T.R.

GEBZE TECHNICAL UNIVERSITY

FACULTY OF ENGINEERING

DEPARTMENT OF COMPUTER ENGINEERING

COMPASS STAR TRACKER

YUSUF ABDULLAH ARSLANALP

SUPERVISOR
PROF. DR. HASARI ÇELEBİ

GEBZE
2022

T.R.
GEBZE TECHNICAL UNIVERSITY
FACULTY OF ENGINEERING
COMPUTER ENGINEERING DEPARTMENT

COMPASS STAR TRACKER

YUSUF ABDULLAH ARSLANALP

SUPERVISOR
PROF. DR. HASARI ÇELEBİ

2022
GEBZE

GEBZE TECHNICAL UNIVERSITY	GRADUATION PROJECT JURY APPROVAL FORM

This study has been accepted as an Undergraduate Graduation Project in the Department of Computer Engineering on 31/08/2021 by the following jury.

JURY

Member
(Supervisor) : Prof. Dr. Hasari ÇELEBİ

Member : Yrd.Doç.Dr. Burcu YILMAZ

ABSTRACT

Compass Star Tracker (CST) is a new method that finds location on Earth. Compass Star trackers can detect location with 1-2 km precision. CST is not a substitute for GPS. CST is not as accurate as GPS. Only at night and in cloudless weather can location determination be made with CST. CST can be used as a backup plan for GPS. In this study, we made a CST mobile application for use on smartphones. With this application, location can be determined by taking a photo of the night sky. When photographing the sky, the optical axis of the smart phone should be aligned, with respect to the local effective gravity field vector.

ÖZET

Compass Star Tracker(CST) Dünya üzerinde konum bulmayı sağlayan yeni bir yöntemdir. Compass Star tracker lar 1-2 km hassasiyetle konum tespiti yapabilmekte. CST GPS'in yerini alacak bir teknik değildir. CST GPS kadar hassas çalışmaz. Sadece gece vakti ve bulutsuz havada CST ile konum tespiti yapılabilir. CST, GPS için bir yedekleme planı olarak kullanılabilir. Biz bu çalışmada akıllı telefonlarda kullanmak üzere bir CST mobil uygulaması yaptık. Bu uygulama ile gece gökyüzünün fotoğrafı çekilerek konum tespiti yapılabilir. Gökyüzünün fotoğrafı çekilirken telefonun kamera ekseni yerçekim ivmesi ile aynı hizada olmak zorundadır.

ACKNOWLEDGEMENT

I would like to express my sincere thanks to those who contributed to the preparation of this study, to my teacher Prof.Dr.Hasari Çelebi and Gebze Technical University for guiding the final version of the work.

In addition, I would like to express my respect and love to my family, who supported me in every way during my education, and to all my teachers who set an example for me with their lives.

Yusuf Abdullah ARSLANALP

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol or Abbreviation		Explanation
CST	:	Compass Star Tracker
GPS	:	Global Positioning System
OA	:	Optical Axis
SPELL	:	Space and Planetary Exploration Laboratory
SOST	:	SPEL-Open Star Tracker

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

For thousands of years, people observed nature for navigating on the Earth. The Sun rises in the East and sets in the West, and we find our direction with this information. With searching Polaris star in night sky, hemisphere can be detected. If we see Polaris star in night sky we are in North hemisphere else we are in south hemisphere. People also invented devices for observing nature and navigating on the Earth. Such as compass and sextant invented. The needle of a compass always points to local magnetic north. Sextant is a mechanical device for detecting location on ships. One of the newest invention for navigation is Compass Star Tracker(CST). In this project we explain what Compass Star Tracker is and present a mobile application developed as a Compass Star Tracker.

There are articles published by Texas A&M University for Compass Star Trackers(CST).[1], [2]. Compass Star Tracker(CST) is a novel way of finding coordinate on Earth. For finding coordinate with CST two things needed. One is a night sky image the other one is the time image was taken. While taking the image the optical axis of the camera is aligned, with respect to the local effective gravity field vector. Using night sky image and a star catalog, attitude of the the camera can be detected. Using attitude of camera and the time image was taken the location can be detected in terms of latitude and longitude. The details of finding location from night sky image will be studied in later in this document

In this project we developed Compass Star Tracker Mobile Application[3]. With this application user takes a photo of night sky and the application shows the location of user on map. User also can pick a night sky image from gallery of smart phone and find location of where the image taken.

Compass Star Tracker(CST) does not substitute of Global Positioning System(GPS). However CST cab be back up of GPS for a failure situation. Because CST does not require any satellite information for finding location like GPS.

2. MOBILE APPLICATION

Compass Star Tracker(CST) Mobile Application is used for detecting location. This application can be used as a back up for GPS. The advantage of CST is it does not require satellite signals. The CST App can be used at clear nights. To detect the location the camera of the smartphone should be directly point to sky and the optical axis of the camera should be aligned, with respect to the local effective gravity field vector. Figure 2.1. shows how position of the camera should be.

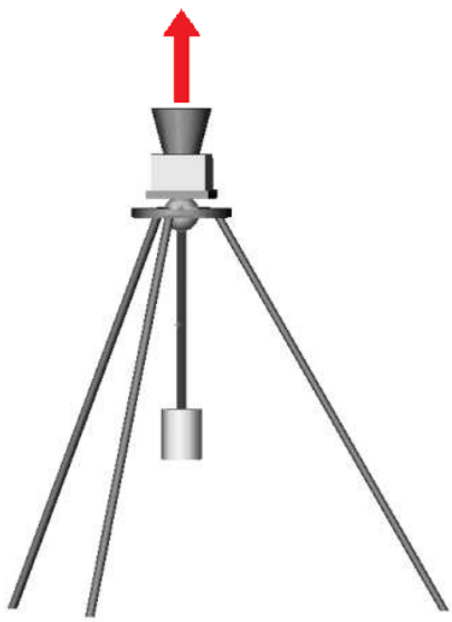

Figure 2.1: while taking photo of night sky the optical axis of the camera should be aligned, with respect to the local effective gravity field vector

[1].

For detecting location with CST the time image was taken also needed. After night sky image taken smart phone writes the time information as meta data in image. So the CST application reads needed time from the meta data of image. So user doesn't have to take any action for recording image time.

Figure 2.2 shows the main screen of the application. There are three button in the application. The first button is info button. When info button pressed a pop up windows open and gives information about the app. Figure 2.3 shows the information window.

When "take photo" button pressed camera of the smart phone opens. User should take o photo like described in figure 2.1 . When "take from gallery" button pressed

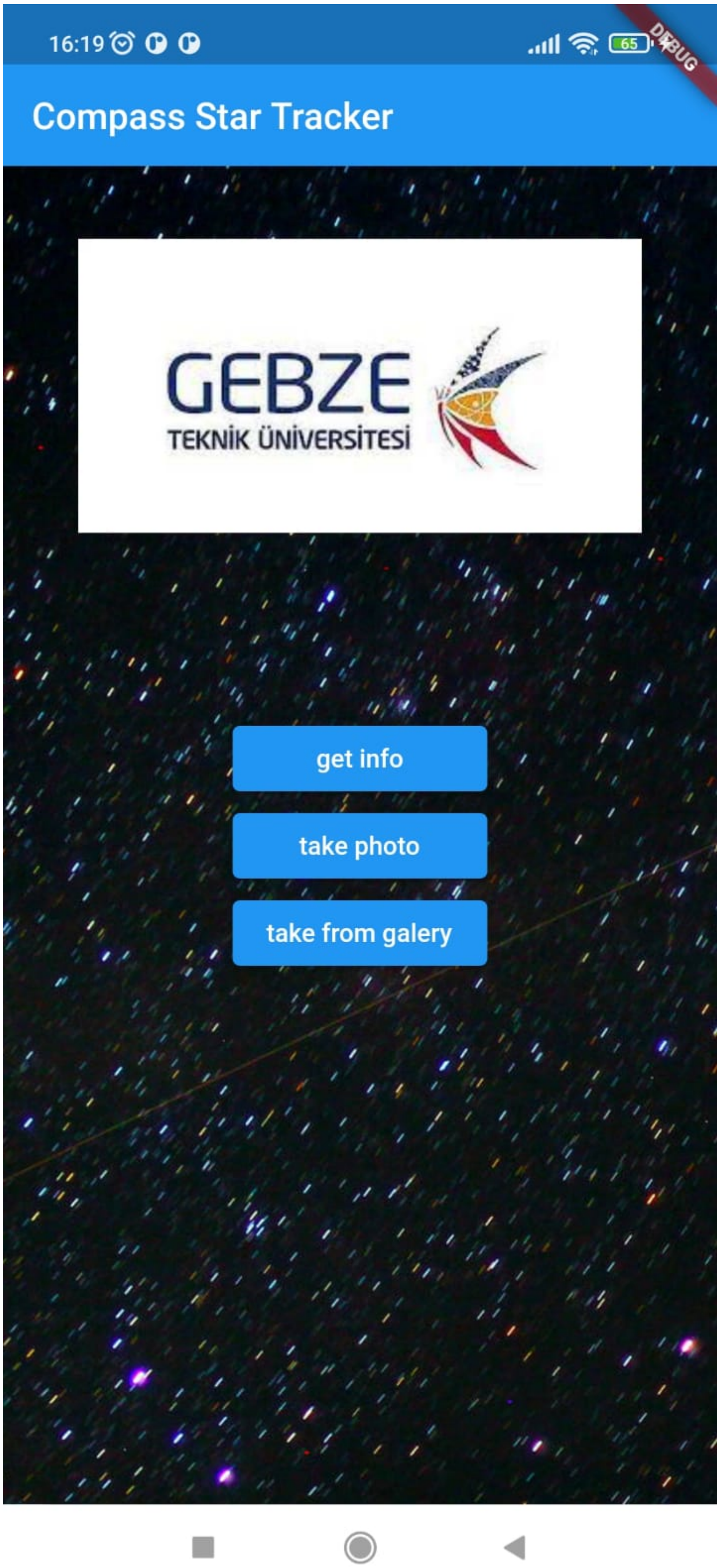

Figure 2.2: Main screen of the application

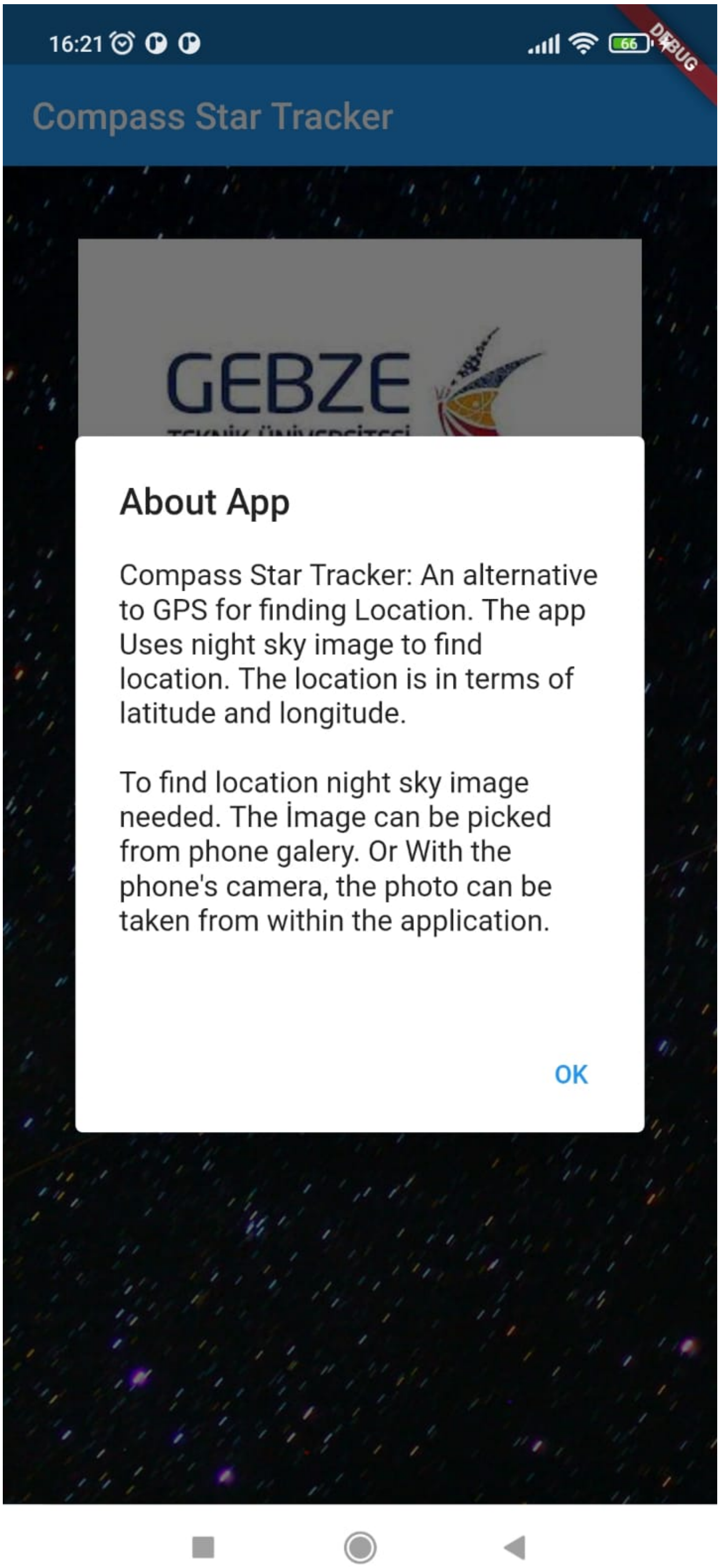

Figure 2.3: Information Window

gallery of the smart phone opens. User can pick an image from gallery. The picked image should be an image described in Figure 2.1 . After user take a photo using "take photo" button or picks an image with "take from gallery" button following steps occurs:

- mobile application sends the night sky image to server
- server receives the night sky images
- server compare night sky image with star catalog and finds attitude of camera.
- server finds coordinate using attitude information and using the time image was taken.
- server send coordinate to mobile application.
- mobile application shows the received coordinate on the map.

After using "take photo" button or "take from gallery" button, detected location shown to user. Figure 2.4 shows how determined location shown to user.

Figure 2.4: The determined location shown to user

3. FINDING LOCATION FROM NIGHT SKY IMAGE

3.1. Problem Formula

In order to develop the local position determination mathematics, one must begin by defining four reference frames: the body frame, the inertial frame, the Greenwich frame, and the local frame (See Figs 3.1 and 3.2). The CST works by determining the attitude between these four distinct reference frames. It should be noted that attitude is defined as the relative orientation between two reference frames. A standard attitude notation convention allows the attitude of reference frame X with respect to reference frame Y to be written as $A^{X/Y}$. The following reference frame abbreviations will be used:

B - Body, or camera reference frame.
G - Greenwich reference frame.
L - Inertial (geocentric) reference frame.
I - Local reference frame.

Using these abbreviations and the aforementioned notation convention, the fundamental equation relating the four reference frames is

$$A^{B/I}A^{I/G} = A^{B/L}A^{L/G}$$

It is important to note the distinction between the local reference frame and the body reference frame. Whereas the local reference frame is located at the same latitude and longitude as the body reference frame, the body frame describes the local bearing and any misalignment that may occur between the camera and the local zenith direction.

Figures 3.1 and 3.2 show some of the basic geometry associated with the four reference frames. The angles and directions shown in Figs. 3.1 and 3.2 are defined as follows.

- ψ is the angle between the vernal equinox (ascending node of the geocentric ecliptic) and the Greenwich Meridian. The angle, ψ , is known as a function of time.
- λ is the longitude.
- ϕ is the latitude.

- $\phi^|$ is the complement of the latitude angle,
- Optical Axis (oa) is the pointing direction of the camera. In Figure 3.2, oa is noted as $z^|$.
- ϵ is the angle between local South and the x-axis ($s^|$) of the camera body frame.
- s,e,z form an orthogonal coordinate system (the local reference frame) where s is local South, e is local East, and z is the zenith direction.
- $s^|$,$e^|$,$z^|$ form the camera body coordinate system where $s^|$ corresponds to the x-axis, $e^|$ is the y-axis, and $z^|$ is the z-axis.

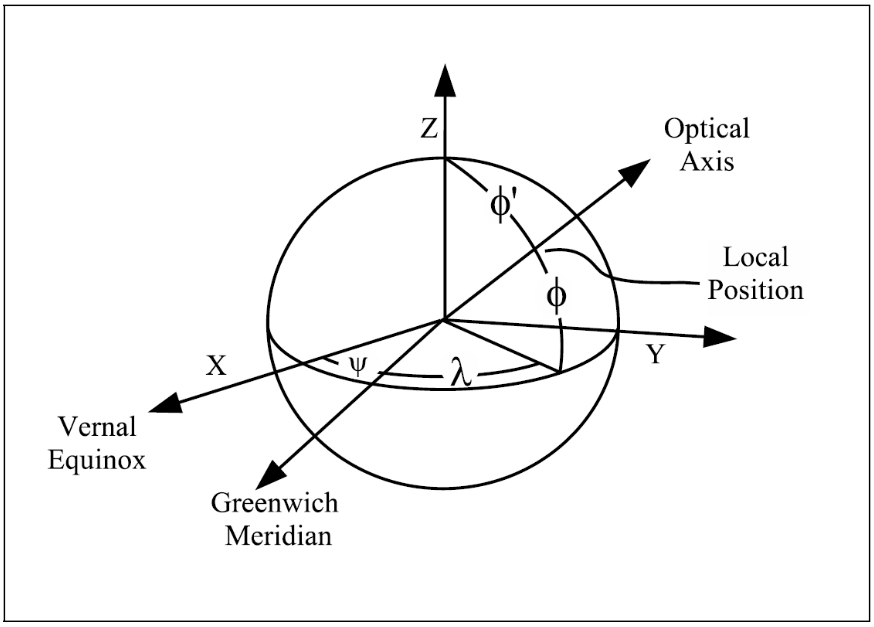

Figure 3.1: The inertial reference frame for the CST [2]

One of the assumptions used in the CST mathematical development is that the optical axis of the camera (oa) is aligned with the zenith direction. Under this assumption, z = $z^|$ = oa in Fig. 3.2. The attitude of the camera body with respect to the local reference frame may then be written as

$$A^{B/L} \equiv R_3(\epsilon) = \begin{bmatrix} cos\epsilon & sin\epsilon & 0 \\ -sin\epsilon & cos\epsilon & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The Local reference frame with respect to Greenwich reference frame may be written as

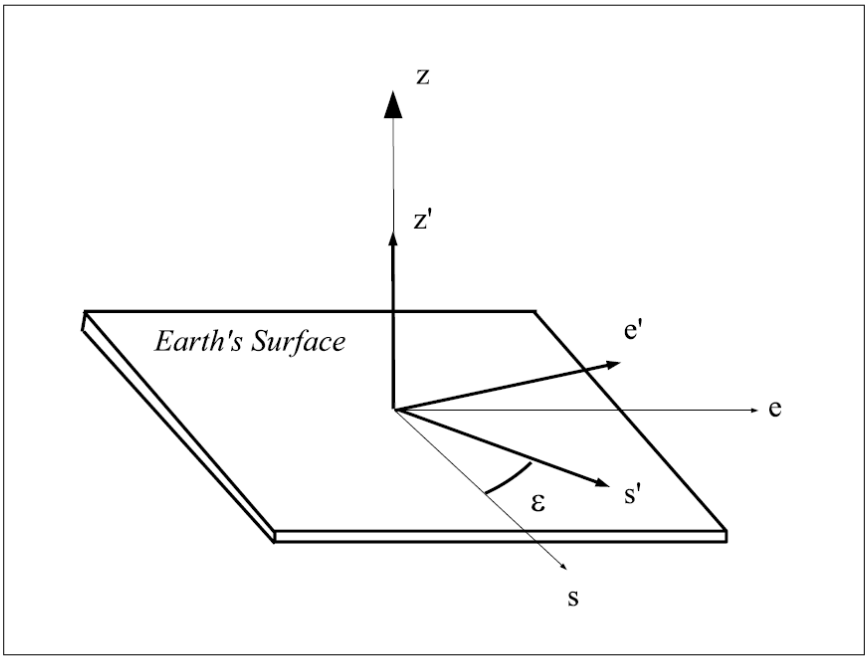

Figure 3.2: The local reference frame for the CST [2]

$$A^{L/G} \equiv R_2(\phi^{|})R_3(\lambda) = \begin{bmatrix} cos\phi^{|} & 0 & -sin\phi^{|} \\ 0 & 1 & 0 \\ sin\phi^{|} & 0 & cos\phi^{|} \end{bmatrix} \begin{bmatrix} cos\lambda & sin\lambda & 0 \\ -sin\lambda & cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A^{L/G} = \begin{bmatrix} cos\phi^{|}cos\lambda & cos\phi^{|}sin\lambda & -sin\phi^{|} \\ -sin\lambda & cos\lambda & 0 \\ sin\phi^{|}cos\lambda & sin\phi^{|}sin\lambda & cos\phi^{|} \end{bmatrix}$$

The Body reference frame with respect to Greenwich reference frame may be written as

$$A^{B/L}A^{L/G} = A^{B/G} = \begin{bmatrix} C_\epsilon S_{\phi^{|}} C_{\lambda^{|}} - S_\epsilon S_\lambda & C_\epsilon C_{\phi^{|}} S_{\lambda^{|}} + S_\epsilon C_\lambda & -C_\epsilon S_{\phi^{|}} \\ -S_\epsilon C_{\phi^{|}} C_{\lambda^{|}} - C_\epsilon S_\lambda & -S_\epsilon C_{\phi^{|}} S_{\lambda^{|}} + C_\epsilon C_\lambda & S_\epsilon S_{\phi^{|}} \\ S_{\phi^{|}} C_{\lambda^{|}} & S_{\phi^{|}} S_{\lambda^{|}} & C_{\phi^{|}} \end{bmatrix}$$

where $C_x \equiv$ cos x and $S_x \equiv$ sin x.
ϕ is latitude and λ is longitude. ϕ and λ can be achieved from $A^{B/G}$ matrix as

follows

$$(latitude)\phi = arccos(A^{B/G}(3,3))$$

$$(longitude)\lambda = arctan(A^{B/G}(3,2)/A^{B/G}(3,1))$$

Latitude and longitude find in terms of $A^{B/G}$. To find $A^{B/G}$, $A^{B/I}$ and $A^{I/G}$ should be find. In the next sections finding $A^{I/G}$ and finding $A^{B/I}$ will be studied.

3.2. Finding $A^{I/G}$

$A^{G/I}$ represents the Earth attitude matrix with respect to J2000. This matrix is known by knowing the current time. It also will take into account the precession and the nutation of the Earth spin axis. The matrix $A^{G/I}$ is calculated at the current time (t) by

$$A^{G/I}(t) = R_3(\psi)NP$$

Neither the plane of the earth's orbit, the ecliptic, nor the plane of the earth's equator are fixed with respect to distant objects. The dominant motion is the precession of the earth's polar axis around the ecliptic pole, mainly due torques on the earth cause by the moon and sun. The earth's axis sweeps out a cone of 23.5 degrees half angle in 26,000 years. The ecliptic pole moves more slowly. If we imagine the motion of the two poles with respect to very distant objects, the earth's pole is moving about 20 arcseconds per year, and the ecliptic pole is moving about 0.5 arcseconds per year. The combined motion and its effect on the position of the vernal equinox are called general precession. The predictable short term deviations of the earth's axis from its long term precession are called nutation. The nutation is the transformation for the periodic effects contributed by the sun and the moon. [1]

The precession-nutation matrix can be written as the product of four rotation matrices as

$$NP = R_1(\alpha)R_3(\beta)R_1(\gamma)R_3(\delta)$$

where the angles γ and δ are the angles that specify the location of the ecliptic pole in the given inertial frame, β is the ecliptic angle of precession, and α is the obliquity of the ecliptic. All of these angles are functions of the current time and may be solved using the following set of equations.

$$\alpha = (84381.442846.8388t0.0002t^2 + 0.002t^3)/3600$$

$$\beta = (0.0431 + 5038.4739t + 1.5584t^2 0.0002t^3)/3600$$

$$\gamma = (84381.447946.814t + .0511t^2 + .0005t^3)/3600$$

$$\delta = (10.5525t + 0.4932t^2 0.0003t^3)/3600$$

where t is the current time calculated by

$$t = (JDT)/T_{century}$$

Here $T_{century}$ is the number of days in one century (=36525), T_0 is the Julian Date at J2000 (=2451545), and JD is the Julian Date at the current time.

Another component of the $A^{G/I}$ calculation is the determination of the Greenwich meridian angle. This angle is also referred to as the Earth rotation angle. The angle, ψ, is found using

$$\psi(T_u) = 2(0.779057273264 + 1.00273781191135448T_u).$$

where T_u is amount of Julian time since J2000

Until now how to find $A^{G/I}$ studied. $A^{I/G}$ can be find from $A^{G/I}$. $A^{I/G}$ is transpose of $A^{G/I}$

3.3. Finding $A^{B/I}$ From night Sky Image

A star tracker is a sensor that detects stars and compares their pattern with known stars from a stellar catalog. Then, it computes the precise orientation in which the camera is pointed at the sky and deduce the camera's attitude[4]. In this work we will use a star tracker developed at the Space and Planetary Exploration Laboratory (SPEL) at the University of Chile. The SPEL Stara Tracker detects attitude from night sky image. Attitude information is used for finding $A^{B/I}$ rotation matrix. $A^{B/I}$ matrix is used for detecting location of camera.

The main code of SPEL Star tracker developed with python[5]. However SPEL Star Tracker uses other two other softwares named Source Extractor and Mach.

Source Extractor is a software used to detect astronomical sources (e.g. stars, planets, galaxies) from an image. In this work, Source Extractor is used to detect stars and calculate their position and brightness magnitude. It generates a list of sources with their brightness relative to the image's background.

Mach used to establish a relationship between two different lists of objects. Match requires two input files with data in columns. Each file should contain at least X position of objects, Y position of objects and Magnitude at point (X, Y).

3.3.1. Star catalog

Star catalog is a database wich consists of segments. Each segment contains information about a list of stars. A sampe segment given in figure 3.3 .

```
-1.63478 -1.88869 3.01 178
-0.77994 -1.13984 1.16 17
-0.64690 -0.62679 3.66 349
1.65262 -0.75748 4.00 514
-0.47227 -0.55488 3.97 508
0.56156 -0.44323 2.04 53
-0.86008 -0.34374 3.27 231
1.42678 -0.40716 3.50 286
0.92190 -0.03424 3.45 273
1.57474 -0.08786 3.73 372
0.25530 0.06075 3.56 306
1.15397 0.06595 3.60 321
-0.91234 0.11066 3.74 378
-1.40577 0.45295 3.84 432
-1.67795 0.51614 2.96 165
-0.58983 0.72088 3.69 359
-1.63888 0.92807 3.53 298
-1.14221 1.19643 3.40 260
-0.79815 1.45888 2.49 92
0.18747 1.43102 2.83 138
1.37428 1.52138 3.62 331
```

Figure 3.3: A sample segment for the star catalog

In a star catalog segment each line represent a star. First two number in a line represents coordinate of the star. Third number represent brightness of star. Fourth number represent the rank of the star in terms of brightness.

3.3.2. Attitude Determination Algorithm

Following is the steps for determining attitude from night sky image.

- The list of brightest objects in the picture is obtained by using Source Extractor. Out put is a list of sources, with the position and brightness of the detected objects.
- The forty brightest objects are selected from the full list of detected objects in previous step.
- The brightest fourty objects are searched in each segment of the star catalog using

Match. The output of this stage is a list of candidates (matched) segments of the star catalog.

- The segment of the star catalog with the largest number of matched objects is selected as the best match.
- Two other iteration performed to improve the accuracy of the matching procedure.
- RA, DEC and Roll angles are find. These values are the attitude of the camera in the inertial coordinate frame.

3.3.3. Euler Angles to Rotation Matrix

In previous section finding attitude information using SPELL Star Tracker is studied. Euler to rotation matrix function used for converting Ra, Dec and Roll values to $A^{B/I}$ rotation matrix. And $A^{B/I}$ rotation matrix is found.

3.4. Night Sky Test

The night sky image can be seen from figure 3.4. The tiny white points in the image are stars. The image was taken at 29 July 2016 20:28. Using the image and the time image was taken location will be determined.

In chapter 3.2 finding $A^{G/I}$ studied. Using the time image was taken $A^{G/I}$ calculated. Transpose of $A^{G/I}$ is $A^{I/G}$. And Figure 3.5. shows value of $A^{I/G}$ for the figure 3.4.

In section 3.3 finding $A^{B/I}$ studied. Using SPELL Star Tracker [5] the attitude of the night image is found. Found attitude value is as follows:

- RA = 215.068
- DEC = -52.104
- ROLL = -72.208

Using the Euler to rotaion matrix function and using the found attitude, $A^{B/I}$ is found. Value of $A^{B/I}$ is shown in figure 3.6

With multiplying $A^{B/I}$ matrix and $A^{I/G}$ matrix $A^{B/G}$ matrix is found. The $A^{B/G}$ is shown in figure 3.7.

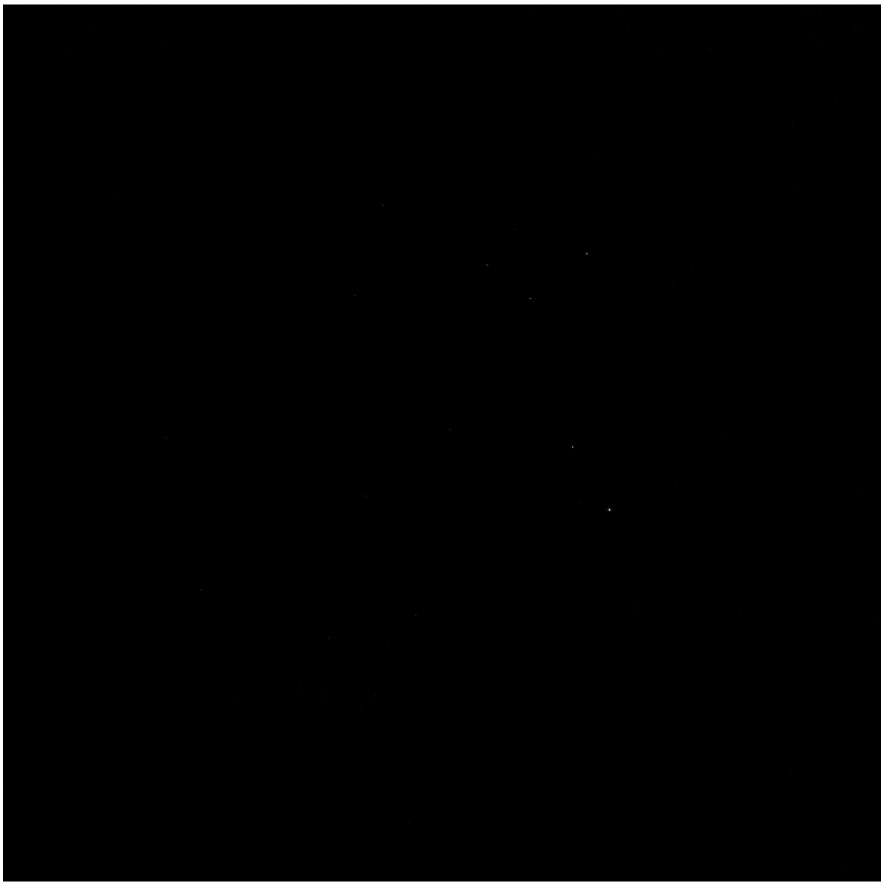

Figure 3.4:   night-sky-image

```
A_I/G:
[[ 0.94048878 -0.25197066  0.22801674]
 [ 0.25801256  0.96613551  0.00342026]
 [-0.22115688  0.05561447  0.9736512 ]]
```

Figure 3.5: $A^{I/G}$ matrix

```
A_B/I:
[[-0.50323493 -0.44087442  0.74322564]
 [-0.35278225 -0.6803187  -0.64242599]
 [ 0.78885949 -0.58548801  0.18682746]]
```

Figure 3.6: $A^{B/I}$ matrix

```
A_B/G:
[[-0.75140741 -0.2578099   0.60738864]
 [-0.36524159 -0.60411746 -0.70826596]
 [ 0.54953206 -0.75403988  0.35977544]]
```

Figure 3.7: $A^{B/G}$ matrix

Using the $A^{B/G}$ the latitude is found as follows:

$$\phi = arccos(A^{B/G}(3,3))$$

$$\phi = arccos(0.35977544)$$

$$\phi = 68.913$$

Using the $A^{B/G}$ the longitude is found as follows:

$$\lambda = arctan(A^{B/G}(3,2)/A^{B/G}(3,1))$$

$$\lambda = arctan(-0.75403988/0.54953206)$$

$$\lambda = -52.916$$

4. CONCLUSION

With this project the location determined from night sky image. The application couldn't test with appropriate image due to cloudy days at night. The application tested with the sample images in SOST repository [6]. The location is determined from the sample images. But the sample images does not taken like described in figure 2.1. So the finded location doesn't same location with the location the image taken. And the sensitivity of location determination unknown.

There are project proves the Compass Star Tracker can detect location with the accuracy 1-2 km [1]. And the source code of Compass Star Mobile Application is published on Github [3]. For this reason Compass Star Tracker Mobile Application worth to work on it until perfect result reached.

BIBLIOGRAPHY

[1] M. Samaan, J. Junkins, and D. Mortari, "Compass star tracker for gps applications," November 2008.

[2] M. J. SWANZY. "Analysis and demonstration: A proof-of-concept compass star tracker." (December 2005).

[3] "Compass star tracker mobile application." (), [Online]. Available: `https://github.com/yusufarslanalp/CompassStarTracker`.

[4] S. T. GUTIÉRREZ, C. I. FUENTES, and M. A. DÍAZ., "Introducing sost: An ultra-low-cost star tracker concept based on a raspberry pi an open-source astronomy software," 2017.

[5] "Spel - open star tracker." (), [Online]. Available: `https://github.com/spel-uchile/Star_Tracker`.

[6] (), [Online]. Available: `https://github.com/spel-uchile/Star_Tracker/tree/master/RPI/Sample_images`.