Attitude and Position Estimation on the Mars Exploration Rovers

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Abstract - *NASA/JPL's Mars Exploration Rovers acquire their attitude upon command and autonomously propagate their attitude and position. The rovers use accelerometers and images of the sun to acquire attitude, autonomously searching the sky for the sun with an articulated camera. To propagate the attitude and position the rovers use either accelerometer and gyro readings or gyro readings and wheel odometry, depending on the nature of the movement Earth-based operators have commanded. Where necessary, visual odometry is performed on images to fine tune the position updates, particularly in high slip environments. The capability also exists for visual odometry attitude updates. This paper describes the techniques used by the rovers to acquire and maintain attitude and position knowledge, the accuracy which is obtainable, and lessons learned after more than one year in operation.*

Keywords: attitude estimation, position estimation.

[1] Laboratory memo.

Mars Exploration Rover

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What and Why?

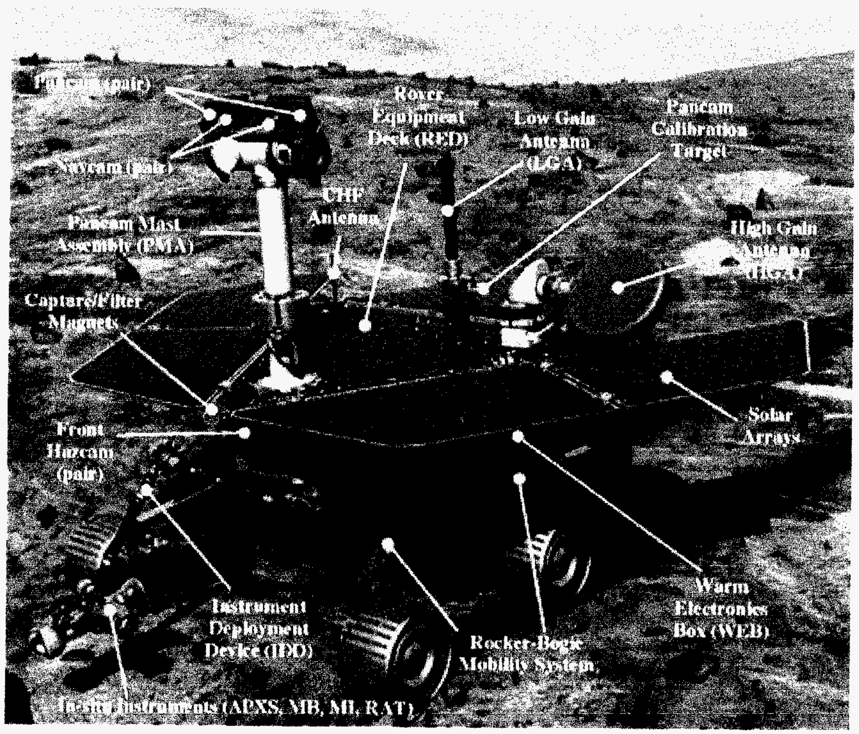
Mars Exploration Rover

- Software running on-board the Mars Exploration Rovers (MER) keeps track of the position and attitude of the rovers.
  - Surface Attitude Position and Pointing (SAPP)
  - Visual Odometry (Visodom)

- Ground operators need position and attitude
  - Plan drives
  - Point cameras
  - Determine expected bandwidth of UHF communications sessions
  - Determine expected power from solar panels due to relative orientation to sun

- Other Flight Software needs position and attitude
  - Plan driving and Instrument Deployment Device (IDD; a robotic arm) maneuvers
  - Perform safety checks
  - Point High Gain Antenna (HGA) at Earth
  - Point cameras and other science instruments in Mars relative frames

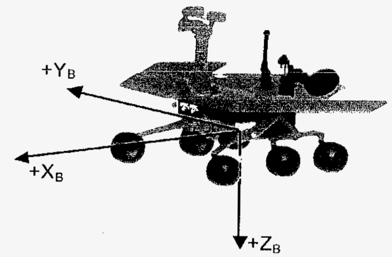
Restrictions and Requirements

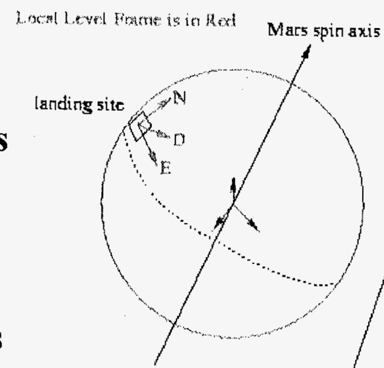


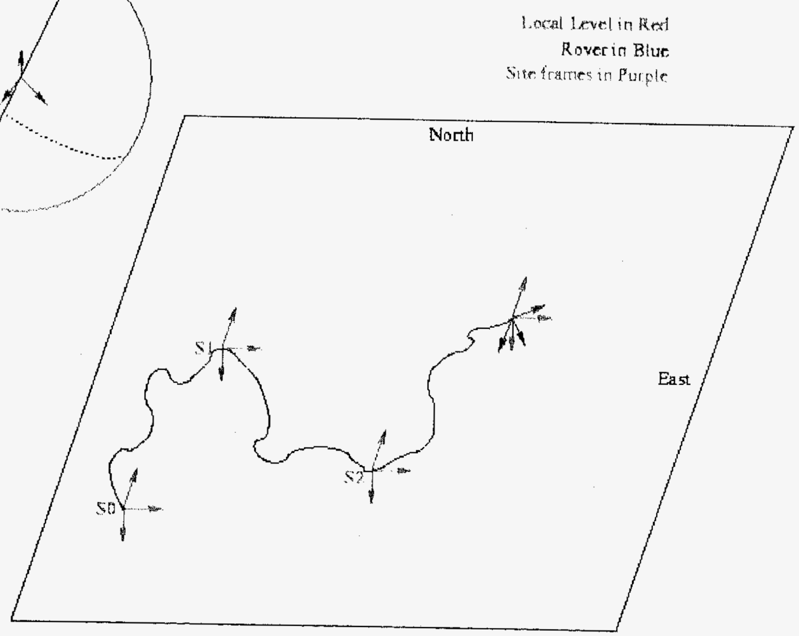
- **Limited sensors available**
  - **Litton LN-200 Inertial Measurement Unit (IMU)**
  - **Articulated camera with a 16° field of view (the left Pancam)**
  - **Wheel encoders**
- **Cannot run estimation software constantly due to power constraints**
- **The High Gain Antenna must be pointed at the Earth to within 2°, 3σ. Accounting for other error sources, this allows for no more than 1.5°, 3σ error in the attitude estimate.**
- **Position error accrued during a drive must be no greater than 10% of the traveled distance, up to a commanded distance of 100 meters.**

Coordinate Frames

- *J2000 Frame* (J): A standard inertial frame used in astronomical work.
- *Rover Frame* (B): The origin is near the bottom middle of the rover. The XY plane is parallel to the plane of the rover deck. The Z-axis points down, the X-axis points forward, and the Y-axis is determined using the right-hand rule. This frame moves with the rover.
- *Local-Level Frame* (LL): The origin is coincident with the Rover Frame. The X-axis points north, the Y-axis points East, and the Z-axis points to the center of Mars. This frame moves with the rover.
- *Site Frame* (S): The orientation is the same as Local-Level Frame. The origin is the same as the Local-Level Frame origin was at time this Site Frame was established (planted). Site Frames are planted by ground command throughout the mission to mark scientifically interesting locales. This frame is fixed to the Mars surface.



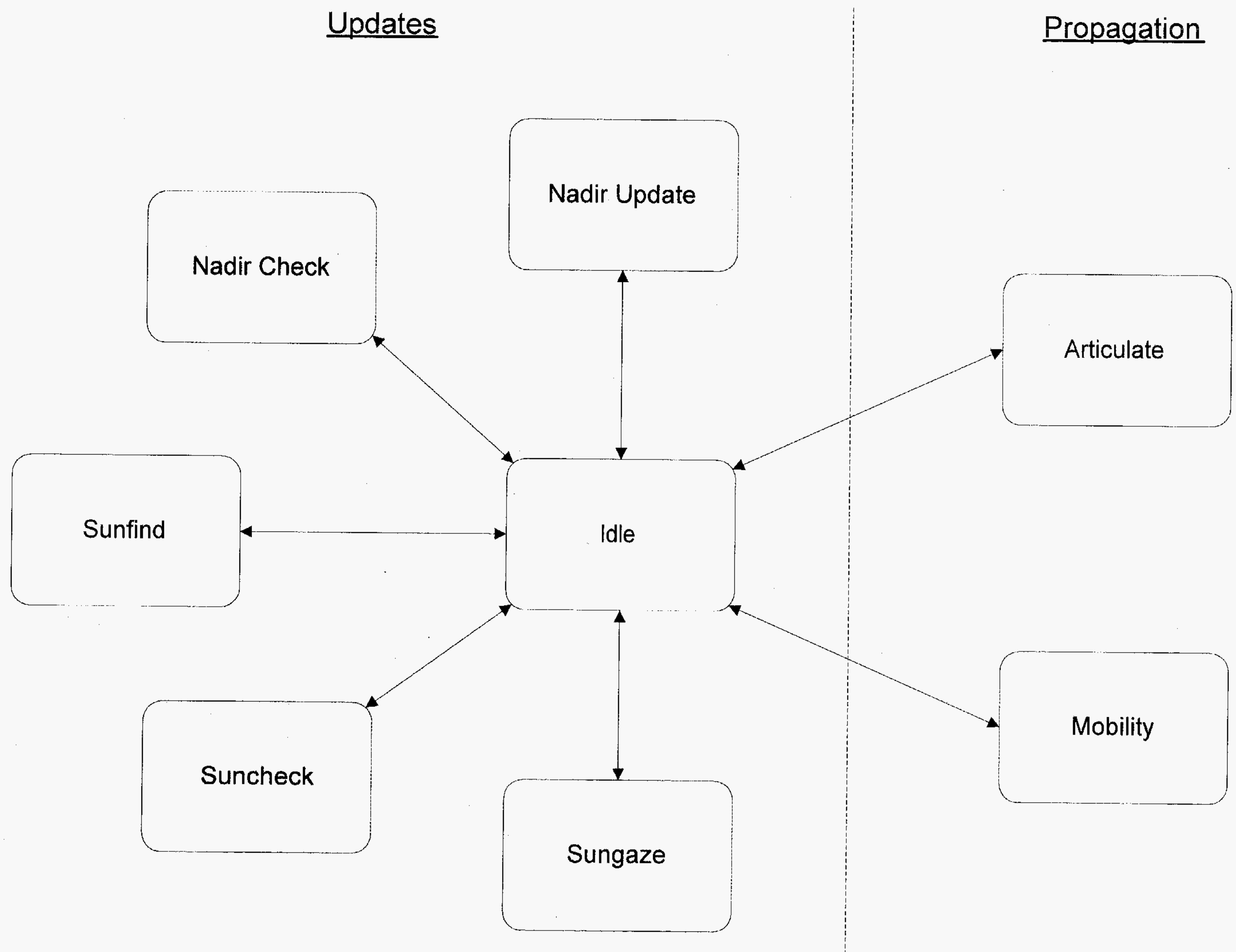




Format of Position and Attitude Information Published by SAPP

- A quaternion ($^{B}q^{LL}$) relating the Local-Level frame to the Rover Body frame.
- Two estimates of rover tilt, one derived from the current attitude estimate, $^{B}q^{LL}$, and the other derived from a single real-time accelerometer reading.
- The rover position, in the form of the Rover's x, y, and z coordinates in the current Site frame.
- An Attitude Quality Flag.

Navigation/Attitude Estimator (NATE)



Attitude Acquisition

- Three attitude acquisition modes (each is described in the following slides)
  - Nadir Update
  - Sunfind
  - Sungaze
- The rover must be stationary during these modes
- Each mode computes a delta quaternion, relating the previous attitude estimate to the new one.
- The delta quaternion is applied to the current attitude estimate via quaternion multiplication to produce a new attitude estimate.

Nadir Update

- **Goal: Determine the rover's roll and pitch.**
- **Averages accelerometer readings over a short period of time to determine the nadir vector (direction of gravity).**
- **Updates the roll and pitch components of the attitude estimate using the nadir vector. Does not alter the yaw component.**

- **Safety checks:**
  - **Rejects average if the IMU marked too many samples invalid**
  - **Rejects average if the gravity vector magnitude does not match the known magnitude of Mars gravity**

Sunfind

Mars Exploration Rover

- Goal: Determine the rover's heading.
- Searches a plane of the sky for the sun using one of the cameras on the Pancam Mast Assembly
  - Starts looking where the sun should be at if the current attitude estimate is correct
  - Searches only the plane at the elevation the sun should be for the current time of day. Uses the current tilt estimate to determine how to point the camera.
  - Stops the search when the sun has been found
- Updates the yaw component of the attitude estimate using the direction to the observed sun and the known position of the sun in the sky at the current time. Does not alter the roll or pitch components.
- Safety checks:
  - Rejects observed sun if it is not at the correct elevation
  - Takes confirming images and rejects observed sun if it does not move the expected amount in these images
  - Performs no update if the sun is at local noon

Sungaze

Mars Exploration Rover

- **Goal: Determine the rover's attitude to sufficient accuracy to point the HGA.**
- **Watches the sun move across the sky for several minutes without moving the camera**
- **Compares the observed sun trajectory in Rover frame with the expected sun trajectory in LLF frame. Uses the QUEST* algorithm to generate an attitude update that reconciles the two trajectories.**
- **Updates roll, pitch, and yaw of the attitude estimate.**

*** Shuster and Oh, 1981**

Attitude Acquisition Machine

- **In addition to low-level commands corresponding to each of the aforementioned modes, SAPP provides high-level commands for acquiring attitude.**

- **GetTiltAttitude performs a Nadir Update**
- **GetCoarseAttitude performs a Nadir Update followed by a Sunfind**
  - **Guarantees that the rover tilt is known before performing the Sunfind**
- **GetFineAttitude performs a Nadir Update, a Sunfind, and a Sungaze, in that order**
  - **Guarantees that the rover tilt is known before performing the Sunfind**
  - **Guarantees that the camera is left pointed at the sun before performing the Sungaze**

Attitude Propagation

- Two attitude propagation modes (each is described in the following slides)
  - Articulate
  - Mobility (also propagates position, as described later)

- In each of these modes, the attitude estimate changes at an 8 Hz rate

Articulate

- **Goal: Propagate changes in attitude when not driving**
- **Starts with the attitude estimate when the mode is entered**
- **Takes a short accelerometer average to use as a *reference vertical***
- **Propagates the attitude estimate at 8 Hz using gyro measurements**
  - **Subtracts out the Mars rotation rate (as determined from the current attitude estimate) from that detected by the gyros**
- **Periodically takes accelerometer averages. Updates the attitude estimate with the relative tilt difference between the *reference vertical* and the current accelerometer average. This helps mitigate error introduced by gyro drift.**

Mobility – Attitude Propagation

- **Goal: Propagate changes in attitude when driving**
- **Starts with the attitude estimate when the mode is entered**
- **Propagates the attitude estimate at 8 Hz using gyro measurements**
  - **Subtracts out the Mars rotation rate (as determined from the current attitude estimate) from that detected by the gyros**

- **There is a submode of Mobility which can propagate the attitude using only wheel-odometry knowledge. This is for use if our IMU ever fails.**

- **For reference, the rover performs turns-in-place at approximately 2.1°/second.**

Mobility - Position Propagation

- Goal: Propagate changes in Site-frame position when driving
- Starts with the position when the mode is entered
- Propagates the position estimate at 8 Hz using wheel-odometry and the newly determined attitude estimate
  - The attitude update is computed using the gyros, as described in the previous slide
  - The position change in Rover-frame is determined from wheel-odometry
  - The delta-position is converted from Rover-frame to Site-frame using the freshly propagated attitude estimate
  - The Site-frame position estimate is updated with the delta-position in Site-frame

- For reference, the rover drives at approximately 3.75 cm/second on flat and level ground.

Visual Odometry

Mars Exploration Rover

- The aforementioned position propagation technique cannot measure translational slip.
- Visual odometry software can be used to update the onboard position estimate.
- Autonomously selects and tracks features in stereo image pairs taken at different locations.
- Requires longer time to drive, so we use it only when we expect large amounts of slip and require a precision drive.

Operations on Mars

- Spirit has driven slightly less than 5 km
- Opportunity has driven slightly less than 6 km
- Successfully propagating position and attitude using a combination of wheel-odometry, gyro readings, and visual odometry
- Sungaze is occasionally used to update attitude
  - The attitude knowledge achieved after a Sungaze is accurate enough for pointing the HGA at Earth during communications sessions
  - Sungaze is used to update the attidue about every 10,000 seconds of active gyro integration (roughly every 20 Sols)
- New Site-frames are occasionally planted to eliminate local position error.
  - Typically, a new Site-frame is planted at each new location where the rover stops to make science observations.

Backup Material

Essential Information Provided by other Flight Software

- **Inertial Vector Propagator software**
  - Provides the locations of various celestial bodies, such as the sun
- **Imaging Services software**
  - Takes images
  - Looks for the sun in an image
  - Uses the camera model to transform the sun's location in an image to Rover Body frame
- **Timing Services**
  - Provides the current time

Attitude Quality Flag

- **Four attitude quality grades:**
  - ***Unknown*: The attitude estimate should not be trusted. This is the initial value after landing.**
  - ***TiltOnly*: The attitude estimate is only good for tilt determination.**
  - ***Coarse*: The attitude estimate is "complete", but is crude.**
  - ***Fine*: The attitude estimate is complete and sufficient for pointing the HGA.**

- **Grades only apply to Attitude**
- **Grades are event-driven. SAPP is NOT keeping a running covariance or any other sort of "continuous" quality estimate.**
- **Quality Grades change when:**
  - **Completing an update action on success or failure**
  - **Too much gyro drift has been swallowed into the attitude estimate**

Attitude Checks

- **There are two NATE modes for checking the accuracy of the attitude estimate.**

- **Nadir Check determines the nadir vector exactly as in Nadir Update**
  - **Compares the observed nadir vector to the expected nadir vector, as determined from the current attitude estimate**
  - **The check passes if the angle between the vectors is less than a tolerance. It fails otherwise.**
  - **Does not update the attitude**
- **Suncheck takes an image of the sky where the sun should be based on the current attitude estimate**
  - **Compares the observed sun vector to the expected sun vector, as determined from the current attitude estimate**
  - **The check passes if the angle between the vectors is less than a tolerance. It fails if the angle is greater or the sun is not found in the image.**
  - **Does not update the attitude.**