On-Board Perception System For Planetary Aerobot Balloon Navigation

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NASA'S Jet Propulsion Laboratory is implementing the *Planetary Aerobot Testbed* to develop the technology needed to operate a robotic balloon aero-vehicle (Aerobot). This cart-based system would be the precursor for aerobots designed to explore Venus, Mars, Titan and other gaseous planetary bodies. The on-board perception system allows the aerobot to localize itself and navigate on a planet using information derived from a variety of celestial, inertial, ground-imaging, ranging, and radiometric sensors. This paper discusses the various sensing modalities available to the aerobot, their applicability to different planetary missions, and the outline of a perception strategy suitable for whole-planet aerobot operation. The implementation of an initial sensor suite for the Planetary Aerobot Testbed is discussed, including inertial sensors for attitude, attitude-rate and lateral motion estimation, and a ground imaging system for ground-track velocity estimation. GPS and magnetic compass data are used to obtain ground-truth information on system performance.

1 Introduction

Managed for the National Aeronautics and Space Administration (NASA) by the California Institute of Technology, the Jet Propulsion Laboratory (JPL) is the lead U.S. center for the unmanned exploration of the solar system. JPL spacecraft have visited all of the known planets except Pluto, and a number of other planetary mission spacecraft are under development. These include the Cassini Saturn orbiter with its Titan probe, the Mars Surveyor orbiter, and the Mars Pathfinder lander with its Sojourner rover.

Planetary exploration has evolved from reconnaissance missions using "fly by" spacecraft, to survey missions involving orbiters and non-mobile vehicles such as landers and probes. The future evolution is towards in-situ detailed exploration using mobile vehicles such as rovers and aerial vehicles. Aerobots - aerial platforms with sophisticated telerobotics capabilities - provide space scientists with a powerful new exploration capability. They can operate much clew to the surface than orbiters thereby enabling improved instrument resolution for imaging and spectroscopy. Aerobots can also be used to deploy miniature instrument packages in the form of surface probes at specified locations, or in response to interesting science data readings from on-board instruments.

The principal aerobot mobility mechanism for planetary exploration is by using IMI-

loons. Balloons have the advantage of requiring little or no on-board energy for their operation as they are carried along by planetary winds. In addition to over-flying science sites, they can be commanded to descend for landings at desired locations. Aerobots also have longer range mobility when compared to rovers, and can access planetary locations that could be difficult for rover operations. Indeed, for certain hostile environments like the surface of Venus, aerobots represent the only viable means of extensive surface exploration. Repeated descent and landing operations 011 the hot surface are only possible if they are followed by a re-ascent to higher, cooler altitudes.

The importance of aerobots for planetary exploration has become widely recognized by the science community and they are strongly represented in the Mission to the Solar System Road Map commissioned earlier this year by NASA, with inclusion of aerobot missions to Venus, Mars and Titis]]. A Planetary Aerobot Test bed (PAT) program has been initiated at JPL to develop and demonstrate in an earth environment, the telerobotics technologies necessary to conduct comprehensive scientific investigations of Venus and Mars using aerobots. The first flight of the PAT system is currently scheduled for the Fall of 1996, with the technologies to be transferred in time to enable emerging (2001 -2[)05) mission opportunities to Mars and Venus.

Technologies such as materials, thermal, power, communication, and systems are obviously important for aerobot operations and form part of an overall aerobot program activity [1, 2, 3], but here we focus 011 the telerobotics technologies needed with the emphasis being 011 on-board perception. We begin by briefly outlining technologies necessary for mobility, and path prediction/planning in Section 2. This provides the context within which the navigation technologies of *Autonomous State Estimation* can be discussed in Section 3. Specific implementation of selected navigation functions on the Planetary Aerobot Testbed is discussed in Section 4 together with an an outline of our plans for future work.

2 Key Telerobotic Technologies

The large-scale, dynamic, wind-driven motions of a Venus or Mars aerobot precludes the possibility of mission operations in which a mission command set is up-linked based on a previous day's imagery returned from the system. Science target sites are unlikely to be re-visited during a mission and target-specific science operations must be performed whenever the aerobot flies over the target. However, round-trip speed-of-light communication delays, and limited communication opportunities prevent real-time earth-based control of the system. Instead target lists are stored on-board, and as the wind-driven aerobot approaches a specific target from the list, this condition must be recognized by on-board autonomous state estimation, and science activities designated for that target must be performed. If on-board control of mobility and path planning/prediction capabilities exist, then the paths may be tailored to steer the aerobot towards the target, maximize the over-flight of the target, or land 011 the target.

2.1 Mobility, Altitude Control and Landing

By using altitude change as the control parameter, balloons can utilize different wind vectors at different altitudes to affect latitude shifts and hemisphere changes. During landing, constant altitude operations, or terrain avoidance, changes in buoyancy can be used to control both the rate of descent as well as to maintain or achieve a desired altitude.

Buoyancy control can be performed by using non-renewable ballast Such as would be the case for a super-pressure balloon operating 011 Mars. A Mars super-pressure balloon would float at a "constant density" altitude corresponding to its average density. Typical float altitude would be anywhere from 6 to 81<111 above the Mars nominal zero level.

However, for planets with atmospheric temperature gradients like Venus (and Titan), a novel renewable means of buoyancy control is possible by evaporating and condensing a reversible-fluid [4]. In this buoyancy concept, most of the buoyancy is provided by means of a primary lifting gas such as helium. The secondary lifting fluid is a reversible fluid. At low altitudes (and warmer temperatures) the fluid is in a gaseous state providing lift. As the balloon ascends to higher altitudes (and cooler temperatures) the reversible fluid condenses back to a liquid thereby causing a lift deficit that makes the balloon descend. The natural behavior of such a system is an oscillatory vertical motion about the altitude corresponding to the condensation temperature of the reversible fluid. The period of this oscillatory behavior is controlled by the thermal lags associated with the heat transfer into and out of the balloon's heat-exchanger, and is of the order of a couple of hours for typical systems. As an example, a Venus aerobot utilizing Methylene Chloride as the reversible fluid would have a condensation altitude of 56 km above the surface with oscillatory excursion of a few kilometers about this altitude.

Two means of altitude control are possible for the reversible fluid mobility system. The first is *Oscillation Waveform Shaping* that alters the oscillatory behavior of the system by changing the time constants associated with reversible fluid condensation and evaporation. This can be achieved by partial and/or intermittent closing of heat-exchanger valves during the condensation/descent phase of the aerobot's sinusoidal motion resulting in the oscillations becoming deeper and/or different "wavelength". The second is *Descent/Hover Control* whereby a descending aerobot's vertical speed is slowed down to permit the aerobot to hover at a desired altitude over the surface or to permit soft landing on the surface. Since the vertical mobility control is one-sided, in that only the rate of descent can be slowed by allowing some additional (previously trapped) fluid to evaporate, control methods require that the system initially plan to under-shoot the desired altitude (or target) and progressively slow the rate of descent to achieve the targeted altitude or vertical landing- velocity.

Landing Control would also require use of on-board models for vertical wind profiles and lateral wind vectors. Sensor feedback using pressure- based, laser or radar altimetry, together with target- relative lateral sensing would be used to steer the aerobot for landing in close proximity to designated tjar.gets.

2.2 On-board Path Prediction and Planning

An aerobot's path through the atmosphere is both a function of its vertical motion as well as the motion through lateral winds. Planetary scale wind motion can be predicted using planetary wind circulation models such as the General Circulation Model for Mars (MarsGCM) [5] and similar cruder models for Venus. These models are exercised on super-computers and provide the global wind-vectors for any point in the 3-dimensional atmosphere of the planet. Parametric, on-board wind-models suitable for real-time use with prediction fidelity over a few days of operation could be used for on-board wind-model prediction in support of autonomous planning functions. These planning functions include those associated with landing as well as those involving])l:]]l(:t:l]j'-scalc path-planning.

Landing Initiation Planning would be used to sequence the valve closuiws at precise points 011 the condensation cycle to trap sufficient fluid leading to a lift deficit that will take the aerobot to the surface. *On-board Global Wind-Model Based Path Planning* would use on-board models of winds and vertical mobility to exploit different wind speed and vectors at different altitudes to over-fly selected regions, achieve a desired planetary location for landing, m perform global maneuvers such as hemisphere changes or latitude shifts.

3 Autonomous State Determination

We now discuss various autonomous perception concepts that enable an aerobot system to perform 011-board localization of the balloon with respect to a planet (i.e. where is it ?), estimate balloon horizontal and vertical motion (i.e. where is it going ?), and determine the balloon gondola attitude (i.e. what is it looking at ?). These capabilities in turn support global path prediction and planning, descent/landing operations, and science instrument pointing.

To achieve this requires a combination of inertial, image, celestial, range and radiometric sensing. As will become clear in the discussion that follows, these sensors differ with regard to their use on Venus and Mars, and are also not applicable all of the time even on the same planet.

3.1 Inertial Sensing

Inertial sensing allows an aerobot to determine or propagate its state without reference to any external sensing sources. Rate gyroscopes provide information on angular velocity and allow the aerobot to propagate the attitude of the aerobot. Accelerometers provide information on true spatial accelerations as well as local gravimetric information by reacting to the direction of the local gravity field i.e. the vertical. Inclinometers provide the same information as accelerometers but at lower bandwidths.

The combination of the inertial sensor data represents a new estimation regime that is different from spacecraft 01' rovers. Unlike a spacecraft the aerobot is not in free-fall, nor like the rover is it in a quasi-static "rest" equilibrium. Instead the aerobot is a platform with pendulum motion that combines aspects of fro-fall as w c]] as "rest" motion. The accelerometers sense a combination of the gravimetric vertical together with the nonfree-fall portions of the spatial acceleration. This can be quite non-intuitive, with for example, an accelerometer located on the "bob" of a fixed pivot pendulum not sensing the tangential acceleration of the "bob" since that is a free-fall motion.

The on-board autonomous state estimator has two roles with regard to the inertial sensors. First, it must be able to provide attitude information so that celestial fixes and ground-imaging line-of-sights can be determined. Here it must use the natural constraints of the pendulum aerobot motion to prevent inevitable rate-gyro random-walk biases from causing the attitude covariance to grow unbounded. This requires an intelligent filtering of the accelerometer readings to maintain an estimate of the long-term vertical attitude 01 the use of auxiliary sensor information such as sun elevation or horizon sensing to provide a fixed point of reference. Second, the estimator must also propagate the overall position of the aerobot. This has to be performed by extracting from the accelerometer readings, those components that are due to inertial accelerations and ignoring those due to orientation dependent gravimetric and centripetal effects.

For Venus aerobots, the ability to propagate the position state is most important since there will be periods where the aerobot is effectively blind with regard to seeing the Sill'fac(' (e.g. during daylight at float altitudes above a few tens of kilometers). However, 011 Mars the attitude estimation of the tilt angle with respect to the vertical is more important since these attitude errors directly feed into errors of the celestially derived global positions as discussed in Section 3.3.

3.2 Ground imaging

The technology of ground imaging is applicable to both Venus and Mars with suitable scaling of the results to accommodate different altitude regimes and recognizing the different infra-red/visible sensing regimes. Ground imaging with wide field-of-view optics allows the determination of the aerobot location using two methods. The first method involves acquiring dual overlapped frames of the ground. The registration of these images is performed using the 6-dof motion parameters of the aerobot as free parameters in the registration algorithm, together with an estimate of the nominal altitude of the aerobot over the terrain. If more information on the attitude change is available from other sensors (sun, inertial) then an easier registration problem involving fewer parameters is possible. In either case the relative motion of the aerobot is obtained for the time interval corresponding to the acquisition of the images, and can be integrated to find the overall long-term motion of the aerobot.

These relative motion estimates can also be utilized to obtain an estimate of the average ground-track velocity of the aerobot. This information can be used as an estimate

of local average wind-speed and provides scientific information on planetary atmospheric behavior.

The second method involves correlating the images to maps of image features. Correlating to global maps of the planet would be more applicable to high altitude images where the images have enough contextual information to allow the correlation to succeed. A similar correlation method could be used in close proximity to targets at lower altitudes to allow terminal, target-relative, precision position estimation.

Daytime ground imaging with sufficient contrast is possible on Venus only below altitudes where the high dispersion of sun-light in the atmosphere does not present a problem by reducing image feature contrast (some estimates place this altitude as low as 15km). At nighttime, however, the high lapse rate in the atmosphere correlates topography to temperature and allows differences in surface topography to be detected anywhere below the Venusian clouds. i.e. below $\approx$ 50 km. The window of view-ability is about 1 μm wavelength in both cases.

The large field-of-view images available at night allows a Venus aerobot to track its global motion. Large fields-of-view imply that sufficient features are highly likely to be present in images to allow frame-to-frame motion to be successfully estimated. Since topographic information is available from Magellan spacecraft radar data, direct correlation of the nighttime images to topographic maps can also be attempted.

For Mars, during daytime all features are visible at the 6-8 km constant-density float altitude of the aerobot unless obscured by heavy dust-storms. During nighttime, no features are expected to be visible even at infra-red wavelengths because of the low thermal inertias of the cold surface. The daytime medium field-of-view images would allow a Mars aerobot to track local motion of aerobot. While local motion could be integrated to derive global motion, this would not be a reliable means of position determination since the aerobot could fly over regions with very little features or ambiguous features.

3.3 Celestial Methods

Sun elevation-angle sensing constrains the position of the aerobot to lie on a "circle of equal altitude" on the planet [6]. The fuzziness of the circle is directly linked to the accuracy to which the sun elevation angle is measured. Since the elevation angle is measured with respect to the vertical, the on-board estimation of the vertical attitude of the dynamic, pendulum-motion influenced platform is critical. Also required is knowledge of the local time and the Sun/Planet orbital geometry. Measuring the sun elevation angle at successive times constrains the aerobot motion to lie on the successive circles. If the aerobot were to be stationary, then the circles would intersect at two points one of which would correspond to the aerobot location. For a dynamically moving system like an aerobot, the sun elevation reading is used by the on-board estimator to constrain the state propagation to be compatible with the sun elevation readings.

Similarly, azimuth-angle sensing COllstl'sills the attitude 1'011 (about the balloon vertical axis) and allows the aerobot to find "true north". This knowledge can 1)(' used to propagate the positional state by integrating velocity information derived from other sensing such as ground image processing or inertial sensors. Knowledge of the roll angle is also useful to support oblique science imaging towards a target.

Celestial sensing in the form of horizon sensing using an imaging or other photometric detector can also be used to estimate the aerobot tilt. However, this method would not be applicable to Venus because of the clouds, and would be complicated on Mars because of the presence of mountain ridge lines along the horizon.

A cruder but simpler form of sun sensing is to monitor the intensity of the sun to detect the terminator crossing. 011- board models for the day/night intensity variation as a function of the terminator crossing path and atmospheric refractive optics can 1 be used to constrain the aerobot's position and trajectory angle with respect to the terminator at the time of the crossing.

The sun may be sensed (crudely) 011 Venus in the Radio Frequency (RF). 011 Mars the sun azimuth and elevation can be easily sensed using standard visual detectors such as spacecraft sun-sensors. Since a Mars aerobot flies at sufficiently high altitudes without clouds or ground occlusion, area integrating sun sensors may be satisfactory. However, area localizing detectors such as imagers with thresholding are preferred to provide robustness to balloon/sky obscurations and reflections of]' the balloon surfaces (which could incorporate reflective thermo-optic coatings). The fi(:ld-of-view of the sensor could be a full hemisphere but higher accuracy solutions might be possible by using a moderate field-of-view sensor sweeping the sky as the aerobot undergoes its natural circular roll motion during its flight. Polarization sensing could also be used 011 Mars to assist the detection if haze is present or if data is required when the sun is just below the horizon. This could be important during "winter" missions when the sun is near the horizon during the entire day.

Star/Satellite sensing provides similar information as sun sensing with the on-board star catalog used to recognize bright stars in the sky. Since multiple star patterns can be recognized in different parts of the sky during a relatively short times, the corresponding constraints can be intersected directly by the aerobot to provide the position of the aerobot on the planet to high accuracies. **As** 1)('few, a more limited field-of-view star sensor can be used with large sky coverage achieved by utilizing the natural roll-motion of the aerobot to sweep the S('11S01" across the sky.

Stars are not visible at Venus and are only visible at nighttime 011 Mars. However, Phobos will be visible on Mars during the day as it rises and sets twice in a day in its (Equatorial orbit provided it is not in the glare of the sun or in shadow. A common sensor can be used to detect both Phobos and stars provided it has sufficient dynamic range. However, the vast difference between the sun and star/Phobos intensities, and the differences in field-of-view needs, preclude the use of a single detector for all Mars aerobot related celestial sensing.

Thus to summarize, Venus celestial approaches would involve crude daytime RF sun fixes and terminator crossing for crude on-board position determination and direction sensing. Unlike the case on Venus, celestial sensing on Mars provides the aerobot with the opportunity to obtain a continuous global position estimate without having to integrate a velocity or do complex map correlations. On Mars Sun/Phobos would be used in daytime with moderate accuracy, and high-precision localization would be possible at nighttime using multiple star fixes.

3.4 Range Sensing

Range sensing to the surface is required from mobility considerations (e.g. altitude hold/hover), safety during landing or over-flying low-terrain (e. g. emergency ballast drops), and interpreting image scale. On Venus, pressure barometry is feasible, with active sensing (e.g. radar) only needed for terminal landing. Altimetry is not a safety critical function since normal float altitudes are well above surface features. However, on Mars, pressure altimetry is infeasible due to the thin atmosphere and active sensing (e. g. laser altimetry) is needed at all times. Altimetry is critical in avoiding (via ballasting) high-terrain features at approximately the same height as typical aerobot float altitudes.

However, range information to the surface also provides an opportunity to obtain positional information of the aerobot with respect to the terrain. This would involve matching the height profile with an on-board terrain database in a manner similar to that used 011 ships with sonar data before the advent of GPS systems [(3]. When the motion of the aerobot is perpendicular to the contour lines, higher precision is possible than when the ground-track is parallel to a contour line. The key to this method lies in the ability to incorporate low-mass, low power/energy ranging sensors.

3.5 Radiometric Sensing

Information from one-way Doppler beacons by spacecraft in orbit about the planet can be used by the aerobot to constrain the global position of the system. These radiometric measurements are periodic (a few times a day for each orbiter) and can help the aerobot to update both current and past state estimates.

A cruder radiometric approach is to use signal acquisition/loss times to correct and constrain the aerobot's position. While this may be feasible for Venus aerobots at high float altitudes, it is more problematic for Mars aerobots because of topographic effects on the signal acquisition/loss.

Very Long Baseline Interferometry (VLBI) can be used to localize the aerobot using the Deep Space Network (DSN) stations on Earth. However, this technique is not real-time and has limited application for autonomous aerobot operations.

3.6 Planet Specific Sensing Strategies

We now briefly outline possible sensor operations for aerobot state estimation 011 Venus and M ars.

3.6.1 Venus Sensing Strategy

A typical sensor operations strategy for Venus aerobots would involve the pressure-based vertical motion estimator being on all the time. During the day, inertial propagation of the aerobot position would be the primary mode of operation with some assistance from crude RF sun elevation/azimuth sensing. Altitude profile matching may also be possible using radar altimeter data.

As the aerobot dips low into atmosphere, and the ground becomes visible, velocity estimation is updated based on frame-to-frame imaging. Ground track velocity estimates are refined as the aerobot passes to the lowest descent point. As the aerobot begins to climb upwards, ground imagery loses quality and the aerobot switches to a more inertial means of determining lateral position.

The inevitable covariance buildup resulting from inertial propagation is corrected with periodic orbiter Doppler beacon fixes, or by noting terminator crossings. At these more discrete sensing events, error covariances are marked down and estimation filters are re-initialized. Previous sensor data can be filtered "backwards" to correct/refine earlier position estimates of locations visited by the balloon.

At night 011 Venus, imaging at high altitudes is used for frame-to-frame motion estimation, and image correlation to maps provides global position information.

Attitude information is obtained primarily through crude sun sensing, inertial attitude propagation, and global correlation of image data to maps.

3.6.2 Mars Sensing Strategy

For Mars the preferred method would be celestial, with inertial sensors used primarily for tilt estimation. During daytime, on-board position information would be obtained from successive sun elevation measurements every few minutes, and successive Phobos measurements during periods when Phobos is visible.

As with Venus, orbiter beacon Doppler profiles would refine the celestially obtained position estimates. Image frame-to-frame motion determination every few minutes would give high-accuracy knowledge of ground-track velocities. Landmark deviation from expected locations could be used in the close vicinity of the target to obtain the target-relative position.

Height measurements using a laser altimeter would be concurrent with ground imaging to allow proper interpretation of image scale. If the altimeter is operated in a continuous manner for collision monitoring, then the data could be used as a backup method for position determination via terrain/profile matching.

At night, on-board position/velocity knowledge would be obtained using successive Phobos and bright-star elevation measurements every few minutes. The ground-track velocity estimate would be obtained by differencing the celestially obtained position measurements.

Daytime attitude information would be obtained by combining the estimate obtained by the inertial estimator with Sun/Phobos azimuth fixes. Nighttime attitude would be obtained in a similar manner using Phobos/Star fixes.

4 Testbed Implementation

The information from these diverse sensors, each with different error properties, data rates, and periodic/aperiodic characteristics, must be combined to provide the overall location and attitude of the aerobot. Each of these sensing techniques also has different constraints and operational uses on Venus and Mars, as well different states of technology readiness with regard to different missions. Therefore it is prudent to develop a general framework, both algorithmically and in software, that could be used for all Venus and Mars missions.

Such an *Autonomous State Estimator (ASE)* engine, with standardized data representation of the various kinematic and measurement chains, standardized filtering methods to propagate states (Kalman and extended Kalman filtering), Bayesian methods for combining and resetting states based on asynchronously received information, "smoothing" methods to update old aerobot location estimates based on new data, and standardized data-flow and sensor/estimation sequencing control, is under development with implementation to be completed over the next two years. A block diagram showing the overall functionality is shown in Figure 1.

In the meantime, the basic algorithms and software to demonstrate two of the navigation techniques - inertial sensing for position/attitude determination, and image frame-to-frame motion estimation, are being developed for flight testing in the Fall of 1996.

The estimator uses a "pendulum propagation model" and an extended Kalman filtering of the 3-gyro, 3-accelerometer system to provide both attitude and position estimates. However, current gyro drift rates for the mass payloads that are feasible do not allow long-term propagation. However, with improvements in low-mass, low-power gyro technology, longer term state propagation will be possible.

The emphasis of the test flight is to demonstrate the feasibility of using inertial propagation on a pendulum platform. Applicability to Venus for long-term state propagation

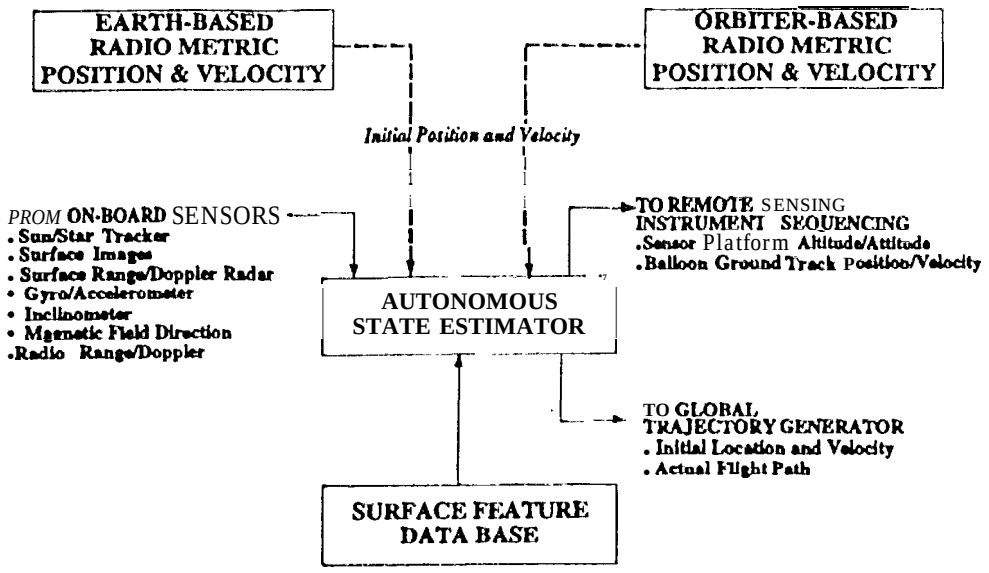

Figure 1: Autonomous State Estimator

during "blind" periods of aerobot motion will be quantified as a function of gyro bias drifts. On-board short-term attitude prediction will be used by the ground imaging system to support successive frame-to-frame imaging based motion determination. Performance of the vertical attitude estimation will be quantified in the laboratory using imaging of fiducial targets mounted on the test platform, as well as post-flight analysis of returned navigation images.

The initial effort in imaging based navigation focuses on the determination of the average velocity of the ground-track motion of the aerobot. The technique is applicable to both Mars aerobots during the daytime as well as Venus aerobots at high altitudes at night, or low altitudes during the daytime. The estimator development initially assumes a nominal "(flat" model of the terrain and nominal estimates of altitude over the terrain. The implementation utilizes a Gauss-Newton algorithm to solve a least-squares motion parameter estimation problem. The following steps are performed as part of the estimation algorithm:

- Acquire 256 x 256 "Model" Image; Time/Attitude/Altitude stamp image; Rectify image; Gaussian/Laplacian pyramid process with fast separable kernels; Smooth Laplacian-of-Gaussian image to reduce local minima effects.
- Set timer to acquire second image based on nominal speed and desired percentage overlap.
- Acquire second "Data" image and process similarly.
- Warp Model Image based on delta quaternion, and elevation change.

- Set initial translation estimate to nominal value (e.g. based on wind model or previous ('s1 imateetc)
- **1** Begin Gauss- Newton Iterations on low-res smoothed images.
  - Translate warped Model image based on nominal translation.
  - Compute Hessian and 1 Residual in overlap region of predicted model and data image.
  - Estimate incremental translation motion and update overall translation estimate
  - Exit iterations if converging i.e. residuals are small.
- 1 Perform optional, simple 1 -pixel wide correlation on higher resolution image for final translation estimate.

4.1 Sensor Set

The inertial sensor suite consists of 3 Systron-Donner - Model QRS1 I rate gyros with nominal range of 50 deg/sec, bias of 0.5 (leg/s(:c, and short term (1 00 sec) drift of 0.002 deg/sec. Power consumption is 0.8 watt max each and the mass is 60 g each. A 3-Axis accelerometer package is from Summit Instruments - Model 34103, with an operating range of $\pm 2.5g$ range, bandwidth of 46 Hz, alignment of $\pm 0.15\ deg$, and nonlinearity of $0.2\%FS$. Power consumption is 125 mW quiescent, and the total mass is 20 g.

Ambient pressure sensing for altimetry and balloon system performance evaluation is provided by an AIR Intellisensor II, with a range from 0 to 1 5 PSIA. Accuracy is $\pm 0.08\%FS$ with resolution of 0. 000 I PSIA. Power dissipation is 96 mW and the mass is 285 g. **A** propeller-type vertical wind-speed sensor is from R .M. Young Company - Model 271 0 6) combined with a Tachometer from MicroMo - Type 1616'J1001" G9.

Imaging cameras are standard 1/3 inch (Xl) systems from Supercircuits - Microvideo Camera Model PC-14XS. The sensitivity is 0.2 lux with a resolution of 380 lines. The field-of- View is 86 degrees with a 3.6mm lens. Power consumption is 1.92 watts each and the mass is 11 g. One imaging camera is mounted for ground imaging and the other serves as a crude sun-sensor emulating possible Venus RF sun sensing.

Ground truth on attitude is obtained by a Fluxgate Magnetometer from Applied Physics Systems - Model APS533. The response range is $\pm$ 1 *Gauss*, with directional accuracy better than 0. 1 degree. Power consumption is 200" mW and mass is 18 g. Ground truth on position is obtained by means of a GPS system.

The on - board controller is implemented on a PC104 bus, Intel 486 SXLC processor together with auxiliary data interface cards. The operating system is VxWorks from Win-(11 River. A real-time control tool-kit, ControlShell from Real-Time Innovations, is used to implement the on-board data-flow graphs and fillitfe-state machines.

4.2 Future Work

Efforts in successive years in the imaging area will focus on relaxing the flat terrain constraints and nominal altitude assumptions by utilizing direct altitude over topography sensing as well as estimators capable of registering images from both known and unknown surface topographies. Additionally, estimation of vertical motions (changes in image scale) as well as attitude estimation (image rotation and foreshortening) will be incorporated. We also anticipate addressing the issue of correlating images with global and local maps.

Celestial sensing aimed at Mars aerobot operations will commence with the integration sun/star/moon sensors onto the PAT platform, as well as all of the associated estimation algorithms into the ASE. The availability of on-board direct range sensing will allow us to explore profile/terrain matching as a navigation tool. We also intend to incorporate radiometric methods to complete the Autonomous State Estimator development.

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