INITIAL POLE ESTIMATION USING INFRARED IMAGERY

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Abstract. *Estimating the pole axis of asteroids is crucial to spacecraft autonomy and shape modeling. Current methods utilize light curves and are very time and resource intensive, and the resultant pole estimates can have large errors. Navigation and shape modeling fidelity are affected significantly by this error. In this study, we present a new pole estimation method that utilizes infrared images from a spacecraft on an approach trajectory to a small body. The benefit of this approach is that it does not rely on feature tracking, does not require prior knowledge, and only relies on the macroscopic properties of the body.*

Introduction. In recent years, there has been an interest in increasing spacecraft autonomy for small body missions. Previous missions have relied on the Deep Space Network to determine the spacecraft orbit and position. The drawback of such an approach that it is affected by communication delays and that it is very resource intensive. Decreasing the reliance on the Deep Space Network is one way to reduce the overall cost of the mission. One technology that can be used in this pursuit is autonomous navigation using on-board cameras. Such navigation methods require some a priori knowledge about the bodies. For small bodies such as asteroids and comets, little a priori knowledge exists. One required a priori for these methods is knowledge of the body frame of the asteroid which requires that the pole axis (the axis around which the body rotates) be known. The pole axis can be estimated by analyzing light curve data over several rotations of the body.[1] This is a very data intensive and time consuming process that is limited by the poor resolution of the small bodies from Earth observations. This has consequences for asteroid shape modeling[2] and visual aided navigation.[3] Alternate approaches estimate the shape and pole concurrently.[4]

In this paper, we present a pole estimation method that utilizes infrared images captured on-board a spacecraft which is on an approach trajectory to the body. In optical images, parts of the body in shadow are not visible. Therefore, only a portion of the total shape is visible at any given time. In contrast, infrared images allow for the shadowed section of the body to be visible. Therefore, infrared images are more robust to any given approach trajectory. Since infrared cameras are often included in the instrument suite of many missions, using that data does not incur any significant increases to mission complexity, design or cost.

Methods. First, lets establish the geometry between the pole and the sun direction. Consider a body fixed frame that is aligned with the inertial frame at some epoch (left side of Fig. 1). As time passes and the body rotates about its pole, this frame rotates with it. By convention, the z-axis of the body-fixed frame is aligned with the pole direction. Over time, this rotation exposes different parts of the body to the sun. The parts facing the sun will experience an increase in temperature and the parts in shadow will experience a cooling. These effects are modeled by the thermal model described in Alg. 1.

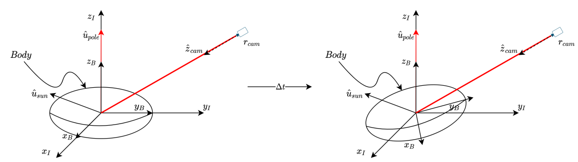

Figure 1. Body Frame and Polar Geometry at Two Times

The motion of points within an image is due to the rotation of the body about the pole axis. This motion will be centered around the point at which the pole axis intersects the surface of the body. This "center of motion" is the projection of the pole into the image plane. Therefore, if we can detect this point in the camera plane, we can use projective geometry to get an estimate of the pole axis. The method is summarized in Algorithm 1.

Algorithm 1 Pole Estimation Using Image Stacking

% **Add N IR images**
$I_S = \sum_{i=1}^{N} I_i$
% **Normalize image w.r.t the max**
$I_n = I_S / max(I_n)$
% **Obtain edge of the stacked image (using the canny operator)**
$BW = edge(I_n)$
% **Identify streaks that approximate an ellipse**
% **For each streak (I_{str}), fit ellipse (using least squares).**[5]
$ellipse_{str} = \texttt{fitEllipse}(I_{str})$
% **Center of this ellipse is the pixel location of the pole**
$[u_{p,str}, v_{p,str}] = center(ellipse_{str})$
% **Average the center estimates**
$[u_p, v_p] = mean([u_{p,str}, v_{p,str}])$
% **Project pixel estimate into inertial frame**
$\hat{u}_{pole,est} = project(u_p, v_p)$

Pole Estimate Projection Correction. We assume that the boresight direction of the camera is pointed towards the center of the body (z_{body}). If we know that the body is roughly convex, we can assume that the edge of the body as seen from the camera is also at z_{body}. Therefore, the center pixel of the image (u_c, v_c) is closer to the camera and that the edge pixels are farther away (approximately at z_{body} from the camera). We utilize this general geometry to compute a scale correction. This is accomplished in three steps:

1. Compute distance between pole estimate and the center of the image:

$$d_p = ||[u_p, v_p] - [u_c, v_c]||_2 \tag{1}$$

2. Find the distance from center to the edge along the direction of the pole point:

$$d_{edge} = ||[u_{edge}, v_{edge}] - [u_c, v_c]||_2 \tag{2}$$

3. Compute the corrected projection scaling using the ratio of these two values:

$$z_{body,corr} = z_{body} - \cos\left(\frac{d_p}{d_{edge}}\right) \tag{3}$$

We use the corrected projection distance shown in Eq. (3) to project the pole estimates into the inertial frame.

Results. A parametric thermal model will be applied to a shape model of the asteroid Bennu to generate the representative infrared-images at different camera geometries relative to the body (see Fig. 2). The proposed pole estimation method will be demonstrated on these simulated set of images. The proposed scale correction will be applied in mapping the pixel estimate to the inertial frame. Despite the correction, we expect a worse error with viewing geometries where the boresight vector is aligned with the pole axis. The irregular shape of the asteroid is the reason for this behavior as it violates the convex assumption made in deriving the correction shown in Eq. (3). The performance of the method will be analyzed for different asteroid obliquities, camera observing angles, and number of images stacked. Fig. 3 represents the results we expect from the method.

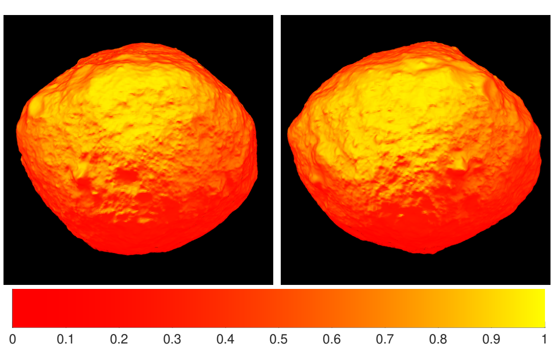

Figure 2. Simulated Bennu IR Images (spaced** 90° **apart in phase angle) and a Colormap of Observed Thermal Intensities

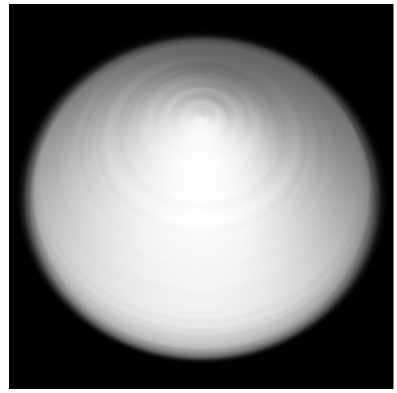

Figure 3. Infrared Images of Bennu Stacked (image set is taken over one rotational period)

The streaks visible in the image above are centered around the pole (projected into the image plane). Identifying these streaked ellipses and their associated center leads to an estimate of the pole.

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