Optical Kinematic State Estimation of Planetary Rovers using Downward-Facing Monocular Fisheye Camera

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Introduction

Knowledge of the kinematic state of rovers is critical to motion control and exploration, especially on rugged train like the surface of the Moon. Existing methods employ many internal encoders, potentiometers, and Hall effect sensors, which add components and wiring to moving parts and are susceptible to mechanical and electronic failures. Sensors may require thermal isolation and wiring that must be routed to prevent bending, flexing, and wear.

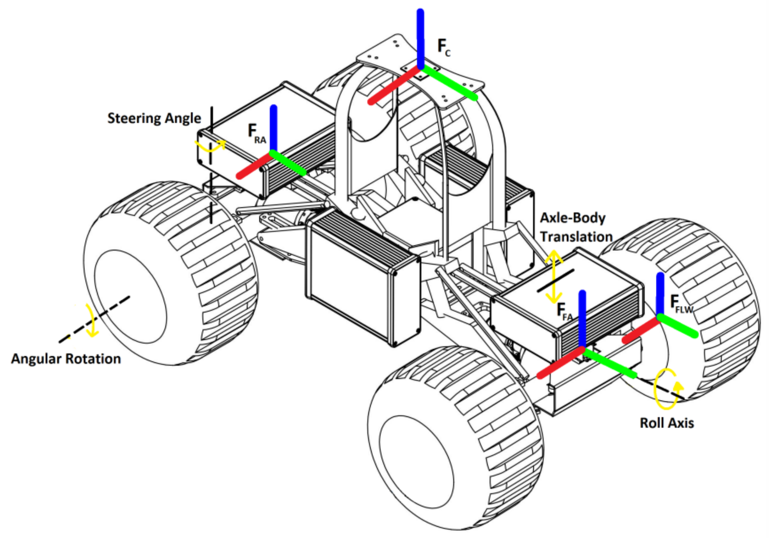
Where miniaturization counts, the limitations on mass, size, and power encourage elimination of sensors wherever possible. When not resource constrained, another sensing modality offers redundancy to proprioceptive measurements

Approach

This research seeks to estimate the kinematic state of rovers by using a downward-facing monocular fisheye camera. The method developed achieves this by defining manifolds along which tracked points of a kinematic link can move relative to its parent link. In any rover, kinematic constraints define the possible motions of a link. As long as the motions of all tracked points on the link do not project to the same point in the image (i.e. all points are moving directly away or directly towards the camera), the position of the link can be estimated with the method presented.

Kinematic Model

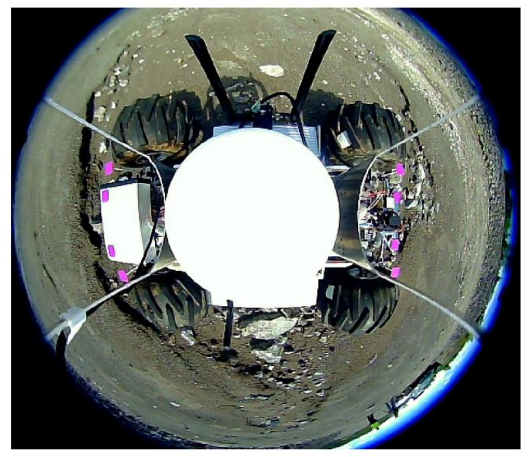
A four-wheel double-Ackermann steered rover is used as a test platform for this work. It has a passive suspension system that allows the rover to maintain compliance with uneven, rugged terrain. Each articulated axle of the dual-axle configuration can roll about the Y-axis and translate along the Z-axis. The steering joints can rotate about the axle frame's Z-axis. All motions are computed relative to the fixed camera frame at the top of the rover.



Depiction of (i) The coordinate frames of the camera, axle and wheels, illustrated with XYZ (RGB) axes. (ii) The permitted rotational and translational motions of the robot about their respective axes.

Camera Model

A downward-facing fisheye camera with a minimally occluding mount allows for near-full visibility of the rover throughout its range of motion. Calibration is performed so that any point in the image can be projected onto a unit sphere with the camera's focal point at its center. This ray that starts at the origin and passes through the point on unit sphere is intersected with various geometries to estimate kinematic state.



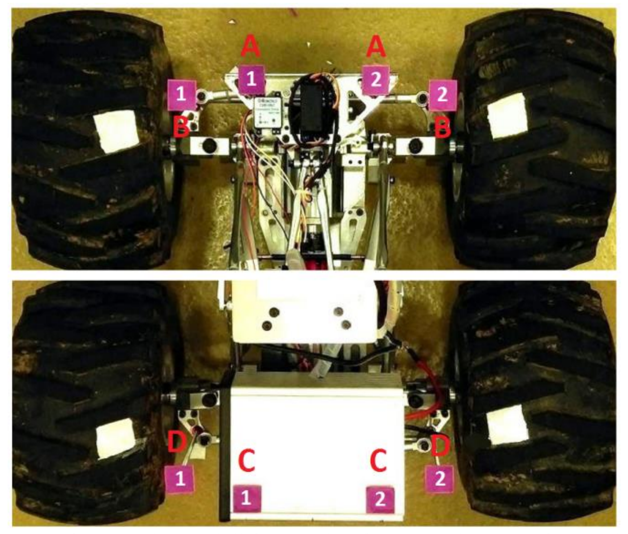
Kinematic Estimation

Axle Roll and Translation

On the test platform, the axle's kinematics constrain the motion of markers on the axle to a plane parallel to the camera's XZ plane, offset in the Y direction. The location of axle markers in 3D space (and thus the pose of the axle) can be obtained by intersecting the camera->marker rays with this plane.

Steering Angle

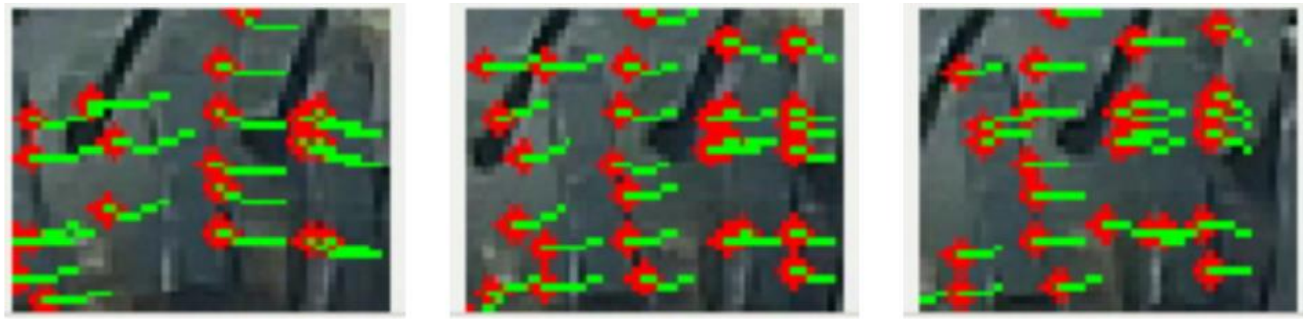
The motion of markers on the steering linkage is constrained to a plane parallel to the axle's XY plane, offset in the Z direction. The location of the markers in 3D space can be obtained by knowing the pose of the axle (from above) and then intersecting the camera-> marker rays with this plane.



Mono-color markers visible on the front and rear axles. Pairs A and C track front and rear axle roll respectively, while pairs B and D track front and rear steering angles. Also seen are the white correction markers present on the wheels.

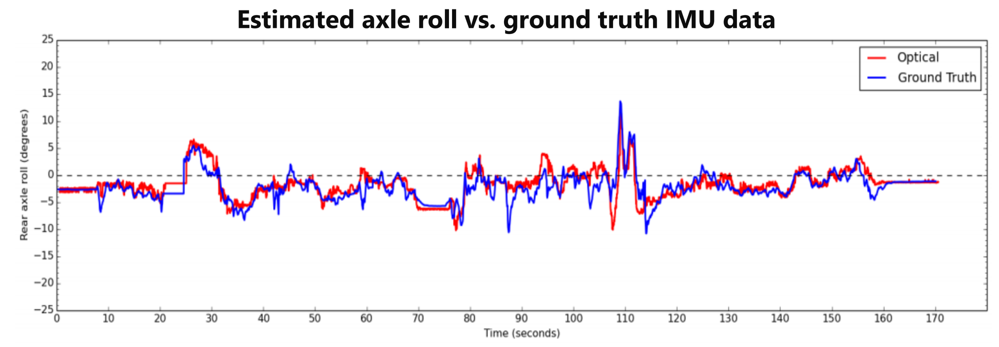
Wheel Rotation Estimation

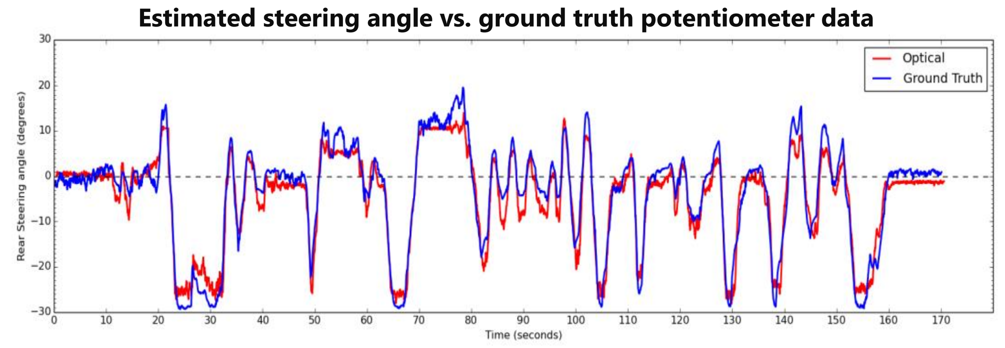
Applying forward kinematics using known joint angles gives a prediction for a region in the image where a rover wheel is. Lucas-Kanade optical flow is applied on the image region to obtain 2D displacement vectors. These vectors are projected onto a cylinder representing the wheel using the camera model and known kinematics, turning them into arc displacements in the wheel frame, which can be used to estimate rotation. Correction markers on the wheels are clearly visible once per rotation and are used to prevent drift in angular rotation.

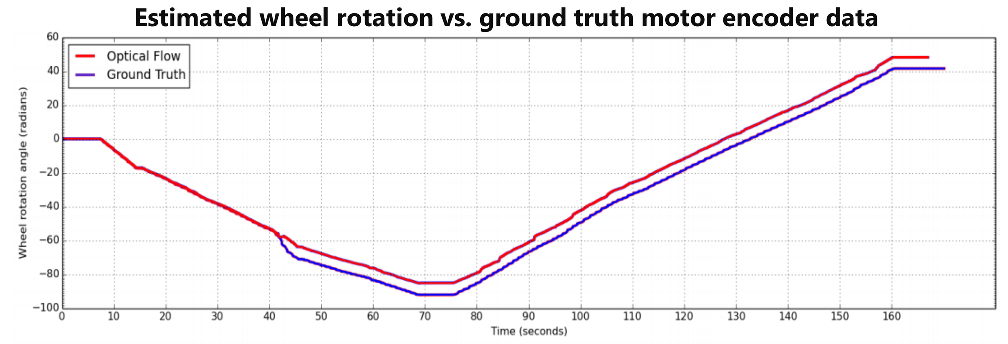


Results

The performance of the method was evaluated on datasets generated from field experiments conducted in a lunar analog site. Ground truth data was obtained from IMUs, potentiometers, and motor encoders onboard the rover.







Mean Absolute Error (MAE) and wheel rotation drift for three independent datasets

Dataset	Duration (secs)	Axle Roll MAE		Steering Angle MAE		Maximum wheel rotation drift (rad)
		Front	Rear	Front	Rear	
Dataset 1	82	1.65°	1.51°	2.49°	1.98°	0.86
Dataset 2	170	1.41°	1.32°	2.40°	2.49°	3.70
Dataset 3	257	2.41°	1.97°	1.86°	2.55°	1.78

The results convey overall agreement between optical and conventional methods. Some sources of error have been identified:

1. Systematic error in calibration results in consistent offsets in estimated steering angle
2. Drop in frame rate results in the loss of continuous data. Frame rate is critical in the case of optical flow, where features are lost
3. Loss of marker positions due to self-shadowing causes gaps in kinematic state data

Conclusions and Future Work

This work introduces a novel approach to kinematic state estimation in planetary rovers. The results demonstrate high confidence in a single camera system to preclude the need for nine proprioceptive sensors and achieve comparable kinematic state estimation.

Future work includes developing an optimized version of the algorithm robust to self-shadowing and abrupt changes in lighting that currently affect the system adversely. In addition, removing the dependence on fiducial markers in favor of shape and contour tracking may solve issues which stem from losing track of a single marker. Also, variances for the measurements can be estimated. Finally, performing visual odometry and optical kinematic estimation in conjunction using a single camera will achieve unprecedented odometry and slip estimation with utmost simplicity.