Pattern Recognition of Star Constellations for Spacecraft Applications

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ABSTRACT

A software system for a star imager for "on-line" satellite attitude determination is described. The system works with a single standard commercial CCD-camera with a high aperture lens and an on-board star catalogue. It is capable of both an initial coarse attitude determination without any a priori knowledge of the satellite, orientation and a high accuracy attitude determination based on prediction and averaging of several identified star constellations. In the high accuracy mode the star image aims at an accuracy better than 2 arc sec. with a processing time of less than a few seconds.

The star imager is developed for the Danish "micro satellite" Oersted.

INTRODUCTION

Almost all spacecrafts need to know their attitude. Several ways to determine the attitude relative to a reference object exist. Table 1 shows reference sources suited for determining the attitude and their corresponding theoretical accuracies [1].

Table 1.

Reference Object	Potential Accuracy
Stars	1 arcsecond
Sun	1 arcminute
Earth (Horizon)	6 arcminute
RF beacon	1 arcminute
Magnetometer	30 arcminute

High precision equipment for satellites has stressed the demand for extremely accurate determination of the attitude. Therefore the latest attitude determination systems have relied on the most accurate reference, i.e., the stars. The principle in attitude determination by the stars is as follows: some image forming device (e.g., a CCD-camera) is directed towards the stars. If the image can be matched to a reference, the direction of the imaging device is known, and thus the attitude of the spacecraft. One approach is to sweep the sky with a spectral sensitive device in order to recognize a known spectral distribution from a specific star. When the star is recognized the attitude control system locks on the specific star. Another approach has been a coarse determination of the attitude by others means (e.g., gyros), and then to fine tune the attitude by utilizing a CCD-camera image including a priori known constellation. Others have simply recorded the image from a CCD-camera together with the measured payload data, and then transmitted the lot to the Earth for further automatic or manual processing. The disadvantages of these systems are high weight (10-50 kg) large power consumption and no possibility to determine the attitude without a coarse estimate of the attitude beforehand. These constraints are however incompatible with the future micro satellites, and therefore new methods of attitude determination must be developed.

The proposed Danish micro satellite "Oersted" is a micro satellite, whose purpose is to map the magnetic field of the Earth. The main instrument is a vector magnetometer with an accuracy better than 2 nT. In order to utilize the extreme precision of the vector magnetometer the orientation must be determined with an accuracy better than 20 arc sec. This implies that the attitude instrument (the star imager) must be placed very close to the magnetometer.

The star imager must meet the following demands:

- weight of the attitude instrument less than 3 kg;
- the power consumption below 8 Watts;
- ability to perform attitude determination without a priori knowledge of the attitude;
- accuracy better than 20 arc sec.; and
- a magnetic "clean" sensor.

Based on a presentation at PLANS 1992.
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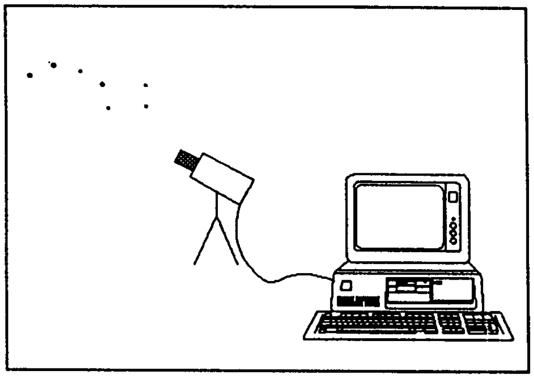


Fig. 1. The Star Imager, Principle of the System

A market survey showed that no available system met these specifications. Therefore a feasibility study was initiated to determine whether it is possible to construct a star imager within these limits. The study revealed the remarkable result that it is indeed possible to construct the star imager with an accuracy better than 2 arc sec! This is even achieved by utilizing commercial available technology. The principle is as follows (Fig. 1). A CCD-camera is pointed toward the stars. The CCD-image is subjected to a number of corrections and compared to an internal star catalogue and thus identified. Based on the known star positions in the sky the attitude of the satellite can be determined. The system is based on state of the art available consumer components and thus has the potential of being a true low cost system.

STAR CATALOGUE AND DATABASE

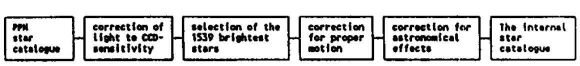
The high precession of the star imager stems from the very accurate knowledge of all the visible stars in the sky and the high reliability of CCD-cameras. In order to differentiate between the single stars some characteristics to identify the stars in the sky are needed. To derive that the following two collections of star data are required:

- A star catalogue (SC); and
- A star database (SDB).

The *star catalogue* is a collection of data including the position of the stars. The *star database* is a collection of data containing position invariant characteristics of the stars. Problems related to the construction of the star database are: how to find well suited features to characterize a star; and how to include the uncertainty on the measured data in the search algorithms.

Construction of the Star Catalogue

The star catalogue includes the declination, right ascension, and magnitude of the stars as detected by the CCD-camera. It includes the 1539 brightest stars, and it is based on the PPM catalogue [4]. It is compiled with the following corrections of the raw star data:



PPM Star Catalogue

The PPM catalogue [4] was selected for the construction of the star catalogue. It is one of the latest and most accurate star catalogues available. The PPM catalogue includes information about the position of the stars, proper motion, magnitude, spectral class, uncertainty, etc.

Correction to CCD-Sensitivity

The light intensities of the PPM catalogue are in the "V" magnitude system (or can easily be converted to that system). The CCD-chip has a spectral sensitivity different from the "V" system, and corrections must be made accordingly.

The "V" magnitude is based on the wavelengths in the interval 480 nm to 650 nm, which almost corresponds to the sensitivity of the human eye. If a star is considered a "blackbody-radiator" and furthermore neglecting that some wavelengths are absorbed in the chromosphere of the stars, the CCD-brightness can be calculated:

$$\langle \textit{CCD brigthness} \rangle = \langle \textit{Visual brigthness} \rangle \cdot C \cdot \frac{\sum_{\lambda=0}^{\infty} M_{e\lambda} \cdot S_{\lambda} \cdot T_{\lambda}}{\sum_{\lambda=0}^{\infty} M_{e\lambda} \cdot V_{\lambda}} .$$

where $M_e\lambda$ = spectral radiation, $V\lambda$ = eye spectral sensitivity, $S\lambda$ = CCD spectral sensitivity, $T\lambda$ = transmission coefficient of the CCD-lens and C is a camera amplifier constant.

Additionally the reflection in the lens depends on the angle of incidence. The stars closest to the rim of the picture reflected the most (i.e., transmitted less). Therefore they will appear weaker than stars in the center of the picture. This phenomenon must be corrected.

Correction for Proper Motion

In the PPM catalogue proper motion and position of the stars are given to epoch 2000. Consequently it is straight forward to calculate the position to a certain time. The star catalogue is constructed to the end of year 1994 (based on the launch).

Precession

The contribution from the precession is irrelevant due to the fact that the satellite is not making Earth observations.

Nutation

As in the case with precession correction is irrelevant due to space operation.

Aberration

Aberration can be divided into contributions from 3 velocities: 1) the solar system velocity; 2) the Earth velocity; and, 3) the satellites own velocity.

1. The star catalogue is already in heliocentric coordinates.
2. The average velocity of the Earth is 29.79 km/sec with a maximum correction on 20.48 arc sec.
3. The "Oersted" orbit is a circular polar orbit at 600 km height, which implies a tangential velocity of 8,3 km/sec. This gives a correction up to 5.7 arc sec.

Parallax

There has not been any corrections for parallax due to the following: 1) the effect only appears on the very few closest stars and with maximum on 0. 85 arc sec, and 2) the determination of the attitude is based on all the stars

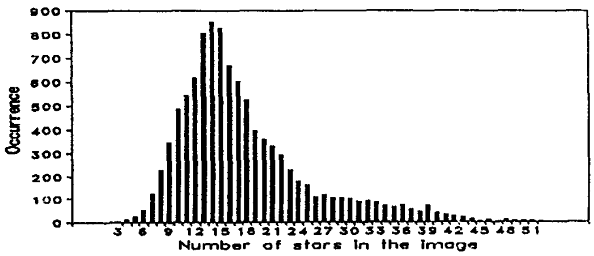


Fig. 2. Number of Stars in the Image. Opening Angle 30°. The CCD-Camera is Registering Stars Brighter than Optical Class 4½. The Average Number of Stars is 18.9 (10,000 Simulations)

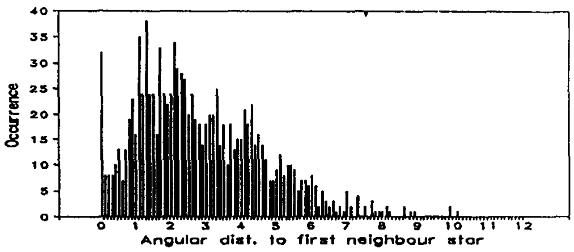


Fig. 3. Distribution of Distances (in Degrees) to First Neighboring Star Based on the 1107 Brightest Stars, the Peak at 0.0-0.1 is Due to Double Star Systems

in the picture. Accordingly parallax error on a single or two stars will not defect the result significant.

Relativistic Light Bending

The CCD-chip is not constructed to point near the sun. Hence stars close to the sun are not registered. Also the maximum deviation of a star position is 0.1 arc sec. due to the relativistic light bending. Therefore the effect is not included.

Star Characteristics

In order to recognize stars in a CCD-image, some characteristics to distinguish between stars must be determined. Since the CCD-image only covers a small part of the firmament (in the present case 30°), it is impossible to search for well-known star constellations like Orion, Big Dipper, etc. Hence more local characteristics of each star must be utilized. Among these are:

- angular distances to the closest neighboring stars;
- spherical angles between the closest stars; and
- the magnitude.

Fig. 2 shows the distribution of the number of stars in the camera field of view, when the orientation of the optical axis is selected at random. An opening angle on 30° was selected, as a trade off between the database size and the quality of the lens.

One obvious feature by which to characterize a star and its nearest surroundings is by the angular distances to the closest neighbors. Fig. 3 and 4 show the distribution of angular distance for the first and second neighboring star (all brighter than optical class 4½ ≈ 1107 stars).

Another major characteristic is the angle between the closest neighboring stars (angle in the spherical triangle: first neighboring star – star – second neighboring star). As presumed the dispersion of angles between two neighboring stars is nearly uncorrelated as Fig. 5 shows. A flat distribution would be expected for homogeneous distributed stars.

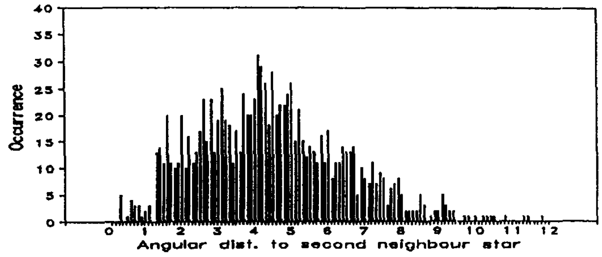


Fig. 4. Distribution of Distance (in Degrees) to Second Neighboring Star for the 1107 Brightest Stars

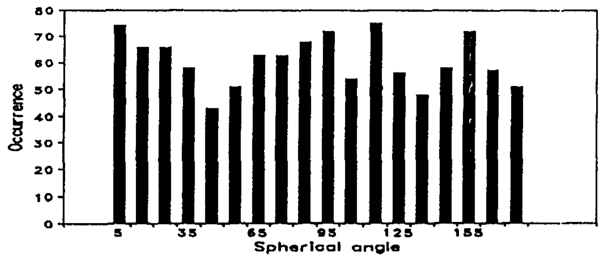


Fig. 5. Angle Between First and Second Neighboring Star

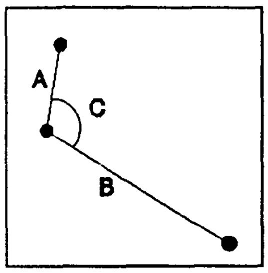


Fig. 6. The Triangular Feature.
A: The Angular Distance to First Neighboring Star;
B: The Angular Distance to Second Neighboring Star;
C: The Angle between the 1. and 2. Neighboring Stars

Another obvious feature by which to characterize a star is its magnitude. However, brightness as such is not applicable in the present case as noise limits the precision with increasing uncertainty for fainter stars. *This implies that the distance to the first and second neighbor and the angle between them* have been chosen as the characterizing parameters for the database (Fig. 6). A subconstellation with these features is named a star triplet and its parameter values the Triangular Feature (TF).

Including Uncertainty in the Database

In the CCD-image the positions and the magnitudes of the stars have an associated uncertainty. Therefore the characteristics of a measured CCD-star are not identical to the original star in the database (Fig. 7 and 8). It is important to develop a search routine that will operate in spite of these uncertainties. This is referred to as an "open-end" structure of

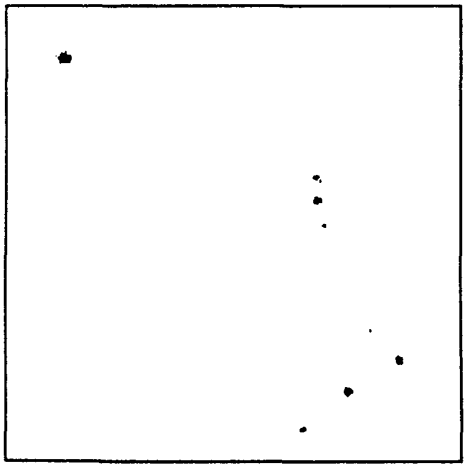


Fig. 7. A Primarily CCD-Image Containing a Part of Orion and Rigel. The Star Not Included in the Star Catalogue is the Orion Nebula (M42).

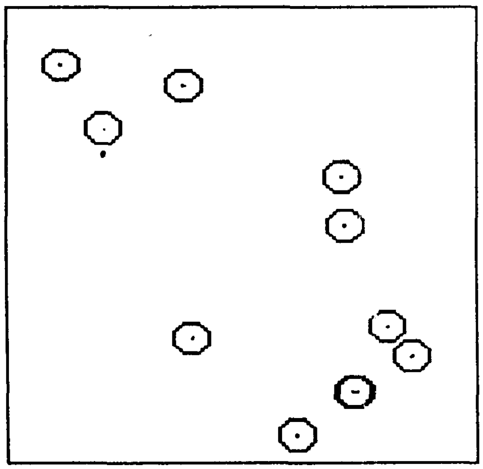


Fig. 8. The Contents of the Star Catalogue. The Stars Not Present in the CCD-Picture are Due to the Uncertainty of the Magnitude. The M42 is the Opposite Picture is not Included in the Database and is Dealt with as a "False" Star (Described Later)

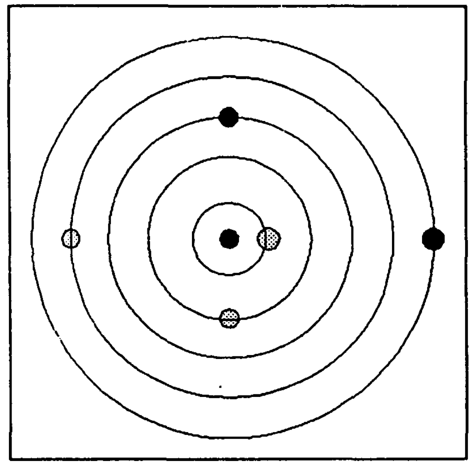


Fig. 9. The Star Which is to be Registered (in the center). A Neighboring Star of the Category "Maybe" is symbolized as ○. A Neighboring Star of the Category "Certain" is Symbolized as ●.

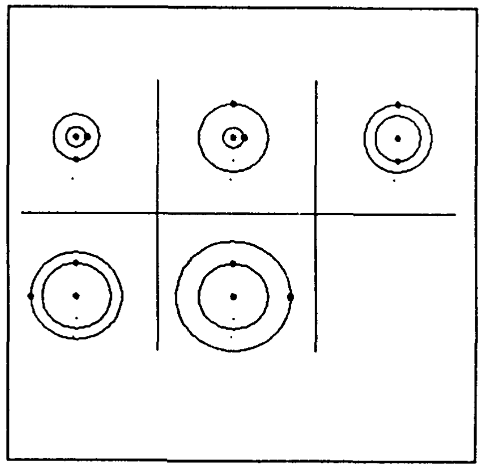


Fig. 10. The Star has to be Registered in the Depicted Constellations

a database, which implies that the search algorithms will operate even when some of the stars occasionally fall below the detection limit.

Inclusion of Position-Uncertainty in the Database

The CCD-star images delivers (by utilizing the hyperaccuracy technique) a star position with a maximum deviation of 3 arc min. (0.05°) from its true position. To identify a specific star the TF is utilized (as described above). When a single star has a maximum absolute deviation on 3 arc min. the maximum deviation of the distance between two stars (relative) is 6 arc min (0.1°). Furthermore data must be quanticed to minimize the memory requirement and processor loads. A reasonable choice is to quantice the distance in multiple of 6 arc min (0.1°) which corresponds to the relative uncertainty. As an example the angular distance 7.65° will be transformed into class number 75, 76 and 77. The uncertainty on the angle between the first and second neighboring star depends on the angular distances. It was decided to quantice the intervals of the angles to 5°. Consequently this will be registered in the same way as the distance.

As an example the TF identifier for a star could be the following:

distance to first neighbor:	5.596°
distance to second neighbor:	8.191°
angle between 1. and 2. neighboring star:	164.204°

This is quanticed into:

distance to first neighbor:	55 (5.596 div 0.1)
distance to second neighbor:	81 (8.191 div 0.1)
angle between 1. and 2. neighboring star:	32 (164.204 div 5)

This is easier written as [55,81,32].

As explained earlier the uncertainty must be included in the database. The uncertainty of the angle is calculated to ± 1.724°. The angle is therefore in the interval [164.204 − 1.724;

164.204 + 1.724] which is transformed into class 32 and 33.

Just to cope with the uncertainty, this specific star must have the following entries in the database.

54	80	32
54	80	33
54	81	32
54	81	33
54	82	32
54	82	33
55	80	32
55	80	33
55	81	32
55	81	33
55	82	32
55	82	33
56	80	32
56	80	33
56	81	32
56	81	33
56	82	32
56	82	33

Inclusion of Magnitude-Uncertainty in the Database

A star is only detected if the magnitude is above a given threshold level compared to the noise. Due to the uncertainty of the magnitude one cannot determine whether a star is above or below the threshold and hence if it will be registered. The uncertainty of the stellar magnitude is being included in the following way: Among the 1100 brightest stars there is an empirical determined uncertainty of 25%. The 1100 brightest stars correspond to a specific brightness threshold value. If a star is below 75% of this limit, one can be sure that the star will not be detected. If the star is between 75% and 125% of the detection limit it might be detected (in this category double stars are included). If a star is above the 125% limit it will positively be detected. Hence there are two categories of stars which have to be included in the SDB namely the "certain" and the "maybe" stars. Registration of the nearest stars requires that all combinations are included.

This is illustrated in the following example.

The following shows a typical star from the implemented database at all its neighboring constellations (NBC).

Distance to first neighboring star °	Distance to second neighboring star °	Angle between 1. & 2. neighboring star °
5,596,	8,191,	164.204
5.596,	8.329,	30.680
5.596,	10.102,	7.542
5.596,	12.306,	58.521
5.596,	12.754,	13.597
8.191,	8.329,	165.117
8.191,	10.102,	156.662
8.191,	12.306,	137.275
8.191,	12.754,	150.607
8.329,	10.102,	38.222
8.329,	12.306,	27.841
8.329,	12.754,	44.276

Each of these NBC's is affected by the uncertainty of the position (described in previous section). Hence entries in the SDB have to be made accordingly. Figure 11 shows all the entries in the database needed to register this specific star.

It may seem odd to include this amount of entries, but attention is called to the fact that the alternative is to operate with the raw SC. This would place a heavy burden on the on-board CPU.

54,80,32	55,100,0	56,123,12	81,122,26	82,126,30
54,80,33	55,100,1	56,124,11	81,122,27	82,127,8
54,81,32	55,100,2	56,124,12	81,123,26	82,127,9
54,81,33	55,101,0	56,126,2	81,123,27	82,127,29
54,82,5	55,101,1	56,126,3	81,124,26	82,127,30
54,82,6	55,101,2	56,127,2	81,124,27	82,128,8
54,82,32	55,102,0	56,127,3	81,126,29	82,128,9
54,82,33	55,102,1	56,128,2	81,126,30	82,128,29
54,83,5	55,102,2	56,128,3	81,127,29	82,128,30
54,83,6	55,122,11	80,82,32	81,127,30	83,100,7
54,84,5	55,122,12	80,82,33	81,128,29	83,100,8
54,84,6	55,123,11	80,83,32	81,128,30	83,101,7
54,100,0	55,123,12	80,83,33	82,82,32	83,101,8
54,100,1	55,124,11	80,84,32	82,82,33	83,102,7
54,100,2	55,124,12	80,84,33	82,83,32	83,102,8
54,101,0	55,126,2	80,100,30	82,83,33	83,122,5
54,101,1	55,126,3	80,100,31	82,84,32	83,122,6
54,101,2	55,127,2	80,101,30	82,84,33	83,123,5
54,102,0	55,127,3	80,101,31	82,100,7	83,123,6
54,102,1	55,128,2	80,102,30	82,100,8	83,124,5
54,102,2	55,128,3	80,102,31	82,100,30	83,124,6
54,122,11	56,80,32	80,122,26	82,100,31	83,126,8
54,122,12	56,80,33	80,122,27	82,101,7	83,126,9
54,123,11	56,81,32	80,123,26	82,101,8	83,127,8
54,123,12	56,81,33	80,123,27	82,101,30	83,127,9
54,124,11	56,82,5	80,124,26	82,101,31	83,128,8
54,124,12	56,82,6	80,124,27	82,102,7	83,128,9
54,126,2	56,82,32	80,126,29	82,102,8	84,100,7
54,126,3	56,82,33	80,126,30	82,102,30	84,100,8
54,127,2	56,83,5	80,127,29	82,102,31	84,101,7
54,127,3	56,83,6	80,127,30	82,122,5	84,101,8
54,128,2	56,84,5	80,128,29	82,122,6	84,102,7
54,128,3	56,84,6	80,128,30	82,122,26	84,102,8
55,80,32	56,100,0	81,82,32	82,122,27	84,122,5
55,80,33	56,100,1	81,82,33	82,123,5	84,122,6
55,81,32	56,100,2	81,83,32	82,123,6	84,123,5
55,81,33	56,101,0	81,83,33	82,123,26	84,123,6
55,82,5	56,101,1	81,84,32	82,123,27	84,124,5
55,82,6	56,101,2	81,84,33	82,124,5	84,124,6
55,82,32	56,102,0	81,100,30	82,124,6	84,126,8
55,82,33	56,102,1	81,100,31	82,124,26	84,126,9
55,83,5	56,102,2	81,101,30	82,124,27	84,127,8
55,83,6	56,122,11	81,101,31	82,126,8	84,127,9
55,84,5	56,122,12	81,102,30	82,126,9	84,128,8
55,84,6	56,123,11	81,102,31	82,126,29	84,128,9

Fig. 11. References in Data Base for a Typical Star. Average in the Data Base is 180 References.

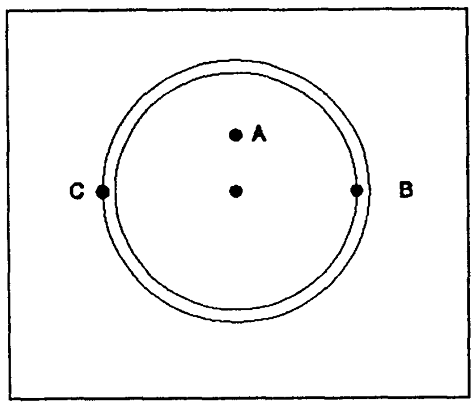


Fig. 12. Star with its 3 Neighboring Stars

Star Exchange Due to Uncertainly on the Position

Due to the uncertainty a possible star exchange has to be considered as depicted in Fig. 12 and 13.

Fig. 12 shows a star with its three neighboring stars which are all in category "certain." Normally the star C will not be

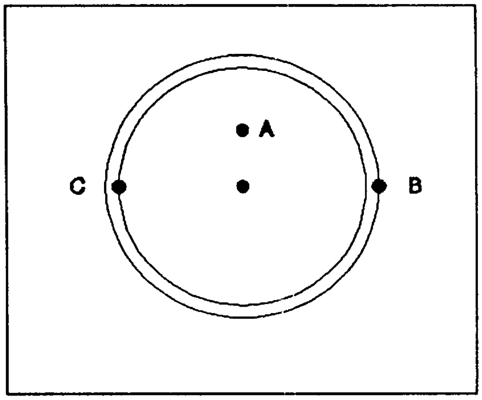


Fig. 13. Star with its 3 Neighboring Stars and Uncertainty of their Position

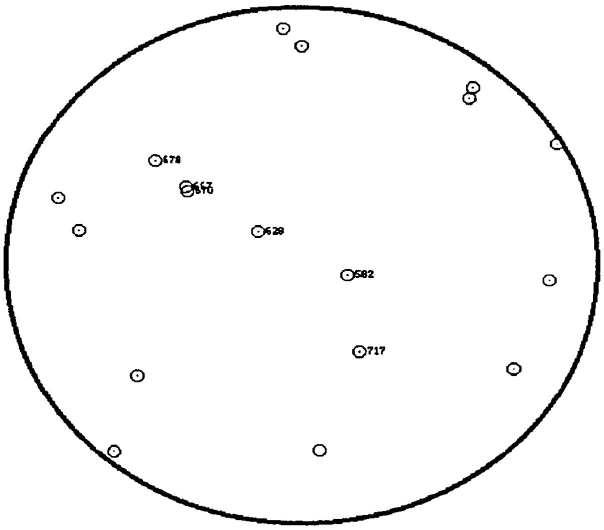


Fig. 14. Image from the IE Routine. Image to be Recognized includes the Big Dipper. There is a Circle Around Every Star. Numbers at Stars Refer to the Internal Star Catalogue. If no Number is Stated the Star is too Close to the Rim of the Picture

used for identification. However, the uncertainty on the angular distance to B and C is inside their respective uncertainties, and therefore the situation can be as shown in Fig. 13, where star C is interpreted as the second nearest neighbor. This possible position exchange occurs only when the exchanged stars are very close to the first or second neighboring star. Hence it is necessary to include them in the NBC entries. If worst-case is included all stars within 4 times the intervals of uncertainty have to be registered.

ALGORITHMS

The objective is to construct a "star-imager" able to perform both a coarse general attitude determination and subsequently a very accurate attitude determination. To reduce the weight and cost of the system, it is based on only one camera and lens. It is convenient to separate the software in two operating modes:

Table 2. Different Error Situations and the Associated Possibility for a Correct IE.
The Probabilities are Calculated Through 500 Simulations with Each Type of Error

Situation	Probability for Correct Guess
All stars included & inside tolerance limits	94.6 %
1 false star	85.2 %
1 star outside the tolerance limits	85.2 %
2 stars outside the tolerance limits	78.6 %
1 star outside the tolerance limits & 1 false star	72.0 %
1 star missing	88.4 %

1. Initial Estimate (IE) is used when no a priori knowledge of the camera orientation exists.
2. Predictional Estimate (PE) is an estimate where the coarse attitude is known. The purpose of the PE routine is to calculate the optical axis with greatest possible accuracy.

The IE routine is typically applied in the tumbling fase, before Earth control has established contact (after the satellite is injected into orbit). When several images have been identified through the IE routine, the rotation of the satellite can be calculated, and the pointing direction of the camera can be calculated as a function of time. At this point the system switches to the PE mode in which a fine-tuning of the calculated attitude is performed.

Initial Estimate

The IE algorithm uses the TF to identify the stars in the image. As a first step all stars are discarded, when the distance to the second nearest neighbor is larger than the star's distance to the rim of the picture (to make sure that the nearest neighbors in fact are in the field of view). The remaining star triplets are searched for in the database. This search will result in a few star candidates fitting the same characteristics. The right candidate is easily selected, as the distances between the right candidates are known. Then the only remaining task is to calculate the optical axis based on the identified and verified stars. The described procedure ensures a necessary system-tolerance in situations where extra objects are in the field of view (e.g., planets or satellites) or when a bright star for some reason should disappear from the view, situations which indeed can occur.

Furthermore it cannot be included if a star is outside its uncertainty limits. All this is error situations which result in either the nearest stars are missing or false artificial nearest neighbors appear. This results in a wrong identification by the star database. A "false" or missing star will then not only be a source of error to its own detection, but will possibly lead to misidentification of the surrounding stars. The only way to reduce this problem is to have many stars in the field of view. For this reason a relatively high opening angle of the image should be chosen. Hereby a high immunity against errors of this character will be obtained. The table below summarizes a statistical analysis of different error situations which might occur along with the success rate of the IE routine.

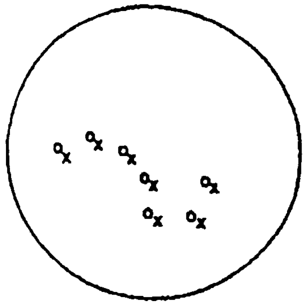


Fig. 15. The CCD-Star Constellation (x) and the Expected Constellation (o)

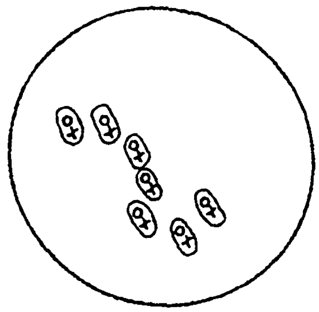


Fig. 16. The Corresponding Stars

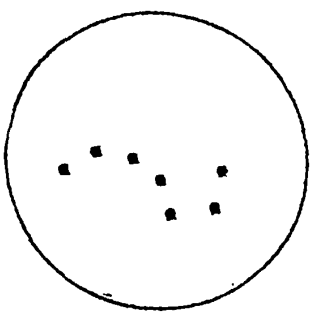


Fig. 17. Adjusted Guess

Predictional Estimate

The PE routine uses the coarse a priori determined attitude to create an image with the expected constellation based on the star catalogue. The stars in this image are matched to the stars in the camera image. This is done by least distance fit between any two stars from the two images. Distance deviations between the corresponding stars are calculated and subsequently minimized by differential variations of the presumed camera rotation and direction. The method is illustrated graphically in Fig. 15, 16 and 17.

The major result in this study is the obtainable accuracy. The accuracy of the optical axis determination depends on the accuracy of the CCD-measurement and the number of stars in the image.

$$\sigma_{optical\ axis} \approx \frac{\sigma_{star}}{\sqrt{Number\ of\ stars}}$$

Table 3. Accuracy of the PE in Different Error Situations.
The Accuracies are Based on 500 Simulations of Each Error Situation.

Situation	Accuracy (Arc sec.)
All stars included and inside the tolerance limits	14,6
1 false star	15,4
1 star outside the tolerance limits	14,7
2 stars outside the tolerance limits	16,7
1 star outside the tolerance limits and 1 false star	19,4
1 star missing	14,6

where σ_{star} is the position accuracy of a single star in a CCD-image and $\sigma_{optical\ axis}$ is the accuracy of the calculated axis. A test was performed with 10,000 random PEs. The accuracy of

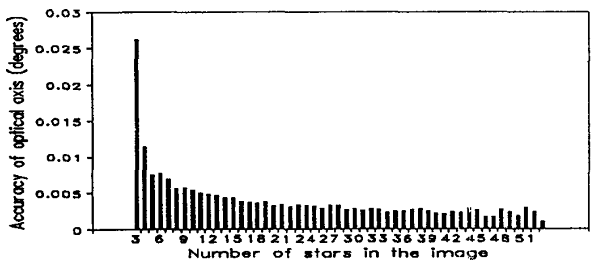


Fig. 18. Accuracy of Optical Axis as a Function of Number of Stars in Field of View. The Average is 14.6 arc sec.

Table 4. Key Numbers

Subject	Result
CCD-chip	NXA 1011
Exposure time	0.8 sec.
Pixels	576 × 604
Lens, opening angle	30°
Lens, Aperture	F:0.8
Accuracy, single star on CCD-chip	1/5 pixel, using hyperaccuracy tech
Number of stars registered with CCD	8000 (1100 brightest are used)
Success rate of IE routine	95%-avg. sit.; 75-90%-abnormal sit.
Typical time in IE-mode before PE-mode	10 sec.
IE, process time	2 sec, 386/387 proc. board, 33 MHz
IE, accuracy, average	0.1°
PE, success rate	100%
PE, process time	½ sec.
PE, accuracy, average	15 arc. sec.
Power consumption	< 8 Watts
Weight	= 3 Kg, depending on baffle const.
Obtainable accuracy, accumulated averages	1 arc sec.
Database size (SDB and SC)	1 Mbyte
Number of entries in database	185.000

the estimate was registered as a function of number of stars in the field of view (Fig. 18).

It is evident that not all images are perfect (as an example a planet might appear in the field of view). Table 3 shows the accuracies obtained in a number of different error simulations.

The accuracy can be considerably increased by calculating accumulated averages of several successive predictional guesses.

The key numbers of the star imager and its attitude determination software are shown in Table 4.

CONCLUSION

The angular distance to the first and second neighboring star and the angle between them give an almost unique identification. It is established that the software must operate in two modes (with and without a priori knowledge of the attitude). The analysis shows that the developed method is able to determine the attitude of a satellite with an accuracy better than 15 arc sec. By accumulated averages accuracies better than 2 arc sec. can be obtained. The method proves itself as accurate, cheap, light-weight and with a low power requirement.

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REFERENCES

[1] Peter Fortescue, John Stark,
"Spacecraft System Engineering,"
John Wiley & Sons LtD., Sussex, England.

[2] C. Elstner, G. Lichtenauer and W. Skarus,
"ASTRO 1M – ein neues Meßsystem für die Astroorientierung von Raumflugkörpern,"
Jenaer Rundschau 3 (1990).

[3] J. Curtis,
"Attitude Monitor for the Jet-X-Ray Telescope,"
Rutherford Appleton Laboratory. Private communications.

[4] S. Roeser, U. Bastian,
"The PPM Catalog,"
Astronomisches Rechen-Institut, Heidelberg, June 1989.

[5] J.L. Jørgensen, A. Damkjær, C.C. Liebe,
"A Project Proposal for a Star Imager for Accurate On-Line Attitude Determination,"
Annual Meeting for Nordic Society for Space Research, 18-21 November 1991, Møn, Denmark.

[6] F. Primdal, P. Anker Jensen,
"Dansk rumforskningsinstituts raket magnetometer ekspirement,"
Gamma 56 (1984).

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