Toward Ground-Based Autonomous Telescope Attitude Estimation Using Real Time Star Pattern Recognition

Christian Bruccoleri*, Daniele Mortari†, Malak A. Samaan‡, and John L. Junkins§

Abstract

This paper introduces a technique that helps amateur astronomers to reduce the problems of initial alignment of the telescope by using the most recent techniques (centroiding, star identification, and attitude estimation) developed for autonomous navigation using star trackers. This has been accomplished by using off-the-shelf components and, in particular, a smart digital camera. The integration of the digital camera with the finder scope of a standard telescope has been outlined and the extension to hand-held computers has been investigated. By this integration the problem of star recognition becomes feasible and enjoyable not only by the amateur astronomer community but also by a much larger audience. The key problems description has been given, and a prototype system analyzed in detail.

Introduction

Star Sensors are widely used to estimate spacecraft attitude with respect to an inertial reference frame. These instruments use the stars as a reference for the attitude

*Ph.D. Candidate, Department of Aerospace Engineering, H.R. Bright Building, Room 620c, Texas A&M University, College Station, TX 77843-3141, Tel. (979) 458-0550, FAX (979) 845-6051, bruccoleri@tamu.edu
†Associate Professor of Aerospace Engineering, Department of Aerospace Engineering, H.R. Bright Building, Room 741A, Texas A&M University, 3141 TAMU, College Station, Texas 77843-3141 Tel. (979) 845-0734, FAX (979) 845-6051, mortari@tamu.edu
‡Ph.D., Department of Aerospace Engineering, 701 H.R. Bright Bldg., Room 611B, Texas A&M University, College Station, TX 77843-3141, Tel. (979) 845-0723, FAX (979) 845-06051, mas1894@aero.tamu.edu
§George J. Eppright Chair Professor, Director of the Center for Mechanics and Control, 722 Bright Bldg., Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843-3141, Tel: (979) 845-3912, Fax: (979) 845-6051, junkins@tamu.edu
estimation, thus they require the integration of a camera, for star image acquisition, and a on board computer for image processing, star identification, and attitude estimation. Because of the constraints imposed by the space environment, the need of CCD thermal control, and the small number of units sold, these are very expensive. However, due to recent advances it is possible to build such an instrument for routine use with Earth-based telescope and camera observation.

This can be done using inexpensive off-the-shelf hardware components. Thus, a professional or amateur astronomer could add to his set of tools an instrument that automatically calculates the attitude of the camera with respect to the local site. The knowledge of the camera attitude with respect to the equatorial mount lays the basis for an autonomous system capable of aligning the equatorial mount before the beginning of the observation session.

This advance will make amateur astronomy more accessible because the telescope set-up will be essentially automated and all stars in the camera view will be automatically identified. A small and inexpensive star sensor could have also many other scientific and engineering applications as, for instance, on board of a manned spacecraft. It would be possible to point this instrument from a window and calculate the attitude of the spacecraft, thus having an emergency backup of the spacecraft’s primary attitude sensors.

Two different configurations are investigated, they are: a) an autonomous camera with an embedded processor (DSP) and b) a camera driven by a PDA computer through an external communication interface (i.e. RS-232, USB, IEEE-1394).

Some configuration issues regarding both software and hardware are briefly discussed. The characteristics of the star catalog and a prototype system, used for validation of the alternatives, are presented.

This results in implementing the star sensor on the specific commercial digital smart camera VC51, equipped with a DSP and a memory, that is connected with a laptop computer where the results are validated and presented.

**Integration With Telescope**

Software and hardware that can guide the telescope using a database of stars are becoming very popular among astronomers. However, the problem of aligning the equatorial mount before the beginning of the observation session, and thus before that current guidance softwares become useful, still remains. Equatorial mounts must be aligned so that the *polar axis* of the telescope is parallel to the rotation axis of the Earth. Alignment errors of a fraction of degree quickly reveals themselves because star images drifts north or south during integration. A correct procedure for alignment is explained in detail in [1].
The actual procedure is a function of the used telescope, but the point is that before you can use the automatic guidance system you need to align the *Polar Axis* of your instrument toward a known star (i.e. *Polaris*) and to input the declination and the right ascension on the guidance computer. This is a two phase process: a rough alignment of 9 step process, and a finer tuning of 7 step process, that takes several minutes to be completed. This process is prone to errors, requires time and some efforts from the operator. However, it could be automated and improved with the help of a small star sensor. Any simplification or help in this area would be, obviously, appreciated by amateur and professional astronomers as well.

Specifically, during the fine tuning phase, it is necessary that you place *Polaris* at the very center of the field of view, that is, aligned with the *Optical Axis* (OA). The accuracy of the alignment can be greatly improved by the use of a star identification algorithm [2]. This provides the inertial direction of the observed stars, thus enabling the software to calculate the OA direction $\hat{o}_a$ in the Earth Centered Inertial Frame (ECI frame) with great accuracy, about $10''$. The reference frame of the telescope is shown in Fig. 1.

![Figure 1: Body Reference Frame for an equatorial mounted telescope: x axis is the Polar Axis, z axis is the Declination axis, and y axis is perpendicular to the xz plane](image)

Once the direction of the *Polar Axis* is known, the alignment with the Earth spin axis (that is, the ECI vector $\hat{k} = \{0, 0, 1\}^T$) can be automatized. In order to achieve such alignment you need to calculate the attitude matrix $A$, which is the usual output of a star sensor, and decompose it in a non singular Euler sequence that maps the $\hat{o}_a$.

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*This is true for the Northern Hemisphere while, for the Southern Hemisphere, a compass and extra efforts are needed*
vector $\hat{p}_a$ onto the vector $\hat{k}$ with a given accuracy. Reference [4] contains some Monte Carlo tests on the attitude error.

This mini star-sensor can be integrated with the finder on the more advanced telescope models: it has a FOV that can vary from $10^\circ$ to $30^\circ$, that matches the usual FOV of a finder (assumed a $8 \times 50$mm finder). For instance, using the pinhole camera model, the FOV of a camera with a CCD of $512 \times 512$ pixels, whose pixel size is $18 \mu m$ is given by

$$\vartheta_{FOV} = 2 \arctan \left( \frac{d_{det}}{2f} \right)$$

where $d_{det} = 18 \mu m \times 512 = 9,216 \mu m$ is the detector side and $f$ is the focal length of the instrument. If we assume that $f = 50$ mm, we have that $\vartheta_{FOV} = 10^\circ31'54''$. Thus the finder and the star sensor can be merged into a single instrument.

This instrument must be equipped with a CCD that has a high sensitivity to star light and its size is calculated to match the desired accuracy. Since the estimation of the direction of the OA depends on the centroiding error, which in turn depends on the pixel size (see [1] and [3]), this is an important parameter. However, many off-the-shelf CCDs meet the accuracy requirements with a reasonably low cost.

**Design alternatives**

There are two main configurations corresponding to two different goals:

**a)** to use the star sensor to guide a telescope, as introduced in the previous section, or

**b)** to build a small, lightweight, inexpensive star sensor using the latest generation of small video-cameras and PDA, that can be proposed to a broader public. A mini star sensor with a proper tailored catalog, can be used to identify the stars in the Field Of View (FOV) and thus if a laptop or PDA computer is available, more information about the stars can be retrieved and presented in real time to the user.

For the **a)** case, the system must be tightly integrated with the guidance system of the telescope. Since the most reliable models already has much of the features needed, it does not require major modifications to the hardware of the telescope. The finder can be substituted by the camera and the star identification must be added to the on-board software.

On the other hand, for **b)** case, one need to develop the software to enable interaction between commercial video cameras and hand-held computer in order to perform
the star identification process. In this case the biggest problem is the lack of a standard platform for wireless devices and hand-held computers that prevents a software written for a specific machine from being reused on a different one.

In Fig. 2 the software modules and their relations are shown. Specifically, we have:

1. The *Centroiding* module. This detects the star’s centroid using image processing techniques as explained in [9] and outputs the centroid coordinates to the *Star Identification Algorithm*;

2. The “*Pyramid*” *Star Identification Algorithm*. This calculates the observed vectors $\hat{b}_i$ for the stars in the body frame and find a match with the corresponding vectors $\hat{r}_i$ in the inertial frame thereby identifying the observed stars;

3. The “*k-vector*” [5] module. This is an essential tool used by *Pyramid*, that performs range searching queries in a very efficient way. It needs three lookup-tables that are stored in a persistent memory (i.e. an EPROM).

4. The *Star Catalog*. Even though a full star catalog is usually already available in most of the existing telescopes, a sub catalog, which can be limited to stars up to magnitude 6.0, to accomplish the star identification is needed. While the catalog used for a star sensor usually does not need anything else beside the inertial directions of the stars, in this case we need to store extra information as, for instance, the star catalog id, the star magnitude, as well as other things such as the spectral type, etc.

5. The *Attitude Estimation* module. This attitude estimator (as, for instance, ESOQ2 [6]), estimates the attitude matrix $A$ based on vector observations, that
relate the *Inertial Reference Frame* with the *Body Reference Frame*. Once the 
attitude matrix is available, then it becomes easy to estimate the direction of 
the *Polar Axis*. In the *Body Frame* this direction is described by the unit-vector 
\( \hat{o}_B = \{1, 0, 0\}^T \), thus in the *Inertial Frame* it becomes \( \hat{o}_I = A \hat{o}_B \), that is the 
first column of \( A \) \( \parallel \).

*Pyramid* is an extremely fast (and extremely robust) star identification algorithm. 
This means that even with a slow computer (i.e. less than 100 MHz clock) *Pyramid* 
will not require more than a couple of seconds to perform the whole process. Once 
the attitude has been estimated, the command to move to align the polar axis to 
the Earth spin axis are sent to the telescope motors. If no alignment is needed then 
*Pyramid* can simply used to identify the observed stars.

**Description of the Prototype**

In order to test the feasibility of this idea we assembled a test-bed environment using 
a smart-camera, Vision Components VC51 as shown in figure 3, as imaging and 
processing environment. Several applications, for both the camera DSP and for the 
integration with Personal Computer have been developed.

![VC51 camera body, 100 × 50 × 36 mm, weight approx 250 g](image)

Figure 3: VC51 camera body, 100 × 50 × 36 mm, weight approx 250 g

The camera is equipped with a 40 MHz clock DSP processor, 8 MBytes RAM, 2 
MBytes EPROM memory, a simple operating system, a number of programming 
libraries, and a C language compiler.

On the other hand, very little utility programs are provided, so virtually every 
needed software and hardware connection has been built from scratch. In particular,
we developed the following application programs: image acquisition and shutter control software, image processing (centroiding), star identification (Pyramid), attitude estimation (Esoq2), download/upload software to/from PC, saving image as file in the EPROM, and calibration software.

The camera has not an output terminal, but rather send its output to the serial port. Thus, an utility program that runs on the PC has been also developed in order to be able to issue commands and see the results of the computation on the PC.

The VC51 is equipped with a Sony ICX059AL Black/White CCD, with the following characteristics: 795 × 596 ** pixels, pixel size is 6.50 × 6.25 µm, variable shutter speed (from 1/50 s to 1/10,000 s), low dark current and excellent anti blooming characteristics, which is important for the long integration time required to take night-sky images. The spectral sensitivity is shown in Fig. 5. This CCD has not been specifically designed for night-sky images, so longer integration times are needed.

The camera has removable lenses thus, through a C adapter, common Nikkor lenses 24mm f1.1, and 35mm f1.2 have been mounted and tested. Every time a lens is removed, it is necessary to recalibrate the system, since the star identification algorithm needs to know the focal length with high accuracy. One of the goal of this system is to make a mini star sensor that would be available for a large number of commercial cameras. For this reason a calibration for each lens change it is not acceptable. If the purpose is to build an instrument connected to the telescope, a fixed lens is highly recommended, with calibration performed only once (by user or by factory).

On the other hand, the technique recently proposed in [10], and called Non Dimensional Star Pattern Recognition, even though it is more slower and less robust than Pyramid, it does not need a precise information of the focal length to accomplish the star identification. As long as no fixed focal lens will be used, this technique appears to be better promising for a larger number of interchangeable cameras, lenses, and hand-held computers. One disadvantage of this technique is the large triangles database that makes it not suitable for a small hand-held device. However, further studies will be carried out in order to optimize the memory required by using a reduced catalog. For this reason, and at this stage, this Non Dimensional Star Pattern Recognition technique can be used efficiently on the PC to guide the calibration of the Camera.

The camera has been mounted on German type equatorial mount with right ascension and declination motors as shown in Fig. 4. The motors are controlled by an external device, that communicate through a serial port, thus it is possible to control it from a computer using a rather standard telescope GO-TO® control language, as the LX200 language.

**752 × 582 effective.**
Tests and Results

In this section a sample of the night-sky tests that we performed is shown. In Fig. 6 a picture of a random region of the night sky in the Hercules Constellation is shown. The camera mounted 24 mm Nikkor lenses and, after the calibration process for which the interested reader may refer to the material in [8], the actual focal length was estimated to be 24.3 mm. In Fig. 7 the small circles around the stars marks the coordinates of the estimated centroid, after the image processing††.

The star identification algorithm produced the following output:

focal 24.3 Threshold: 5.3 Number of stars loaded = 2306
Number of stars from centroiding: 8 Identification:

<table>
<thead>
<tr>
<th>Star #</th>
<th>Cat #</th>
<th>RA</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>311</td>
<td>16 19</td>
<td>44.438</td>
</tr>
<tr>
<td>2</td>
<td>310</td>
<td>16 08</td>
<td>46.173</td>
</tr>
<tr>
<td>3</td>
<td>309</td>
<td>16 02</td>
<td>47.856</td>
</tr>
<tr>
<td>4</td>
<td>312</td>
<td>16 34</td>
<td>6.187</td>
</tr>
<tr>
<td>6</td>
<td>308</td>
<td>15 52</td>
<td>40.622</td>
</tr>
</tbody>
</table>

††The background image is shown as negative for clarity.
Figure 6: Image of a sky region in the Hercules Constellation.

Figure 7: Negative of Fig. 6 with centroid marked by a circle.
Attitude quaternion: $Q = \langle 0.366, -0.153, -0.053, 0.916 \rangle$

Angle between observed and reference directions [arcsec]

1: 3.643123'' 2: 6.245104'' 3: 3.976046'' 4: 5.625631'' 6: 10.037307''

There are two stars not identified, because they are not present in the reduced catalog, that is limited to magnitude 5.3 for this test. In order to verify this result, we compared the identified stars with an astronomic software, like The Sky”, centering the view of the star atlas to star 1 as shown in Fig. 8, 16h19m44s right ascension, 46°18m48.2s declination and matching the FOV we verify that this star is $\tau$ Herculis, while star number 2 is $\phi$ Herculis.

![Figure 8: Star atlas image matching Fig. 6 obtained using ”The Sky” software](image)

**Conclusion**

In this paper we traced a road map on how to build an inexpensive star sensor for ground-based application. In particular we examined how to integrate it with a telescope or a PDA. Two different configurations have been examined and a first prototype for one of them have been built. In the future work, this prototype will be implemented to drive a telescope.
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References


