Measurements & Instrumentation Systems
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Technical University of Denmark

Assessment Study of Autonomous Optical Navigation for an Asteroid Impact Mission

-Executive Summary-

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Applicable Documents

[EXPRO] - App 1 Statement of Work, 24/05/2016

[AD1] – Asteroid Impact Mission – System Requirements Document

[AD50] Asteroid Impact Mission - Mission Objectives, Issue 1, Rev. 1, 26/10/2015

[RD1] CDF Study Report AIM3P – Payload Assessment, November 2014.

[RD2] Asteroid Impact Mission – Mission and Payload Operation Scenario 24/06/2015

[DTU1] MicroASC instrument onboard Juno spacecraft utilizing inertially controlled imaging 2016

[DTU2] VBS – The Optical Rendezvous and Docking Sensor for PRISMA

[DTU3] Flight Demonstration of formation flying capabilities for future missions (Acta Astronautica 2014)

[DTU4] Advanced stellar compass deep space navigation, ground testing results (Acta Astronautica 2006)

[DTU5] Enhanced mission performance from autonomous instrument guidance (Acta Astronautica 2006)

Introduction

The Asteroid Impact Mission (AIM) is part of the Asteroid Impact and Deflection Assessment (AIDA). The intention of AIDA is to send two spacecraft, AIM and Double Asteroid Redirection Test (DART) to the binary asteroid 65803 Didymos, to investigate the kinetic effects of crashing an impactor spacecraft into the smaller body of the binary asteroid, hereafter called Didymoon. The large body is called Didymain. Ultimately the mission hopes to test whether a spacecraft could successfully deflect an asteroid on collision course with Earth. The ambition of AIM is to arrive prior to the impact spacecraft and determine the binary asteroid dynamics and properties and evaluate the effect of the impact, by comparing the orbit characteristics both before and after the impact. In addition to the collision avoidance test, the project hope to advance our knowledge of the asteroid system and to demonstrate novel technologies including optical communication, landing a spacecraft on the asteroid and operate several CubeSats.

The ambition of this work is to assess the applicability and feasibility of a potential on-board fully autonomous visual based navigation sensors' system for a mission with the ESA's Asteroid Impact Mission profile. The activity covers the assessment of the mission's potential needs for, and benefits from, an on-board optical navigation sensors' suite, across all the mission phases. In addition, the activity covers the sensors' system's optimization and trade-offs analysis.

Visual Imaging System Objectives

The AIM spacecraft is to be equipped with a Visual Imaging System (VIS) which is intended as a dual purpose navigation and scientific camera system. The VIS is essential to achieving most of the scientific objectives by acquiring visual images of the binary system, before and after the arrival of DART. From the optical observations, descriptive parameters are extracted: mass, volume, size, rotation and rotation periods, topography, granularity of surface materials and the shape of both Didymos and Didymoon. In addition, the VIS is intended to acquire images of the binary system to support the relative navigation. Furthermore, the VIS should support relevant scientific operations like searching for the presence of dust in the surrounding of Didymoon, support the remaining scientific instrument with relative pointing, and assist the landing spacecraft MASCOT-2 during the descent and enable its localization after touch-down.

The AIM baseline presented in earlier work AD1, RD1, RD2, AD50, is design such that all the visual imaging system objectives can be accomplished by downloading images and performing the image analysis on ground. This approach abides with the standards of past decades of spacecraft design by minimizing risk, complexity and development. However it also waives from potential scientific and navigational gains, and novel technological demonstrations. The intent of this work is to identify these opportunities and evaluate the potential advantages that can be acquired through performing the computation autonomously on-board the spacecraft.

Visual Autonomy for AIM

Over the last decades, autonomous systems have successfully demonstrated the extension of the scientific gain, offering unique capabilities and support to flight operation. However, the pace of adoption has been relatively slow and the rebuttal can be identified as reliability, complexity and development cost. Autonomy increases the potential risk of a mission, brings complexity to what might otherwise be a fairly straightforward system and add to the development cost of software. In addition, the conventional downloading of images brings intelligence in form of a human observer, reduces requirements on onboard processing capabilities and provides the possibility to process the images once the scene have been fully modelled or understood.

The only significant drawbacks are the inherent time-of-flight delay in combination with a limited communication budget and coverage by the Deep Space Network. The time-of-flight delay removes any capabilities for real-time operation, and the limited coverage puts an upper limit on the amount of images that can be acquired. The consequence is a limitation in the temporal resolution of the images and ultimately on the scientific and navigational accuracy that can be obtained. By performing some of the VIS capabilities autonomously onboard, it is possible to circumvent these shortcomings and enhance the scientific outcome.

In this work, a fully autonomous solution was investigated, however it was found that the added intelligence and verification associated with downloading the images is essential for AIM. As a result, most of the autonomous solutions that are presented in this work should not necessarily be seen as a replacement for downloading images, but as a combination building on the strength of each method. The proposed solution seeks to combine the high temporal resolution, the high data compression and real-time capabilities of the autonomous system, with the intelligence and risk reduction from the downloading the images. In practice, this means running the autonomous system continuously, while downloading images according to the AIM baseline. The advantages of this solution are summarized in Figure 1.

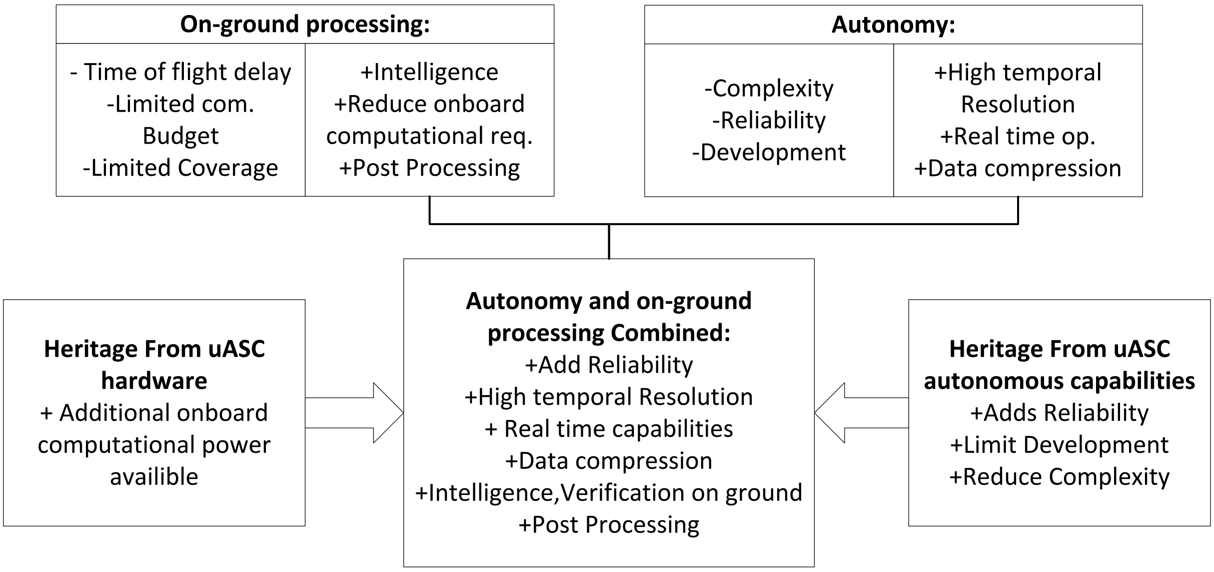


Figure 1, summarization of the trade-off study between on-ground processing and autonomy. The proposed solution builds upon the strength of each method in a combined autonomy and on-ground processing. Building on the heritage from previous DTU µASC missions, the major disadvantages of autonomy can be circumvented; development, complexity and reliability. The µASC system digital processing unit supports the additional computation, without additional cost for AIM.

While reliability can be partly assured by verification during on-ground processing, complexity and development are still major disadvantages to this procedure. The development time is especially critical for a mission with the AIM profile, due to the relatively small time window that is available before launch. To bypass the development and minimize complexity, the proposed solutions chosen based upon the heritage algorithms in the DTU µASC processor.

The DTU System

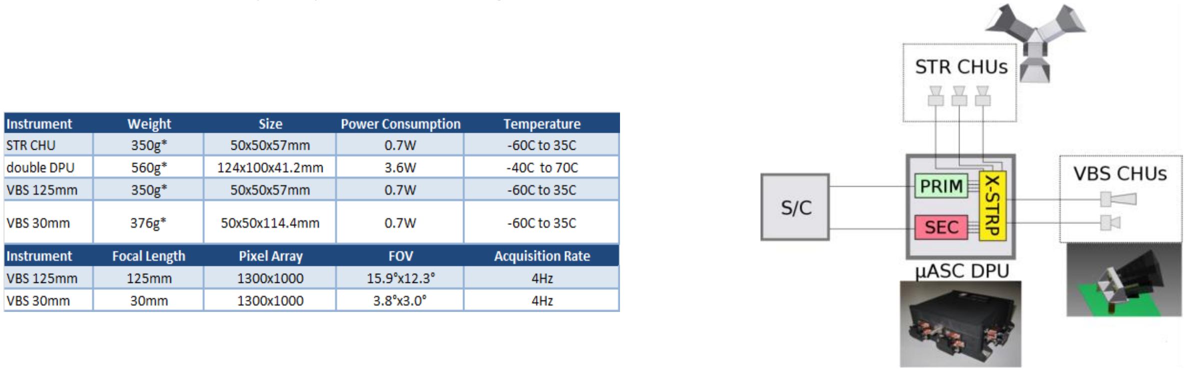
The micro Advanced Stellar Compass (µASC) is a flight proven, high accuracy star tracker, featuring reliable and fully autonomous functionality. The first µASC was successfully launched in 2008 and has operated successfully since then. The µASC has by now accumulated 60 years flight heritage and currently 25 µASC instruments are flying in space, covering NASA, ESA, CNES, and JAXA missions. The instruments are flying in largely varying orbits - ranging from LEO, GTO, lunar orbits and at Jupiter onboard the JUNO spacecraft.

The µASC consists of a data processing unit (DPU) that drives up to four camera heads (CHU). The CHU enables up to 22 attitude solutions per second, however as the CHU is photon limited; full accuracy can only be achieved by running the CHU at maximum 8Hz. Consequently the µASC has considerable amount of computing power available for other applications that can be triggered or implemented depending upon the mission profile. These 'add on' modules run separately on the DPU, and will not impact the performance of the µASC as an attitude sensor. Such an extended feature is the Vision Based Sensor (VBS) system, which provides the µASC with the autonomous functionalities of detection of planetary bodies, non-Stellar object tracking, rendezvous- and docking navigation, and terrain relative navigation.

The Proposed Hardware Platform

The main design goal is to inherit as much of the μASC instruments as possible, while still allowing for improvements to augment the performance envelope. By utilizing the heritage μASC digital processing unit, it is possible to adopt the flight-proven VBS software directly, including the core centroiding and pattern matching functions and the autonomous VBS functionalities. These past experience in space, which can be directly applied, are highly valuable to AIM when the performance criteria are to be established.

The proposed instrument consists of separate units: 3 Star Tracker (STR) Camera Head Units, 2 VBS science and navigation CHUs, and a double DPU. Each CHU is connected by *pigtail* cable to the DPU and the double DPU is internally fully redundant (Figure 2).



Instrument	Weight	Size	Power Consumption	Temperature
STR CHU	350g*	50x50x57mm	0.7W	-60C to 35C
double DPU	560g*	124x100x41.2mm	3.6W	-40C to 70C
VBS 125mm	350g*	50x50x57mm	0.7W	-60C to 35C
VBS 30mm	376g*	50x50x114.4mm	0.7W	-60C to 35C

Instrument	Focal Length	Pixel Array	FOV	Acquisition Rate
VBS 125mm	125mm	1300x1000	15.9°x12.3°	4Hz
VBS 30mm	30mm	1300x1000	3.8°x3.0°	4Hz

Figure 2 Illustration of the proposed VIS for AIM. The system consists of a double digital processing unit connected to 3 star trackers and two science cameras. The star trackers and the science cameras are proposed to be located on an optical bench, such that the orientation of the scientific cameras is determined by the star trackers and the inter-calibration between these. The double DPU offers a fully redundant design, capable of switching between the primary and secondary isolated computing unit in case of failure.

The single science and navigation camera proposed by the AIM baseline (RD1), is replaced by a dual CHU system of 125mm and 30mm focal length. This design effectively comply with the AIM navigational requirements of having both Didymos and Didymoon inside the field of view of the 30mm CHU, while the 125mm CHU enables a higher resolution of the scientific images compared to the single CHU baseline. As an added bonus the two cameras brings redundancy to a system, which is critical for obtaining most of the scientific objectives. Finally the design takes heritage from the similar VBS onboard PROBA V, which leads to a reduced development time and mission risk.

The dynamical range between the stars and the Didymos system exceed the capabilities of modern camera systems, this necessitates an inter-calibration, such that the orientation of the science cameras can be extrapolated from the orientation of the star trackers. Consequently, the proposed solution contains a combined package of both star trackers and VBS cameras. The inter-calibration is proposed to be performed during the cruise phase when both systems are observing the starry sky. Utilizing the same computing unit removes any bias between various star tracking software and enables star tracking on the VBS cameras without adding extra development. Combining the VBS and star tracking allows for simultaneous of STR and VBS images, thus removing any need to extrapolate the solution in time and enabling a highly accurate orientation. Furthermore the internal communication between the VBS and STR allows for a much simpler implementation while the heritage allows for past experiences to be directly applied and reduces development time.

Table 1 lists the autonomous functionalities that have been identified as significant improvements to the AIM mission. The major system advantages have been listed in the bottom row.

Cruise	Approach + Science	Science	Landing
Safe Mode Recovery and **OPTEL-D demonstration**	**Relative Navigation**	**Feature Point Tracking** and **Edge Detection**	**MASCOT-2 Tracking** and **Hazard Detection**
Risk Reduction Cost Reduction Technology Demonstration	Navigation Accuracy Data compression	Improved Science	Risk Reduction

Autonomous Opportunities for AIM

The proposed instrument package is based upon heritage and experience from past missions. With a foundation in this knowledge, each of the AIM mission phases has been analyzed to identify the opportunities for autonomy. The opportunities are listed in Table 1, where the potential value has been identified as; cost, risk, data compression, technology demonstration, navigation accuracy and improved scientific return. A description of each of these opportunities is listed in this section.

Cruise Phase

The AIM cruise phase is expected to last approximately 18 months containing at least one deep space maneuver. The cruise phase can be characterized as rather uneventful, with the primary design driver being the heliocentric navigation. During the cruise phase two major autonomous opportunities have been identified, namely safe-mode recovery and OPTEL-D demonstration.

Safe Mode Recovery

A unique feature of the VBS is its capability to determine the position and the orbit of the spacecraft without any a-priori knowledge. The position is determined by the observation of the apparent angular position of the planets w.r.t the background stars. This capability is of interest to AIM as it enables the spacecraft to autonomously re-point the on-board antennas or optical communication to ground in case of a broken link due to the spacecraft going into safe mode. In (RD1), it is stated that the deep space network (DSN) coverage was adjusted from once per month, which is sufficient for deep space navigation, to once per week due to the risk of losing the spacecraft during a safe mode. In fact, in case of loss of contact, the ground stations are powerless to re-gain control of the vehicle to re-establish the communications and, normally, the spacecraft can only set itself in the safe configuration with no capability to actively seek the Earth. However, given the rough position estimation from the VBS, the spacecraft will be able to autonomously point the antenna toward Earth and re-establish contact. This opportunity is highly relevant for AIM as it reduces in the mission risk and potentially the operation cost due to a reduction in DSN tracking.

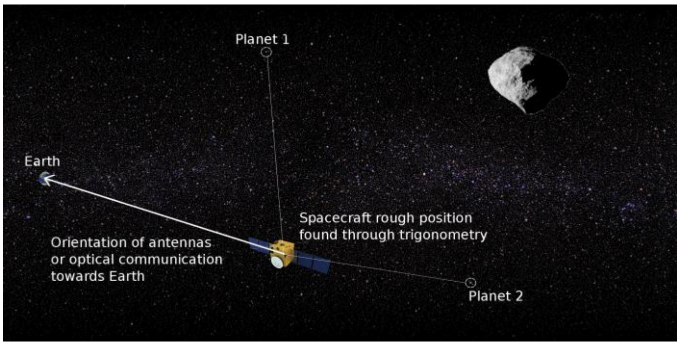


Figure 3 illustrates AIM determining its position from the relative position of planetary bodies in the sky. Given the rough position estimation, AIM is capable of orientating the antennas or optical communication towards Earth.

OPTEL-D demonstration

As part of the Technology Mission of Opportunity, AIM seeks to push the capabilities of optical navigation by carrying the OPTEL-D instrument as part of the science suite. This instrument is capable of obtaining an end-to-end optical communication with ground segment on Earth, and the objective is to perform an in-orbit-demonstration of its capabilities to transmit data from large distances in deep space.

A fundamental shortcoming of deep space optical communication is the dependency upon radiometric measurements to determine the heliocentric position of the spacecraft in order to orientate the laser communication. This leaves deep space missions dependent upon two instruments with high mass and power budget, on missions where both are a scarce resource. In theory the ranging and Doppler radiometric measurements could be replaced by similar optical measures, which would significantly improve the measurements accuracy. However, the optical communication lacks the unidirectional capabilities that is necessary to establish the communication link or regain contact subsequently to safe modes. The VBS safe-mode recovery effectively bypasses this limitation, and potentially enables a fully optical communication and navigation solution. While the full system is confined to future spacecraft, the AIM mission offers a unique opportunity to demonstrate the autonomous acquisition of an optical communication link. It is therefore proposed that AIM performs a simulated "lost in space" scenario during a DSN track, to prove the viability of this novel technology and take a quantum leap towards the future with respect to spacecraft design.

Relative Navigation

The AIM approach to the Didymos system is proposed as a five-maneuver insertion sequence (RD1), designed such that the maneuvers become consecutively smaller. The maneuvers are spaced by seven days to leave ample time for orbit determination, thruster calibration and preparation of the next maneuver in the sequence. The target point of the insertion sequence is a 35km formation flying station. The primary objective of the visual imaging system during the approach phase is to accommodate the S/C navigation. For the majority of the approach phase the binary system will appear as a point source that will move slowly with respect to the stars. In the proximity to manoeuver #4 the binary system becomes resolvable and the visual separation of Didymain and Didymoon will become possible. The asteroids will continuously expand during the approach up to several hundred pixels when reaching the 35km science station. During the approach the sun will illuminate the asteroid at an angle to the approach vector, with the consequence of only a part of the asteroid system being visible at any given time. The S/C navigation is achieved by determining the relative orientation of the asteroids with respect to the background stars, supported by the apparent size once the asteroids become resolved. These optical measures will be affected by the observation conditions and will change over the course of a body's rotation and the systems orbital period. However, until the asteroid system has been sufficiently modelled and a high precision state vector can be acquired from the downloaded images, the navigation must be based on these simple optical measures.

The centroiding and isolation of planetary objects on an image containing the night sky are common star tracking challenges and the VBS feature this capability. The centroiding is performed by the same software that detects the stars, and the asteroid is identified by removing known stellar objects and hotspots. The identification is further confirmed from a time sequence detecting the apparent movement on the night sky, including time averaging and outlier rejection. This functionality is highly relevant to AIM as it improves the accuracy of the navigation by more than a decade and limits the DSN communication to a bare minimum.

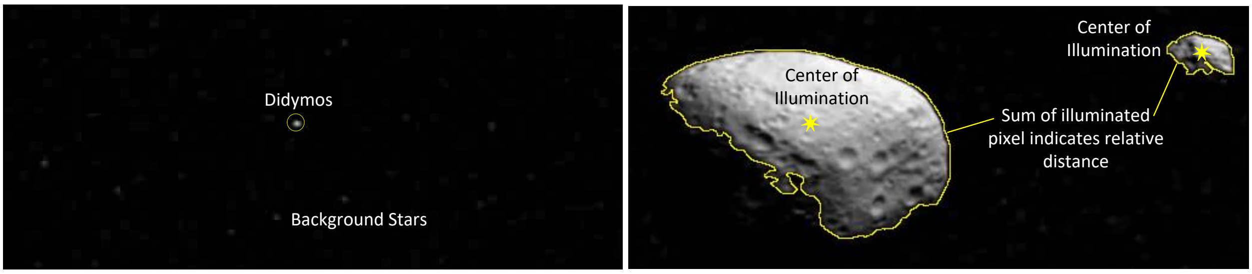


Figure 4, Left: Illustration of approach, the asteroid system is isolated from the background stars. Right: Illustration of Didymos during close proximity, the optical observations are limited to center of illumination and relative size.

Science phase

In the science phase the spacecraft is positioned at two stations; 35km and 10km, describing the relative distance to Didymos. The science phase constitutes an increased uncertainty due to the unknown nature of the asteroids. However, the characterization of Didymos is a well-defined problem, and is identified as an area where autonomy can support the mission. The VBS has the capability to identify and tracks low level features (keypoints) in order to determine the motion of the observed target. The algorithms determine autonomously the most prominent features and acquire a uniformly distributed set from the observed scene. As these keypoints have a physical connection to the terrain from which they are picked, they can be used to univocally characterize its morphology as well as its motion. In practice a data series with these feature point acquired at a high temporal resolution, will enable a full characterization of the asteroid system. Combined with the data compression and on-ground verification, the characterization of the system can be completed with an improved accuracy in a matter of days instead of weeks.

In addition, the VBS features an autonomous edge detection algorithm, which is capable of extracting the apparent edge of the asteroids in the images. Running this algorithm over the course of an orbital and rotation period, the edge information enables an early estimation of the shape of the asteroids, and assists the on-ground data processing of the keypoints.

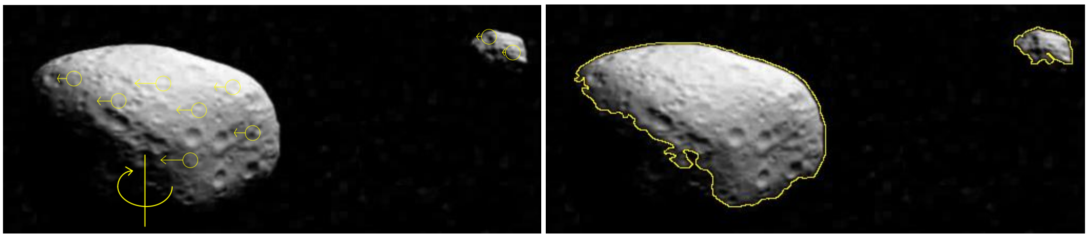


Figure 5 illustrates the autonomous functionalities during the science phase. Left; key point tracking enables the determination of the orbit characteristics. Right; edge detection algorithm supports the early shape determination.

Landing phase

As part of the scientific investigation of the Didymos system, the AIM spacecraft will be carrying a lander spacecraft called MASCOT-2. According to (RD2), the AIM spacecraft should be capable of tracking and reconstructing the MASCOT-2 descent and localize the lander after touchdown. The VBS has the capability of inflight detection and tracking of spacecraft vehicles, enabling accurate and robust Rendezvous, Docking and Formation Flight between two or more vehicles. The VBS has heritage from the Swedish PRISMA mission that consists of a small satellite pair flying in closed loop formation at LEO. The tracking capabilities of the VBS are directly applicable to these requirements. During descent MASCOT-2 can be tracked in real-time, delivering high resolution measurements, allowing for accurate trajectory determination and after touchdown, the VBS can easily locate the MASCOT-2 vehicle by cooperative means.

The cooperative technology necessitates an illumination source placed on the landing spacecraft. For PRISMA the illumination source consisted of a special pattern of LEDs, enable a 6 degrees of freedom solution. In order to comply with the requirements, the MASCOT-2 is recommended to be, at least, equipped with a light beacon for context mapping post landing. This beacon will allow for a less restrictive flight schedule as the beacon is detectable regardless of the ambient illumination. The beacon is suitable to the limited budget of a lander, as the technology utilizes a powerful flash synchronized with the CHU light integration. This capability holds high value to the science recordings obtained from MASCOT-2 payloads, as the local measurements are correctly mapped to the body of the asteroid for context.

Conclusion

In this work, a mission with the ESA's Asteroid Impact Mission profile has been analyzed and the applicability and feasibility of a potential on-board fully autonomous visual based navigation sensors' have been assessed. A full sensors' system have been proposed combining the star trackers and visual imaging system into a single package. The proposed hardware solution is an off the shelf, miniature, low power, light weight and flexible yet high performing. The package effectively complies with all of the AIM requirements for both systems, while offering redundancy and improved scientific and navigational performance with its dual camera system. The combination offers a minimization of the S/C resources and internal communication, unrivaled accuracy on orientating the science camera and the heritage allows for past experiences to be directly applied.

The Asteroid Impact Mission has been analyzed based upon the autonomous capabilities of the VBS system. Several potential functionalities have been identified that would enable improved scientific and navigation accuracy, and reduced mission cost and risk, these include relative navigation, feature tracking and landing support. In addition, the combination of the optical communication instrument OPTEL-D and the VBS safe mode recovery represent a disruptive technology that has the potential to change the way spacecraft are built. Autonomy has a great potential for AIM and the mission profile present a unique opportunity to demonstrate these autonomous functionalities, and set a new standard for spacecraft design, in a progressive and low risk manner.