ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

AUTONOMOUS NAVIGATION OF SPACECRAFT IN DEEP SPACE MISSIONS

Antonio Gil Vicente de Brum
Universidade Federal do ABC - UFABC/CECS. Av. dos Estados, 5001. Sto André, SP
antonio.brum@ufabc.edu.br

Hans Ulrich Pilchowski
National Institute for Space Research – INPE. Av. dos Astronautas, 1758. SJC, SP
hans@dem.inpe.br

Sérgio Donizete Faria
Universidade Federal de Minas Gerais – UFMG. Av. Antônio Carlos, 6627. Belo Horizonte, MG.
sergiofaria@ufmg.br

Abstract. *This article is dedicated to the navigation of space vehicles in deep space missions to explore mainly small bodies of the solar system. Special attention is driven to the encounter and proximity phases of the missions where autonomous optical navigation is required. This is done today with use of images acquired and processed on board, and with the help of additional equipment, such as a laser rangefinder. This subject is important, in view of the deep space exploration missions carried out recently, in progress or under planning, as is the case of the ASTER mission, a planned Russian-Brazilian cooperation to explore the triple asteroid 2001-SN263. In such missions, because of the huge distances involved, the availability of autonomy in the navigation of the spacecraft is an essential item to the accomplishment of the mission objectives. A brief description of the methods utilized in the past together with those used in recent missions is presented. A method initially proposed by the author to determine only the attitude of a spacecraft with use of images of the target surface is reviewed. A discussion on the applicability of this method, adapted, in conjunction with other successful approaches used in past missions, for the general case where autonomous optical navigation is required, is carried out in order to raise a proposal for the navigation strategy to be used in the upcoming mission ASTER.*

Keywords: *deep space mission, ASTER, autonomous optical navigation, ephemeris and attitude estimation, on-board image acquisition and processing.*

1. INTRODUCTION

The navigation of aerospace vehicles with use of imaging data is a matter of great importance to aeronautics and astronautics and has been studied extensively in the last decades. The applications of this research field range from the navigation of unmanned aerial vehicles to the autonomous space navigation around small celestial bodies. The main focus of this article is the autonomous navigation of space vehicles with use optical data. In this case, many techniques have been described in the last years.

1.1 Importance of the deep space exploration of small solar system bodies

Small solar system bodies are of great interest for space exploration for several reasons. Often, asteroids and comets may have diverted their orbits to become near-Earth orbits and, in this case, represent a great danger to the security of entire populations and even for life on the planet. In scientific terms, the study of the composition of these celestial bodies can reveal a lot about the early formation of the solar system and the origin of life on Earth. In technological terms, the large number of technologies involved in this kind of exploitation offers motivation and opportunity for scientific and technological developments that can be performed with robotic space probes in low cost missions. For these reasons, various missions to asteroids and comets were made in the recent past. This is the case of the Hayabusa mission, Near-Shoemaker and Stardust. Others, such as the Rosetta mission, are in progress and there are still others that are in planning, Hayabusa 2 and ASTER (to be presented in more detail later) are examples.

Past explorations revealed that bodies such as asteroids may have different features, especially as to its composition and density, ranging from the denser ones, composed of rocks and minerals, to the less dense ones composed mainly by dust and rubble piles. Such explorations and studies help to better understand these bodies and may be useful in the future, in the possible exploitation of mineral resources of these bodies or in the case where one of them is identified in a collision course with Earth.

2. DEEP SPACE NAVIGATION OF SPACECRAFT

Deep space missions involve enormous distances (in the order of astronomical units, AU). The Voyager spacecrafts, for example, according to the Mission Control Center (JPL/NASA, 2013), are currently more than 100 AU distant from Earth. In these cases, the navigation is performed using standard radio navigation techniques for orbit determination and trajectory prediction in the future. Radio navigation is performed as follows. The space vehicles emit radio signals in the direction of the Earth. These signals are very weak and are detected by large antennas (Fig. 1). The measurement of the distance to the spacecraft is made from the time the waves take to get to the receiving station. Doppler data are also obtained and allow accurate measurement of the speed of the spacecraft with respect to screening station that receives the signals.

Figure 1 – Deep Space Network (DSN) 70 m diameter antenna, in Camberra/Australia.
Souce: deepspace.jpl.nasa.gov

2.1 – Optical Navigation

In conjunction with radio-navigation, optical navigation has also been used for orbit determination and trajectory calculation. Initially, in the encounter phases with solar system bodies (planets, asteroids and other), the images taken by on-board camera containing images of those bodies against the background of stars were transmitted to Earth. This sort of image contains information about the directions of the objects in it (line-of-sight). On Earth, the images were processed and directional vectors were calculated. This information was then combined with standard radio-navigation data, enabling determination of the orbit and the spacecraft's trajectory calculation. The corrections and maneuvers that were required were also computed on ground and transmitted to the spacecraft, where they were executed.

The fundamentals of this type of navigation are simple. Basically, almost all the proposed techniques utilize the angles measured between two solar system bodies (planets, asteroids, celestial bodies with well-known heliocentric positions), and two stars in determining the position of the spacecraft (Scull, 1966). An example of such a situation is shown in Fig. 2. The angle between star 1, S_1, and planet A localizes the spacecraft in a cone with origin in A, axis directed to S_1, with semi-angle α_1; similarly, the angle between star 2 and planet A localizes the vehicle in a cone with origin in A, axis directed to S_2, with semi-angle α_2. The two cones with origin in A intersect in two straight lines, one of which contains the position of the vehicle. The ambiguity related to the two straight lines is resolved with sparse knowledge of the vehicle position. The above procedure is reapplied to planet B. This way, another straight line by Planet B and the vehicle is determined. The intersection of the two straight lines obtained determines the vehicle position. To determine the trajectory of the vehicle, the speed also needs to be determined. The direct measurement of the speed with the use of stellar spectral shift or relativistic methods does not result in accurate enough values (± 100 m/s) due to fluctuations and/or non-uniformity of brightness of stars. The most suitable method seems to be the speed calculation from the taking of two or more positions in time intervals. The combination with navigation data is used to improve the state estimation. A review of the fundamentals of orbits determination with use of optical data can be found in Bhaskaran *et al.* (1996).

The Voyager 1 encounter with Jupiter, in March 1979, was the first time the optical navigation was necessary for the success of an interplanetary mission (Riedel et al., 1996).

The current navigation images differ from normal scientific images by the differential processing suffered on board, resulting in lighter images (few kbits) and containing only what is relevant for the vehicle navigation.

ISSN 2176-5480

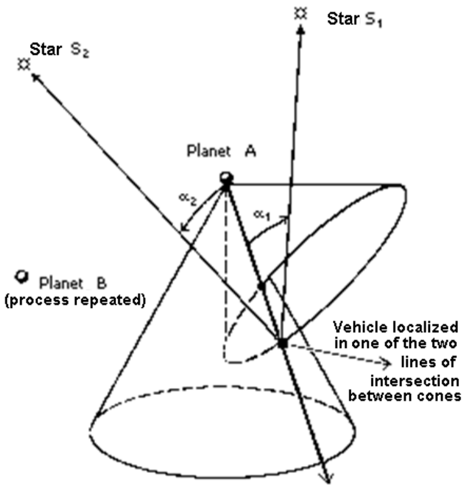

Figure 2 – Geometry of the conventional interplanetary optical navigation. Source: Scull (1966).

As the distance Earth-spacecraft increases, the round-trip time of the EM waves can vary from minutes to hours, and the intensity of the signal sent by the probe reduces with distance. In this sense, the search for greater autonomy in navigation probes became important to the success of space missions, especially in the mission phases where faster navigation solutions need to be found and taken. This is the case of missions where there are one or more scheduled encounters (rendezvous). This need has led to the development of the autonomous optical navigation.

2.2 Autonomous optical navigation

Because mission operations is a significant part of the mission cost, space agencies have explicitly included autonomy in the guidelines to deep space missions. For its New Millenium Program, starting with the Deep Space 1 mission (DS-1), NASA aimed a reduction in requirements for Deep Space Network (DSN) tracking of spacecraft to be achieved from the placement of a complete navigation capability on board the spacecraft. In addition, autonomous navigation capability also required a smaller navigation team during flight (Rayman *et al.*, 2000). In Bhaskaran et al. (1995), a discussion on the image based autonomous optical navigation is presented.

A description of how the automation of the image processing subsystem can be accomplished is shown in [3]. Such subsystem formed the core of a completely autonomous optical navigation system, based on images acquired by the on-board camera, which started to be also processed on board. This system was developed for the DS-1 Mission (launched in October 1998 and deactivated in December 2001) and hired pattern-recognition techniques that were used on the Galileo mission (launched in October 1989 and ended in September 2003).

In Riedel *et al.* (1996), one can find a more detailed description of the autonomous navigation system created for the DS-1 mission. AutoNav was the first complete autonomous optical navigation system successfully tested then.

During encounter, in deep space missions with or without landing, starting from certain target to spacecraft distances (of the order of some thousands of kilometers, depending on the target dimensions), the image of the target body ceases to occupy a few pixels of the imaging camera's field of view (FOV) and begins to occupy a larger part of the FOV. This occupied part increases with the ship's approach, until the target occupies practically the entire FOV. At these distances, common optical navigation images lose their utility because the extraction of lines-of-sight directions is impossible or infeasible. Another sort of optical navigation is used then. Some techniques dedicated to this proximity phase are briefly described in the next paragraphs. Fig. 3 illustrates the relationship between the distance to the target and the navigation type commonly used.

2.3 Proximity autonomous optical navigation

The approach with the target with detailed exploration goal requires additional instrumentation. The more complex the agenda of activities to be carried out, the greater complexity of instrumentation is required. From certain distance, $\pm$ 50 km, the distance meter instruments can now be triggered (a laser rangefinder) and the images taken will reveal features of the target surface. In small bodies' research missions, the detailed investigation of the target body begins in this phase.

Fundamentally, all approaches studied for navigation at this stage make use of target surface images taken and processed on board for selection and acquisition of reference points that will be identified and tracked in new images. The windows with image fragments that contain these references (templates) are chosen and extracted autonomously. Normally, the distance between the ship and the tracked references is measured with the help of additional equipment, a laser rangefinder for example. The information gathered from the measurements and from the image processing with identification of references are used for autonomous navigation, that is, determination of position and velocity with respect to the target body.

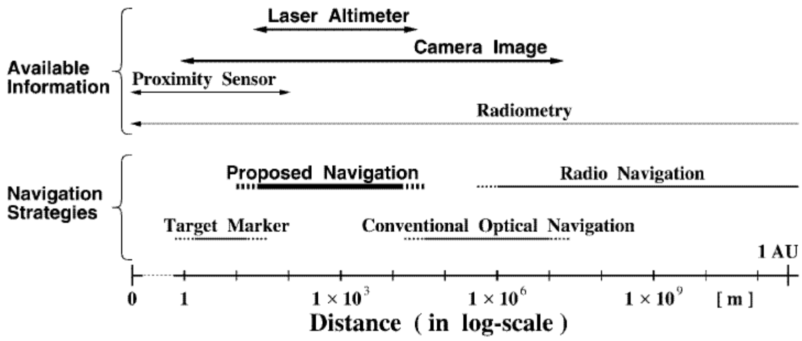

Figure 3 – Available information and navigation strategies. The proposal of Misu *et al.* (1995) for the optical navigation of the Hayabusa spacecraft in the proximity phase with asteroid Itokawa.

According to the type of information available on board, also the attitude (relative or absolute) can be estimated. This type of navigation is much more critical in missions where there is a scheduled landing, because, in this case, a location for the landing should be selected and traced. The choice of location can be made with ground support team, but the requirements of autonomy at this stage are crucial to the success of the mission.

With respect to the templates containing the reference points, the use of fixed landmarks visible on the surface of the target is common and has been studied before (White et al., 1975). The landmarks constitute visible and traceable references on the images and often there is availability of equipment to measure the distance from the vehicle to them, which helps in the composition of the relative navigation. However, not always one can rely on the existence of landmarks. The surface of the target body can be very flat and devoid of visual characteristics that stand out in the landscape. In this way, the navigation based only on their identification becomes subject to faults. This fact has led to the development of new techniques for selecting fixed references on target using surface features that are identified from the image processing.

The identification and selection of patterns in images uses many techniques from image processing area. Among them, one can commonly find measures of correlation using FFT, brightness variance measures, filtering, etc. Different approaches to templates selection, identification of these in new images and tracking of reference points contained in images are found in the literature. Next, we remind some of them.

2.4 Optical navigation in missions of exploration of small solar system bodies

In this section, a brief description is presented of the main aspects of optical navigation in some important missions of exploration of small bodies in the solar system. The missions concerned are: Hayabusa, Near-Shoemaker, DS-1, Deep Impact.

Mission Hayabusa

Kawaguchi et al. (1997) proposed an optical navigation method for the proximity to the target phase. The method utilizes optical correlation between successive pictures of the surface taken independently and also makes use of the altitude information acquired on board. In this method, multiple reference windows fixed (templates containing visual characteristics of the imaged surface) and an image processing algorithm based on fast Fourier transform in two dimensions (FFT) are used for the establishment of the correlation and for tracking visual features in successive images.

Misu et al. (1995) proposed another method for optical navigation and autonomous guidance of the Hayabusa probe. The method is based on the acquisition of target images, with selection and extraction of fixation points (FPs) in them. The method of selection of FPs and of image processing used makes use of a band pass filter to highlight features in the image that are of the size of the tracking window, and uses the local variance of the filtered image as a criterion for extraction of FPs. The FPs are selected and automatically tracked in subsequent images. The information acquired from the tracking of points (coordinates of image), along with the distance to each of the FPs (measured with a laser rangefinder with gimbals), is used to determine relative position, velocity and attitude. The processing technique that correlates the shadowing patterns of successive images is used to track the FPs. In case of loss of some FP, because of the relative target ship motion, the FP is changed in advance so that the new one can inherit its 3D relation from that of the previous ones. Once acquired (inherited) the 3D relation, an optimal control strategy (in terms of fuel, for example) can be applied to guide the ship to the desired site. This procedure enables a few FPs on the surface of the target to be tracked visually and have their distances measured automatically, which allows the autonomous navigation of the ship.

ISSN 2176-5480

The method also includes an extended Kalman filter for the resolution of the observational noise and to increase the accuracy of the navigation. The whole process of processing of acquired images is carried out in three phases: Phase of target designation (landing): Dsk-phase; tracking phase, with taking range measures and thrusters control: Trk-phase; and fixation point (inheritance) acquisition phase: Inh-phase.

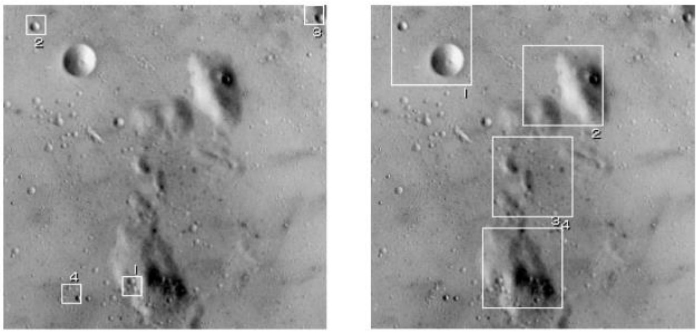

Figure 4 – Images used in the proximity autonomous navigation of the mission Hayabusa (Extraction of templates of different sizes. Left: Extracted areas (16x16). Right: Extracted areas (64x64). Source: Misu et al (1995).

Mission NEAR-Shoemaker

The optical navigation method that gives greater precision to proximity navigation uses stereophotoclinometry in combination with range information obtained by instruments on board (LIDAR or RADAR) (Gaskell et al., 2008).

Stereophotoclinometry is a technique for composing a 3D map of a portion of land or target landscape from at least three images of the region taken with different lighting angles. The lighting differences create different shading patterns in each image, wich are compared and used to reveal in detail the topographical features of the imaged terrain. This technique was proposed by Gaskel (2001) and was applied in 2002 in the mapping of the asteroid Eros. The application of this imaging technique offers as main data output a collection of maps with the surroundings of prominent geographical points on the surface of the ground (L-maps or Landmark maps), high-resolution maps of topography/albedo (HRTMs) of varied resolution that divide the surface of the body into many pieces. Because these maps may have a resolution comparable to the resolution of the best images and can be located in a global reference system with high precision, L-maps provide a significant improvement in the discriminatory power of the surface features of small bodies.

The L-maps are used in the production of a default global topographic model (GTM) of the target and can also be combined to produce high-resolution topographic maps that describe local areas with much greater detail than the global model. When combined with nominal predictions from other data sources and data available from other instruments, as a LIDAR or RADAR, they provide the most accurate solutions available today for the position of the spacecraft and the pointing of the camera.

An important comment regarding the use of this technique in proximity autonomous navigation of spacecraft must be done. As a result of the processing of several images taken of a portion of land with different angles of sight, the L-Maps can be obtained independently, but with a high computational cost. The most common case, however, seems to be the one where the creation of these maps is done on the ground, from the images and LIDAR/RADAR information sent by the probe. Its primary use in determining a global map describing precisely the shape and topography of the target uses many thousands of L-Maps. Of these, some that have been created can be sent to the probe to be used as templates in the image processing to be performed on board, thereby increasing the accuracy of local navigation carried out autonomously.

The creation of L-maps sufficient to cover the entire surface of an asteroid, resulting in a global high-precision model containing the shape and topography of the body investigated is an exhaustive task performed on the ground. This occurred, for example, with the images of the asteroids Nereus (NEAR-Shoemaker mission) and Itokawa (mission Hayabusa). In some cases, the image processing for obtaining the final global model is still in progress.

Deep Space 1 (DS-1)

AutoNav, one of the most important technologies for deep space missions, was successfully tested on DS-1 mission. The AutoNav is a complete navigation system created to perform on board, autonomously, all the tasks related to the spacecraft navigation in all phases of the mission (cruise, maneuvers and encounter with the targets). To do so, AutoNav was composed of various subsystems. One of them, the NavRT, had to provide critical ephemerides to other subsystems, such as ACS, responsible for the spacecraft's attitude control. Another subsystem, the NavExec was responsible for the planning and execution of navigational actions, such as image acquisition and processing, activation of ion propulsion thrusters (IPS) and execution of trajectory correction maneuvers (TCM). The ImageProcessor subsystem was used to carry out the processing of the images. OD was the subsystem responsible for the orbit determination calculations and the ManeuverPlanner subsystem was responsible for calculations related to TCMs and IPS activation. Figure 5 illustrates the autonomous optical navigation processes carried out aboard the DS-1 with use of AutoNav.

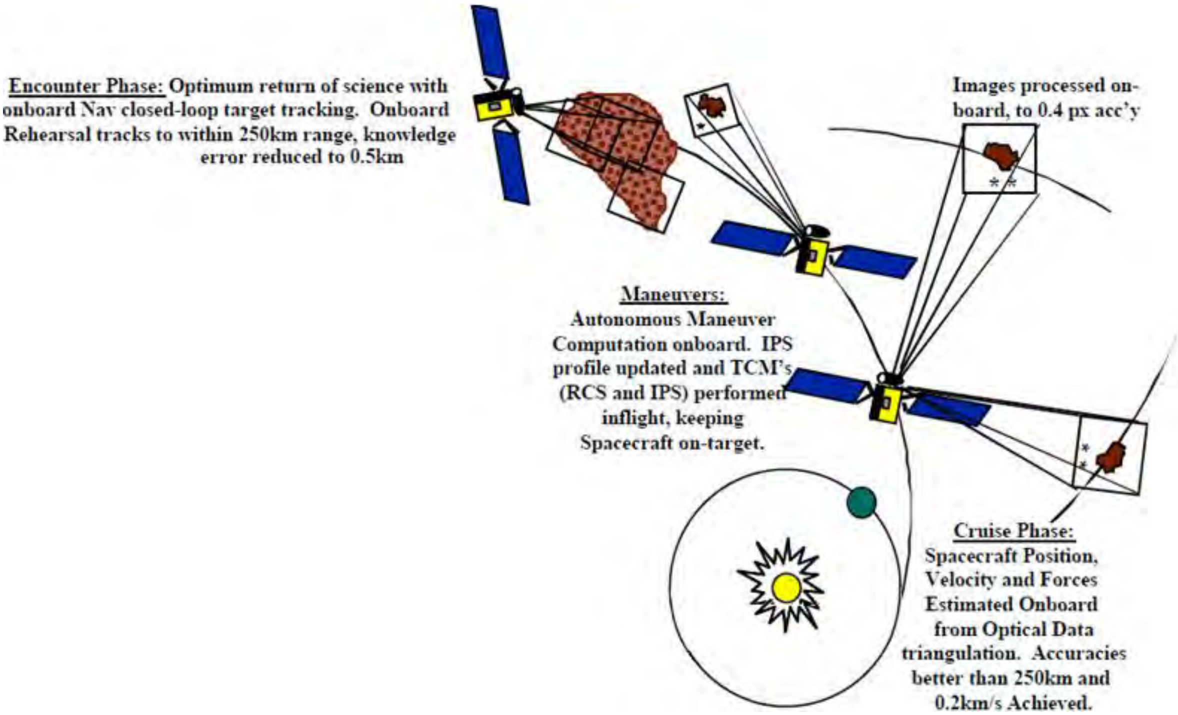

Figure 5 – Autonomous Optical Navigation (AutoNav) for DS-1 mission. Source: Desai et al. (2000), p. vii.

A simplified description of a part of the operations performed by AutoNav is presented below. A full and detailed description of these operations can be found in Desai *et al.* (2000) and Raymani et al. (2000).

In the DS-1 mission, the AutoNav needed data stored on board to be able to operate. These data included a nominal trajectory generated and optimized in Earth, ephemeris of celestial bodies (mission targets), distant asteroids and all planets, and an stellar catalog with 250,000 stars (created from the Tycho star catalog). The system was triggered once per week, within the sequence of operations, to enable the acquisition of optical navigation images. To perform this task, AutoNav issued commands to the ACS, to properly turn the spacecraft and the camera, so the camera could take pictures of asteroids, each with an asteroid against a background of stars. The on-board processing of the acquired images allowed precise extraction of the apparent position of each asteroid with relation to the stars, being this information used to estimate the ship location. The heliocentric orbit was computed then from a sequence of these estimated positions combined with estimates of the solar pressure, gravitational disturbances and with the on-board stored knowledge about the history of the accelerations due to ionic and RCS thrusters (propellant hydrazine-based, also present and available for attitude control, by the ACS). The estimated trajectory was then propagated up to the encounter with the next target with course corrections generated by the ManouverPlanner system. In General, these trajectory corrections were implemented from changes in direction and duration of the IPS, however, in certain cases, the maneuvers were performed by dedicated activations of the IPS or by maneuvers using the RCS.

After the parameters of AutoNav were tuned in flight, autonomous determinations of heliocentric orbit differed from those obtained radiometrically (calculated on the ground and used for comparison) for less than 1000 km in position, and less than 0.4 ms, in speed. In fact, the removal on the ground of some navigation images allowed even more precise orbit determination, with less than 400 m and 0.2 ms. it is worth mentioning that an algorithm was created then to check the images to be used in the determination of the orbit. This algorithm was sent by telemetry and implemented for use in the system.

During encounters, the navigation is made in relation to the target and the required accuracy was ~3 km (1 σ). AutoNav also tracks targets in this phase, in order to obtain precise pointing information (provided to ACS) and initiates the encounter sequences based on its estimates of the time remaining for the next encounter.

The complete system of autonomous optical navigation AutoNav was validated in the DS-1 mission. The success and the lessons learned have created a milestone for future missions. AutoNav represents today the state of the art in terms of complete systems of autonomous navigation in deep space.

ISSN 2176-5480

Deep Impact

The Deep Impact mission (launched in January 2005) also used AutoNav . The complexity of autonomous navigation performed was higher in this case because of the simultaneous control of two spacecrafts, the impactor and the main spacecraft, both with distinct goals to meet, that were completed successfully. The success achieved with use of this technology makes it today the main navigation system candidate to flight in future exploration missions. Kubitschek et al. (2006) describes the autonomous optical navigation performed with use of AutoNav in the mission DI. Reference Riedel et al. (2006) describes proposed improvements to extend the capabilities of AutoNav ("AutoNav Mark 3") with a view to future missions, such as the MSR Mission (Mars Sample Return, highly technological mission with landing, collecting samples and return to Earth). AutoNav is also under evaluation for other proposed research missions to asteroids (with or without landing, with or without collection of samples to return).

3. ATTITUDE ESTIMATES WITH THE USE OF IMAGES OF THE TARGET BODY

The idea of the orbit and attitude determination of spacecraft with use of stars and landmarks is not new. In 1975, White et al. (1975) have proposed an integrated method for the determination of attitude and ephemeris. The article proposes the determination of ephemeris and attitude in a joint way, with the taking of all the necessary measures on board (on-board sensors of attitude: star trackers, and a multispectral imager for observation of landmarks). It should be noted that, in this case, the two sensors are required and the degradation of the quality of the information of attitude influences directly in the precision of the determination of ephemeris (which makes use of the camera images), as is to be expected. Therefore, once taken all measures on board (sight of stars for the determination of attitude and sight of landmarks to determine the position/velocity of the ship), the knowledge on the attitude, as determined on board, definitely influences the accuracy of the determination of position/velocity with sighting of landmarks.

The up to date star trackers offer end-to-end solution for on board attitude determination (arc seconds precision), which enables the determination of the vehicle state on board with use of landmarks, once available on board an imaging sensor.

4. REVISION OF AN ATTITUDE DETERMINATION METHOD WITH USE OF LANDMARKS

The original method (Brum and Pilchowski, 1999) was first proposed to determine the attitude of an imaging vehicle in low Earth orbit. Originally, its application is based on the acquisition and processing of images by the on board camera. Because of its systematic approach, this method is reviewed and proposed for application on board, as a part of a larger autonomous navigation system for the proximity phase of an asteroid exploration mission where a proximity investigation phase is planned (as the ASTER mission).

The above method works as follows. Starting from a panchromatic remote sensing image, some visible points (landmarks) with well known (mapped) geographic coordinates (latitude, longitude and altitude) are selected in it and listed. From the processing of this image, the extraction of templates containing the small portion (window) of the image with one landmark only in it is accomplished. These templates are as small as possible (a few square pixels) to permit positive identification. After that, a database containing the list of landmarks associated with the known geographic information related to each one of them is created.

Similarly to the operation of star sensors, the creation of a database listing all the selected landmarks in the vicinity of the target area has to be accomplished in advance.

Following in the procedure, pattern recognition software using mathematical morphology background is used to perform a complete search for templates in the acquired image (Fig. 6). The correlation between the template and the image identifies the image coordinates of the identified landmark in the original image of the surface. Once identified one such landmark, its geographic data are immediately associated to that identification.

The process of calculating attitude from landmark identification is similar to the process of calculating attitude from stars identification. Given: i) t_i, instant of image acquisition; ii) (I, J) row and column numbers (image coordinates) of at least two landmarks in one image; iii) (latitude, longitude, altitude) - geographic coordinates of the identified (in one image) landmarks, it is possible to determine the attitude of the imaging vehicle, or to refine the previously known vehicle attitude. The technique makes use of the geometric modelling of the imaging instrument to calculate the vector directions of the identified landmarks in the body fixed system of coordinates. This direction depends on t_i and on (I,J). With its geographical coordinates, the Cartesian terrestrial coordinates of the landmark are directly calculated and the direction of the vector from the spacecraft to the landmark is calculated.

This way, with use of the same direction in body coordinates and in terrestrial coordinates, the relative attitude can be calculated. With proper rotations, the inertial attitude can be calculated. The calculations are done as follows.

After processing the image, some points are identified as landmarks by the pattern recognition software. Taking an identified point with known geographic coordinates, one can calculate the time of its imaging, t_i, and the Cartesian terrestrial coordinates of the point on the surface of Earth, $\mathbf{P}_{XCT}$. From $\mathbf{P}_{XCT}$, using proper rotations one can get the geocentric inertial coordinates of this point, $\mathbf{P}_{int}$. At the instant of acquisition of line "I", t_i, vehicle position, in

ISSN 2176-5480

geocentric inertial coordinates is known to be **P**(u,v,w). With use of $\mathbf{P}_{int}$ and **P**(u,v,w), we are able to obtain the vector from the satellite centre to the actual imaged point on the Earth surface, $\vec{a}$, $\mathbf{P}_{int} = \mathbf{P} + \vec{a}$.

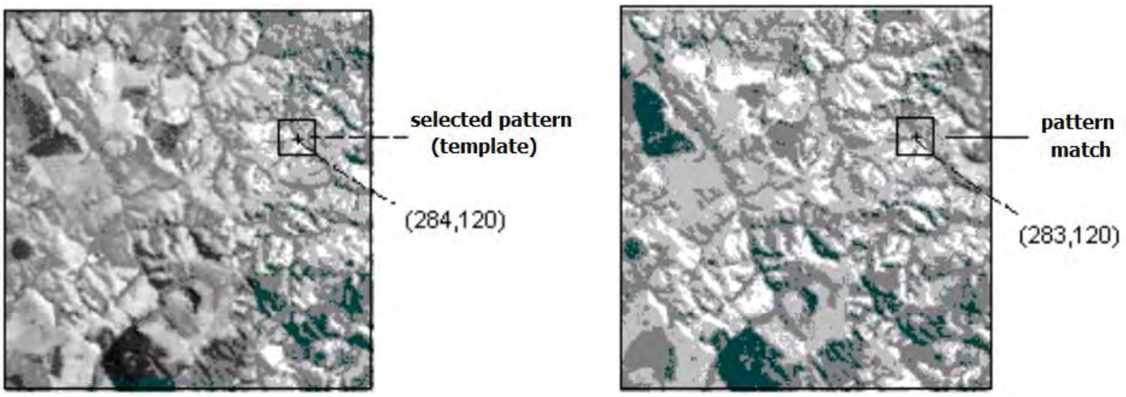

Figure 6 – Example of images: a) reference image, b) search image.
Source: Banon and Faria (1997).

From $\vec{a}$, we obtain the optical axis direction $\hat{\mathbf{a}}$ in geocentric inertial coordinates and, comparing this vector with the same vector in body coordinates, one can determine the attitude by any known method of attitude determination. Of course, the availability of more than two identified landmarks in one image can be used to better estimate the attitude related to all available information, as occurs in the case of attitude estimation with modern star trackers.

A simulation of the whole process was accomplished and is described in Brum and Pilchowski (1999). The complete task performed to validate the method involved (starting from a panchromatic SPOT image): a) Templates selection and extraction (in the spot image, corresponding to visible known landmarks); b) SPOT image processing; c) determination, from the image analysis, of the image coordinates of the identified points, via template matching; d) association of the identified points to their actual geographic coordinates, by means of a database; e) attitude calculation.

Considering the characteristics of the process, a proper programming environment was chosen. A package of mathematical morphology tools for image processing was developed for the Khoros System and implemented in a UNIX environment, including tools for the processing of SPOT images. For this reason, that environment was chosen for the development and implementation of the complete task.

The method described was successfully tested (simulations). The results attained, roll (0.035 ± 2.5x10-6)º, pitch: (-0.039 ± 7.1x10-5)º, and yaw: (0.432 ± 0.0228)°, showed also the applicability of the method on the imaging vehicle attitude refinement, as obtained by another means, considering the SPOT attitude determination precision at the time, 0.15^{o}.

An important conclusion made: the precision of the refinement in attitude attainable is clearly a function of the knowledge on the vehicle state, spatial resolution of the image utilized, and the precision of the database used/constructed (geographic coordinates of landmarks).

5. EXTENDING THE POTENTIALITY OF THE METHOD FOR THE ASTER MISSION

In this section, an analysis on the potentiality of the method described in the last section is done keeping in mind its applicability to the proximity navigation phase of the ASTER mission.

The ASTER mission (Shukanov *et al.* (2010), Macau *et al.* (2011)), a Russian-Brazilian cooperation, plans to send a robotic probe to investigate the Near Earth (triple) Asteroid 2001-SN263, with possible launch in 2017. The probe is based on a Russian MetNet platform. The scientific instrumentation to fly will collect asteroid data for approximately 1 year and the main scientific objectives include determining the size, mass, volume, gravity field and rotation of the triple asteroid members, together with the identification of the composition, morphology and topography of the surface of each body. An investigation of the system dynamics will be conducted to obtain evidences of the system formation. There exists little knowledge on this asteroid and, up to now, the main investigation is planned to occur during rendezvous, with subsequent approximation phases, as occurred with the mission Hayabusa.

The technology mission will use an ionic propulsion system and the navigation will comprise three main phases: cruise, rendezvous and proximity. In terms of instrumentation on board that may be useful in the navigation of the probe, the ASTER mission plans to have: cameras (narrow and wide field), a star tracker and a laser altimeter. All three will be fixed on the probe body.

As a low budget mission, remembering that Brazil does not dispose of a deep space network and that the costs related to the hiring one such structure are high (together with the navigation team personnel), it is clearly mandatory the use of autonomous navigation. In the light of the missions discussed earlier, a proposal of a navigation strategy is presented here.

ISSN 2176-5480

Phase 1: cruise

Because of the low budget, the maximum possible use of autonomous optical navigation to supplement radio navigation (weekly) raises as a good option. The use of autonomous optical navigation strategies dedicated to orbit determination and spacecraft ephemeris estimation is a minimum requirement. As the DS-1 mission, together with the Deep Impact mission, have many similarities with this mission, it seems reasonable, in this phase, to develop and use a kind of autonomy similar to that implemented and tested in those missions (AutoNav algorithms) nonetheless in a simpler version.

Phase 2: rendezvous

Prior to entering this phase, the level of activities involving optical navigation (image acquisition and processing) increases notably. Computadas e executadas as manobras orbitais que tiram a nave do cruzeiro e a colocam na condição de encontro, when a distance to target of about 100 km is reached, the cruise phase ends and the rendezvous phase begins. Porque muito pouco se sabe sobre o asteroide triplo alvo (Fig. 7) uma investigação estendida dos alvos e de seu entorno deverá ser realizada aqui e deverá tomar algum tempo. Esta fase possivelmente será comandada de Terra e envolverá extensa atividade das câmeras de bordo e do pessoal de terra. Decidida a estratégia a adotar na aproximação, esta será iniciada.

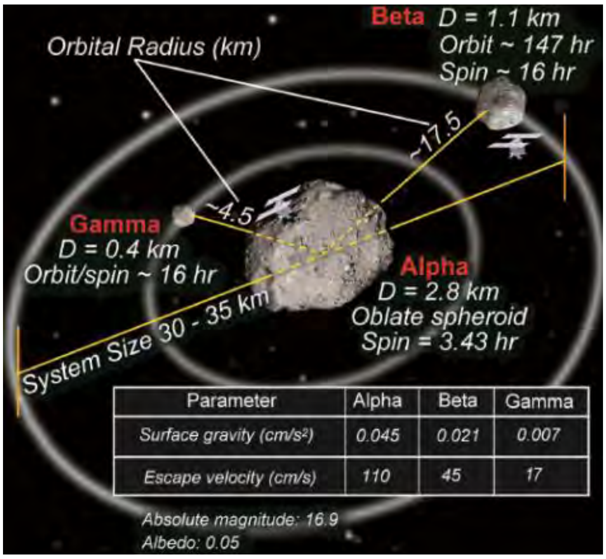

Figure 7 – What is known about the triple Asteroid system 2001 SN263. Source: Jones et al. (2011).

Distances < 50 km: at this stage, the main target images already show characteristics of its surface. The investigation of the triple system occurs here. The images of science combined with laser altimeter information will be used in the composition of a detailed map describing the shape and topographical characteristics of the surface (use of stereophotoclinometry (Gaskell et al., 2008)). This map is useful to identify points of reference for the relative navigation that can be performed in the following stages.

Phase 3: proximity

Once the main scientific research, the decision for a closer approach in order to optimize scientific results should be taken (with or without touchdown, this is not clear yet). Fig. 7 shows the triple system has a diameter between 30 and 35 km. Fang et al (2011) concluded by the existence of a small mutual inclination between the orbits of bodies Beta and Gamma (around 14 degrees), which makes it difficult but not impossible to get closer to the inside bodies while still in encounter, included the possibility of landing on the main body. Two other possibilities are conducting internal passages and orbital insertion.

The information obtained during the investigation phase of the system will be key to the decision of the approach strategy that will be adopted. In all these cases, mainly in including the touchdown, the relative proximity of navigation should be performed with the highest degree of autonomy possible. To this end, images autonomously taken and processed may be used with the help of a method still to develop, but it will be similar to those presented in the previous sections, like the one used in the Hayabusa mission.

ISSN 2176-5480

This process will probably incorporate autonomous optical navigation elements, as those discussed earlier, as the selection of reference points for relative navigation, calculation of their local coordinates (this part will depend on the topographical map of the surface that will have been created previously), calculation of the spacecraft relative state, identification of reference points on the surface of the target (templates), template extraction, identification and choice of a land site (not necessarily autonomously), completion of the landing procedure (including the tracking of the landing site and final synchronization in terms of relative attitude). Concerning the sensors available to perform this procedure, the probe will count on a laser altimeter (30 m minimum range), an imaging camera and a star tracker.

6. RESULTS AND CONCLUSIONS

This work has discussed many strategies adopted in the deep space navigation of spacecraft with main focus on the optical navigation and optical autonomous navigation, in all phases it comprises. A brief revision of the approaches used in past missions was accomplished and one more detailed description of a previous related method developed by this author was conducted. Finally, an analysis with proposal of optical navigation esqueme for the ASTER mission was accomplished.

7. REFERENCES

Banon, G. J. F.; Faria, S. D., 1997. “Morphological approach for template matching”. In: *Brazilian Symposium on Computer Graphics and Image Processing.* Campos do Jordão, Oct. 14-17. *Proceedings*. *Los Alamitos: IEEE Computer Society*. p. 171-177.

Bhaskaran, S., Riedel, J.E., Synnott, S.P., 1995. “Demonstration of Autonomous Orbit Determination Around Small Bodies”. *AAS/AIAA Astrodynamics Conference*, Halifax, Nova Scotia, Aug. 1995. <http://hdl.handle.net/2014/30376>.

Bhaskaran, Shyam; Riedel, Joseph E.; Synnott, Stephen P., 1996. “Autonomous optical navigation for interplanetary missions”. In *Proceedings of SPIE* 2810, Space Sciencecraft Control and Tracking in the New Millennium, 32 (October 28, 1996); doi:10.1117/12.255151. < http://hdl.handle.net/2014/26120>.

Brum, Antonio Gil Vicente de; Pilchowski, Hans Ulrich. 1999. “SPOT imaging instrument (HRV) modeling for interaction with the attitude determination and control system of the imaging satellite”. In: *XV Congresso Brasileiro de Engenharia Mecânica - COBEM, 1999*. Águas de Lindóia. Anais do XV Congresso Brasileiro de Engenharia Mecânica.

Desai, S., Han, D., Bhaskaran, S., Kennedy, B., McElrath, T., Null, G. W., Riedel, J. E., Ryne, M., Synnott, S. P., Wang, T. C., Werner, R. A., Zamani, E. B., 2000. “Autonomous Optical Navigation (AutoNav)”. *DS-1 Technology Validation Report.* JPL Publication. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

Fang, Julia; Margot, Jean-Luc; Brozovic, Marina; Nolan, Michael C.; Benner, Lance A. M.; Taylor, Patrick A., 2011. “Orbits of Near-Earth Asteroid Triples 2001 SN263 and 1994 CC: Properties, Origin, and Evolution”. *The Astronomical Journal*, 141:154 (15pp). May 2011. doi:10.1088/0004-6256/141/5/154.

Gaskell, R. W., 2001. “Automated landmark identification for spacecraft navigation”. *AAS/AIAA Astrodynamic Specialist Conference*, Quebec City, Quebec, Canada. 30-Jul-2001. <http://hdl.handle.net/2014/12954>.

Gaskell, R. W., Barnouin-Jha, O., Scheeres, D., Konopliv, A. S., Mukai, T., Abe, S., Saito, J., Ishiguro, M., Kubota, T., Hashimoto, T., Kawaguchi, J., Yoshikawa, M., Shirakawa, K., Kominato, T., Hirata, N., Demura, H., 2008. "Characterizing and Navigating Small Bodies with Imaging Data." *Meteoritics & Planetary Science* 43, Nr 6, 1049–1061.

Jet Propulsion Laboratory - JPL/NASA, 2013. “Voyager The Interstellar Mission”. April 2013 <http://voyager.jpl.nasa.gov>.

Jones, T., Lee, P., J. Bellerose, R. DeRosee, J. Chartres, J. McCarthy, D. Mayer, P. Bhavsar, G. Mungas, D. Osterman, T. Prettyman, J. Goldsten, D. Lawrence, D. Dunham, J. Horsewood, H. Sanchez, J. Heldmann, P. Smith, B. Williams, E. Fahnestock, M. Gaffey, M. Nolan, P. Thomas, A. Hildebrand, R. Farquhar, G. Benedix, J. Veverka, H. Yano, R. Elphic, 2011. “A Lander to Investigate a C-type Triple Near-Earth Asteroid System: 2001 SN263”.

ISSN 2176-5480

Presentation. SETI Institute. <http://multimedia.seti.org/PhD2011/presentations/4-Poster%20Session/PhD2-2011-Jones-Poster-%5B11-003%5D.pdf>.

Kawaguchi, J., Hashimoto, T., Kubota, T., Sawai, S., and Fujii, G., 1997. "Autonomous optical guidance and navigation strategy around a small body". *AIAA Journal of Guidance, Control, and Dynamics*, **20**, 5. (Sept.—Oct. 1997), 1010—1017.

Kubitschek, Daniel G., Mastrodemos, Nickolaos, Werner, Robert, Kennedy, Brian, Synnott, Stephen P., Null, George, Bhaskaran, Shyam, Riedel, Joseph E., and Vaughan, Andrew T., 2006. "Deep Impact Autonomous Navigation: The Trials of Targeting the Unknown". *American Astronautical Society. 29th Annual AAS Guidance and Control Conference*. Breckenridge, Colorado. February 4-8.

Macau, Elbert E. N.; Winter, Othon C.; Velho, Haroldo F. Campos; Sukanov, Alexander A.; Brum, Antonio G. V. de; Ferreira, J. L.; Hetem Jr, Annibal; Sandonato, Gilberto M.; Sfair, Rafael., 2011. "The ASTER mission: exploring for the first time a triple system asteroid". In: *62nd International Astronautical Congress*, Cape Town, South Africa, 3 – 7 October 2011. Paper no. IAC-11, B4-2-7.

Misu, T.; Hashimoto, T.; Ninomiya, K., 1999. "Optical guidance for autonomous landing of spacecraft," *IEEE Transactions on Aerospace and Electronic Systems,* , vol.35, no.2, pp.459-473. doi: 10.1109/7.766929.

Rayman, Marc D., Varghese, Philip, Lehman, David H., and Livesay, Leslie L., 2000. "Results from the Deep Space 1 technology validation mission". *50th International Astronautical Congress,* Amsterdam, the Netherlands, 4-8 October, 1999, IAA-99-IAA.11.2.01. *Acta Astronautica 47, p. 475.*

Riedel, J., Bhaskaran, S., Synott, S., Bollman, W., and Null, G., 1996. "An Autonomous Optical Navigation and Control System for Interplanetary Exploration Missions". In *Proceedings of 2nd IAA International Conference on Low-Cost Planetary Missions*. <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/25043/1/96-0682.pdf>.

Riedel, J. E., Shyam Bhaskaran, Dan B. Eldred, Robert A. Gaskell, Christopher A. Grasso, Brian Kennedy, Daniel Kubitschek, Nickolaos Mastrodemos, Stephen. P. Synnott, Andrew Vaughan, Robert A. Werner., 2006. "AutoNav Mark3: Engineering the Next Generation of Autonomous Onboard Navigation and Guidance." *AIAA Guidance, Navigation, and Control Conference and Exhibit*. 21-24 August 2006, Keystone, Colorado. AIAA 2006-6708.

Scull, J.R., 1966. "Spacecraft Guidance and Control". *Space technology* - vol. 4. NASA, Washington D.C.

Sukhanov, A.A., Velho, H.F. de C. , Macau, E.E. , Winter, O.C., 2010. "The Aster Project: Flight to a Near_Earth Asteroid**"**. *Cosmic Research*, Vol. 48, No. 5 pp. 443–450. Pleiades Publishing, Ltd., 2010. Original Russian Text: A.A. Sukhanov, H.F. de C. Velho, E.E. Macau, O.C. Winter, 2010, published in *Kosmicheskie Issledovaniya*. Vol. 48, No. 5, pp. 455–462. ISSN 0010_9525.

White, R. L., Adams, M. B., Geisler, E. G., Grant, F. D., 1975. "Attitude and orbit estimation using stars and landmarks". *IEEE Trans. Aerospace Electron. Syst.*, AES-11 (1975), pp. 195–203.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.