A FAST ON-BOARD AUTONOMOUS ATTITUDE DETERMINATION SYSTEM BASED ON A NEW STAR-ID TECHNIQUE FOR A WIDE FOV STAR TRACKER *

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This paper describes, for a spacecraft equipped with a wide Field-Of-View (FOV) startracker, a fast and robust autonomous attitude determination system, consisting of a new star identification technique, here developed, working with a mixed *EULER-q*/*QUEST*-2 attitude estimation algorithm, presented in [4]. The stars identification is based on the stars angular separation. Stars are directly identified within an overall large stars catalog without using the magnitude information. A first proposed star-pair-ID technique is based on a best fitting criterion while a second faster one uses three vectors of integers. A proposed "reference-star" criterion is then used for star-matching identification. The algorithm robustness is such that, after spikes being deleted, at least three true stars are still available. An overall software block diagram of the proposed system is depicted. Extensive tests have been performed and the results are shown by plots.

Introduction

Star observations are widely used by spacecraft as a primary means of attitude determination. Currently, startracker sensors based on Charge-Coupled-Devices (CCD) allow to obtain the best spacecraft attitude estimation because of the high accuracy data provided. Three-axis attitude estimation algorithms need (at least) the knowledge of two different directions, therefore narrow FOV startrackers are commonly used with other less accurate attitude sensors. On the contrary, wide FOV startrackers can be used autonomously and, therefore, provide a high accuracy data set to the attitude estimation algorithm. However, when wide FOV startrackers are used, velocity and reliability of the star identification technique are of capital importance just as velocity and accuracy are important for the algorithm estimating the spacecraft attitude. This paper satisfies the above requirements by proposing a) two fast star-pair-ID techniques, b) a new star-matching method and, c) an attitude estimation algorithm which uses both *EULER-q* and *QUEST*-2 [4].

Although CCDs have been getting quite good, the "CCD magnitudes" are still somewhat uncertain and non-standard because various CCDs have different spectral responses. The CCD is best at determining spatial positions so that should be the primary criteria for any star-ID algorithm. Magnitude could be used to limit the search time. However, it is to be noted that the sensitivity may change with time so only relative magnitudes can be relied on. The magnitude range will depend on the lens aperture (FOV size) and integration times. Typical trackers have 8×8, 20×20 and 32×32 degree FOV and integration times of 0.05 to 1 sec. These values are selected to yield at least 4-5 stars in the FOV (at least 4-5 stars are required to get a reliable identification if the positions are accurate, more are needed if the accuracy is lower). Thus, for the 8×8 FOV something like 6^{th} magnitude is needed while for the 20×20 FOV it is enough to detect down to about 4.5-5.0 magnitude and a 2.5-3.5 magnitude for the 32×32 FOV. With these limits there may b

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e a few "holes" where there are fewer than 4-5 stars.

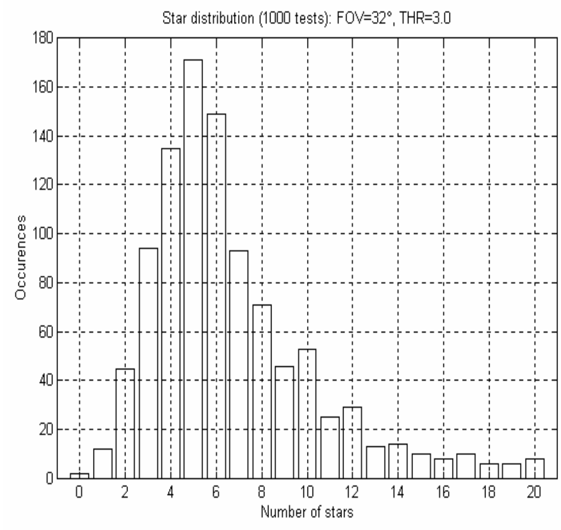

Figure 1

Figure 1 shows the histogram, obtained by NT=1000 random spacecraft attitudes, of the stars distribution for a startracker having a 32×32 FOV and the magnitude threshold set to 3.0. In this paper such a unit, providing observed stars directions with ε=1 arcsec of accuracy, is chosen as the reference one.

Another problem is what to do about stars that are on the edge of the star camera detection threshold. The catalog contains only magnitude estimates accurate to ±0.2 magnitude. Since the number of stars is exponential with magnitude, 20% of stars in any FOV will lie at the edge of the detection threshold. This means that any star detected has almost 20% chance of not being in the catalog. However, looking at ways to use the brighter stars in preference over dimmer ones implies the problem of having holes in many directions because the instrument FOV cannot be just of any size.

Therefore, being the accuracy of the magnitude information often poor and not stable with time, a basic philosophy of the identification technique should use only the information of the stars angular separations. The use of the magnitude information could, at least, be restricted to the ambiguities only when they actually occur (e.g. when only n=2 stars are available). However, any star-ID techniques which do not take advantage of the use of the magnitude information depend to a greater extent on the stars direction precision detected by the CCD camera. This precision will become better as the studies on the centroiding methods (how much one should defocus stars to improve the accuracy of their centroid prediction and how best to weigh the pixels to work out where the center of the star is) will be improved. Since the star-ID method described in this paper uses only the information of the stars angular separations, its reliability and robustness will improve with the CCD's camera accuracy.

All tests performed in this paper employ the stars catalog, located in the "pub/star_catalogs" directory of the "s3gsun1.jhuapl.edu" workstation, identified as "MSX_SIM_cat.dat". This catalog lists 12620 stars covering the magnitude range from -1.5 up to 6.4. For operating spacecraft application, even though the effects of the stars proper motions and the star-light aberration are very small, they should be added in order to bring all stars as close as possible to their positions, at the operating time.

Any complete stars-ID technique can be considered as consisting of two identification steps. The first one, called here *star-pair-ID* phase, identifies a small set of likely catalog star-pairs from the stars catalog and for each observed stars angular separation. The outputs of this ID-technique will then be the basis of the second ID phase, called *star-matching* phase, which identifies the correspondence between observed stars angular structures (simple separations, triangles) and those built from the list of the likely detected ones by the star-pair-ID phase.
This paper contains two different new star-pair-ID techniques ("*Best-fitting*" and "***K***-*vector*") and a new matching ID technique ("*Reference-star*"), which will be explained in the following three paragraphs, respectively.

Star-pair identification

Let us consider a star catalog consisting of n stars as described by the $3\times n$ matrix $\boldsymbol{V}$

$$V = [\ v_1\ ,\ v_2\ ,\ \dots\ ,\ v_n\ ] = \begin{bmatrix} v_1(1) & v_2(1) & \dots & v_n(1) \\ v_1(2) & v_2(2) & \dots & v_n(2) \\ v_1(3) & v_2(3) & \dots & v_n(3) \end{bmatrix} \tag{1}$$

where $\boldsymbol{v}_i$ indicates, in the inertial reference system, the unit-vector pointing to the i^{th} star direction. If $'_{FOV}$ is the angle indicating the startracker FOV width, two generic stars $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$ might simultaneously be wit hin the instrument FOV, provided that

$$v_i^T\ v_j \geq \cos\ \vartheta_{FOV} \tag{2}$$

Let us build the m "admissible" star dot products[1] $\boldsymbol{P}(k)=\boldsymbol{v}^T_i\boldsymbol{v}_j$, (where $1\leq k\leq m$ and $1\leq i\neq j\leq n$), satisfying th e aforementioned condition and record the relevant indices into the vectors $\boldsymbol{I}_P$ and $\boldsymbol{J}_P$

$$P = \begin{Bmatrix} \vdots \\ P(k) \\ \vdots \end{Bmatrix} = \begin{Bmatrix} \vdots \\ v_i^T\ v_j \\ \vdots \end{Bmatrix} I_P = \begin{Bmatrix} \vdots \\ i \\ \vdots \end{Bmatrix} J_P = \begin{Bmatrix} \vdots \\ j \\ \vdots \end{Bmatrix} \tag{3}$$

where $\boldsymbol{I}_P(k)=i$ and $\boldsymbol{J}_P(k)=j$ establish the corresponding relationships between $\boldsymbol{I}$, $\boldsymbol{J}$ and $\boldsymbol{P}$. Let us now arran ge the $\boldsymbol{P}$ vector in ascending order into the $\boldsymbol{S}$ vector, and define $\boldsymbol{I}$ and $\boldsymbol{J}$, respectively, the associated integ er vectors which, so as $\boldsymbol{I}_P$ and $\boldsymbol{J}_P$ do with respect to $\boldsymbol{P}$, maintain the corresponding relationships with $\boldsymbol{S}$.

Therefore these vectors

$$S = \begin{Bmatrix} \vdots \\ P(k) \\ \vdots \\ P(l) \\ \vdots \end{Bmatrix} I = \begin{Bmatrix} \vdots \\ I_P(k) \\ \vdots \\ I_P(l) \\ \vdots \end{Bmatrix} J = \begin{Bmatrix} \vdots \\ J_P(k) \\ \vdots \\ J_P(l) \\ \vdots \end{Bmatrix} \tag{4}$$

are such that, if

(5)

it results that

[1] By setting the magnitude threshold of a 32×32 FOV startracker to 3, then m will be approximately 5250.

$$\cos\vartheta_{FOV} \le P(k) < P(l) \le 1 \text{where :} \begin{cases} I(i_k) = I_p(k) \\ I(i_l) = I_p(l) \end{cases} \text{and} \begin{cases} J(i_k) = J_p(k) \\ J(i_l) = J_p(l) \end{cases} \quad (6)$$

By using the m-long vectors ***S***, ***I*** and ***J***, it is possible to devise a fast way to identify, in the vector ***S***, the indices of the admissible star-pairs which could provide the observed dot product cos′. For a binary search technique, as the one described in [3], the resulting identification routine may be executed, for a m-long ***S***-vector, in a time proportional to $L=log_2(m)$, because it involves approximately a $L=log_2(m)$ of logical equalities (for example: is $X>Y$?). In the following paragraph a star-pair-ID technique based on a best-fitting criterion, able to decrease the amount of logical equalities L, is presented. Then, a second star-pairs-ID method, which does not use best-fittings and which is based on the appropriate integer ***K***-vector, reducing this amount to the absolute minimum, is described.

"Best fitting" star-pair-ID technique

Let us plot the ***S***-vector. Figure 2 shows ***S*** as a function of its indices, for the referenced star catalog and startracker. At a first glance the ***S***-vector appears to increase with a linear slope. Therefore the idea to represent the m points [i,***S***(i)] by the best fitting linear function _=α_+β, arises. Performing the linear best fitting means to solve

$$\sigma^2 = \sum_{i=1}^{m} [\bar{I}(i) - i]^2 = \sum_{i=1}^{m} [\alpha S(i) + \beta - i]^2 = \min \quad (7)$$

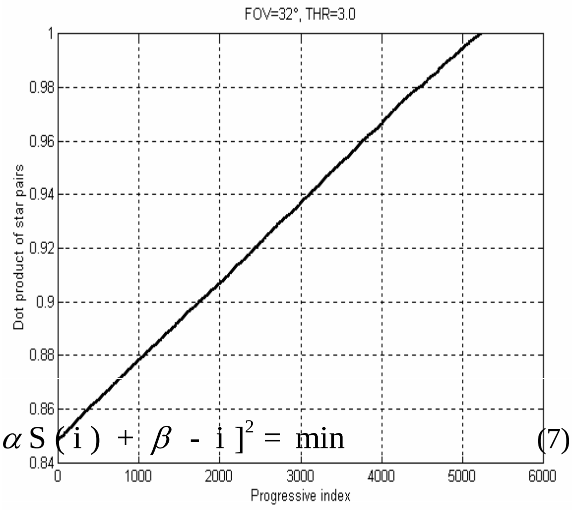

Figure 2

the solution of which is

$$\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} = \begin{bmatrix} \Sigma_i [S(i)]^2 & \Sigma_i S(i) \\ \Sigma_i S(i) & m \end{bmatrix}^{-1} \begin{Bmatrix} \Sigma_i \, i \, S(i) \\ m(m+1)/2 \end{Bmatrix} \quad (8)$$

The best fitting straight line _=α_+β can be considered a good tool to estimate the indices of the two observed stars spatially separated by the angle ′. In fact, k=int[αcos′+β], where int[z] is the function providing the integer number closest to z, represents a good guess at the right element-index of the ***S*** vector which gives the dot product cos′. Therefore, a likely star-pair is identified, in the star catalog ***V***, by the indices i=***I***(k) and j=***J***(k), where

$$k = int[\alpha \cos\vartheta + \beta] \quad (9)$$

Since the indices (i,j) represent a good guess at the right ones, the latter are therefore located in the ***S*** vector or close to the k^{th} index. A local search about the computed index k means to search about the star-pair [***V***(***I***(k)),***V***(***J***(k))] and this can be accomplished by varying k about the value provided by equation (9).

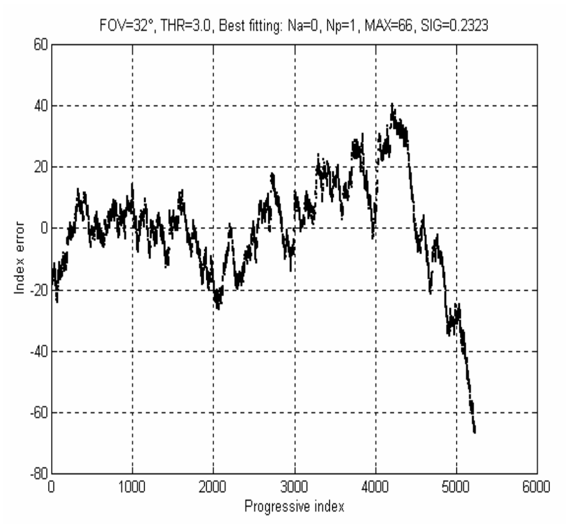

Figure 3

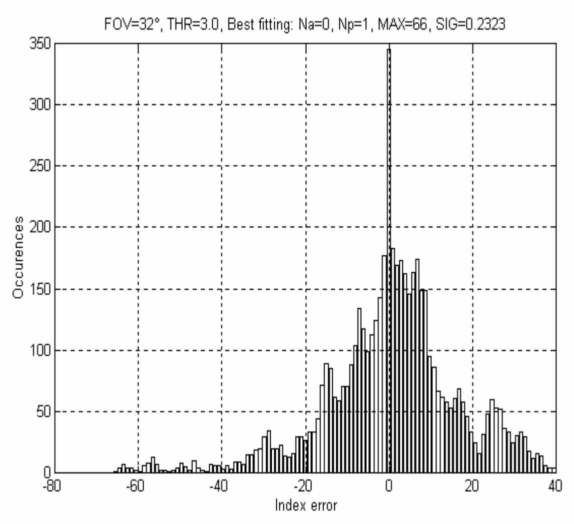

Figure 4

Figure 3 plots the index error (i-k), that is the difference between the true index i and its approximation evaluated by using the linear best fitting function k=$int[\alpha\mathbf{S}(i)+\beta]$, as a function of the index i. Figure 4 shows the associated histogram of the index error (i-k).

The more the best fitting function describes data the more k approximates the true index i. It is possible to reduce $|i-k|$ by substituting the linear best fitting function with a more suitable one, which can be, for instance, the polyno-harmonic function

$$\bar{I} = \sum_{j=0}^{n_p} a_j \bar{S}^{j} + \sum_{j=1}^{n_a} A_j \sin[\omega_j \bar{S} + \varphi_j] \qquad (10)$$

The n_p+1+3n_a unknown coefficients of this function (n_p+1 coefficients a_j and the n_a coefficients A_j, ω_j and _$_j$) are determined in such a way that $\Sigma\,|\mathrm{int}[\_]-i|$ is at a minimum. This best fitting has been performed by using the CAM-best fitting technique (see the annex of [2]). Numerical tests show that

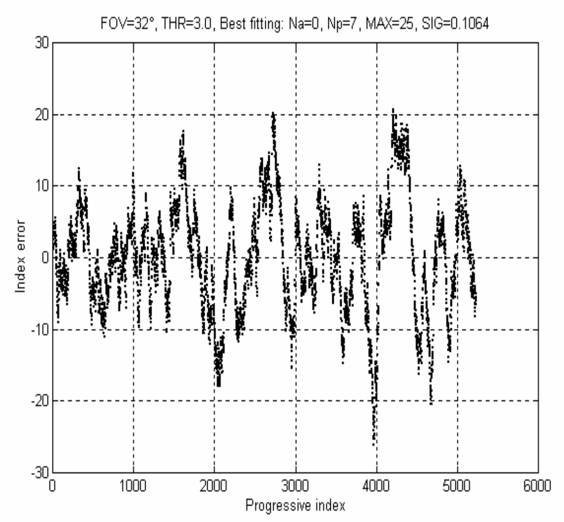

Figure 5

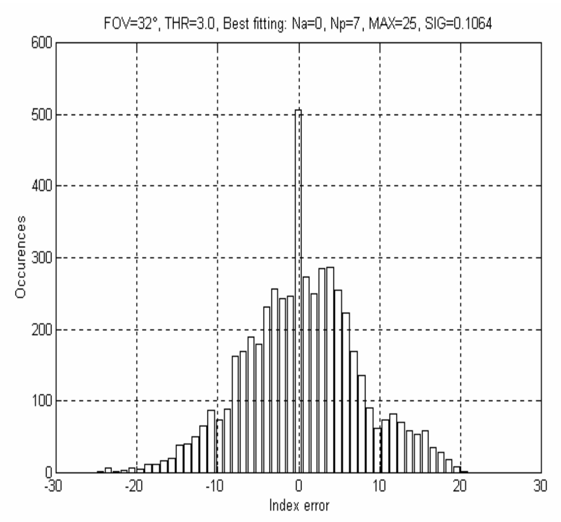

Figure 6

the harmonical term in equation (10) does not improve the fitting while the polynomial term describes data properly up to the seventh degree. Polynomials of higher degree imply, in the best fitting algorithm, an inversion of a quasi-singular matrix. Instead of the exponential polynomials it is possible, for instance, to use the Legendre orthogonal polynomials. This has been done too but no advantages have been found. As a further thorough study a FFT analisys of Figures 3 and 5 data must be done. Figures 5 and 6 show the error index and its histogram for a seven degree polynomial best fitting, respectively. The improvement, with respect to the linear best fitting, is rather clear.

"*K*-vector" star-pair-ID technique

As previously said, a great advantage can be obtained by the hereinafter following technique, which uses the *m*-long integer vector ***K***. This vector, which has been devised in order to skip the searching phase of the best fitting techniques previously described, is able to provide directly the extreme indices of the searching range.

Let us consider the straight line connecting the first and last ***S***-vector elements

$$\cos\vartheta = a_1 k + a_0 \quad \text{where:} \begin{cases} a_1 = \dfrac{S(m) - S(1)}{m - 1} \\[2ex] a_0 = \dfrac{m\,S(1) - S(m)}{m - 1} \end{cases} \tag{11}$$

Starting with ***K***(1)=1, the integer vector ***K*** is then built as follows

$$K(k) = l \quad \text{where: } S(l) \le a_1 k + a_0 < S(l+1) \tag{12}$$

where $k=2,\dots,m$. The k^{th} element of this vector represents the number of elements ***S***(l) below the value $\cos' = a_1 k + a_0$. Once this vector has been built, it is easy to find, in the star catalog, a very small range of star-pairs within which to find the true star-pair correspondent to the observed one.

Let us consider, for instance, the two observed stars $\mathbf{s}_i$ and $\mathbf{s}_j$, separated by the angle ′, and whose precision is ε. The problem is to find the lower and upper indices of the range of ***S***-vector elements so that their values fall into the interval [cos(′+2ε), cos(′-2ε)]. This problem can easily be solved thanks to the ***K***-vector structure.

These two indices are given by

$$\begin{cases} l_{bot} = bot\{\ [\ \cos(\ \vartheta + 2\,\varepsilon\ )\ -\ a_0\ ]\ /\ a_1\ \} \\ l_{top} = top\{\ [\ \cos(\ \vartheta - 2\,\varepsilon\ )\ -\ a_0\ ]\ /\ a_1\ \} \end{cases} \quad where: \cos\vartheta = \mathrm{s}_i^{\mathrm{T}}\ \mathrm{s}_j \tag{13}$$

where the function $top(x)$ is defined as the larger integer number next to x, and $bot(x)$ is the integer number immediately below x. When l_{bot} and l_{top} are evaluated the star-pairs [$\mathbf{v}_i$,$\mathbf{v}_j$] to be considered are those included in the range $k_{start} \leq k \leq k_{end}$, where it results that

$$\begin{cases} i = \mathrm{I}\,(\,\mathrm{k}\,) \\ \mathrm{j} = \mathrm{J}\,(\,\mathrm{k}\,) \end{cases} \text{and}\ \mathrm{k}_{\mathrm{start}} = \mathrm{K}\,(\,\mathrm{l}_{\mathrm{bot}}\,)\ +\ 1\ \leq\ \mathrm{k}\ \leq\ \mathrm{K}\,(\,\mathrm{l}_{\mathrm{top}}\,) = \mathrm{k}_{\mathrm{end}} \tag{14}$$

Equations (11) and (12) are the solving equations of the identification technique based on the ***K***-vector, which is built as explained in equations (9) and (10).

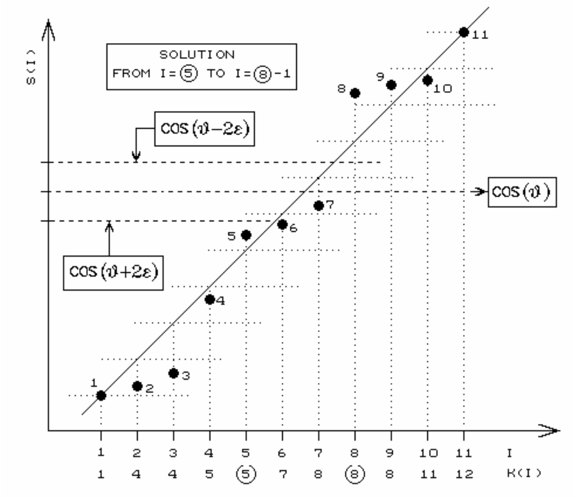

Figure 7

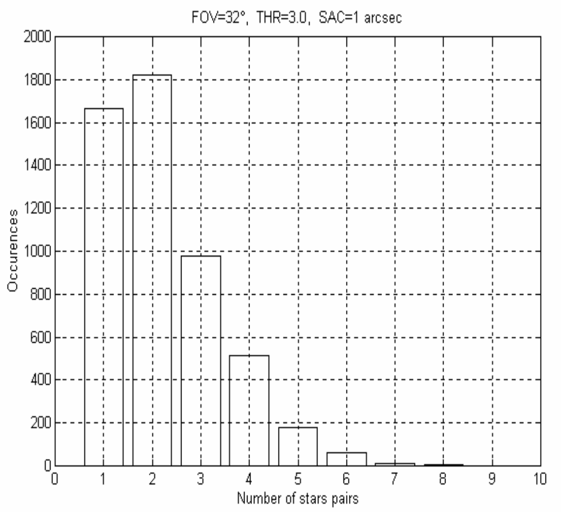

Figure 8

In the sake of clarity Figure 7 shows the construction of the ***K***-vector for m=11 dot products only. The ***K***-vector i^{th} element represents the number of data equal to and less than the value $a_1 i + a_0$, plus one. With these data the three vectors of integers have 5233 elements. Figure 8 shows the histogram of the number of likely star-pairs associated to two observed ones with a dot product range from cos$'_{FOV}$ and 1. This figure shows, compared to figures 4 and 6, the improvement of the ***K***-vector technique with respect to those based on the best-fitting. Both the best fitting and the ***K***-vector star-pair-ID techniques can be implemented in almost all star-ID matching algorithms. In the next paragraph a new star-matching technique, based on a privileged "reference-star", is explained.

"Reference-star" star-matching-ID technique

The next identification problem is to find, from a set of possible star-pairs, the correspondence with the observed ones. This is here accomplished with a method, called "reference-star", which is able to identify and discard possible spurious data (spikes).

Let us indicate with n the sum of the n_s spikes and the n_t true observed stars $\boldsymbol{s}_i$, provided by the sensor. Let us also consider the generic r^{th} observed star $\boldsymbol{s}_r$ as the reference one. Starting from this star, which may be any (even a spike), the $\boldsymbol{K}$-vector technique is applied to all the star-pairs $[\boldsymbol{s}_r,\boldsymbol{s}_k]$ (with $k\neq r$), spatially separated by the angles $'_{r,k}$. Let us now start by setting r=1.

If ε is the observed star vector accuracy (this means that the true k^{th} star direction falls inside the cone of $\boldsymbol{s}_k$ axis with angle ε) the range defined by the angular separation is $[{'}_{r,k}-2\varepsilon,\ {'}_{r,k}+2\varepsilon]$. Assuming that the star-pair-ID technique finds $h(r,k)\geq 0$ of likely star-pairs falling in this range, any observed "r-k" star-pair (with $1\leq k\leq n$ and $k\neq r$) will provide the two indices vectors $\boldsymbol{I}_{r,k}$ and $\boldsymbol{J}_{r,k}$

Star	k	k	...	k	k
$\boldsymbol{I}_{r,k}$ (ID indices) $\boldsymbol{J}_{r,k}$	$i_{r,k,1}$	$i_{r,k,2}$	...	$i_{r,k,h-1}$	$i_{r,k,h}$
	$j_{r,k,1}$	$j_{r,k,2}$	...	$j_{r,k,h-1}$	$j_{r,k,h}$

The (n-1) integers vectors $\boldsymbol{I}_{r,k}$ and $\boldsymbol{J}_{r,k}$ can be arranged together to form the indices vectors $\boldsymbol{I}_r$ and $\boldsymbol{J}_r$

k^{th}-star ($k\neq r$)	1	2	...	n-1	n
$\boldsymbol{I}_r$ (ID indices) $\boldsymbol{J}_r$	$\boldsymbol{I}_{r,1}$	$\boldsymbol{I}_{r,2}$	...	$\boldsymbol{I}_{r,n-1}$	$\boldsymbol{I}_{r,n}$
	$\boldsymbol{J}_{r,1}$	$\boldsymbol{J}_{r,2}$	...	$\boldsymbol{J}_{r,n-1}$	$\boldsymbol{J}_{r,n}$

Therefore, the $\boldsymbol{I}_r$ and $\boldsymbol{J}_r$ vectors contain all the star-pairs indices involving the r^{th} observed star with all the others. If $\boldsymbol{s}_r$ is not a spike, then in the index vector $\boldsymbol{M}_r=[\boldsymbol{I}_r,\ \boldsymbol{J}_r]$, obtained by linking $\boldsymbol{I}_r$ with $\boldsymbol{J}_r$, the true index related to the r^{th} observed star appears (n_t-1) times, at least. Let us accept a spike presence of up to 25% of n, that is up to $n_{smax}\leq \text{bot}(n/4)$. This means, for example, that only the presence of one spike is accepted if the observed stars are in the range from 4 to 7, two spikes in the range from 8 to 11, and so on. Obviously if n=3, no spikes are accepted.

Based on the following steps/rules, the star-matching-ID is derived:

If the indices vector $\boldsymbol{M}_{r,k}=[\boldsymbol{I}_{r,k},\ \boldsymbol{J}_{r,k}]$ has no elements, this could means that a) the k^{th} star is a spike b) the r^{th} reference-star star is a spike or, c) both stars are spikes. Let us define with n_x the number of $\boldsymbol{M}_{r,k}$-vectors having no elements.

If $n_x > n_{smax}$, it means that data are too noisy or the selected reference-star is a spike. In this case the index r is increased by $r=r+1$, and the corresponding vectors of indices $\boldsymbol{I}_{r,k}$ and $\boldsymbol{J}_{r,k}$ are evaluated. If r becomes greater than n-3 then data are declared too noisy and the star-ID is aborted.

If $n_x \le n_{smax}$, then a histogram of the associated $\boldsymbol{M}_r$-vector is performed. Let us call with f_1 and f_2 (where $f_1 \ge f_2$) the two highest values of this histogram, which are associated to the indices l_1 and l_2, respectively.

If $f_1 > 3n/4-1$ and $f_2 < 1+int(n/5)$, then the index of the r^{th} star is defined to be l_1; otherwise another reference star is chosed by increasing the index $r=r+1$.

Once the reference star index has been identified, the remaining stars are easily identified by the analysis of the smaller indices subvectors $\boldsymbol{I}_{r,k}$ and $\boldsymbol{J}_{r,k}$. The k^{th} star ($1 \le k \le n$ and $k \ne r$) is declared to be the $l_k^{\ th}$ of the catalog if l_1 appears <u>only one time</u> in the $\boldsymbol{M}_{r,k}$-vector.

When this happens, we have

$$\begin{cases} if \quad \mathrm{I}_{r,k,h} = l_1 \quad \text{then} \quad \mathrm{J}_{r,k,h} = l_k \\ \text{if} \quad \mathrm{J}_{r,k,h} = l_1 \quad \text{then} \quad \mathrm{I}_{r,k,h} = l_k \end{cases} \text{with}: \; 1 \le h \le rk \qquad (15)$$

When using a startracker with a FOV smaller than our reference one, this star-matching technique may result too restrictive because of the small number of observed stars. In this case a triangle star-matching technique, which is more reliable but slower than the proposed one, may be used and/or the magnitude information should be included in the identification process. Due to lack of time the study on the effects produced on the proposed star-ID algorithms of the set magnitude threshold and FOV width variations, is not included in this work. These effects will be the subject of another paper.

Software structure description

The proposed overall software structure is shown in the flowchart of Figure 9. Software programs are currently written in *MATLAB*-language [5] and, therefore, can easily be translated into the compiled *C*-language. They consist of two main programs: a Ground-run Program (*GP*) and an On-Board-running Program (*OBP*).

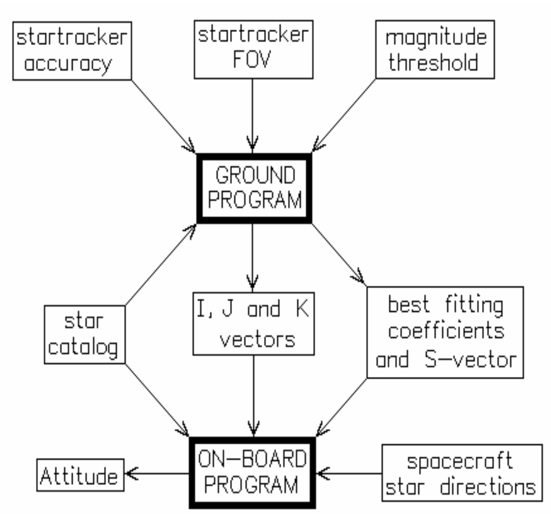

Figure 9

The *GP* is carried out only once prior to the spacecraft launching. It is fed by a) the star catalog data, b) the startracker characteristics (the direction of its boresight axis, the maximum lens aperture $'_{\text{FOV}}$ and the stars unit-vectors accuracy) and, c) the magnitude thresholds. The *GP* provides the *OBP*, for some nominal magnitude thresholds, with either the three $\boldsymbol{I}$, $\boldsymbol{J}$ and $\boldsymbol{K}$ integer vectors or the best fitting coefficients together with the $\boldsymbol{S}$-vector, depending on which star-pair-ID technique is adopted. Since the $\boldsymbol{K}$-vector method requires, with respect to the best-fitting one, less extra storage memory and is also less time consuming, i t is highly recommended.

The *OBP* permanently accomplishes star-ID and attitude estimation during flight. It is fed by a) the star c atalog data, b) the observed stars unit-vectors from the CCD camera and, c) the outputs from *GP*. In orde r to attain the maximum computational speed, the attitude estimation is evaluated by using either the *EU LER-q* or *QUEST*-2 algorithms [4], depending upon the number of the observed stars. Specifically *EULE R-q* is used if n<5 and *QUEST*-2 otherwise.

Numerical Tests

In order to validate the proposed star identification t echnique, proper tests, described below, have been c arried out. Simulation tests (Figures 10, 11 and 12) a re performed on a 33Mhz-DX2-486PC, on a basis of *NT*=1000 random spacecraft attitudes. The chosen s tar-pair-ID technique is that based on the ***K***-vector. There have been added to the spacecraft stars unit-ve ctors both noise and an amount of spikes, up to 5% o f the observed true stars. The noise in the stars direct ions is applied by a rigid rotation about a random axi s perpendicular to the star direction by a random ang le not greater than the instrument accuracy. Tests are related to the reference startracker and to the *MSX_ SIM_cat.dat* catalog.

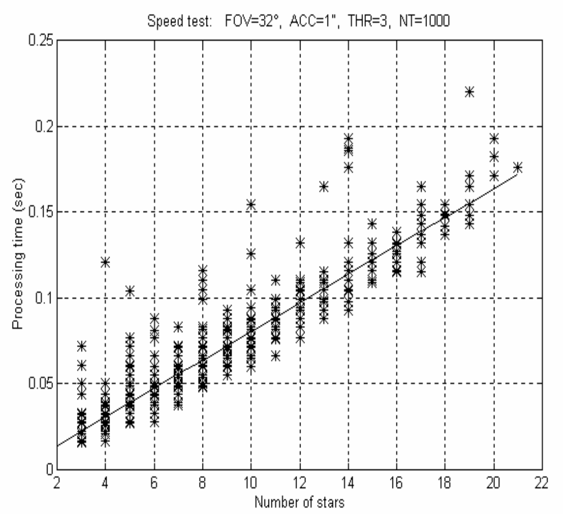

Figure 10

Figure 10 shows the consumed time (in seconds) as a function of the observed stars number n, obtained by using the *MATLAB* function "*cputime*" [5].

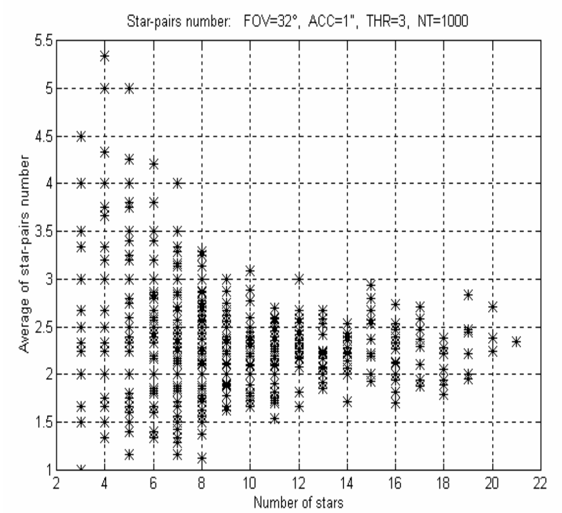

Figure 11

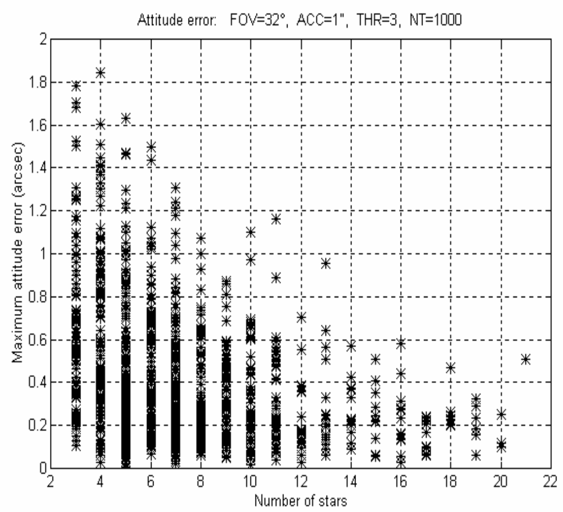

Figure 12

Figure 11 plots the average number of admissible star-pairs, which are those falling in the interval [k_{start}, k_{end}] defined in (14), for each performed test as a function of the number of the observed stars.

Finally, Figure 12 displays the maximum attitude error δ, defined in [4] as the rotational error, between the true attitude matrix $\boldsymbol{T}$ and the estimated one $\boldsymbol{A}$, always as a function of the number of the observed stars. This error is the Euler angle associated with the corrective attitude matrix $\boldsymbol{A}\boldsymbol{T}^T$, that is the angle $\delta=\cos^{-1}\{(trace[\boldsymbol{A}\boldsymbol{T}^T]-1)/2\}$.

Conclusion

In this paper a new attitude determination system based on a new star identification technique, has been presented. This star-ID method, which does not use the magnitude information, is obtained by marrying star-pairs and star-matching identification techniques. Two star-pair-ID techniques are proposed: the first is based on a best-fitting criterion and the second on a suitably devised ***K***-vector. The proposed two star-pair-ID techniques can be regarded as general procedures which can be included in almost all existing star-matching algorithms. The herein proposed star-matching algorithm is based on a reference central star. Its capability to identify and discard spikes (due to electronic noise, planets, light reflections, etc.) demonstrates the algorithm robustness. In order to rapidly evaluate the optimal attitude a mixed *EULER-q*/*QUEST*-2 algorithm is used. The resulting overall software structure has been presented. Numerical tests demonstrate that the proposed attitude determination system is fast, reliable and autonomous. This system is specially suitable if many observed vectors are available, as for spacecraft equipped with a wide FOV star tracker.

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