Telescope Automatic Alignment and Pointing using Pattern Matching

Y. A. Azzam\textsuperscript{1,2}, K. Kosuge\textsuperscript{2}, Z. Wang\textsuperscript{2}, A.A. Alawy\textsuperscript{1}, Y. Hirata\textsuperscript{2}

\textsuperscript{1} National Research Institute of Astronomy and Geophysics, Cairo, Egypt
\textsuperscript{2} System Robotics Lab., Dept. of Bioengineering and Robotics, Tohoku University, Japan

\textbf{Abstract}

We present a new method to align and point small telescope systems. The method is based on synthesizing of the image of the batch of sky to which the telescope is pointing using a database star catalogue. An image of the sky is acquired which is processed and matched with the synthesized image. Point pattern matching is used first to identify some stars in both images, then normalized correlation matching is used to ensure and precisely match both of the acquired and synthesized images. An image processing and frame grabber board is used to draw stars of the synthesized image and to extract star centers as well as their areas. This process solved the main problem of polar alignment of small and movable telescopes, which was tedious and very time consuming. In addition, it is used in precise pointing. The system is composed of a small inexpensive CCD camera coupled to a wide field lens and a frame grabber and image processing board. As the images of the stars are used to control the telescope, neither precise timing nor precise encoders are required.

\textbf{1 Introduction}

Astronomy has become an interdisciplinary science that combines aspects of Physics, Chemistry, Biology and Mathematics, and it is also at the forefront of Technology and Engineering [1]. In the past two decades, developments in technology have given amateur astronomers a chance to join the astronomy field. The combination of inexpensive CCD detectors and cheap, powerful computers permits any motivated individual to measure quantitatively the position and brightness of tens of millions of celestial sources. For example, in [2], the author (professional astronomer) attended the meeting of the International Amateur-Professional Photoelectric Photometry (I.A.P.P.P.) and appreciated the enthusiasm, skill, and sophistication of the many amateur astronomers who have embarked on programs of photoelectric photometry of various stars. In [3] some of the amateurs constructed their own equipment and used it to conduct a survey of bright stars near the celestial equator. In addition, astronomy education requires providing and developing low cost small telescopes for students at different levels of educations. Moreover, over the past decade, small automated robotic telescopes have been developed which were prepared to be remotely controlled through Internet. This necessitates that the telescope control system must be cheap, easy, fast and precise.

By far the most common type of mount for both large and small telescopes is the equatorial mount. This mount has one axis (the polar or right ascension axis) aligned to the Earth’s rotation axis while the declination axis is perpendicular to the polar axis (see Fig. 1). Because of the simplified tracking that equatorial mounts offer, these mounts have been popular for over a century.

One of the tedious and time consuming tasks associated with equatorially mounted non fixed telescopes is polar-axis alignment. In polar–axis alignment, the telescope axis is made parallel to the earth’s axis of rotation as shown in Fig (1). This must be done as accurate as possible before every observing session so as to minimize both the amount of guiding needed and the effects of field rotation or declination drift and also to improve the pointing accuracy. For short-focal-length lenses and moderate exposures it is possible to dispense with guiding completely [4].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Polar axis alignment process}
\end{figure}

There are many ways to do such an alignment process manually. The most famous are iterative and star drift, which, are very time consuming particularly if accurate alignments are required for photography or photometry [5]. These methods depends on pointing the telescope as accurate as possible towards the north pole star, then centering it to another bright star near the meridian, making
the scope to track it and watching the drift of the star from the center. According to the direction of the drift, the telescope azimuth and elevation screws are adjusted appropriately. This process depends on the experience of the user because the drift is not uniform over the entire sky and even can change its direction.

Modern automated telescope systems use another method for polar alignment called three stars alignment. In this method, the telescope is slewed to three reference stars where the user has to recognize and manually center each chosen star in the field of view by motor keys then aligning (synchronizing) them with the telescope controller. There are many problems in applying these methods:

1. the chosen stars have to be far apart from each others.
2. these stars have to be the brightest stars in the area where the telescope is pointing.
3. they have to be easily recognized for the observer who must has enough experience about star charts and star constellations.
4. if the user wrongly identified reference star, the calculations will be totally wrong and both the pointing and tracking accuracies will be very low.

These problems make it very difficult for a beginner or inexperienced amateur to use the telescope.

Getting accurate automatic pointing has also many advantages. Some of them are: it provides a check on the polar axis alignment, improves operating efficiency and may discover mechanical problems (e.g. bearing runout and insecure optics) for which there may be a remedy. In order to get such an accurate absolute pointing, both of astronomical and telescope mechanical corrections have to be calculated and be taken into account in the control loop. The corrections calculations have to be made repeatedly, which is computationally intensive and may keep the computer busy.

One famous method (TPoint) that is being used for improving the pointing accuracy for both professional and amateur telescopes is based on fitting a mathematical model for the discrepancies between the calculated apparent places of the stars and the dial or encoder readings [6]. That mathematical model contains expressions describing a variety of anticipated telescope defects. In order to do such a model, a sequence of tens of stars spaced about 10-20 degrees apart in right ascension (α) and declination (δ) all over the sky has to be observed1. By getting such model the mechanical coefficients can be known and the mechanical defect errors can be eliminated. Although this model can lead to an improvement of the accuracy of pointing, it has many disadvantages. First, it needs much time to conduct a large amount of star observations. Second, the errors have to be repeatable and consistent; random errors (like when the mechanics of the telescope are weak or marginal) can not be tolerated. Third, the previous mentioned problem of the need to center the image of each star in a reticle eyepiece which necessitates the observer intervention who must has enough experience about star constellations. To provide few arcseconds pointing accuracy means proper management not only for star position data but also the position in the focal plane into which the star image is to be sent. This requires artful presentation, powerful on-line calibration tools and meticulous setting up each night [9].

In order to overcome those problems, we proposed and developed our system to align and point the telescope easily by the use of image processing and pattern matching techniques. Because the proposed system uses the image of the sky as a reference, there will be no need to correct for most of the astronomical and mechanical errors. In our discussion here we suppose that the telescope drive actuators are of the DC servo type. However the same concepts can be applied to stepper motor drives.

2 Pattern matching telescope control method

The proposed method is based on synthesizing the image of the batch of the sky around the reference star selected. In classical closed loop servo systems there are angle position encoders on each axis of the telescope and a computer that compares the actual position given by the encoders with the desired position given by the corrected place of the star. The computer issues an appropriate command to bring these positions closer together. In our proposed system we do the same comparison between the telescope actual position (in terms of its actual acquired image at the place to which it is pointing) and the image of the corrected places of the stars around the target star. The main difficulty with the classical approach is that it senses the errors at the telescope axes, not the stars themselves. As the ultimate goal is to point the telescope at something in the sky, any unmodeled errors are ignored in the classical approach. This task is not easily accomplished and can load down the computer [10]. In our system we try to detect the error at the stars themselves and as the error is detected and corrected here, no complex calculations are needed and the computer is not loaded down. Fig. 2 shows the proposed system setup and Fig. 3 shows the block diagram for the proposed algorithm. Each process of image processing, point pattern matching and template matching will be described in the following sections.

2.1 Image synthesize

For the purpose of synthesizing the image of the stars around the reference star we got a database for the brightest stars in the sky from the bright star catalogue for Epoch 2000 [11]. The database contains equatorial coordinates (α, δ), proper motions in α and δ, visible intensities and star

---

1 Right ascension and declination are star coordinates and are simply equivalent to the earth’s longitude and latitude respectively. See [7] and [8] for more information.
names. We made corrections to these coordinates for proper motion, precession and nutation. The mathematics of these corrections is very long and is out of the scope of this paper. The corrected coordinates have been converted to proper motion and names of some of the known objects in both images are used to do point pattern matching and so on.

A correction for refraction \( R \) (bending of light due to the earth’s atmosphere) has been implemented by adding \( R \) to the true calculated altitudes \( (h_0) \) to predict the apparent altitudes \( h \) as follows [12]:

\[
h = h_0 + R
\]

where \( R \) is the refraction correction in minutes of arc, \( T \) is the temperature in °C and \( P \) is the atmospheric pressure in millibars, \( h \) is the true altitude of the star in degrees and \( C \) is a constant added such that the refraction \( R \) at \( h=90° \) is equal to zero; \( C=0.0019279 \).

The whole process can be summarized in the flowchart shown in Fig. 4. First the telescope polar axis is positioned towards the north celestial pole. Then it is automatically commanded through the serial port to slew from its home position to a selection of three reference stars all over the sky. Instead of asking the user to identify and center the reference star, this will be done automatically by the use of image synthesizer. At each star and after the movement is achieved, the altitude \( (h_i) \) and azimuth \( (A_i) \) of the star moved to are being compared to the altitudes and azimuths of the positive altitude stars of the database. If the stars are within the field of view of the camera, a correction is made to their \( h \) & \( A \) coordinates for perspective distortion arising from the wide field of view lens used. Star undistorted coordinates \( x_i, y_i \) are calculated by the following equations.

\[
x = \sin(A - A_c) \cos(h)
\]

\[
y = \sin(h) \cos(h_c) \cos(h) \sin(h_c) \cos(A - A_c)
\]

where \( h_i, A_i \) are the \( i \)th star altitude and azimuth respectively and \( h_c, A_c \) are respectively the altitude and azimuth of image center (reference star coordinates).

Standard least square solutions are used to determine the scale of the synthesized image compared to actual image. Some of the known objects in both images are used to do this step. The corrected scaled coordinates are normalized to the dimensions of the image frame (512×440 pixels) and drawn at the proper positions. Normalizing is executed in such a way that the reference bright star is at the image frame center. The size of each object is proportional to its scale of the synthesized image compared to actual image. The whole process can be summarized in the flowchart shown in Fig. 4. First the telescope polar axis is positioned towards the north celestial pole. Then it is automatically commanded through the serial port to slew from its home position to a selection of three reference stars all over the sky. Instead of asking the user to identify and center the reference star, this will be done automatically by the use of image synthesizer. At each star and after the movement is achieved, the altitude \( (h_i) \) and azimuth \( (A_i) \) of the star moved to are being compared to the altitudes and azimuths of the positive altitude stars of the database. If the stars are within the field of view of the camera, a correction is made to their \( h \) & \( A \) coordinates for perspective distortion arising from the wide field of view lens used. Star undistorted coordinates \( x_i, y_i \) are calculated by the following equations.}

\[
x = \sin(A - A_c) \cos(h)
\]

\[
y = \sin(h) \cos(h_c) \cos(h) \sin(h_c) \cos(A - A_c)
\]

where \( h_i, A_i \) are the \( i \)th star altitude and azimuth respectively and \( h_c, A_c \) are respectively the altitude and azimuth of image center (reference star coordinates).
location \((x, y)\), \(b\) is the background level, \(x_i\) and \(y_i\) are the centroids in \(x\) and \(y\) directions, \(s\) is a scale factor chosen such that the maximum DN value is at the star center and \(\sigma\) is the full width at half maximum; \(\sigma = M_{\text{min}} - M_i\), where \(M_{\text{min}}\) is the minimum magnitude of the star in the catalogue and \(M_i\) is the magnitude of star \(i\). In our case we made \(b=0\), \(s=256\) and \(M_{\text{min}}=5\). After all stars above the horizon within the field of view have been drawn, the image frame is stored in BMP format for later processing and matching. Also the whole data calculated are stored in text files for later extraction. Samples of a synthesized and an actual image frames in an inverted mode are shown in Fig. 5. The lens used in acquiring the image is a 16 mm focal length and the CCD used is a TV video camera, which has 768 × 494 pixels with a pixel dimension of 8.4 × 9.8\(\mu\)m. This lens-camera combination will give a field of view of 23° × 17° which gives a resolution of 1.79×2.06 arcmin/pixel. The resolution can be improved by using a longer focal-length lens that can give smaller field of view.

\[\text{Figure 5. Sample of the synthesized (a) and actual image (b)}\]

2.2 Image processing

In this process basic image processing is made for both of the synthesized and acquired image frames for the purpose of star identification. Both frames have to be put at the same scale for pattern matching. To do this, both frames are converted to binary form after removing noise from the acquired frame. Picking noise is carried out in such a manner that a single white pixel is eliminated. Thresholds used in the digitization process are chosen such that almost similar areas of stars in both frames are produced, background is totally removed from the acquired frame and also depending on the expected minimum magnitude. The stars in each frame are found using a rapid search execution where a concatenation labeling process is performed to assign numbers to linked objects. An area filter according to a given threshold is used in this labeling process. Sorting of such labeled areas follows this. The area filter threshold is chosen so as to stop the operation in case of clouds passing or fault observation of the moon or any big illuminated artificial object. This process is followed by an extraction of the center of gravity coordinates and area of each labeled star and storing them in tables for the next step of pattern matching. The coordinates are given in a sub pixel values. Fig. 7 shows the stars found by the image processing task surrounded by circles.

2.3 Point Pattern matching

Pattern matching techniques have many uses in astronomy as well as in other fields like robotics, photogrammetry and machine vision. In astronomy, this frequently involves matching points found in two lists of two-dimensional coordinates where the coordinate systems are not the same and the matching must be based on the identification of similar geometrical configurations of points in both lists. Different approaches have described matching star lists given by their two dimensional coordinates [15] and [16]. In computer vision, examples include pattern matching, automated visual inspection and registration of images. Approaches used to solve this problem can be found in [17] and [18]. Our application is related to the former problem found in astronomy; pattern matching of two point patterns A and B in the plane, where the cardinality (number of points) is not the same. Pattern A includes the point set of star centers of the acquired image frame while pattern B is the point set of the generated or cataloged star centers.

Two constellations are said to match if the stars inside them have the same mutual distances. In practice, as measurements are not exact, there must be a certain range of tolerance to make matching. Matching is implemented based on separations (distances) between stars, \(d_{ij}\), \(d_{mn}\) on each frame. It does not explicitly rely on stars brightness, i.e., no comparison is made on catalogued versus measured intensity, but as the image processing results of both frames are sorted in order of decreasing area, matches are first attempted on the biggest area stars. A flow chart showing the process of point match is shown in Fig. 6. Stars separated by at least 20 pixels are considered; that is to avoid false matching. If it is found a distance in the second image that lie within the tolerance value of the first image, it is reported as a potential match and the two stars are marked. The separation tolerance \(\Delta d\) chosen is 2 pixels, a fairly stringent requirement to prevent an undue number of false search paths to be followed. At least three matches (corresponding to the minimum of 4 stars) for each of the
first three highest matched stars must be achieved to consider matching successful. The angles between the line connecting each two of these first three stars and the horizontal x-axis are compared to the angles between the lines connecting the matched stars in the second image. If the three angles lie within a tolerance angle $\Delta \theta$ (2 degrees was chosen) then the three matched stars are considered initially as correct match. The average of these three angles is calculated and is considered as the angle that the synthesized image frame has to be rotated to match the orientation of the acquired frame. The rotation center is at the frame center such that the reference star remains at its center. Similar algorithms to this were presented for satellite attitude control in [19] and [20].

Rotation of the synthesized image frame may affect the stars in the original frame such that some will appear and some will disappear. For this reason, point matching has to be conducted again to get the knowledge of which star of the candidate pair is which.

After getting the precise match from the normalized correlation matching that will be discussed in the next section, the stars will be identified in both images and as the orientation will be the same, offset will be easily calculated. We used three stars to calculate the average of the offset that the telescope has to move in x and y directions to center the reference star in the field of view. Sample of the matched-rotated image and that of the acquired image are shown in Fig. 7. Stars passed the pattern matching are surrounded by rectangles. It is shown that the orientation of both images is the same and that there are offsets in both x and y directions where the telescope has to be moved to the direction to make offsets equal to zero.

2.4 Normalized Correlation Matching

Registration of an image with respect to a reference pattern has a wide range of applications in machine vision and robot guidance. In this process, a reference pattern is searched within an image under consideration by shifting it to every location in the image. One main difficulty of this method is the high computation time it requires. Many techniques have been developed to reduce this computation time (for example see [21], [22]).

In our application here, we used this process to ensure that the point pattern matching process was correct as well as getting the precise rotation angle for adjusting the orientation of the synthesized and actual image frames. In order to speed up the process, we used a binary matched filter template for both of binary images which is ANDED to the input binary image and the results are outputted to gray-scale screens. The template size chosen was set to $9 \times 9$ pixels and contains all ones (in order to search for white areas in black background). A normalized correlation process is then executed to these gray scale screens to locate three registered templates in the rotated synthesized image within the actual image. In doing this process, the following arithmetic operation is performed between the template ($g$) and target screen ($f$).

$$r^2 = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} f(i,j)g(i,j) - \left( \sum_{i=1}^{N} f(i,j) \right) \left( \sum_{j=1}^{N} g(j,i) \right)}{\left( \sum_{i=1}^{N} f(i,j) \right)^2 - \left( \sum_{i=1}^{N} f(i,j) \right)^2}$$

\[ (9) \]
where: $r$ is the correlation value (the range is 0 to 1), $u$ is the pixel X-coordinate value, $v$ is the pixel Y-coordinate value, $p$ is the template X size, $q$ is the template Y size and $N$ is the template effective pixel count.

Registering of the template windows is being implemented automatically according to the first three highest magnitude stars such that each star is positioned at any of the corners of the template window, since corners are good indicators of orientation of a square-shaped template. We adopted three templates for this step to avoid getting only templates that contain one star which would give non-correct high correlation match. A raster scan mode from up-left direction to right-down direction was chosen to implement the normalized correlations process. A correlation threshold value of 0.4 is chosen for the correlation process result. Fig. 8 gives a sample of the normalized correlation process applied to the images in Fig. 7. The given SX and SY are the coordinates of the up-left corner of the template. As shown, the correlation value of the template 1 near the image center is approaching 1 while those of the other templates are smaller. This is likely due to residual errors in the optical distortion calibration.

For the processes of pattern matching to be successful, a correlation value of 0.75 is put as the necessary value to ensure correct matching. Precise rotation of the synthesized image around its center is implemented in both directions where normalized correlation is conducted at each position to get the highest correlation value and its corresponding rotation angle needed to make best match for the orientation of the synthesized and actual images. Fig. 9 shows the results obtained by making such successive rotations at a value of 0.5 degree.

### 3. Alignment and Pointing Performance

In order to test the performance and the effectiveness of the proposed method we mounted the CCD camera on a gimbal with its optical axis parallel to 80 mm, f/11 amateur refractor telescope that was valid to us at system Robotics Lab, Tohoku University, Japan. The camera center is aligned to telescope focus center. The telescope mount polar axis was initially put roughly towards the north direction and alignment process executed for three stars, followed by pointing to forty different stars spaced roughly about 15° in the sky. It was clear that all the stars included in both alignment and pointing processes were placed into the 150x reticle eyepiece without any need for a finder. An accuracy of one pixel at the camera focus, which is equivalent to two arcminutes at the telescope focus, was achieved. Results are shown in Fig. 10. These results have been obtained by measuring the position of the star pointed.

![Figure 8. Normalized correlation results for images shown in Fig. 5 with their template coordinates and correlation values. SX, SY are the coordinates of the up-left corner of the template](image1)

![Figure 9. Correlation value as a function of rotation angle](image2)

![Figure 10. Pointing accuracy for the 80 mm, f/11 telescope. One pixel at CCD finder camera focus is equal to 1.79 arcminutes(H) and 2.06 arcminutes(V)](image3)
to within the image acquired by a similar CCD camera fixed at the telescope focus. This camera gives a resolution of 1.9×2.22 arcseconds/pixel. The calculation time for each single process in the alignment process was recorded and the average values are given in Table 1 in seconds. These computation times were achieved with a Pentium 4 PC (2 GHz) running under LINUX and the algorithm has been coded in C computer language.

It should be noted that the amount of time spent in the pointing process after finishing the alignment process is much more less than this time. That is because after the alignment, the telescope is almost perfectly aligned to the north pole and the position of the telescope after pointing to any star will have limited deviation from the correct position. This will not necessitate either making the correlation matching process or drawing of the rotated images. The previous methods used to make the alignment and pointing processes did not give explicit times for the execution as the time depends mostly on the observer experience as well as on the number of stars used to make the pointing model to achieve specific accuracy. But roughly speaking, it can be said that those methods take an average of thirty minutes for the alignment of a non fixed telescope and the pointing model can take even more.

Table 1. Calculation times for different processes (second)

<table>
<thead>
<tr>
<th>Process</th>
<th>Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude-Azimuth calculation</td>
<td>0.30</td>
</tr>
<tr>
<td>Draw 1 image of the field containing 7 stars</td>
<td>1.96</td>
</tr>
<tr>
<td>Point match</td>
<td>1.16</td>
</tr>
<tr>
<td>Draw of 10 rotated images</td>
<td>12.00</td>
</tr>
<tr>
<td>Correlation Matching for 3 different templates</td>
<td>148.64</td>
</tr>
<tr>
<td>Pointing match of 1 rotated image</td>
<td>1.17</td>
</tr>
<tr>
<td>Total processing time</td>
<td>165.23</td>
</tr>
</tbody>
</table>

4. Conclusion

The problems of alignment and pointing of small and movable telescopes have been addressed. An algorithm suitable to make fast and precise alignment has been proposed by synthesizing of a reference image and pattern match it with the actual acquired image. Point pattern match and template correlation matching have been used in the matching process.

The proposed algorithm has been tested under many different situations. The run time for the whole process is reasonably small compared to that of manual alignment and pointing. Most of the calculation times are spent in making template matching. This time can be decreased by adopting smaller template sizes and conducting this process to limited number of rotated images in the neighborhood of the initially calculated rotation angle.

Good accuracies have been achieved which can be increased by the use of a longer focus length lens and more database catalogue stars. Also by fixing another camera at the telescope focus can give very high accuracy for fine centering. The proposed system does not need neither precise timing nor precise encoders which can give support to produce cheap amateur and small telescopes for the public and supports the filed of automatic robotic telescopes. In addition, it does not need neither an experienced user nor his intervention to enjoy looking at beautiful sights in the sky and get very accurate and beautiful images.

REFERENCES


Copyright ©2004 The Japan Society of Mechanical Engineers