Toward an autonomous feature-based pointing system for planetary missions

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ABSTRACT

Although the analytical groundwork for understanding two-dimensional object images and various aspects of computer vision has been laid, we have not yet applied these concepts to automating the process of obtaining science images during space exploration missions. Our current approach in specifying pointing-command sequences relies heavily on target predicts, based on predicted target and spacecraft ephemerides, that propagate the target position as a function of time during pointing operations. However, because the actual position of the target is never measured on board, the tracking loop must be closed through the ground processing operation. This round-trip conmwnication-time limit can place severe limits on pointing accuracy, particularly during brief moments of closest approach, Furthermore, since a priori pointing uncertainty can sometimes bc larger than the target itself (owing to estimation uncertainties in the pre-launch positional knowledge of the target), opportunities to capture quality science images maybe lost by spending the majority of the observation time staring into blank deep space.

in this paper, wc formulate and outline autonomous feature-based pointing requirements that can support a wide range of space science missions. The issues addressed include target-position estimation; acquisition and tracking of unresolved, partially viewed, and close-up targets; operation, and validation of point designs. Detailed algorithms and test results based on Voyager image data are also presented.

1. INTRODUCTION

Future planetary missions will be accomplished by small spacecraft with a minimum number of components to minimize development and operational costs. In the attitude determination and control subsystems for new spacecraft, imaging instruments will often be hard-mounted to the spacecraft body in a manner similar to that of the redesigned Cassini spacecraft.[1] This design option requires a more capable tracking system for providing attitude reference. The new star tracker must now provide full-sky recognition of stars, since it will not be able to slew toward or lock onto a particular star, such as Canopus. In addition to the star-tracking function, the small, low-cost spacecraft approach must also provide target recognition and tracking functions to improve science coverage during the brief periods of close approach.

With a new NASA directive to provide space missions that are low cost, versatile, and yield maximum science return, closed-loop pointing capability (in which the target position is measured and estimated on board) may bc employed to achieve these goals. In missions such as Pluto Fast Flyby,[2] where the period between distant encounter and near encounter is less than the round-trip communication time, the success in acquiring high-fidelity science images may depend on a tracker that can recognize such planetary features as limb, terminator, craters, etc. and that can track a planet's center of mass or local terrain to provide necessary correction updates during the mosaicking, which is prc-planned, and other targeting operations, Charge-coupled device (CCD) star trackers[3-4] can be configured to provide both the star identification/tracking and target recognition/tracking functions. Autonomy in the target recognition and tracking operations for planetary missions is essential to meeting the goal of developing small, low-cost, and highly capable spacecraft. overall system cost and performance will be significantly improved by minimizing the dependence on ground processing and operations to capture planetary images. Here, by extracting target information measured on board, the spacecraft equipped with target-position predicts and pre-planned operational sequences will be able to update target positions, correct pointing commands, and generate onboard operational sequences as required to meet the mission objectives.

Perhaps the most difficult problem in target recognition and the tracking of celestial bodies occurs during the near or close encounter period of a mission, Here, terrains may completely fill the tracker's field of view, "J'bus, positional information regarding the target's center of mass or its limb must be referenced by some known planetary features. In addition, the capability of finding serendipitous targets on unexplored targets (satellites, comets, asteroids, etc.) may require an intelligent vision system, i.e., "eyes" on the spacecraft,

Skeptics may argue that this feature recognition and tracking problem would be extremely difficult to solve, based on research experience in machine vision. However, the geometric simplicity of planetary features relative to more complicated scenes addressed by robotics, greatly simplifies this problem. Although the feature and background definitions have become somewhat nebulous, some predictable features, such as circular spots, craters, riverbeds, mountains, valleys, and line markings are character stic of surveyed planets and satellites in our solar system (see Fig. 1).

The term "pointing" is employed to describe the system operation, based on processed tracking images, of controlling spacecraft attitude to capture science images. We also define "features" as image properties that permit classification of objects, and "targets" as objects or measurements of objects used in providing some type of positional reference, The proposed system is designed to autonomously acquire and track targets that can provide necessary positional references to complete the spacecraft precision-pointing operations. Technical issues to be addressed are noise/background suppression, feature extraction, geometric representation and object classification, tracking initialization and target tracking, topography and target characterizat ion, and operat ion.

Autonomous feature-based pointing capabilities are new to planetary spacecraft projects. '1'ethnology suitable for these applications has, to some extent, been developed in various disciplines, e.g., automatic target recognition, computer vision, image-processing, and pattern recognition. In this paper, wc discuss in detail various technical issues related to feature-based pointing, present an operational description, identify requirements, and provide simple solutions to various image-processing, target recognition and tracking problems that are typical in planetary missions, Examples using real images from Voyager image data are also presented. These solutions offer an attractive capability and a feasible alternative for accomplishing future missions; they pave the way to an unprecedented achievement in planetary exploration.

2. FUNCTIONAL FLOW

Figure 2 depicts a simplified overview of the autonomous feature tracking system for planetary spacecraft, The system is initialized with relatively high-level ground commands stored on board in the form of a timed sequence. These commands begin the process and generally describe what should be tracked (e.g. stars, centroid of a small target, center found by limg-fitting, crater, albedo feature, etc). Commands are assumed to be not capable of specifying the desired target in detail, such as would be the case if an image template were part of the command, The impact of this assumption will be thoroughly evaluated as the system is developed,

After receiving commands, one or more initialization frames will be taken to verify the exposure and perform coarse repainting if required. We are assuming a CCD similar to that being flown on the Cassini mission which has the capability of summing pixels to give a coarser resolution image. Thus the initial processing can be performed with a large pixel image (e.g. 64x64 pixels) with more resolution added only when needed, At the other extreme, the full 1024x 1024 resolution can be used for generating precise offset tracking vectors on a target that only covers a small portion of the field. In this way the system is able to provide both a large field for tracking large targets or correcting large initial pointing, and high angular resolution when high accuracy is requ ircd.

Once the target is found and the integration adjusted for correct exposure, a frame covering the entire target at the desired resolution is stored in an onboard frame buffer. 'l'his may be the entire frame at full resolution or some smaller data subset. By storing the image, it is possible to utilize multiple-pass processing to extract the desired information. Detailed steps in this processing arc described in the following sections.

It should be noted that autonomous tracking can include processes that recognize star patterns using stored star catalogs for attitude initialization. Although longer exposure times are usually required, the same instrument can be used for tracking both stars and target bodies. Much work has been already accomplished in the star identification problem.[5-8]

3. NOISE/BACKGROUND SUPPRESSION

in any image-processing application, pre-processing of raw CCD images is normally required, For space science applications, one must isolate intensities corresponding to the desired target from background intensities. Noise or background may include random spots caused by proton hits, shot noise, read noise, stray-light, cloud and dust (for cornets), and textures on planetary surfaces. Random noise events can be handled by processing multiple frames of images. Isolating a planetary body from dark sky can be achieved through fundamental segmentation schemes. For example, a simple thresholding scheme based on the histogram mode-seeking technique can be applied to planetary images (see Figs. 3 and 4). Autonomy in this process is obtained by approximating each of the two modes in the histogram by the Gaussian distribution. To simplify the parametric optimization process, we assume that the mean for each mode is determined by using the mode's peak value. Hence, the threshold value (x) for segmenting target intensities from background occurs at the intersection between the two Gaussian distributions (each distribution is completely described by the mean value μ and standard deviation σ), which can be obtained by solving the following quadratic equation:

$$(\sigma_2^2 - \sigma_1^2)x^2 - 2(\sigma_2^2\mu_1 - \sigma_1^2\mu_2)x + [(\sigma_2^2\mu_1^2 - \sigma_1^2\mu_2^2) - \sigma_1^2\sigma_2^2 \ln(K_1/K_2)] = 0. \tag{1}$$

Note that K_1 and K_2 in the above equation represent the normalizing constant $(1/\sqrt{2\pi}\sigma)$ for the Gaussian density function.

For other types of background, such as cloud or surface textures, multi-regional segmentation based on a multi-modal histogram of more than two modes or based on general texture analysis[10] may be required.

4. FEATURE EXTRACTION

Once undesired noise and background arc removed from the raw image, image features such as spot, edge, line, curve, ribbon, hole, contour, boundary, and texture that describe celestial objects must be extracted prior to continuing this hierarchical image analysis. Many algorithms[11] designed to extract these types of features exist and are applicable to planetary images. Figure 5 depicts a typical edge-enhancement technique, used here to highlight contour features of Jupiter by means of the Sobel operators.]z In this example, the simple contour-detection scheme is based on searching for surrounding edges in 16 different directions (see Fig. 6).

'1'bus, a given pixel that is not an edge point and is surrounded by edges that enclose a 40-pixel window is designated as a "hole." Boundaries separating hole and "not hole" regions become "contours", which are also used for highlighting the contour features and thinning the edges on the edge-enhanced image. Figure 7 illustrates this type of contour extraction for the Jupiter images.

Additional effort in the derivation and selection of appropriate algorithms to be used in extracting necessary features for several classes of celestial objects is required. In addition, feature-extraction performance based on some types of signal-to-noise metrics and on characterization of background texture is desirable and will allow us to set required specifications for imaging instruments and target environments, Currently, we are focussing on the derivation of appropriate measures to assess the system's abilities to carry out noise/background suppression and feature extraction, and further results will be generated in this area.

5. GEOMETRIC REPRESENTATION ANI) OBJECT CLASSIFICATION

In order to isolate and classify objects on the basis of extracted image features, some sort of geometric description and representation is required. In the case of celestial images, we can safely assume a restricted set of geometric patterns consisting only of a polygon (star groupings), circle/ellipse (limbs, craters, and contours), and line/curve (furrows, ridges, and channels). Although, there are many approaches to describing the geometry of extracted features (such as edge points), many algorithms designed to solve a wider class of shapes tend to overkill and impose serious limitations in terms of computational/memory burden and noise sensitivities.

1/or example, the dimensional complexit y of the generalized Hough transform technique,[13] used for detecting objects of a specified shape, will grow with the complexity of the object shape. This is true because edge points represented in two-dimensional Cartesian coordinates are transformed into something different in the N-dimensional parameter space required to describe the shape, i.e., two parameters for lines (slope and intercept), three for circles (XY-center position and radius), five for ellipses (XY-center position, major and minor diameters, and rotational angle), etc. In addition, analyzing the N-dimensional parameter space to detect the specified shape in the presence of noise is not trivial. It appears that for geometric representations restricted to planetary targets, a simpler, one-dimensional signature based on contour curvature[14] would be more practical. Although the major problem in this one-dimensional signat ure approach is that each possible boundary point must be traced and analyzed individually, the sparseness of space objects makes the technique suitable for limb and large planetary terrain characterization.

An example of extracting circular-shape information from the planet limb (once the necessary target/background segmentation and feature extraction mentioned in the previous section have been carried out) can be given using any two points on the limb ($[x_1,y_1]$, $[x_2,y_2]$), the length of the chord connecting the two points (c) and the area cut off from the circle by that chord (A). (See Fig. 8). By solving for the central angle θ using

$$A = c^2 (\theta - \sin \theta) / 4(1 - \cos \theta), \tag{2}$$

the radius of the circle (r) can then be estimated by

$$r = c / 2\sin(\theta/2). \tag{3}$$

q'bus, the center of the circle $[\bar{x}, \bar{y}]$ can be computed from the two reference points as follow:

$$\bar{x} = (b_2 - b_1) / (m_1 - m_2), \tag{4}$$
$$\bar{y} = m_1\bar{x} - b_1, \tag{5}$$

where

$$m_1 = \tan[\pi - (\pi-\theta)/2 - \alpha], \tag{6}$$
$$m_2 = -\tan[\pi - (\pi-\theta)/2 - \beta], \tag{7}$$
$$b_1 = x_1 - m_1 y_1, \tag{8}$$
$$b_2 = x_2 - m_2 y_2, \tag{9}$$
$$\alpha = -\tan^{-1}[(x_2 - x_1)/(y_2 - y_1)], \text{ (if } \alpha < 0, \alpha = \pi + \alpha), \tag{10}$$
$$\beta = \tan^{-1}[(y_1 - y_2)/(x_1 - x_2)], \text{ (if } \beta < 0, \alpha = \pi/2 - \beta). \tag{11}$$

Figure 9 shows the results of using a circle description for partial] y viewed planetary limbs of Jupiter and Miranda. There is also a simple, exact solution[15] for estimating the position of the center of a circular arc given a set of edge points. We are currently investigating this solution, which is based on non-iterative least-squares techniques, to estimate elliptical boundaries of objects. We are also extending the approach to detect circular and elliptical arcs, given noisy edge-images.

Requirements for the geometric representation and object classification of celestial objects go beyond detecting and estimating circles, ellipses, or polygonal (star) patterns from the processed images. In order to support a precision pointing system, continuous updates of the target-relative position of the spacecraft will be required. in the case of a near encounter, the limb, terminator, and other large features may not be useful (because of insufficient boundary curvature information) in estimating the target position. "J'bus, recognizing distinctive surface features will be required. A shape descript ion and recognition technique based on a structural model of shapes[16] may also prove useful, Nevertheless, a challenging problem lies ahead in characterizing the detailed representation and classification of terrains, such as a crater, contour, furrow, ridge, channel, hill, valley, etc. (features like these will be mapped out and updated during the spacecraft approach) for use at all possible viewing perspectives. Further discussion on the subject of creating topographic maps and characterizing surface features of candidate targets will be presented in Section 7. Current activities in representing and classifying objects involve (1) scale/rotation invariant characterization of features with hard edges by using boundary curvature and viewing-perspective correction, (2) texture representation of regions with smooth changes in intensity gradients, and (3) quantification of performance based on contrast and some type of regional distinguishability metric.

6. TRACKING INITIALIZA"J'1ON AND TARGET TRACKING

One aspect of the target-tracking problem is the estimation of a planet's center of mass, given a partial view of the planet. If the planet body resembles a sphere and a significant segment of its limb is viewed, the circle extraction approach discussed in Section 5 is applicable. Irregularly shaped bodies such as cornets and asteroids require further work. However, the issue of tracking the center of mass of irregularly shaped targets has been briefly investigated as part of the closed-loop target-tracking methodology planned for the now-cancelled Comet Rendezvous/Asteroid Flyby (CRAF) rni ssion.[17]

Without onboard correction to the predicted location of the target, the pointing performance for CRAF could not have met the required specifications. 'l'he approach employed a distance map that is a function of an object's 3D surface normals (vectors perpendicular to the surface points' tangent planes). Each number associated with a surface normal represents a distance between the corresponding tangent plane and its parallel that passes through the target's center of mass. CRAF mission scenarios assumed ample time for ground processing to establish the required 3D characteristics of the target prior to pointing operations during science data gathering phase, and for a fast flyby mission such as the exploration of Pluto, the ground processing of the target's 3D model may have to be automated onboard. This automated-processing issue is currently being addressed in our target-tracking research.

The main purpose of having an on board target-tracking capability is to continuous] y provide precise relative positional information on the target (e.g., its center of mass and other reference positions), based on images captured during the science operations. If only a close-up, frame-filling view of the planet is available, matching with a model of known surface features or terrain will be required to extract necessary target-relative positional information. This type of target-tracking methodology, even though supported by a comprehensive research effort in many applications in the past few decades, still suffers from several limitations that prevent its transformation into a reliable autonomous tracking system. In this section, we address many of the difficulties associated with our experience with the popular correlation-based tracking techniques.

The feature-tracking problem typically requires initialization to establish the a priori target position, and subsequent tracking to update the target position may assume a different processing path, For example, as shown in Fig. 10, to acquire the feature of interest (a bright spot on Jupiter) autonomous y, the raw image is first edge-enhanced to highlight contour features, using the approach discussed in Section 2; then the desired contour (based on the spot's diameter) is selected. Once the a priori target position and the reference intensity description (i.e., the template) are established, initial processing involving feature extraction and feature geometry can be bypassed, and matching of the desired target to a priori knowledge can done directly on subsequent images within a restricted search area by using template correlation,

Although minimizing the mean-squares error (i.e., ℓ_2 norm) between the two real-valued image signals (f(x) and g(x), $x \in \mathbf{R}^2$) is equivalent to maximizing a signal correlational*

$$\min \int |f(\xi) - g(\xi-x)|^2 \, d\xi = \min \int |f(\xi)|^2 + |g(\xi)|^2 - |f(\xi)g(\xi-x)| \, d\xi = \max \int |f(\xi)g(\xi-x)| \, d\xi, \tag{12}$$

actual application of the correlation when based on selecting a smaller template, g(x), and larger search area, f(x) often leads to mismatches, This is because once g(x) is truncated into a smaller region, the term $|f(\xi)|^2$ is no longer a constant, and the above relationship (Eq. 12) is no longer valid, In our experience with selecting relatively small templates, we have found that finding the position (x) that minimizes $\int |f(\xi) - g(\xi-x)|^2 \, d\xi$ instead of maximizing $\int |f(\xi)g(\xi-x)| \, d\xi$ produces a more reliable result. Furthermore, minimizing the ℓ_1 norm ($\int |f(\xi) - g(\xi-x)| \, d\xi$) tends to produce sharper match peaks and to be computationally more efficient, since it does not usc multiplications; this minimization of the ℓ_1 norm is the technique used in Fig. 9.[19] Nevertheless, improper sizing of the template in connection with the search-area size, image distortions, and the type of scene (especially those with gradual changes in intensity pattern) often will cause failures in correlation-based schemes.

This problem of defining an appropriate template size, appropriate scene content, and the amount of di stortion from one image-acquisition frame to another is also consistent with the results of the previous JPL tracking study of planetary terrain, based on correlation techniques.~ It was found that all the correlation techniques employed were highly sensitive to geometry distortions and modelling errors, and that in order to be successful in locating the correct target position, even in the ideal case, the template size must be a large fraction of the search area size. Selecting a large template places an enormous demand on the hard ware's computing power, and the current state of processing hardware may not be able to handle the required template and search-area sizes (on the order of tens by tens or hundreds by hundreds of pixels) that will ensure a robust correlation tracking technique, even in the absence of distortions. Long processing time between frames means larger changes in the image because of geometric projection effects and other factors, and the matching method becomes less effect ive. However, ongoing research at JPL to develop flexible processing hardware and reliable target-tracking technique for real-time vision systems[21] will address many of the computational and tracking issues discussed here.

7. TOPOGRAPHY ANI) TARGET CHARACTERIZATION

We can model the target-characterization process after the standard 3D-graphics visualization technique in which a computer file of grid points and associated photometric properties can be used to render or predict the appearance of an image, given a specific viewing condition, This pointwise approach will require an impractical amount computing power and memory storage,. An alternative is to analytically describe the model for a vision system (hat is able to see as humans do. How we design the system to understand images ob.served in the planetary applications will be closely tied to the image-processing algorithms for feature extraction, and object representation, classification, and tracking. Based on the particular representations selected, the derived system may have limitations in its ability to "perceive" and "understand". This type of restriction seems acceptable in our specific attempt to develop an autonomous celestial-sensing system for planetary applications.

The first-level characterization of a celestial-object model can be described by a sphere or an ellipsoid expressed in spherical coordinates (latitude and longitude). The next level is to topographically assign and label planetary features (cataloged targets) on this body, thus allowing terrain recognition and perspective correct ion. Although it is relative] y trivial to place various labels on the globe (i .e., the spherical or ellipsoidal model), the problem of characterizing these markings as a function of illumination and viewing condition will require major effort. Some characteristics of computer-simulated topological mappings of martian surfaces[22] and Phobos[23] (which will allow researchers to describe analytically planetary terrains and arbitrary-shaped planet bodies) may also be applicable.

This mapping and image understanding process is usually clone by ground processing to update spacecraft position and estimate target orientation and motion. Figure 11 illustrates a typical topological mapping and limb fitting function, used to update spacecraft-target position and the motion of surface features on Jupiter, This process exploits information (such as sun direction, spacecraft orientation, and target position), that is already available on board, Furthermore, the shape of Jupiter and characteristics of its distinct surface features can be easily described analytically with circles and ellipses. "1'bus, achieving a fully autonomous sensing system for spacecraft-pointing operation is not beyond the realm of possibility.

Another issue is that there might be an advantage to keeping and automating the mapping and target-characterization function at the ground processing level, since much more capable computing hardware can be employed there than in space, Although many of the current planetary missions (e.g., Cassini, Asteroid Comet Micro-Explorer (ACME) and Pluto Fast Flyby) may find ways to complete their missions without having onboard topographical mapping capabilities, we feel that onboard technology in this area will be essential for lowering costs and maximizing science return.

8. MOSAICKING EXAMPLE

In this section, we briefly discuss issues concerning the integration of various functional components to solving a particular pointing problem. We will focus as an example on the mosaic command, which is one of the most important pointing operations in planetary exploration. A typical mosaic pointing operation usually involves the following steps:

a. Establish the spacecraft attitude by using an attitude estimator that includes Sun, star, and gyro information. (onboard)
b. Predict target inertial position from a navigation database. (onboard and ground)
c. Specify mosaic window and positions based on target shape, target size, the imaging instrument's field of view, and position uncertainties. (ground)
d. Command reaction wheels or thrusters to point inertially to a base attitude by using the attitude estimator to provide control feedback information. (onboard)
e. Point to an offset position at a specified rate and acceleration profile, wait for the spacecraft to settle, then take a picture. (onboard)
f. Continue to turn and stop the spacecraft at pre-specified positions until the completion of the mosaics. (onboard)

Note that although spacecraft maneuvers (Steps d-f) were performed onboard, calculations for command parameters were done by ground processing. In addition, the conventional way to perform pointing operations never closed the position loop around the direct positional information of target images. One approach would be to reference (update) the center-of-mass information, given a particular target scene. By measuring the target position and size accurately on board, the spacecraft will be able to set up a sequence of pointing positions that capture the mosaic of the target image by extracting necessary information from a small segment of limb curvature without assistance from the ground (see Fig. 12), This type of approach allows maximum opportunity to capture quality science images (especially during a fast flyby) by reducing the amount of time and image area allocated to blank deep space and overlapping spaces, Continuous closing of the pointing-control loop around target-position information measured during the mosaic-targeting operation will enhance the current precision pointing operation and improve fidelity of science images.

The systems engineering issue here is whether to employ many sensing and position database elements (to increase reliability) or few elements (to minimize cost) to carry out pointing operations. If the target-relative positions and rates, target shapes, and surface features can be extracted from the intensity profile of target images, this slew, stop and stare pointing operation (mosaicking) can ideally be accomplished with only one sensing clement (the CCD celestial sensor). This vision of an intelligent tracker is quite feasible. Efforts to develop an autonomous star tracker that recognizes any star field without a priori attitude knowledge for spacecraft-attitude initialization arc on-going. The application of a CCD star tracker for updating attitude reference and rate data has also been considered.[24] This type of autonomous star tracker will provide necessary attitude determination and control operation without the use of gyros and sun sensors.

Although extracting attitude information from stars is easier than detecting planetary features, we have shown in this paper that advancing autonomous celestial-sensor technology to also capture planetary features is plausible. Detailed systems engineering research to address operational requirements, system specifications, placement of the celestial sensor and its characteristics (with respect to the imaging science instruments), and quantitative performance assessments for several classes of missions will be required. A clue to the magnitude of the potential payoff can be seen by considering, for example, the number of quality images that could have been captured, beyond those shown in Fig. 13, if this autonomous onboard pointing capability had been available during the Jupiter-bound Galileo spacecraft's encounter with asteroid Gaspra.

9. SUMMARY

"l'he feature recognition and tracking examples presented here merely demonstrate the feasibility of achieving autonomy in planetary spacecraft-pointing operations. In order to establish technology that can be ported to various flight projects, development of algorithms that can address various scenarios, together with laboratory demonstrations of this autonomous feature recognition and tracking technology, will be required. Algorithms must be developed and tested for locating the center of mass of arbitrary-shaped objects, for onboard cataloging, and for recognizing planetary features. The foeus of our research will be to develop these tools and integrate them into autonomous systems capable of responding to high-level ground commands. A variety of testbeds and simulation tools will be utilized to demonstrate the applicability of this technology and gain project acceptance. Various tracking and operational algorithms geared toward potential technology users, such as ACME and Pluto Fast Flyby, will be completed by the end of 1995. The long-term goals of this research are (1) to establish a library of portable feature recognition and tracking software modules for various flight projects, (2) to establish a fully autonomous celestial-sensing system and operational architecture that can be readily quantified in terms of its performance and capabilities, and (3) to develop application-specific integrated circuits (ASIC's) and sensing hardware essential to feature recognition and tracking technology.

The proposed feature-based pointing technology will be one of the major contributors to achieving the goals of the new NASA directive: to provide space missions that are low-cost, innovative, versatile, and yield maximum science ret urn. Using authentic planetary images from the Voyager mission, we have demonstrated that autonomy can easily be achieved for limited test cases. Although there are some technically challenging issues that have yet to be addressed, we feel confident that this advanced technology, in terms of algorithm development, will be ready for usage by early 1996.

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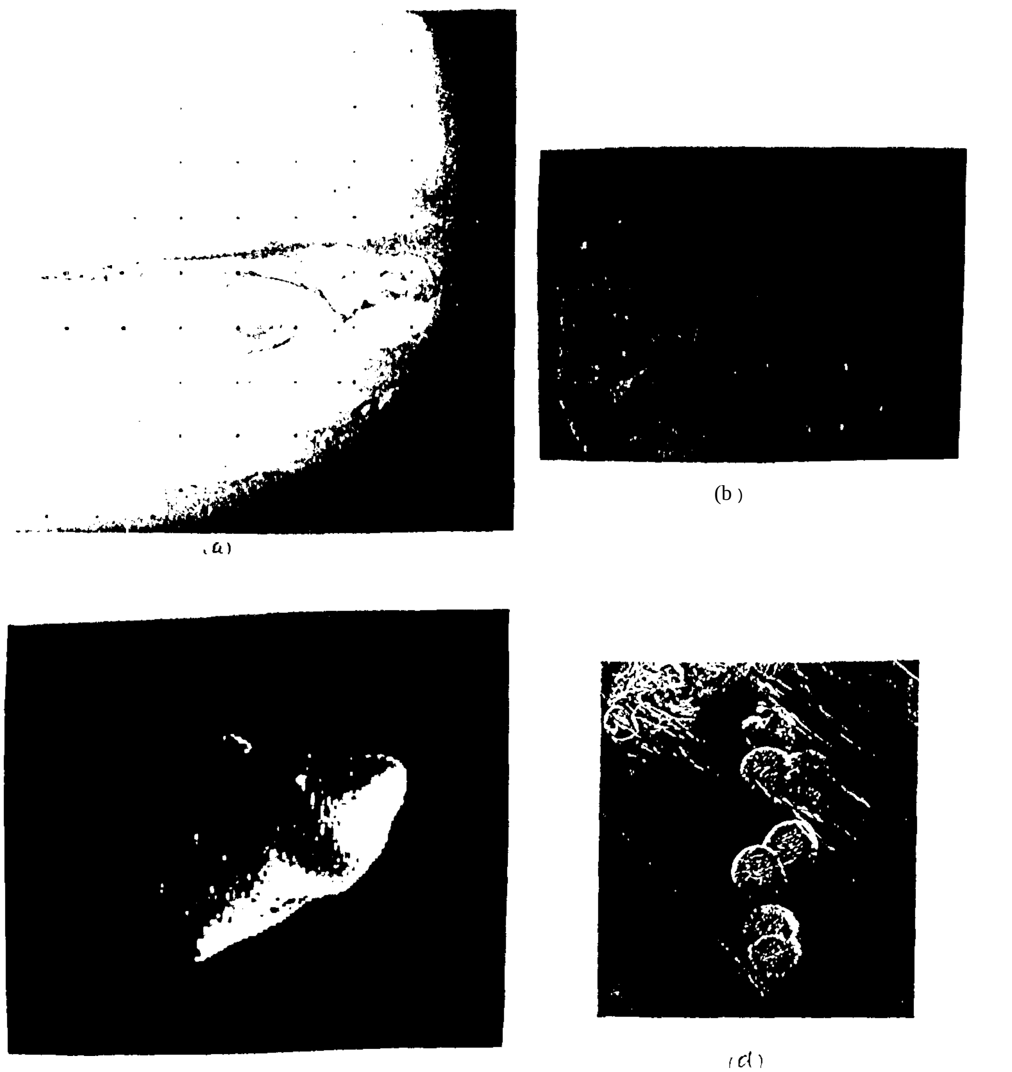


Fig. 1. Typical planetary features that maybe encountered in some unsurveyed planets, comets, or asteroids: (a) Jupiter, (b) Miranda, (c) Gaspra, and (d) Venus.

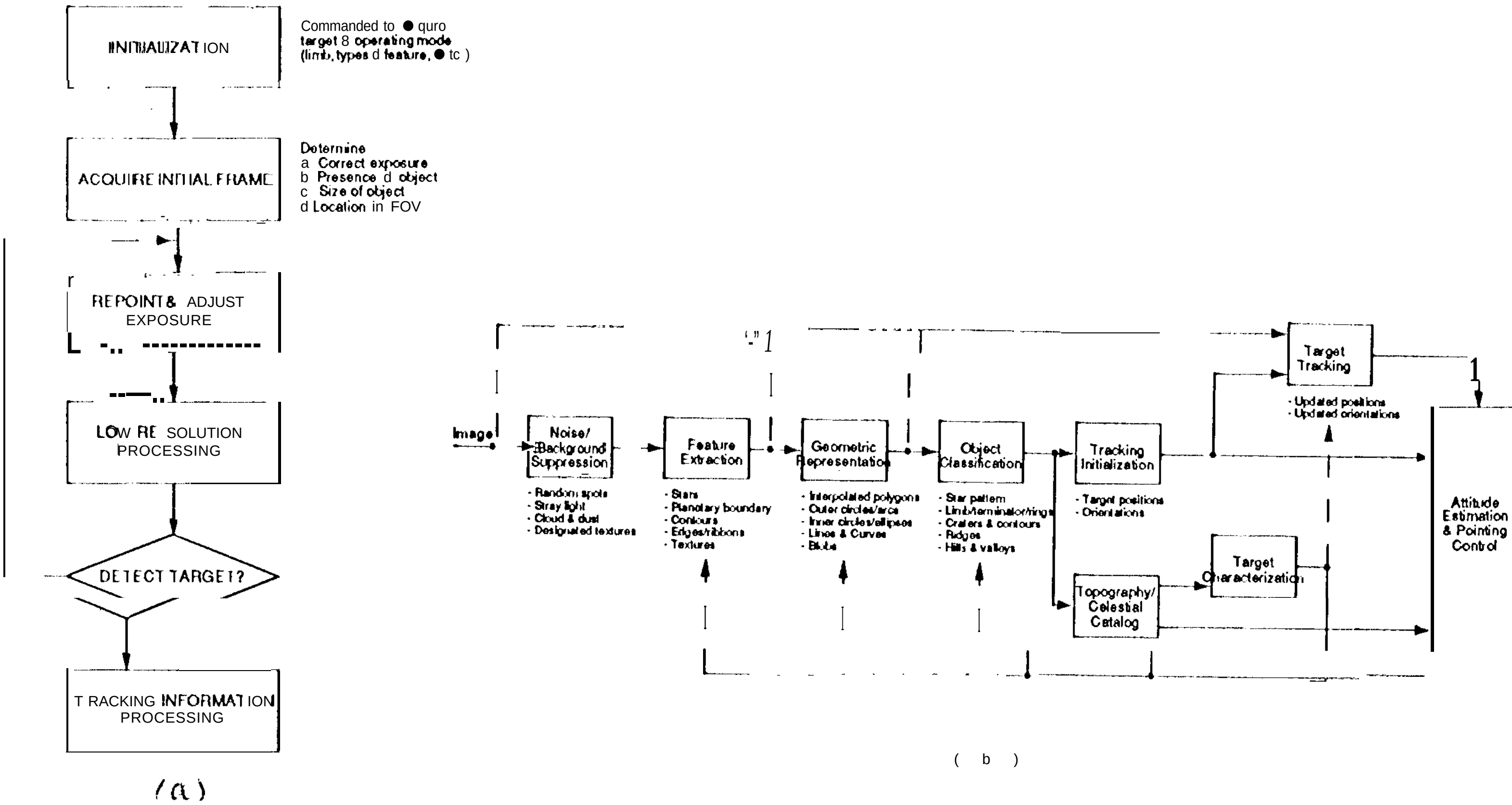


Fig. 2. Overview of an autonomous feature-based pointing system, based on attitude determination and control: (a) high level flow and (b) processing breakdown.

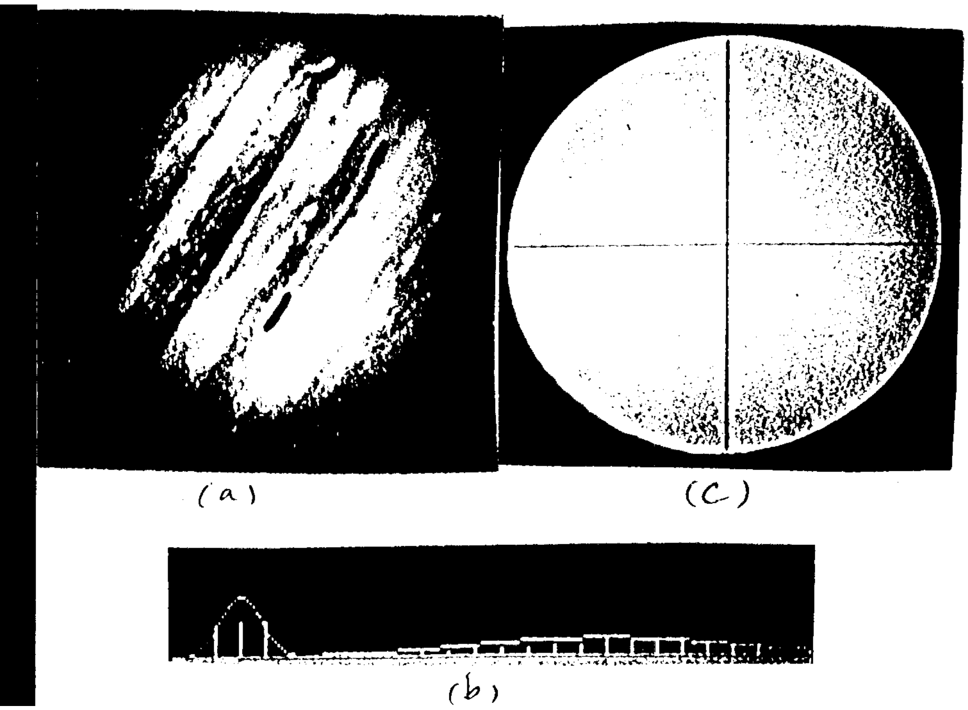


Fig. 3. Automatic target/background segmentation for Jupiter: (a) original image, (b) histogram and bi-modal Gaussian estimation, and (c) final image.

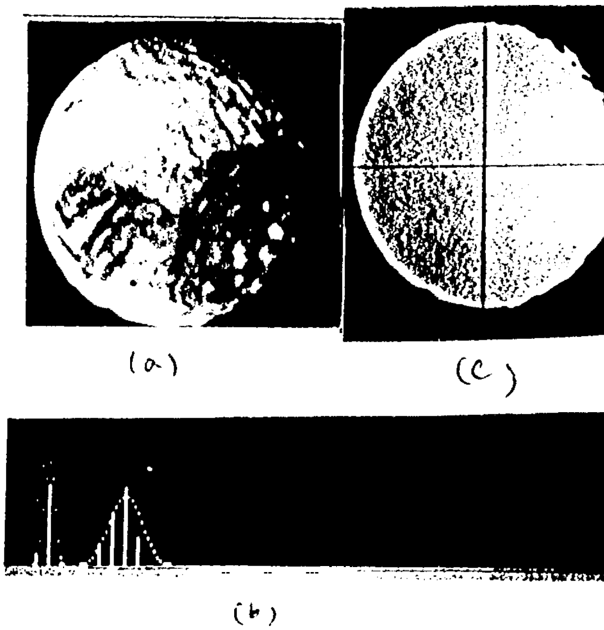


Fig. 4. Automatic target/background segmentation for Miranda: (a) original image, (b) histogram and hi-modal Gaussian estimation, and (c) final image.

Fig. 5. Edge extraction using the Sobel operators,

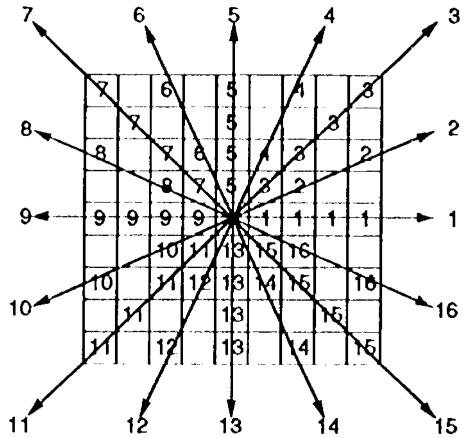


Fig. 6. Contour-detection search directions, Edges detected along the search directions will be used to decide whether there is a contour surrounding the center pixel.

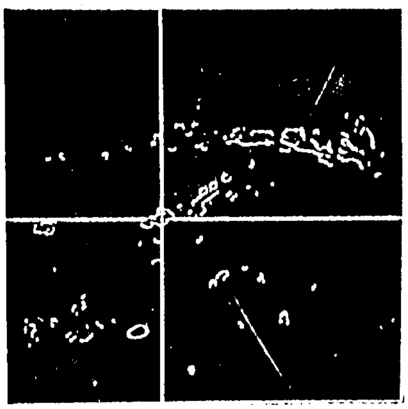


Fig. 7. Contour image detected by using the 16-directional edge check.

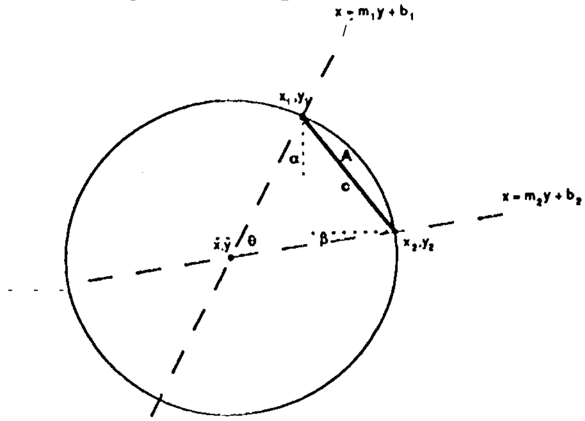
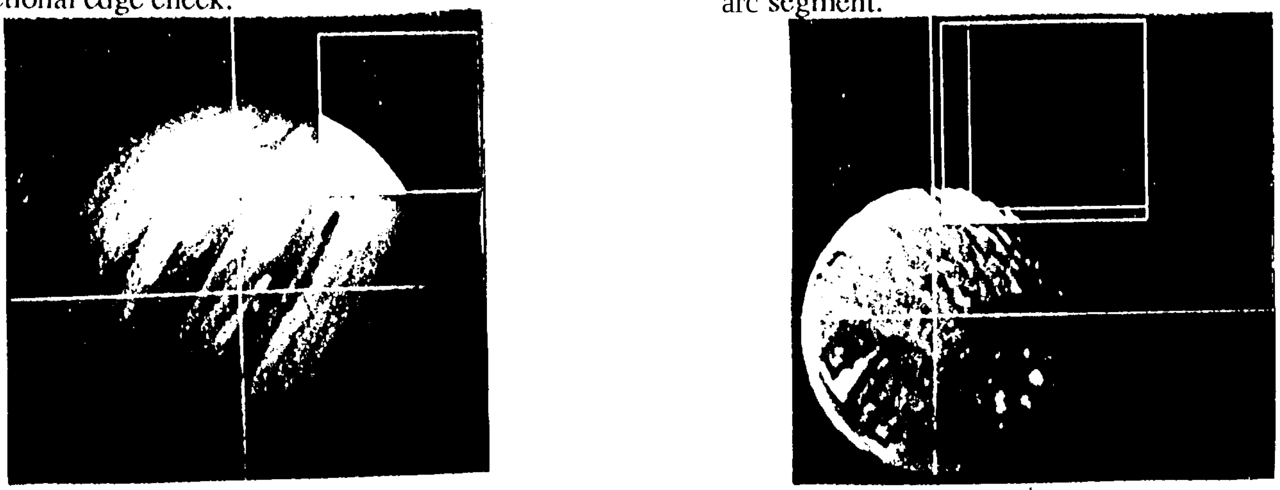


Fig. 8. Estimation of a circle's center using an arc segment.



(a) (b)

Fig. 9. Results of the technique for estimating the center of a circle, which is based on extrapolating from the two endpoints of an arc segment: (a) Jupiter and (b) Miranda.

(a) (b) (c)

Fig. 10. Tracking of designated planetary targets on Jupiter: (a) target designation based on detected contours, (b) tracking the target on an image frame subsequent to 10(a), and (c) multiple-target tracking.

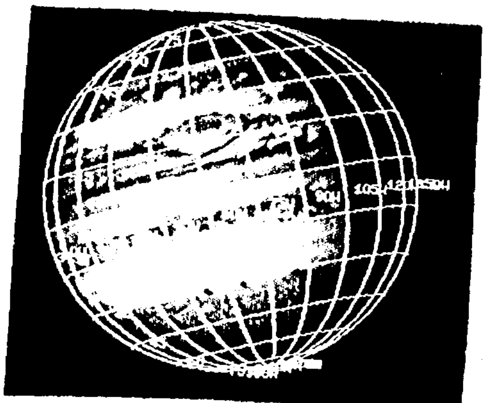


Fig. 11. Estimated position, orientation, and limb of Jupiter with assigned longitudes and latitudes.

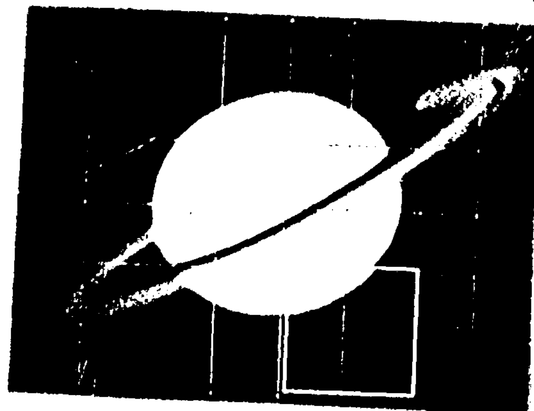


Fig. 12. Estimated mosaic windows and positions for Saturn using only a partial limb from the lower-right portion of the planet,

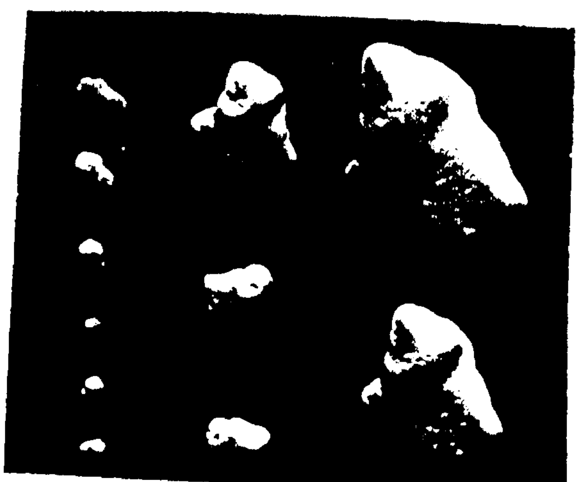


Fig. 13. Pictures of asteroid Gaspra taken by the Jupiter-blfti d Galileo spacecraft.