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Small-body gravity science using compact imaging-lidar devices

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Abstract

Light detection and ranging (lidar) is a remote sensing technique which has been successfully implemented for the reconstruction of surface topography by small-body orbiters at asteroids Eros, Itokawa, Ryugu and Bennu. In the first three occasions, the lidar sensor of choice has been a single-beam altimeter. Only at Bennu a multi-beam scanning device is being operated [3]. This sensor incorporates an optical mirror which is mechanically rotated to point the laser beam along a *zig-zag* scanning pattern. During the last few years, development of semiconductor optical beam-forming devices have led to the successful assembly of small form-factor imaging lidar sensors, containing no moving parts. Such devices, also known as *time-of-flight cameras* or *flash-lidars* collect dense range images of the target scene at rates of 1 Hz and faster. As compared to optical camera images, lidar range images provide direct scale information reducing uncertainty in the relative orbit determination problem. The fusion of traditional microwave Doppler tracking with lidar image processing in the proposed fashion could pave the way for a new class of gravity science experiments by small satellites.

1. Introduction

The goal of this study is to assess the usability of lidar images for spacecraft orbit determination and, consequently orbit model improvement. Improved knowledge of force modelling parameters leads to an accurate solution of the body's gravitational potential. Through modelling, a precisely known gravitational potential can give insight into the body's interior structure, its bulk density and density distribution [4][5].

This paper investigates the usage of range-texture information in lidar images for spacecraft orbit determination around small solar system bodies. In particular, the image co-registration problem with no a-priori knowledge of the observer attitude and position is addressed. A combination of 3D feature-matching and iterative point-cloud alignment techniques is investigated. In the following we discuss a six degree-of-freedom (6-DOF) sensitive descriptor for coarse kinematic orbit determination.

2. Geometrical Descriptor

Several geometrical descriptors have been proposed for object identification in robotic applications. The goal of a descriptor is to uniquely describe an object in mathematical form. Most descriptors are purposely designed as scale and rotation invariant, hence ensuring the robustness of the identification under any viewing geometry. A remarkable exception is the Oriented Unique Repeatable Clustered Viewpoint Feature Histogram (OUR-CVFH)[1]. The OUR-CVFH descriptor involves a robust scheme for 6-DOF pose estimation. It involves the definition of one or more reference coordinate frames for a partial view (i.e., the observed lidar point cloud) which are unique and statistically repeatable.

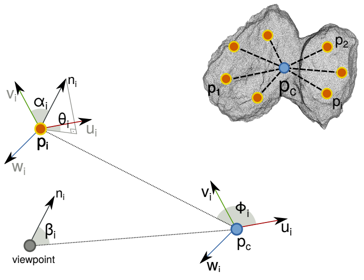

Figure 1: Local Darboux frame for a point p_i and angular components of the OUR-CVFH descriptor.

Given a lidar point cloud with centroid $\mathbf{p}_c$ and surface normal vector $\mathbf{n}_c$, we first define a local Darboux frame $(\mathbf{u}_i, \mathbf{v}_i, \mathbf{w}_i)$ for each point p_i in the cloud (see fig. 1), such that $\mathbf{u}_i = \mathbf{n}_c$, $\mathbf{v}_i = \frac{\mathbf{p}_i - \mathbf{p}_c}{\|\mathbf{p}_i - \mathbf{p}_c\|} \times \mathbf{u}_i$, and $\mathbf{w}_i = \mathbf{u}_i \times \mathbf{v}_i$.

Next, a tuple of 4 angles is calculated for each point, namely $[\alpha_i, \beta_i, \phi_i, \theta_i]$. This tuple defines the orientation of the Darboux frame with respect to the sensor viewpoint.

The points are then clustered in sets C_k (see fig. 2) according to their Euclidian distance t_d and deviation of their surface normals t_n, such that $\forall p_j \in C_k, \|\mathbf{p}_j - \mathbf{p}_i\| < t_d \wedge (\mathbf{n}_i \cdot \mathbf{n}_j) < t_n$.


(a) Exemplary scan nr. 1 (b) Exemplary scan nr. 2

Figure 2: Simulated lidar point-cloud with highlighted OUR-CVFH clusters. The SHAP4 shape model of comet 67P/C-G was adopted for this simulation [6].

Each cluster is characterized by the scatter matrix M, whose three first eigenvectors define a Semi-Global Unique Reference Frame (SGURF). In eq. 1, M is defined in terms of the maximum radius R of the i-th cluster C_i, and the distance d_k from the k-th point $\mathbf{p}_k$ to the cluster centroid $\mathbf{c}_i$.

$$\mathbf{M} = \frac{1}{\sum\limits_{k \in C_i} (R - d_k)} \sum_{k \in C_i} (R - d_k)(\mathbf{p}_k - \mathbf{c}_i)(\mathbf{p}_k - \mathbf{c}_i)^T \tag{1}$$

3. Kinematic State Estimation

The kinematic pose estimation pipeline using OUR-CVFH descriptors consists of the following steps: (a) describe each partial view by means of OUR-CVFH and retrieve the best N candidates (i.e., state hypothesis) from a training dataset; (b) perform the SGURF alignment and successively refine using iterative-closest point [2]; and (c) select the best hypothesis by means of inlier and outlier metrics.

Let T_s be the affine matrix representing the transformation between the SGURF frame of an observed surface S and the lidar sensor frame. Let P_M be the equivalent transformation between a model candidate point cloud and the observed surface S. A template database would have been generated a-priori by digitally rendering views from a shape model. In such case, the set $(T_{M_0}, T_{M_1}, \cdots, T_{M_N})$ of transforms relating each model SGURF to the sensor frame is known. The affine matrix P_{M_i} defining the transformation between the best fitting hypothesis i and the observed surface can be derived as $P_{M_i} = T_S^{-1} \cdot T_{M_i}$.

4. Summary and Conclusions

The optimization (i.e., parameter tuning) of the OUR-CVFH descriptor algorithm for orbit determination will be assessed using simulated lidar data from an available shape model of sufficient texture. The performance of the proposed kinematic pose estimation pipeline will be evaluated for scenarios where the descriptor database is generated on a lower resolution model, resembling real mission conditions. Preliminary results on sun-synchronous orbits about Itokawa indicate that position residuals can be reduced to few hundred meters (1-σ) without any filtering, but are subject to stochastic mismatch. An adaptive tuning strategy is likely required.

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