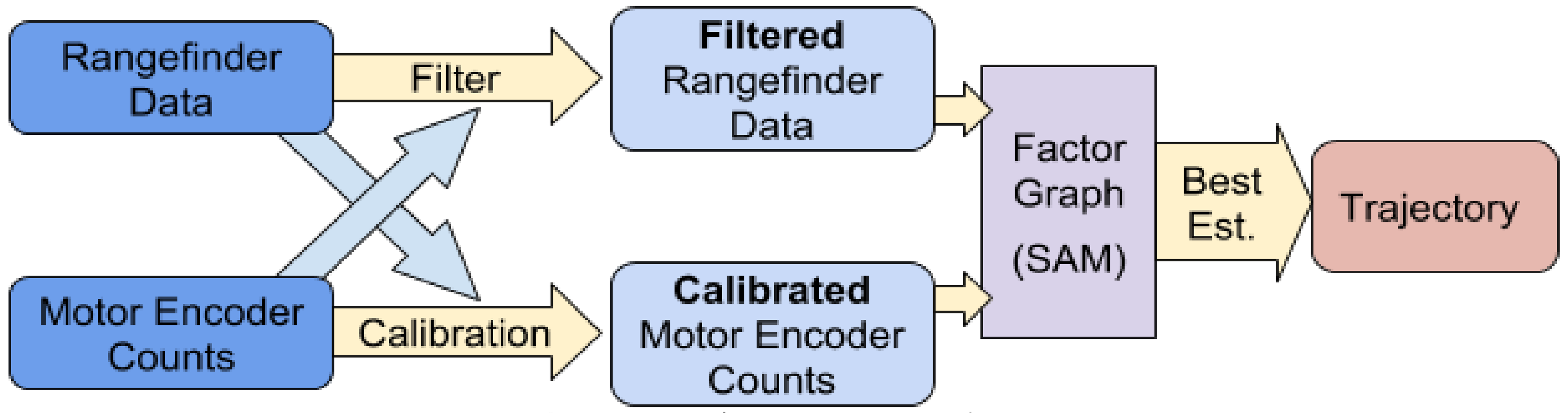

Fig. 4: Localization procedure

Iterative sensor filter and calibration:

- For n=0, coefficient C(counts/inch) is initialized by theoretical calculation based motor configuration, and

$$Location_{est}[0] \leftarrow 0$$

- Following $n = 0$, for any given sample index k, the steps below are taken to obtain $Location_{est}[k+1]$:
  1) Estimate $Location_{est}[k+1]$ with encoder counts:

  $$Location_{est}[k+1] = Location_{est}[k] + \frac{Counts[k+1] - Counts[k]}{C}$$

  2) Decide whether to update $Location_{est}[k+1]$ with rangefinder data. $thres$ is a selected value.
     if $|(Location_{est}[k+1] - Range[k+1])| > thres$
     then $Eliminate\,this\,sample$
     else $Location_{est}[k+1] \leftarrow Range[k+1]$
  3) If $Range[k+1]$ was a valid sample in *step(2)*, update the coefficient C.

Factor graph optimization (GTSAM):

- Down sample sensor data to save computation;
- Insert position estimates as nodes and measurements as edges in the graph;
- Edges for encoder counts are inserted with large variance
- Edges for rangefinder measurements are inserted with small variance
- Optimize for the maximum likelihood trajectory

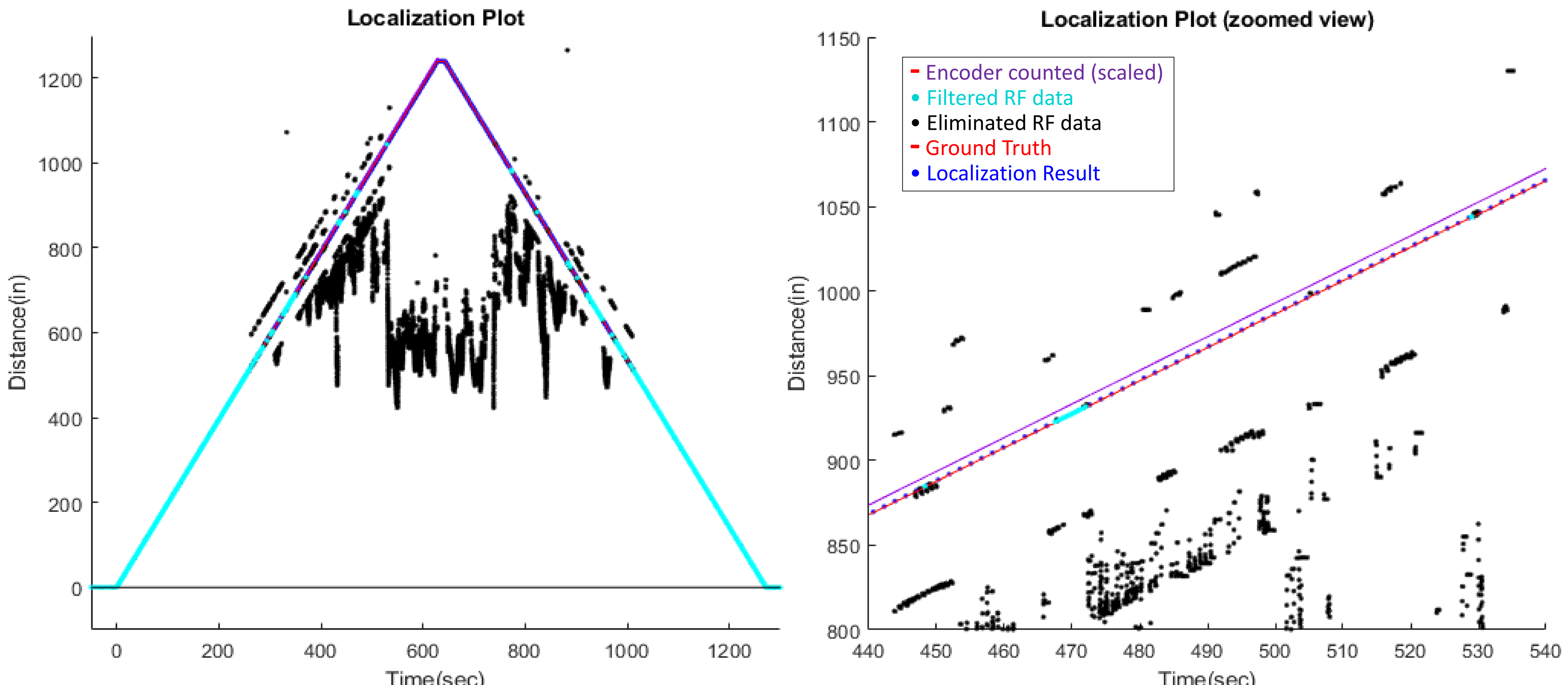

Fig. 5: Localization Result Plot

Experiment Validation

Evaluation I – Ground truth comparison

Error between the result and ground truth (from 8 100ft-long test runs): **Max. is 0.724in, Ave. is 0.106in and Std Deviation(SD): 0.0017 in.**

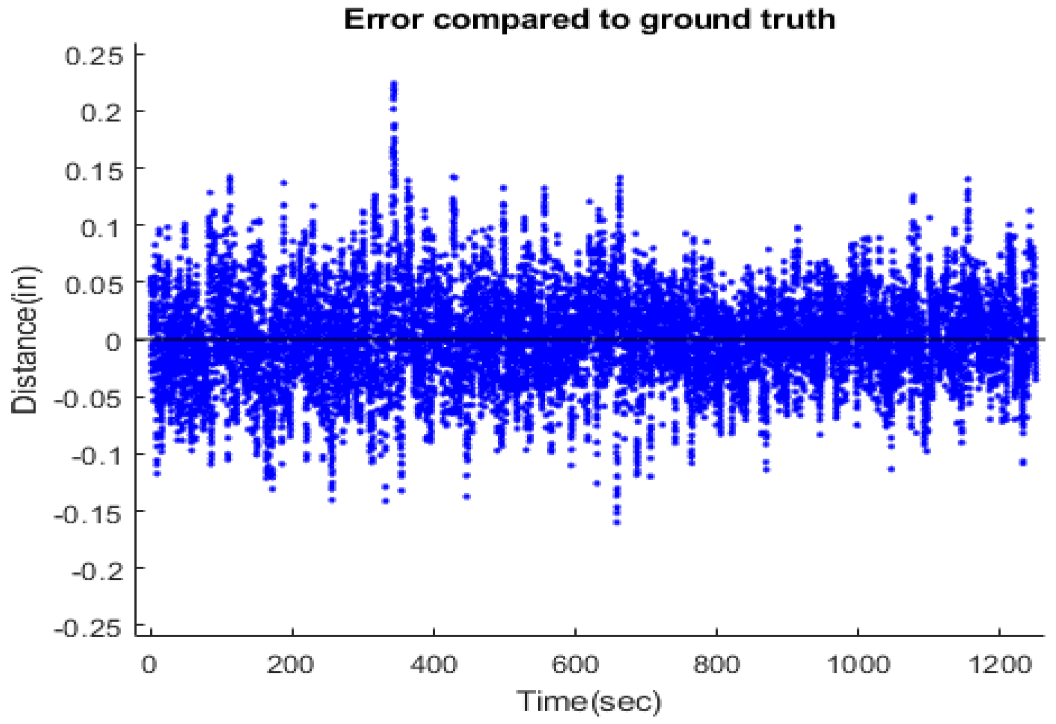

Fig. 6: GT-Res error from one run

Evaluation II – Block test

Comparing its own forward and reverse distance measurements, **the Max. error in between is 0.35in, Ave. is 0.11in and Std Deviation is 0.0024in.**

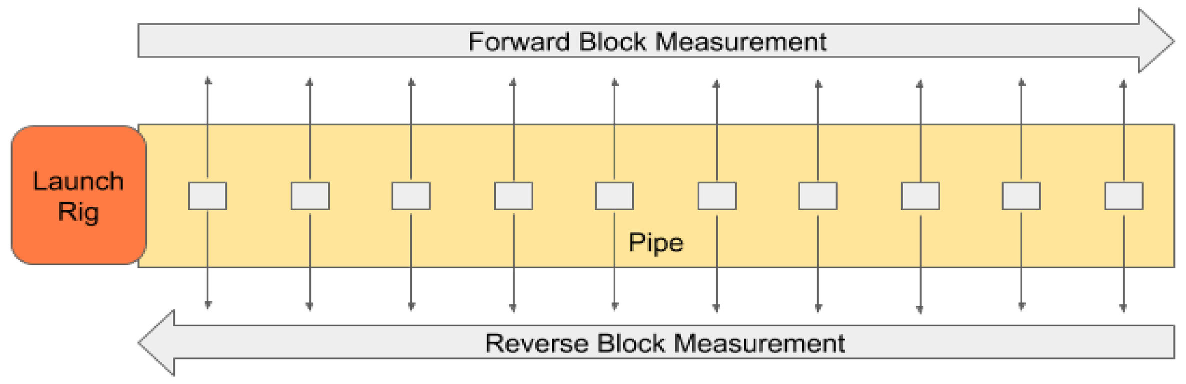

Fig. 7: Block test illustration

Future Work

Currently, the trajectory beyond 80ft is merely derived from encoder counts without any calibration, because rangefinder is no longer available after 80ft.

A promising solution is to visually recognize special features in pipe as landmarks and feed them into the existing factor graph.

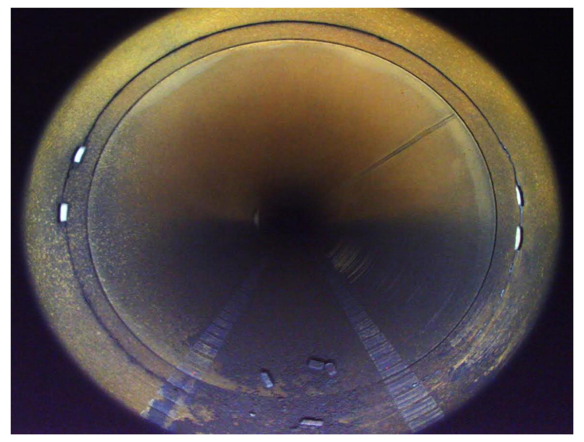

Fig. 8: Pipe joint

Conclusion

The proposed localization method is able to filter and calibrate sensor data successfully and generate an accurate trajectory for in-pipe robot.