# Stellar Optical Photography Annotator

Robert Wilson
Department of Electrical Engineering
Stanford University
Email: rwilson4@stanford.edu

***Abstract*—Abstract here.**

## I. INTRODUCTION

Star photography is a popular hobby amongst those graced with a clear, dark night sky. While a knowledge of astronomy is by no means a prerequisite, it lends a greater appreciation for the photographer's place in space and time. Part of the appeal is knowing the constellations we see at night are virtually identical to those that guided the earliest mariners. Stellar navigation is still used today, not only in terrestrial applications but also for attitude determination for Earth-orbiting satellites [1]. Clearly, identifying stars continues to be a crucial task.

Today this task is performed most frequently by specialized devices such as star trackers, which translate an image of the sky into an attitude which is used to inform attitude control algorithms onboard satellites. Quick, robust, and precise star tracker algorithms form the backbone of any Stellar Inertial Attitude Determination (SIAD) system. These algorithms typically compare the magnitude and the inter-stellar angles of the brightest points in an image with values in a database to determine which constellation is within the field of view. The identity and orientation of this constellation then uniquely determines the attitude of the spacecraft.

Identifying stars taken from generic, ground-based cameras presents many challenges star-trackers do not face. Star trackers take photographs specifically for the purpose of determining attitude. The recognition algorithms are tailored specifically for the camera in use, and the camera concept of operations is designed to result in a high probability of successful recognition. Atmospheric noise is negligible, the field of view is clear, and the lens properties including focal length, aperture size, and aberration, are known. This project faced challenges star-trackers do not encounter, but these were addressed by the concepts and techniques of Digital Image Processing discussed in EE368: color coordinate frames, image thresholding and binarization, region labeling and deblurring via Wiener deconvolution.

## II. ELIMINATING CLUTTER

Fifteen images were selected from the author's collection, taken over the years in various locations far from light pollution. Some pictures contained only astronomical objects (stars, galaxies, and one image that appears to include Venus), while others included trees, clouds, and airplanes. The first task was to remove as many of the non-stars as possible. A flexible framework was developed to permit the user to filter out clutter via several methodologies.

### *A. Filtering in the HSV Domain*

Stars, although small, tend to be brighter than other objects in the night sky. Filtering based on the hue, saturation, and value of pixels permitted the removal of most of the clutter including trees and clouds. Because stars come in all colors, filtering on hue would eliminate stars; however, used in conjunction with the color information from a star catalog, this might actually be desirable. This stage is optional. Example outputs of this stage are shown in Fig. 2b and 4b.

### *B. Locally Adaptive Thresholding via Otsu's Method*

Some images contained more light pollution than others, having a red background instead of black, motivating the use of Otsu's method for binarization. Many of the images prominently featured the Milky Way, so the density of stars and background brightness varied across the image. Consequently, a locally adaptive approach was employed. The image was divided into steps, and Otsu's method was applied in the vicinity surrounding each step. The step was binarized according to the pixel values in this vicinity. This methodology ensured the threshold did not change drastically from step to step. To reduce the overall number of stars in the image, this step restricts the fraction of pixels in each step that may be non-zero. Steps containing too many stars are erased completely. Fig. 3b shows the result of this procedure. Note that much of the Milky Way has been removed. There are so many stars in this region, that it cannot be reliably used with our algorithm due to small uncertainties in position.

### *C. Filtering Based on Area*

Though they vary greatly in apparent magnitude, all stars appear as point objects.[1] If they occupy more than one pixel in an image, it is due to imperfections in focusing ability, due to chromatic aberration, for instance. Star trackers are intentionally defocused slightly for just this reason. Nonetheless, since stars are small, it makes sense to eliminate any residual objects larger than a certain size. This is a simple application of region labeling. Fig. 4c shows an application of this procedure. Note that some pixels from the trees remain.

[1] One of the largest and most luminous stars in the universe, Betelgeuse subtends an angle of $5.57\mathrm{e}{-2}$ arcseconds, based on its actual radius and distance from Earth.

## D. Suppressing Star Trails

The rotation of the Earth leads to the apparent motion of the stars in circles about the celestial pole at a rate of $360^\circ$ per sidereal day or a quarter of a degree per minute, leading to a star trail of length dependent on the duration of image capture. Often these star trails add æsthetic value, but just as often they are an unfortunate side-effect of our angular momentum. They are an example of nonlinear motion blur, and are discussed thoroughly in [6].

Small star trails are approximately linear and can be deblurred via a Wiener filter using a point-spread function corresponding to the length and orientation of the star trail itself. The noise was assumed constant across the entire image and was estimated by dividing the grayscale image into tiles, computing the variance of each tile, and then selecting the tenth percentile value.

Both the length and orientation of the star trails depend on the location of the star relative to the celestial pole and hence vary across the image. Like the locally adaptive thresholding stage, the binary image was divided into steps, and the star trails within the vicinity of a step were examined to determine an average length and orientation. This was used to deblur the corresponding region of the grayscale image. The image was then re-binarized. This methodology didn't work very well, unfortunately, as Fig. 5c illustrates.[2]

# III. Spherical Trigonometry

After the filtering stages, the centroids of the remaining objects were determined via region labeling. The angles between triplets of stars were computed. These were then compared against the angles computed from the SKY2000 Master Catalog [4].

The SKY2000 Master Catalog contains information on nearly three hundred thousand stars. To simplify the search problem, we used only stars having an observed visual magnitude brighter than five. The catalog contains the right ascension and declination of each star. The right ascension and declination determine the location of a star on the celestial sphere, which is a sphere of infinite radius centered at the center of the Earth. Declination is measured with respect to the celestial equator which lies in the same plane as the equator of the Earth and can be thought of as celestial latitude. Right ascension is measured eastward from the vernal equinox and can be thought of as celestial longitude.

Finding the arclength between two stars is equivalent to finding the distance along the surface of the unit sphere between two points. The cosine of this angle is simply the dot product of the two vectors pointing from the origin to the points on the surface having the appropriate latitudes and longitudes. For a point at latitude $\theta$ and longitude $\phi$, the

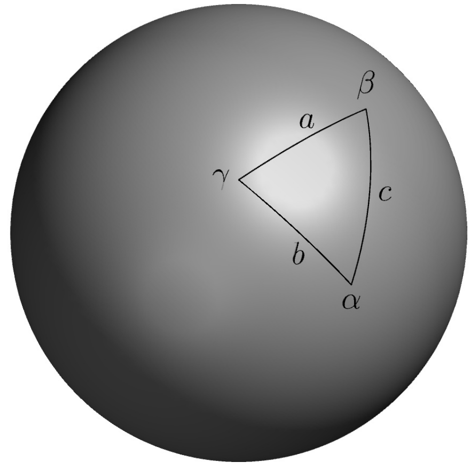


Fig. 1. Spherical triangle

corresponding vector in Cartesian coordinates is

$$\vec{v} = \begin{bmatrix} \cos(\theta)\cos(\phi) \\ \cos(\theta)\sin(\phi) \\ \sin(\theta) \end{bmatrix}$$

so the arclength $a$ connecting two points at $(\theta_1, \phi_1)$ and $(\theta_2, \phi_2)$ is given by

$$\begin{aligned} \cos(a) &= \cos(\theta_1)\cos(\theta_2)\cos(\phi_1)\cos(\phi_2) \\ &\quad + \cos(\theta_1)\cos(\theta_2)\sin(\phi_1)\sin(\phi_2) \\ &\quad + \sin(\theta_1)\sin(\theta_2) \\ &= \cos(\theta_1)\cos(\theta_2)\cos(\phi_1 - \phi_2) + \sin(\theta_1)\sin(\theta_2) \end{aligned} \tag{1}$$

To compute the angles between triplets of stars, the spherical law of cosines may be used:

$$\cos(c) = \cos(a)\cos(b) + \sin(a)\sin(b)\cos(\gamma) \tag{2}$$

where $a$, $b$, and $c$ are the arclengths separating the stars at the vertices of the triangle, and $\gamma$ is the angle subtended at the vertex opposite side $c$ (see Fig. 1).

Given the right ascensions and declinations of three stars we can compute the arclengths of the segments connecting them using (1), and use these in (2) to determine the angle $\gamma$ between a triplet of stars.

# IV. Identifying Stars

Star trackers and other applications use a variety of algorithms for identifying stars [5], all starting from a carefully chosen subset of a star catalog. Because a good star catalog will contain every star an Earth-bound observer might see, using the entire catalog virtually guarantees a match. However, the curse of dimensionality rears its ugly head in most cases, as we will see shortly. Thus it is important to use as small a subset as will permit a high probability of successful detection.

Polygon algorithms compare constellations of $n$ bright stars found in the image with constellations from the catalog, considering the distance between stars as well as the angles

[2]A disproportionate amount of time was spent on this feature relative to the benefits it granted. C'est la vie.

between star triplets. Some additionally filter on the observed visual magnitude, but this is less reliable due to a variety of factors, including numerical issues for faint stars[3].

The simplest polygon algorithm, the triangle algorithm operates on triplets of stars. For our applications, using the distance between stars was not an option, since this depends on the angle of view, which in general is unknown. Contrast this against a given star tracker, that always has the same angle of view. The angles between triplets of stars are also distorted depending on the angle of view and position of the vertex within the field of view. The sum of the angles of a spherical triangle always exceeds one; Girard's theorem states that the angular excess is proportional to the surface area of the triangle. The image of the spherical triangle on the focal plane is a planar triangle, whose angles sum to $180^\circ$. Thus, the true vertex angles of any given constellation will exceed those captured in an image, with greater distortion for constellations taking up a larger portion of the sky. Position uncertainties in star locations will also distort these angles, with greater distortion for smaller constellations. Both these problems can be overcome by choosing the angle of view to be within an appropriate range. Unfortunately, without knowing the angle of view, the amount of distortion is indeterminate, so we use a tolerance in the matching algorithm.

Including more stars in our constellation compensates for the larger number of matches anticipated in light of the preceding discussion, but the number of constellations increases combinatorially with the number of stars per constellation. Thus, as stated in [5], 'star constellation is hard and complicated to identification.[sic]'. It is a balancing act: choosing a field of view that is large, but not too large, using catalogs and constellations with as few stars as possible while using enough stars to provide robustness against angular distortions.[3]

Our algorithm relies on a properly prepared constellation definition file. A constellation is defined as three stars, sorted by magnitude so that the first star is the brightest. A constellation has three angles associated with it (since the angles don't sum to $180^\circ$ as usual). Thus our constellation definition file has six columns: three for the star numbers and three for the angles.

A subset of the star catalog was created consisting only of stars having magnitude brighter than five, with roughly $800$ entries. There are roughly $90$ million unique constellations consisting of three stars from this list. This list was pared down by limiting the angular separation of the stars within a constellation. Stars must be separated by at least $1^\circ$ and at most $45^\circ$, giving a list of roughly $2.4$ million suitable constellations.

The constellations in the image were considered similarly. Starting with the brightest stars, constellations are formed, and their angles compared against the database. Keeping in mind the brightness of stars cannot be perfectly trusted, the order of the angles must be permuted in all six possible ways when comparing. If no matches are found, the next brightest constellation in the image is considered, and so on. The first match found is considered correct. A better solution would be to add a fourth star to the constellation and compare those angles against the database, but this was not completed due to time constraints.[4]

## V. Future Work

The Wiener deconvolution step could be improved using the techniques discussed in [6]. The final identification step still needs to be tested more thoroughly.

## Acknowledgment

The author would like to thank Richard Fowell and Carlos Luna for motivating discussions on star trackers and space-based image processing.

## References

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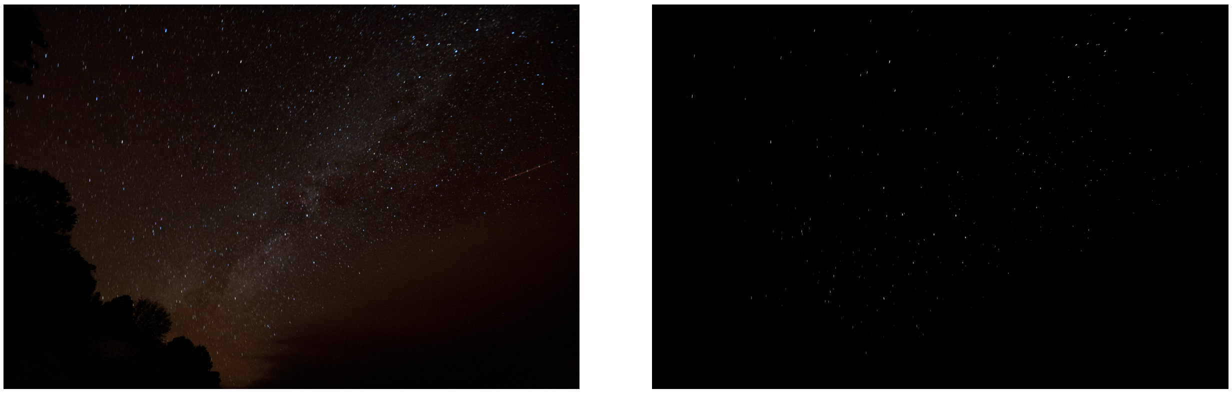
[5] Meng Na, Peifa Jia. *A Survey of All-sky Autonomous Star Identification Algorithms*. Systems and Control in Aerospace and Astronautics, 2006.

[6] Woodley Packard and Steven Stanek. *Removing Motion Blur from Astrophotographic Images*. http://www.sweaglesw.com/cs448/ Accessed May 27 2012.

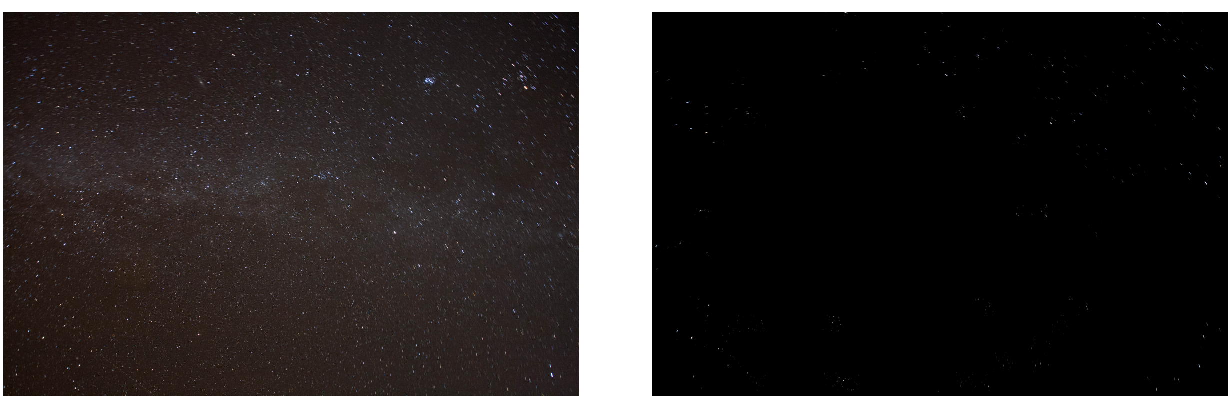
[3] We do not even consider here more advanced matching algorithms which utilize neural networks or genetic algorithms, citing the oft-quoted adage, 'If you're using neural networks to solve your problem, you now have two problems.'

[4] Frustratingly enough, Matlab is still churning away looking for a match.



(a) Original image (b) Image after HSV filtering

Fig. 2. Effects of HSV filtering



(a) Original image (b) Image after binarization

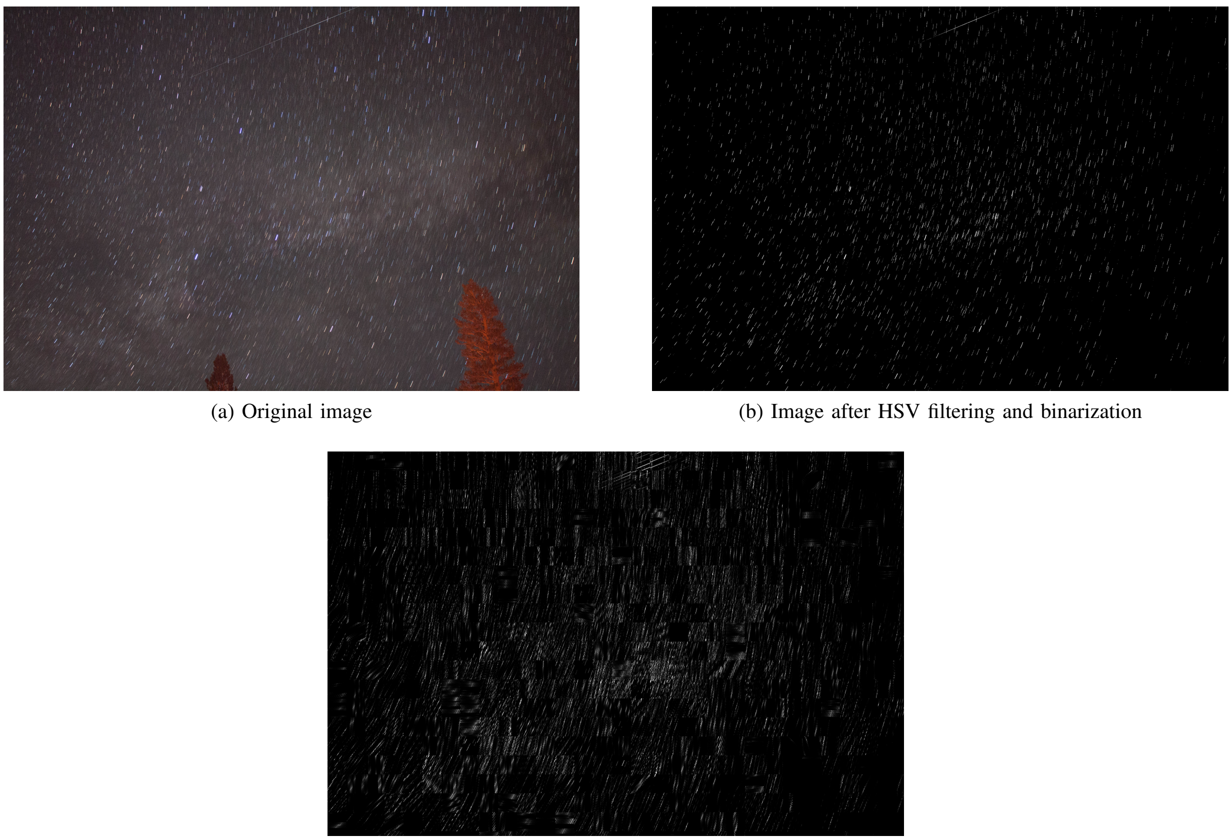
Fig. 3. Locally adaptive thresholding

(a) Original image

(b) Image after HSV filtering

(c) Image after area filtering

Fig. 4. Effects of HSV and area filtering



(a) Original image

(b) Image after HSV filtering and binarization

(c) Image after Wiener deconvolution

Fig. 5. Effects of star trail suppression