Acta Astronautica 131 (2017) 1–9

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Real-time star identification using synthetic radial pattern and its hardware implementation

Yang Zhao, Xinguo Wei*, Gangyi Wang, Jian Li

School of Instrumentation Science and Opto-electronics Engineering, Beihang University, 100191, China

ARTICLE INFO

Keywords:
Star identification
Star sensor
Radial pattern
Hardware implementation

ABSTRACT

Star identification algorithm has always been the core strategy of star sensors. For the time being, the identification speed is becoming the bottleneck of satisfying real-time requirements (e.g. high-speed maneuvering applications, power breakdown and so on) on the premise of the robustness. To solve this problem, this paper proposes a novel lost-in-space star identification algorithm based on the synthetic radial pattern, which is dedicated to the pipelined parallel architecture of FPGAs (Field Programmable Gate Arrays). The synthetic radial pattern consists of two single radial patterns connected by their two respective polestars. In the algorithm, the polestar-pair is firstly matched and optimum identification results can be obtained after the follow-up radial pattern filtering. Then, the number of spurious matches can be reduced to a much less level and a mathematical model is also developed to demonstrate the efficiency compared with conventional radial algorithms. Simulations show that the approach is very robust towards various noise conditions and the quantified identification time is less than 1 ms at a low resource cost when it is implemented on FPGA platforms.

1. Introduction

Autonomous attitude determination devices have rapidly developed in the past decades as an accurate and fast attitude is more and more essentially required by almost all flying vehicles. Among many types of attitude measurement sensors including sun sensors, geo-magnetometers, gyroscopes and star sensors, novel star sensors are the most accurate and characterized by a high degree of autonomy and fast fault recovery capability. The autonomous attitude determination process for a star sensor involves capturing a star image from a star camera, extraction of the brightness and centroid location of stars from the image, identification of sensor stars and the final attitude calculation [1]. As more and more high-speed maneuvering applications like space weapons and near space vehicles work at an angular velocity over 10°/s, or a sudden power breakdown, a correct real-time attitude updated in several milliseconds is more and more essentially needed. This situation can be defined as a lost-in-space problem where the prior attitude is nearly unknown. In addition to excellent image sensors, the typical difficulty to solve such problems lies in a highly robust and efficient full-sky star identification algorithm inside a high-dynamic star sensor. So, implementing an even faster identification strategy on the premise of good robustness is a worthy challenge in our study.

Many full-sky autonomous algorithms have been proposed to solve the lost-in-space problem [2] and the great majority of them can be partitioned into two classes [3]. The first tends to approach star identification as a subgraph isomorphism. It uses angle separations or polygons to structure its database. These algorithms include triangle algorithms [4,5], pyramid algorithm [6], geometric voting algorithm [7] and iterative algorithm [8]. Typically, two types of angle separation database lookup methods, the star pair table method [9] and k-vector approach [10], were proposed and a comparison was also carried out in [9]. The second class tends to approach this problem as a sort of pattern recognition. Each star is associated with a unique pattern by analyzing its geometric distribution in the neighborhood. And then a match can be achieved by finding the closest pattern in the catalog. The most representative one is the grid algorithm [11]. Later, the radial-pattern-based algorithms, like the polestar algorithm [12], radial and cyclic features algorithm [3] and log-polar transform strategy in [13]. Compared with the grid algorithm, the radial-pattern-based algorithms are more accurate to fit more situations. Considering the FOV size and robustness towards sensor measurements, the two kinds of approaches have their own properties and a detailed comparison was carried out in [14].

These algorithms are mostly implemented on fast processors like DSP and ARM. Codes can be easily written and optimized but complicated and sequential logic operations limit the execution speed.

* Corresponding author.
E-mail address: wxg@buaa.edu.cn (X. Wei).

http://dx.doi.org/10.1016/j.actaastro.2016.11.015
Received 4 July 2016; Accepted 6 November 2016
Available online 14 November 2016

Nomenclature

B	onboard guide star catalog
P	star pair catalog
R	star radial pattern catalog
N_C	number of onboard catalog stars in **B**
N_S	number of stars in pattern
s, c	sensor star, catalog star
spat, ***cpat***	sensor star's and catalog star's radial pattern
score	similarity between ***spat*** and ***cpat***
PR	pattern radius
PL	pattern vector length
dr	radius used for distinguishing double stars
σ	angle separation measurement error, deg
θ	measured angle separation, deg
m	discrete angle separation
λ	range of each group in **P**, deg
β	threshold used for filtering candidates
$L(m)$	number of different stars in the *m*-th group of **P**
$np(m)$	number of star pairs in the *m*-th group of **P**
$f(m)$	occurrence frequency of an angle separation *m*

What's worse, more budgets of such hardware are needed if less execution time is going to be made. Recently, FPGA-based systems have become a topic of strong interest due to larger capabilities, lower costs of reprogrammable logic devices and higher performances with parallel processing compared with sequential processing. They contain an array of computational elements, known as logic blocks, slices or adaptive logic modules (ALM), of which the functionality is pre-determined and thus time for reading instructions from memory can be saved. Besides, plenty of embedded memory resources can be utilized to satisfy the requirement of the fast data processing. Actually, more and more star trackers are designed based on novel embedded hardware platforms like FPGA with a CPU core like DSP or ARM. The solution has been successfully verified in real space missions. Current researches are focusing on dedicated methods that can further take advantage of the FPGA's parallel processing architecture.

Solutions involving the parallelizable neural network have been made in [15,16]. It seems to be appropriate in FPGAs. However, they are very sensitive to the brightness noise and waste hardware resources. In this paper, a very fast and highly robust algorithm based on the synthetic radial pattern is proposed. It assimilates ideas from the first kind of approach where the typical star pair match strategy and radial pattern are used. The proposed algorithm consists of simple logic operations only and is dedicated to FPGA-based devices. In this way, it allows high-dynamic star sensors to acquire valid and unique identification pairings less than 1 ms, which is less relevant to the budget or performance indicator of the hardware platforms.

The rest of this paper is organized as follows. In Section 2, an overview of radial algorithms is firstly given to facilitate following descriptions and a synthetic radial pattern is also derived based on a novel analytical model. In Section 3, details and performance tests of our algorithm are presented. In Section 4, the feasibility of FPGA implementation of the algorithm is discussed. Section 5 gives a conclusion of the paper and some future works.

2. Preliminaries

We first give an overview and some discussions of the conventional radial-pattern-based algorithms. Then, to analyze the identification efficiency towards various noise conditions, we develop a mathematical model, with which the identification idea using a synthetic radial pattern is formulated.

2.1. Overview of conventional radial algorithm

2.1.1. Radial pattern generation and match method

As reliable as the raw angle separation feature, the radial pattern is rational-invariant and can only be determined by the distribution of its neighborhood.

Given the pattern radius *PR* and the discrete ring strip interval λ, the radial pattern is generated for the catalog polestar *c* as shown in Fig. 1. The parameter *dr* is defined for the consideration of the binary star interferences. (Binary stars are two stars that seem to be close in the direction of line-of-sight, and their spots are too close for the centroid resolution to resolve them separately on the focal plane). A bit vector ***cpat***(1, ...*m*, ..., *PL*) of length *PL* (pattern length) is derived for the catalog star's pattern. In the vector, there is 1 on bit *m* if the angle separation θ between the pivot and a neighbor satisfies the equation m=ceil(θ/λ), and other bits are 0. Typically, let *PR* be FOV, then *PL* equals to ceil(FOV/λ) consequently. (ceil(*x*) rounds *x* to the nearest integer not less than *x*).

Sensor star radial pattern vectors by ***spat***(1...*m*...*PL*) are derived for a sensor star *s* similarly. To identify a sensor star, the idea is to perform a logic AND operation between $\boldsymbol{cpat_I}$ and $\boldsymbol{spat_i}$ representing the catalog star c_I and the sensor star s_i respectively, then count the number of "1". Supposing that there are N_C catalog stars in total and N_S sensor stars in a radial pattern, this match is formally given as

$$score(I,\ i) = \sum_{t=1}^{PL} (\boldsymbol{cpat}_I \& \boldsymbol{spat}_i)_t = \sum_{k=1,k\neq i}^{N_S} \boldsymbol{cpat}_I(m_{ik}) \tag{1}$$

where I=1, 2, ..., N_C, i=1, 2, ..., N_S and m_{ik} indicates the *k*-th discrete angle separation originated from s_i. The result written *score*(*I*, *i*) represents the similarity between c_I and s_i. It is obvious that the catalog star which has the highest score is most likely to be the correct correspondence.

For matching efficiency and memory savings, the two cited radial algorithms [3,12] use a lookup table (LT) to realize the match. The LT has *PL* entries each of which corresponds to a strip in the radial pattern. The *m*-th entry contains all catalog stars' indices whose *m*-th bit in the radial vector is 1. That is, if $\boldsymbol{cpat_I}(m)$=1, c_I is added to the *m*-th entry LT.*m*. We denote the number of different stars in the entry LT.*m* by $L(m)$. It is known that $L(m)$ is proportional to *m* and the greater λ is, the greater $L(m)$ will be. In the light of LT, Eq. (1) can be calculated as: in terms of *score*(*I*, *i*) associated with s_i, it is added by 1 only if c_I is found in the m_{ik}-th entry.

2.1.2. Disadvantages

In the case of star identification, an angle separation inside a sensor star pair cannot be precisely obtained due to sensor measurement errors. Given a sensor star s_i to be identified and one of its measured

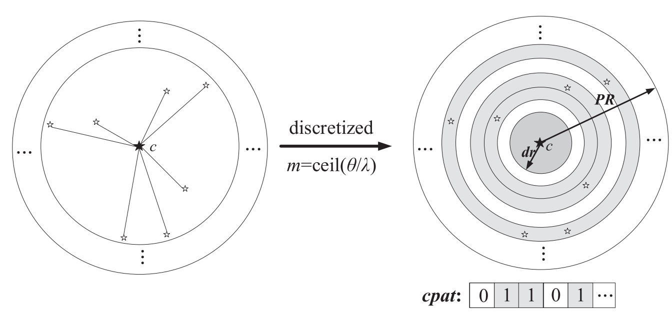

Fig. 1. Radial pattern generation scheme. The *m*-th bit is set to 1 only if a neighbor exists in the *m*-th strip.