SAFE NEAR RANGE NAVIGATION BASED ON 3D TIME-OF-FLIGHT CAMERAS

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ABSTRACT

Reliable characterization of the working environment in the near vicinity of a robot is crucial for autonomous avoidance of collisions in a broad spectrum of space applications, including planetary rovers, formation flying, as well as rendezvous & docking to passive objects. This contribution provides a survey on the potential of time-of-flight cameras to generate 3D-images in real-time for autonomous reaction capabilities in time critical scenarios. Hardware-in-the-loop simulations are employed to generate results from realistic performance evaluations.

1 INTRODUCTION

Safety aspects provide in space exploration challenging requirements for autonomous reaction capabilities, because communication links are often interrupted or remote control is not possible in time-critical situations due to signal propagation delays. Ranging systems are crucial for landing on planets, comets and asteroids with respect to navigation in relation to the surface, but also for planetary rovers regarding distances to obstacles [7]. In addition to distances also the roughness of the environment is to be analyzed in order to avoid hazards during autonomous operation periods. Similarities to terrestrial robotics can be exploited, where approaches based by example on laser scanners, lidars, radars, and monocular or stereo vision cameras are frequently used [3]. The combination of these classical approaches with innovative time-of-flight cameras such as the 3-D Photonic Mixer Device (PMD) provides a more reliable basis for decision making. Similar information on relative distances as well as on relative attitudes like from stereo vision systems can be obtained from the PMD sensor at much smaller mass and volume, in almost real-time, without huge data processing needs. In order to achieve reliable performance typically by sensor data fusion several measurements from different sensor types are to be combined to compensate related deficits.

This contribution focusses on sensor principle of time-of-flight cameras and analyses its suitability in different space exploration scenarios.

2 TIME-OF-FLIGHT CAMERAS

The sensor principle of time-of-flight cameras materialized in first products around 2000 and provided a new approach to 3D environment characterization [12]. Meanwhile several products from different manufacturers are offered on the market. The technology is based on active illumination by emission of modulated light and measurement of the phase shift between received reflected light and reference signal. Thus there is a limit for the unbiased derivation of the distance determined by carrier frequency / wavelength. When two different modulation frequencies are used, the difference between both measurements the unambiguity range detection can be further extended [9].

Figure 1: CamCube2.0 typical time-of-flight camera with two LED-illumination units at the side

Three types of images are generated related to depth, amplitude and intensity, in particular provides each pixel also distance information at high frame rates. No post-processing to generated 3D-images is required. The camera is compact and contains no movable mechanical components.

Adaptation of crucial parameters have been analyzed in [11], [10] with respect to calibration procedures and with the objective to optimally combine integration time, frame rate, field-of-view, and accuracy.

3 APPLICATION SCENARIOS

Space exploration scenarios, which could benefit from application of time-of-flight cameras, are discussed in the following. In the critical near vicinity range, in all scenarios multiple sensors and different sensor types need to be combined to guarantee the required high reliability.

3.1 Obstacle Avoidance for Planetary Rovers

For exploration of planetary surfaces, the mobility by rovers allows to characterize much larger areas and to access selected places of interest for more detailed analyses [7]. So far rovers have been operated on the surface of the Moon and Mars. Remote control is complicated by significant signal propagation delays and is thus to be combined with autonomous driving capabilities. While autonomous driving significantly extends the operations range within a given period of time, nevertheless safe mobility is mandatory. This is based on reliable characterization of the operations environment by sensor data. Here 3D-cameras are a meaningful contribution to detect obstacles (such as rocks, crevasses) and allow derivation of a promising strategy to efficiently as well as safely handle it by passing or detouring the obstacles. Research activities for rovers are related to compensation of noise, induced by relative motion as well as by outdoor illumination background. Strategies for selection of appropriate exposure time and sensor data post-processing were derived [11].

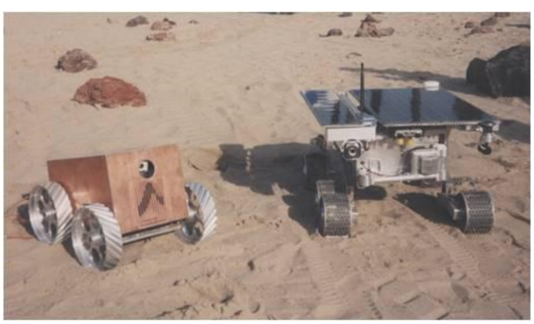

Figure 2: The small planetary rovers MIDD (developed for ESA) and Rocky VII (from JPL/NASA) during training for Mars environment.

3.2 Rendezvous and Docking to Passive Objects

For space debris removal, in-operational satellites should be inserted into graveyard orbits, before they disintegrate due to collisions with other space objects [8]. Thus servicer satellites are discussed, which need to safely approach the target and to perform a rendezvous&docking maneuver with this passive object. In the DEOS scenario, finally a fixed connection between servicer and target was established by a robotic arm before transfer into a graveyard orbit could be initiated. Safe operations are mandatory for the servicer satellite in the vicinity of the tumbling target to avoid collisions with appendages like antennas or solar arrays. Thus a careful prediction of the dynamics of the target satellite is needed to enable synchronization of the motion of both satellites before a safe final approach can be initiated. 3D-measurements of the in-operational satellite's dynamics by the servicer provide the basis for a safe approach.

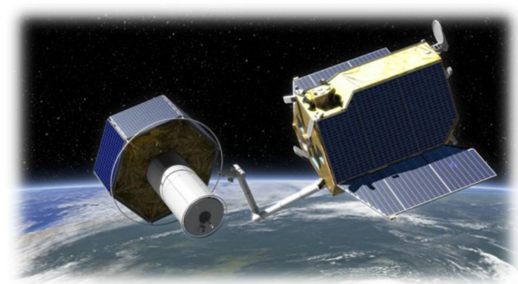

Figure 3: The DEOS scenario, where the servicer satellite with robot arm approaches the in-operational satellite at the left (image courtesy of DLR).

3.3 Near Range Formation Flying

In formation flying [1], [2], [6], cooperating satellites continuously exchange relative positions and orientations in order to allow joint observations of given targets (Earth surface points, stars, planets,…). Thus in scenarios for space debris removal as well as for formation flying relative positions and attitudes are to be determined as crucial inputs to operations. This is often based on absolute measurement of position by an on-board GPS and of attitude by a combination of star, sun, and magnetic field sensors, but need to be complemented by relative position and attitude determination (by example by inertial sensors and cameras) in order to reach appropriate accuracies.

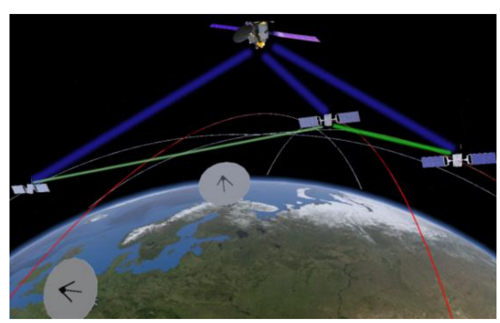

Figure 4: satellite sensor networks self-coordinating in-orbit for performance optimization.

For rendezvous & docking as well as in formation flying, 3D-cameras use feature extraction and tracking methods to derive dynamic models for the evolution of the 3 translational and the 3 rotational degrees of freedom between the satellites [4], [5]. For the combination with the other sensors appropriate sensor data fusion methods had been implemented. In combination with appropriate orbit dynamics models efficient fusion schemes have been developed.

4 PERFORMANCE TESTS

In hardware-in-the-loop tests with rovers as well as in a robotic dynamic satellite simulator performance characteristics were documented, encouraging the use of PMD cameras as valuable contribution to increase safety for time-critical autonomous obstacle detection and avoidance.

Figure 5: The MERLIN test vehicle with sensor suit for obstacle detection and avoidance in front of a precision tracking system component.

The rover test environment is supported by several MERLIN rovers for outdoor environments and an high performance tracking system providing a measurement accuracy of 1/3 mm for dynamical systems as external reference to enable assessment of the on-board sensor performance.

For the satellite scenarios a near range test environment for two satellites is composed of two robot manipulators to simulate the dynamics with respect to orbit and attitude. The robot's position repeatability is 0.05 mm. Black Molten material provides with respect to illumination space environment conditions. It reduces multipath reflections of the modulated light of the 3D-camera as well as it eliminates background light. Further a simulation of the Sun spectrum at close distances can be added.

In the near range of 10 m all relative motions for docking and for formation control can be properly evaluated. Thus noise effects of reflective surfaces in combination with relative satellite motions can be realistically be assessed in order to derive strategies for optimum parameter adaptions.

Figure 6: Robots simulating the relative dynamics in rendezvous & docking of the servicer's 3D-camera (right) to a defect spacecraft (left).

5 CONCLUSION

Time-of-flight 3D-cameras provide valuable additional sensor information for relative navigation, with respect to position and attitude, in near range. For quick autonomous reaction capabilities, like in collision avoidance, the provided real-time performance is very valuable. Hardware-in-the loop test facilities enable suitable performance evaluations of the 3D-cameras alone as well as of their integration into more complex sensor systems.

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