

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 Problem statement

For over a year, the Mars Exploration Rovers, Spirit and Opportunity, have been driving their way across the surface of Mars, gathering a wealth of information about the planet. As they travel, onboard flight software keeps track of their position and attitude, which is needed by other flight software and by ground operators (*i.e.*, Earth-based mission operations personnel).

Ground operators use the position and attitude of the rovers to make numerous decisions and predictions. The attitude is used to determine the expected bandwidth of UHF communications sessions, how much power the rovers can get from the solar panels due to their relative orientation to the sun, how much the rover will slip while driving, whether it is safe to use the Rock Abrasion Tool (a rock drill) without causing the rover to slip, etc. Ground operators use the position to plan drives and determine where to point the cameras and other science instruments.

Other flight software uses the position and attitude as well. The navigation, driving, and Instrument Deployment Device (IDD; a robotic arm) software uses the position and

attitude to plan maneuvers and perform safety checks. Standup software, which unfolded the rover after landing, used the attitude to perform safety checks. The High Gain Antenna (HGA), Pancam Mast Assembly, and Payload software use the attitude and position to point the HGA, cameras, and other science instruments.

1.1 Restrictions

Each rover has two sensors that are used in the nominal situation to determine its attitude. There is a Litton LN-200 Inertial Measurement Unit (IMU), and an articulated camera with a 16 degree field of view. The IMU and encoders on the wheels are used to propagate the rover's position.

The attitude estimation software does not run constantly. Since the rovers are solar powered, there is a limited amount of power available for use each day. The IMU uses too much power to keep it on constantly. Because the rover is stationary the majority of the time, the IMU is only turned on when the rover's attitude is expected to be changing. This also prevents the introduction of gyro drift errors while the rover is known to be stationary.

The flight software responsible for keeping track of the rovers' attitude and position has requirements it must meet. The most stringent requirement on the attitude knowledge derives from the need to point the High Gain Antenna (HGA) at the Earth to within 2 degrees, 3σ . After accounting for the other error sources involved with pointing the HGA, this allowed for no more than 1.5 degrees, 3σ error in the attitude estimate. The requirement on the position knowledge propagation was that the position error accrued during a drive must be no greater than 10% of the traveled distance, up to a distance of 100 meters.

2 SAPP

The Surface Attitude Position and Pointing (SAPP) software, which runs onboard the rovers, is responsible for keeping track of the rover's position and attitude on the surface of Mars. SAPP uses four coordinate frames,

described in Table 1. SAPP estimates the rover’s attitude with respect to Local-Level Frame. It can produce an attitude estimate while stationary using the accelerometers and a panoramic camera. It propagates the attitude estimate using the gyros while driving and using the gyros and accelerometers while moving the IDD and during parts of the Standup process. SAPP maintains an estimate of the rover position with respect to the current Site frame. It can do this using wheel-odometry or a combination of wheel-odometry and gyro readings.

Table 1. Frames used by the attitude and position estimation software.

Name	Description
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.

SAPP provides the position and attitude information to other flight software and the ground operators in the form of the following:

- A quaternion (${}^Bq^{LL}$) relating the Local-Level frame to the Rover Body frame.
- Two estimates of rover tilt, one derived from the current attitude estimate, ${}^Bq^{LL}$, 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.

As mentioned above, SAPP does not continuously update the rover’s attitude and position. The SAPP task processing runs at a rate of 8 Hz, but most of the time, it is in an Idle state in which it does not update its estimates.

The Navigation/Attitude Estimator (NATE) is a subsystem of the SAPP software that does the actual computation to determine and propagate the attitude and position. NATE is controlled by the state machine shown in Figure 1. NATE consists of three modes for acquiring attitude, two modes for checking the current attitude estimate, and two modes for propagating the attitude, one of which also propagates the position. Each of these modes is described in more detail in the following sections.

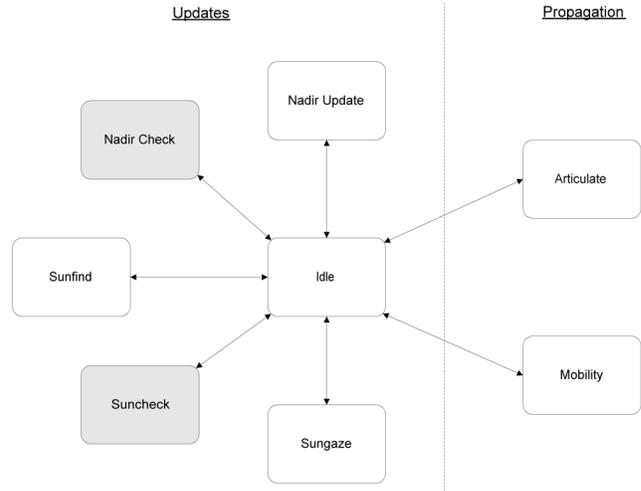


Figure 1. Navigation/Attitude Estimator (NATE) state machine.

Some of the NATE modes perform a single update of the attitude estimate and then automatically transition the NATE state machine back to the Idle mode when they are complete. Those modes are shown on the “Updates” side of Figure 1. The modes on the “Propagation” side continuously update the attitude estimate or both the attitude and position estimates. These modes only return NATE to Idle mode when SAPP receives a command to stop propagating. Nadir Update and Sunfind inherit parts of their algorithms from the techniques used on the Mars Pathfinder mission [4].

Almost all numerical values used by SAPP’s algorithms are parameters which can be set by the ground operators. This includes threshold values, minimum and maximum bounds, etc.

SAPP relies on other onboard software for some services. A software module called the Inertial Vector Propagator (IVP) provides the locations of various celestial bodies, such as the sun. IVP uses conic approximations to model the movement of these bodies. SAPP also uses the Imaging Services software to take images of the sky, look for the sun in an image [3], and transform the sun’s location in the image to Rover Body frame. Other software also provides SAPP with the current time.

2.1 Attitude Quality Flag

SAPP is usually in Idle mode, paying no attention to new data, and so no running covariance is kept. Instead, SAPP provides an Attitude Quality Flag to other flight software and ground operators. The flag is an indication of the completeness of the estimate, rather than an indication of the accuracy.

The SAPP Attitude Quality Flag has four possible values:

- 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.

Typically, the flag only changes value when NATE exits one of its non-Idle modes. The sections below describe the effect of each mode on the Attitude Quality Flag.

Other flight software uses the Attitude Quality Flag value to determine if the attitude knowledge is complete enough to safely perform an activity. For example, the Miniature Thermal Emissions Spectrometer (MTES) cannot be pointed at the sun. So the MTES software requires Coarse or better attitude knowledge when pointing at the sky in order to avoid the sun.

2.2 Attitude acquisition

NATE has three modes for attitude acquisition: Nadir Update, Sunfind, and Sungaze. It is necessary for the rover to be stationary for these modes to work properly, although a variation of Sungaze can handle small perturbations of the rover attitude during attitude acquisition. We describe each mode below.

Each method computes a delta quaternion, relating the previous attitude estimate to the new one. The current attitude estimate is then updated via quaternion multiplication.

2.2.1 Nadir Update

The goal of Nadir Update is to determine the rover’s roll and pitch using the nadir vector, or direction of gravity. This mode takes a running average of accelerometer measurements over a short period of time (typically 10 seconds). The IMU and its driver software do some basic

validity checking, so that invalid samples are not included in the average. The magnitude of the averaged gravity vector \bar{g}^B is compared to the known magnitude of Mars gravity. If the difference is greater than a threshold, or too few valid accelerometer measurements were collected, then the mode terminates unsuccessfully.

Otherwise, SAPP computes an update to the attitude estimate. The algorithm uses the current attitude estimate to compute an estimate of the nadir vector \bar{n}^B . If \bar{n}^B and \bar{g}^B are not collinear, then the algorithm determines a delta quaternion δq^B to update the current attitude estimate’s tilt. The update rotates the current estimate along the cross-product of \bar{n}^B and \bar{g}^B , leaving the yaw unchanged.

SAPP sets the Attitude Quality Flag to TiltOnly and applies δq^B using (1), where \otimes represents the quaternion multiplication operator.

$${}^B q_+^{LL} = \delta q^B \otimes {}^B q_-^{LL} \quad (1)$$

If Nadir Update terminates unsuccessfully due to too few accelerometer measurements or a failed gravity magnitude check, then the SAPP attitude estimate is left unchanged and the SAPP Attitude Quality Flag is changed to Unknown.

2.2.2 Sunfind

The goal of Sunfind is to determine the rover’s heading from the direction to the sun and the current tilt. The rover searches a plane of the sky for the sun at the appropriate elevation for the time of day. There are two phases to the process, the search phase and the confirmation phase. The algorithm assumes that the rover’s tilt has been determined by Nadir Update and does not change it.

In the search phase, the rover takes a picture of the sky in the direction the sun should be, assuming the starting attitude estimate is correct. If the sun is not found in the image [3], then it takes additional pictures, moving the camera between each image. The camera is moved along a plane perpendicular to the nadir direction, as determined by the current attitude estimate, and at the known sun elevation for the current time. If the sun is identified in an image, the algorithm moves to the confirmation phase, otherwise it continues taking pictures until it has examined the entire search plane.

In more detail, the search phase applies a heading adjustment δq_i^{LL} to the current attitude estimate ${}^B q_i^{LL}$ to generate a “guess” ${}^B q_i^{LL}$ at the true attitude, as per

$${}^B q_i^{LL} = {}^B q^{LL} \otimes \delta q_i^{LL} \quad (2)$$

Initially, the adjustment is the identity, so that the first guess ${}^B q_0^{LL} = {}^B q^{LL}$. Using this guess, the algorithm computes where the sun should be, $\vec{p}(0)$, and takes a picture there, as shown in Figure 2. If the sun is not identified in the image, the algorithm computes a new adjustment per

$$\delta q_i^{LL} = \begin{bmatrix} 0 \\ 0 \\ \sin((i \cdot \Delta\xi)/2) \\ \cos((i \cdot \Delta\xi)/2) \end{bmatrix} \quad (3)$$

where i is incremented with each guess and $\Delta\xi$ is the angle between each guess. The angle $\Delta\xi$ varies with the camera field of view and the image elevation.

Once the sun is identified, the confirmation phase begins. The algorithm performs an elevation check, comparing the observed sun's elevation with the known elevation of the sun at the current time. If the potential sun is rejected due to a large elevation error, then the algorithm returns to the search phase. If the elevation check passes, the rover takes two confirming images. Each confirming image is pointed using an adjustment δq_i^{LL} computed from the heading to the potential sun in the previous image. The algorithm performs another validity check, comparing the movement of the observed sun between the images. If the distance moved does not match the expected movement of the sun, the potential sun is rejected and the search phase continues from the point it left off.

After finding and confirming the sun, Sunfind computes a final adjustment δq^{LL} , and applies it to the official attitude estimate per

$${}^B q_+^{LL} = {}^B q_-^{LL} \otimes \delta q^{LL} \quad (4)$$

At local noon, however, when the sun is within a small region of the sky around the Local-Level $-Z$ -axis (the zenith), the heading cannot be determined using this technique. In this case, Sunfind completes successfully (since it found the sun), but the attitude estimate is not updated.

A successful Sunfind will set the SAPP Attitude Quality Flag to Coarse, while a failed Sunfind will set the flag to Unknown. When Sunfind completes, it leaves the camera pointed at the sun. This sets things up for a Sungaze to follow.

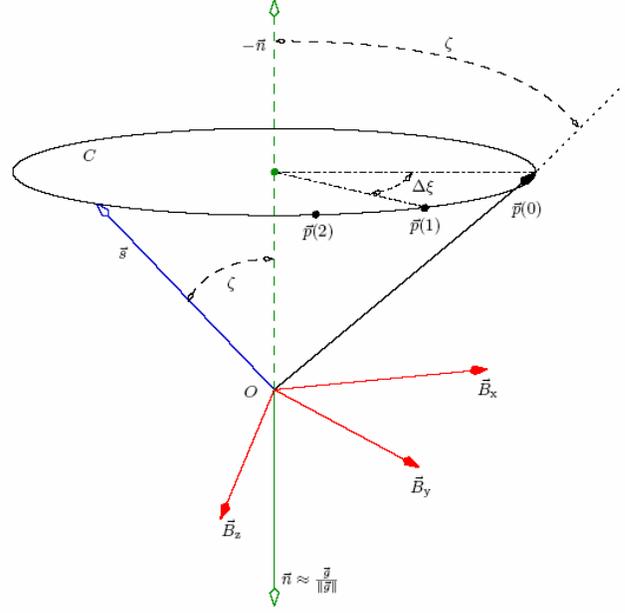


Figure 2. Sunfind. For a given landing site and time, the sun \vec{s} is known to lie at a constant declination ζ from the local zenith $(-\vec{n})$. The cone C , formed by sweeping the inertial sun vector about the zenith forms the basis for the Sunfind activity. An initial candidate camera aiming point $\vec{p}(0)$ is chosen on the cone C , and then rotated in succession about the zenith in $\Delta\xi$ steps until the Sun is seen.

2.2.3 Sungaze

Whereas Sunfind assumes the rover tilt knowledge is correct, Sungaze starts with no assumptions about the rover's attitude knowledge, and determines the complete attitude of the rover. Sungaze "watches" the sun move through the sky, taking images at regular intervals, without moving the camera. These sun observations are transformed to Local-Level Frame using the current SAPP attitude estimate, forming a set of observed sun-vectors. A corresponding set of expected sun-vectors in Local-Level Frame is obtained from IVP for the same times as the observed vectors. Both of these sets are fed into the QUEST algorithm [6] for quaternion estimation.

With each new measurement, QUEST computes a new attitude estimate and covariances. Sungaze continues taking images and feeding them to QUEST until a timer (currently ten minutes) expires, although there is an option to terminate early if the covariances converge to the 1.5° , 3σ level before the timer expires.

If the covariances converged, the attitude is updated with the QUEST results, and the Attitude Quality Flag is set to Fine. Additionally, a gyro measurement counter, or "timer", is reset to zero. Section 2.4 explains how the gyro measurement counter is used. If the covariances did not

converge, no attitude update occurs and the Attitude Quality Flag is set to Unknown.

SAPP also has three variations on the basic Sungaze technique, but the details are beyond the scope of this paper. The variations use additional sensors and add some functionality to that of the basic mode.

2.2.4 Attitude Acquisition Machine

Each of the three NATE modes described above for acquiring attitude can be executed directly by a command to SAPP. Two of the modes, however, make initial assumptions. Sunfind assumes that tilt knowledge is known, and Sungaze assumes that the camera is pointed at the sun. When using the primitive commands, there is no guarantee that those assumptions are correct.

SAPP provides high-level commands for acquiring attitude. The `GetTiltAttitude`, `GetCoarseAttitude`, and `GetFineAttitude` commands attempt to achieve the corresponding attitude quality. The Attitude Acquisition Machine in SAPP handles these commands by executing the primitive NATE modes in an order that guarantees that each mode's assumptions are met.

The `GetTiltAttitude` command performs a Nadir Update. This command is not any different than the primitive Nadir Update command, but it is provided for symmetry with the following two commands.

The `GetCoarseAttitude` command performs a Nadir Update and then a Sunfind. If the Nadir Update fails, then the process is aborted without performing the Sunfind.

The `GetFineAttitude` command performs a Nadir Update, a Sunfind, and a Sungaze, in that order. If either the Nadir Update or Sunfind step fails, then the process is aborted without performing the remaining NATE modes.

2.3 Attitude checks

NATE has two modes for checking the attitude estimate, namely Nadir Check and Suncheck. These modes take a new measurement and compare it to an expected value derived from the current attitude estimate. If the measured value is within a tolerance of the expected value, then the check passes. Otherwise, it fails.

Neither mode changes the attitude estimate, regardless of success or failure. Successful checks do not change the Attitude Quality Flag either, although a failed check sets it to Unknown.

2.3.1 Nadir Check

Nadir Check determines the nadir vector in exactly the same manner as Nadir Update, averaging accelerometer

readings. It performs the same sanity checks as Nadir Update, checking that enough valid samples have been collected and comparing the magnitudes of the observed gravity vector and known Mars gravity. A failed sanity check causes the mode to abort without changing the Attitude Quality Flag.

Once the average is computed, and the sanity checks passed, the observed nadir vector is compared to the expected nadir vector, as determined from the current attitude estimate. The check passes if the angle between these vectors is less than a parameterized tolerance and fails otherwise.

2.3.2 Suncheck

Suncheck takes a single image of the sky where it believes the sun should be based on the current attitude estimate. If the sun is not in the image, then the Suncheck fails. If the sun is in the image, then the observed sun vector is compared to the expected sun vector, which is based on the current attitude estimate. The check passes if the angle between these vectors is less than a parameterized tolerance and fails otherwise. Suncheck leaves the camera pointed at the sun.

2.4 Attitude propagation

In the Articulate and Mobility modes, SAPP propagates the rover's attitude. Mobility mode also propagates the rover's position, described in Section 2.5. In each of these modes, SAPP's attitude estimate is changing at an 8Hz rate, rather than only when the mode exits, as with the attitude acquisition modes.

The SAPP Quality Flag is never improved by propagation. If the attitude was Unknown, Tilt-Only, or Coarse at the start of the mode, then the flag will be unchanged at the end. If the flag was Fine when the mode began, it is possible that it will be downgraded to Coarse if the gyro measurement counter exceeds a tolerance (currently 15 minutes worth of propagation) while SAPP is in the mode. The gyro measurement counter is incremented each control cycle while in Articulate or Mobility mode.

2.4.1 Articulate

The goal of the Articulate mode is to propagate changes in attitude. Articulate mode is intended for use when the IDD is in use, as well as during certain parts of the rover Standup process. This mode starts with the SAPP attitude estimate at the time Articulate mode is entered. It uses the gyros and accelerometers to propagate this estimate forward at an 8 Hz rate.

The gyros detect the motion of the rover in an inertial frame, reporting the sum of both the rotation of the rover

relative to the Local-Level Frame and the rotation of the Local-Level Frame relative to an inertial frame. The latter rotation is due to the rotation of Mars on its axis. Since we only want to incorporate the rotation of the rover relative to the Mars surface when integrating the gyros, we must subtract out the Mars rotation, which IVP provides in Local-Level Frame for our position on Mars. SAPP converts the Mars rotation vector to Rover Body Frame using the current attitude estimate and then subtracts it from the rotation the gyros measured. The remainder is the rotation of the rover relative to the surface of Mars, which is used to propagate the rover's attitude.

Since there is some gyro drift, propagating on the gyros will slowly introduce attitude error. To partially mitigate this, accelerometer measurements are used to detect changes in tilt. An initial average, or *reference vertical*, of accelerometer measurements is taken at the beginning of the Articulate mode. Then, regular accelerometer averages are conducted throughout the rest of the mode. The algorithm updates the attitude estimate with the relative tilt difference between the reference vertical, converted to Rover Body frame using the latest attitude estimate, and the latest accelerometer average. Yaw knowledge is not changed by this operation, although it is by the gyro integration.

2.4.2 Mobility

The goal of the Mobility mode is to propagate the attitude and position of the rover. We discuss attitude propagation here and position propagation in Section 2.5. Mobility mode is intended for use when the rover is driving. This mode starts with the SAPP attitude estimate at the time Mobility mode is entered. It uses only the gyros to propagate this estimate forward since the quality of the gyros in our IMU is sufficient and this keeps the software simple. The maximum drift in the LN-200 IMU specification is 3°/hour, although we have seen much lower drift than this. Mobility mode uses the same algorithm as Articulate for propagating the gyros, but it does not use accelerometer readings to update the tilt. SAPP samples the gyros at an 8 Hz rate during the integration, while the rover performs turns-in-place at approximately 2.1 degrees/second.

SAPP's Mobility mode has a submode in which it does not use the gyro to propagate the attitude. This off-nominal mode is intended to be used if the gyros are known to be faulty. This submode propagates the attitude with knowledge gained from wheel-odometry. The details of the wheel-odometry algorithm are given in Section 2.5.

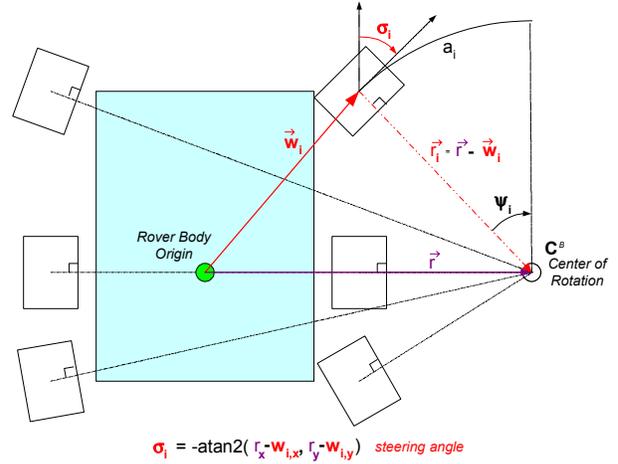


Figure 3. Wheel odometry

2.5 Position propagation

In the Mobility mode, SAPP propagates the rover's position in Site frame. The position propagation is done by wheel-odometry, based partly on [1][2][7], using the attitude changes determined from the gyro. During each control cycle Mobility mode updates the attitude estimate first, as described in Section 2.4.2. Then it computes the position change in Rover Body Frame using the algorithm described below. It converts the position change to Site frame using the freshly propagated attitude estimate. Finally, the algorithm propagates the current position estimate with the Site frame position change. The position updates are calculated at an 8 Hz rate, while the rover drives at approximately 3.75 cm/second on flat and level ground.

If the driving software commands a straight or near-straight drive, then the rover determines the position change as follows. For each of the six wheels, the arc length a_i that the wheel rotated through is computed from the angle that the wheel rotated and the wheel radius. The change in position along the Rover Body frame XY plane is then computed in (5), where σ_i is the steering angle for wheel i , as shown in [7]. The steering angle σ_i is defined as zero for a wheel pointed straight ahead and increases with clockwise rotation (viewed from above) of the wheel.

$$\begin{aligned}
 (\Delta x)^B &= (\sum_{i=1}^6 (a_i \cos \sigma_i)) / 6 \\
 (\Delta y)^B &= (\sum_{i=1}^6 (a_i \sin \sigma_i)) / 6 \\
 (\Delta z)^B &= 0
 \end{aligned} \tag{5}$$

When the driving software commands an arc with center position of C^B in Rover Body frame and turn radii of $\|\vec{r}_i\|$ for each wheel i , SAPP uses the following method. For each of the six wheels, SAPP computes the arc length

(a_i) that the wheel rotated through as described above. It determines the angle of the arc traveled by wheel i per

$$\psi_i = \frac{a_i}{\|\vec{r}_i\|} \quad (6)$$

The algorithm computes the average angle (ψ_{ave}) from the angles for each wheel, but if C^B is at the center of a wheel, then it excludes that wheel from the average. The average angle and center position for the arc are used to compute the position change per

$$\begin{aligned} (\Delta x)^B &= \psi_{ave} C_y^B \\ (\Delta y)^B &= -\psi_{ave} C_x^B \\ (\Delta z)^B &= 0 \end{aligned} \quad (7)$$

SAPP has a variation of this position propagation technique that uses information from wheel odometry and the attitude change previously computed from the gyro, weighting each component based on the turn radius of the arc being driven. This variation is beyond the scope of this paper.

In all of the position update methods, the delta position $[\Delta x, \Delta y]^B$ is converted to Site frame using the current attitude estimate and integrated into the rover's current position estimate in Site frame.

3 Visual odometry

While the nominal means of updating rover position combines wheel-odometry with heading updates from the gyro, that technique cannot measure purely translational slip. This slip might occur on high slopes, in sandy terrain, or when a wheel pushes up against a rock. So when time and power permit, the rovers can be commanded to update their onboard position estimate during a drive using onboard *Visual Odometry* software. This software works by autonomously selecting and tracking features in stereo image pairs taken at different locations [5].

Our Visual Odometry system computes an update to the 6-DOF rover pose ($x, y, z, \text{roll}, \text{pitch}, \text{yaw}$) by tracking the motion of autonomously-selected "interesting" terrain features between two pairs of stereo images in both 2-dimensional pixel coordinates and 3-dimensional world coordinates. A maximum likelihood estimator is applied to the computed 3D offsets to produce the final motion estimate. If any of the many internal consistency checks fails, too few feature points are detected, or the estimation procedure fails to converge, then no motion estimate update will be produced. The computed pose can be selectively input to SAPP, overwriting the estimates for position, attitude, both, or neither.

Although the Visual Odometry algorithm provides attitude deltas as well as position deltas, nominally only position updates are commanded because our attitude propagation using the IMU continues to provide reliable attitude knowledge onboard.

4 Operations on Mars

At the time of this writing, the Mars Exploration Rovers have been operating on the surface of Mars for over a year. Spirit has driven over 4.5 kilometers, and Opportunity has driven over 5 kilometers. The rovers have been successfully propagating their position and attitude, using a combination of wheel-odometry, gyro readings, and visual odometry, with occasional attitude updates from Sungaze as needed.

As the rovers drive, error builds up in the position estimate. This is due to slippage of the wheels, gyro drift, and inaccurate estimates of how deep the wheels are sinking into the terrain, which changes the effective wheel radius. To counteract the accumulation of error, a new Site frame is "planted" every so often. Planting a Site frame simply attaches a new frame affixed to the Mars surface with the same origin and orientation as the current Local-Level frame. Since the rover's position in the new Site frame is at the origin by definition, it eliminates the position error with respect to the new Site frame. New Site frames are typically planted at each new location where the rover stops to make science observations. Pointing coordinates for the science instruments are given in either Rover Body frame or the current Site frame.

Opportunity, driving in the Meridiani plains, typically experiences very small amounts of slip. As such, the wheel-odometry and gyro readings are sufficient to propagate the position and attitude for our purposes. When driving in Endurance crater, we experienced larger slippage (up to 100%) on the crater walls, and used visual odometry to update the position.

Spirit, currently driving in the Columbia Hills of Gusev crater, often experiences large amounts of slip, sometimes as much as 100% or more. A combination of wheel-odometry, gyro readings, and visual odometry is used to propagate the position. Additionally, the ground operators try to avoid terrain and maneuvers that cause high slip. When the slope of the ground is high, the rover drivers try to drive on areas of gravel, which provides more traction than loose sand. Turning in place while on a steep slope causes large slips, so driving arcs is favored over a combination of straight drives and turns in place.

The attitude knowledge achieved after a Sungaze is accurate enough for pointing the HGA at Earth during communications sessions. Ground operators keep track of the number of seconds of IMU integration time since the last time the rover performed a Sungaze. By monitoring

the signal strength received during HGA communications sessions, it has been determined that the rovers need to reacquire attitude after accumulating about 10,000 seconds of IMU integration time. Based on the current usage, this is roughly every 20 Sols (Martian days). With attitude updates at this frequency, the rovers are able to maintain solid communications signal when using the HGA to communicate directly with the Earth.

Initially, the GetFineAttitude command was used to acquire attitude. It is no longer used, however, in order to save time and power. Instead, because the propagation error is small enough that the rovers maintain accurate enough attitude knowledge to point the cameras at the sun, the operation team now employs a shortcut. They send a sequence of commands to do a Suncheck followed by a Sungaze. This works because Suncheck leaves the camera pointed at the sun, and Sungaze can determine the full attitude so long as the sun is in the field of view. The Suncheck takes less time than the Sunfind, but still leaves the camera pointed at the sun for the subsequent Sungaze. This technique also avoids the Nadir Update step, allowing us to save power by not turning on the IMU.

On relatively flat terrain, using the IDD arm does not cause any movement of the rover, even when drilling rocks with the Rock Abrasion Tool. Another shortcut used is to not put SAPP into Articulate mode when using the IDD on flat terrain. This avoids using power for the IMU and waiting for the reference vertical acquisition. Articulate mode is still used when operating the IDD on terrain with a high slope, as there is a small chance that the rover could move unintentionally.

5 Conclusions

There are some lessons that have been learned from the experience of operating the rovers on Mars. For instance, the SAPP software should have included a high-level command to acquire attitude by executing a Suncheck followed by a Sungaze. Also, while it was not needed, it would have been comforting if the software had the capability to perform gyrocompassing. This involves determining the Mars rotation vector from gyro readings when the rover is stationary. The rover attitude can be estimated using the observed Mars rotation vector and the rover's position on Mars. While this technique would generate only a rough attitude estimate, it could be used if the cameras failed.

The current onboard capabilities, while not perfect, are providing excellent attitude and position estimation capabilities. The attitude and position knowledge has been sufficient to perform all pointing and driving tasks for over one Earth year. The rovers continue to drive, make new science observations, and communicate the results with the ground operators. Hopefully, they will do so for many more years.

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