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INTELLIGENT MODULAR STAR AND TARGET TRACKER - A NEW GENERATION OF ATTITUDE SENSORS

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ABSTRACT *- Star sensors developed in the last years can be enhanced in terms of mass reduction, lower power consumption, and operational flexibility, by taking advantage of improvements in the detector technology and the electronics components. Jena-Optronik GmbH developed an intelligent modular star and target named „Stellar and Extended Target Intelligent Sensor" (SETIS) . Emphasis was placed to increase the sensor adaptability to meet specific mission requirements. The intelligent modular star and target tracker shall generate positional information regarding a number of celestial targets or shall act as a navigation camera. The targets will be either stars or extended objects like comets and planetary objects, or both simultaneously. Design drivers like simultaneous tracking of extended targets and stars or searching for new objects during tracking of already detected objects require a powerful hard-wired digital data pre-processing. The paper describes the technical approach and shows some first test results performed with the SETIS EM model.*

1 - INTRODUCTION

The project, under which the development activities at DJO are running, is split into two phases; phase 1 which was concluded with the realisation of a fully detailed instrument design at the end of 1996 and phase 2 which covers the engineering model (EM) manufacturing and functional tests. The sensor EM will be available at the end of 1997. The project runs under the ESA GSTP programme with the abbreviation SETIS - Stellar Extended Target Intelligent Sensor [Schm 97].

The aim of the development activities was to design, manufacture and test an upgraded and enhanced CCD intelligent star and target tracker based on modular design principles. Special attention is paid to an autonomous attitude determination capability. The new features are the low budgets referring to mass, volume and power at a high measuring performance, the modular concept and the flexible use because of the wide field of view design in connection with a high accuracy. Therefore the modular star and target tracker can be configured as a simple tracker up to an attitude determination sensor or a navigation camera.

There were two major design driving requirements. *Firstly*, the celestial objects to be tracked are stars as well as extended objects like planets, asteroids, comets etc.. These objects shall be simultaneously processed, which means tracking of already acquired targets and searching for new objects (e.g. appearing at the edge of the FOV) during one update period or CCD read-out interval respectively. The number of celestial targets to be tracked simultaneously shall be up to 8 stars and/or up to 2 extended targets. Both, simultaneous track and search and star&extended target processing require a powerful hard-wired digital pre-processing for an on-line data reduction and object extraction.

Secondly, it was required that the sensor shall provide its line of sight in inertial co-ordinates. That means the sensor shall determine the attitude of the spacecraft without any a-priori information. Therefore an additional module was introduced, named „high level image data processing module". The attitude determination will be performed by the flight-proven star pattern recognition algorithm developed by Jena-Optronik GmbH using an internal guide star catalogue [Elst 92.1], [Elst 92.2].

2 - DESIGN APPROACH

The outline of the sensor is shown in Fig. 1. The sensor was designed axis-symmetric and mounted from the lens flange because this minimises the change of thermo-mechanical instabilities caused by thermal gradients and differential expansion. The electronic modules are mounted to the rear of the sensor mounting flange. Each of the module printed circuit boards (PCB's) is housed in an axis-symmetric frame. These module frames can be configured as a stack. Therefore optionally electronic modules can be exchanged, added or replaced easily. There are the following modules defined:

- CCD-camera head module
- CCD-camera ADC- and housekeeping module
- Digital data processing and interface module
- Star identification and attitude determination module
- Power supply module

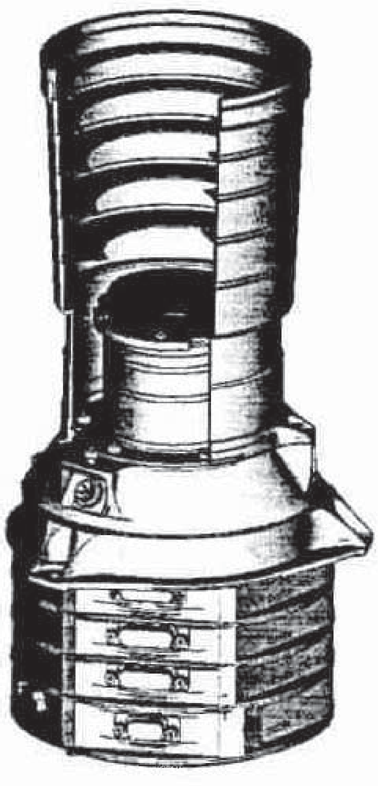

Fig.1: mechanical outline of the sensor

The main sensor parameters were driven by the autonomous attitude determination function. For this capability it has to be guaranteed to detect a sufficient number of stars in all directions over the whole celestial sphere. In order to meet this requirement a trade off referring to the sensor field of view (FOV), the limiting magnitude (sensitivity) and the sensor update rate (maximum exposure time) was performed. For this design approach a probability of 100% for a 4 star detection was taken as a requirement. Using a star catalogue (Hipparcos, SKYMAP) and special S/W tools (e.g. taking into account the real sensor instrumental magnitudes) the limiting magnitude can be calculated as a function of the FOV for a given number of stars and their corresponding detection probability [Abre 93]. The final sensor configuration was defined for an update rate up to 5Hz, a field of view of 14.8° x 14.8° and a limiting magnitude of 6.5mv, considering a G0 star spectrum and luminosity class V. The limiting magnitude covers also some ageing effects during the mission lifetime. With this approach for an autonomous attitude sensor a detection probability of 100% for 4 guide stars and 99.7% for 5 guide stars over the whole celestial sphere can be achieved. The on-board guide star catalogue holds 2000 stars including some redundancy for robustness reason.

One of the applied design rules for star trackers was to minimise the necessary memory size for reliability, power and volume reasons. The design driving requirements mentioned above like simultaneous searching for new objects and tracking of already acquired objects usually call for the use of a complete image frame buffer in connection with a digital signal processor which would be the opposite to this design rule. Therefore a hard-wired digital pre-processing was designed in order to carry out an on-line image data reduction.

The main sensor parameters are:

Field of view:	14.8° x 14.8°
Accuracy:	noise ≤ 1.0 arcsec (1 sigma) for pitch and yaw using 6 identified stars bias ≤ 1.0 arcsec (1 sigma) for pitch and yaw using 6 identified stars
Update rate:	tracking & attitude determination: 1Hz...5Hz single bright star tracking: 10Hz
Slew rate:	object acquisition: no limit (any object which appears above the adaptive detection threshold can be acquired by the co-ordinates of its surrounding rectangle) object tracking: up to 0.3 deg/sec attitude determination: up to 1.0 deg/sec
Detector:	charge coupled device (CCD), 1k x 1k pixels, frame transfer type, electronic shutter, anti-blooming, integrated Peltier cooler
Sensitivity:	-5.0mv up to 6.5mv (ref. to a G0 star spectrum, luminosity class V)
Star catalogue:	2000 guide stars within the on-board catalogue
Budgets:	mass ≤ 3.4 kg (without baffle), ≤ 4 kg (with baffle) power ≤ 7.0 W (add. max. 5W Peltier Cooler necessary at 55°C operational IF temperature)
Size:	≤ 150x150x330 (L x W x H) [mm] (with baffle)

Fig. 2 shows the sensor electronics functional blocks and their modular configuration. PCB1 and PCB2 form the CCD-camera module. CCD clocking and read-out are performed in the usual way. The CCD sequencer is programmable via a serial link. Some read-out modes like binning or windowing can be commanded by the sensor microcontroller. The dark reference levels of each CCD line will be clamped to the ADC reference level. So any slope effects during the CCD read out or an increased dark current caused by radiation will not lead to a shift of the ADC reference level.

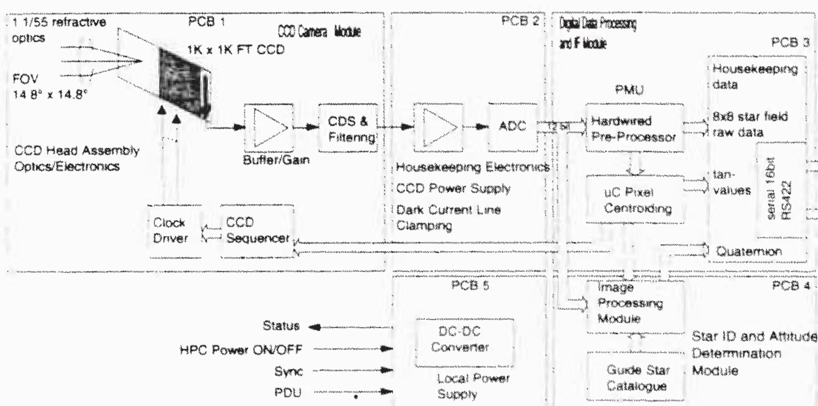

Fig. 2: sensor electronics functional block diagram

The digitised 12bit image signal is lead to the pre-processing management unit (PMU) and in parallel (optionally) to a second module frame, the star identification and attitude determination module (PCB4). The PMU consisting of a hard-wired pre-processor and a microcontroller is realised within a rad-hard ASIC design and covers all star tracker-related functions of the sensor. The data interface is a serial synchronous 16bit interface using the RS422 standard. The star identification and attitude determination module qualifies the sensor to be an autonomous attitude determination sensor. If this module will be omitted, only a simple star tracker is configured. This module contains a signal processor and the on board guide star catalogue. It operates in a slave function to the PMU microcontroller by receiving the tan-values of the tracked stars and transmitting the calculated attitude in quaternions to the data interface of the sensor.

The most important challenge within this design was the real-time hard-wired image signal processing for data reduction and object extraction purposes. In the following the corresponding processing flow will be described in more detail.

3 - DIGITAL SIGNAL PROCESSING

The already mentioned design drivers require a powerful hard-wired digital pre-processing for an on-line star tracker related data reduction and object extraction.
Because of the limited time frame of 200ms (5Hz update rate) in conjunction with an image read-out time of approx. 120ms an on-line data processing is necessary. Fig. 3 shows the digital data processing flow and the corresponding sensor timing diagram.

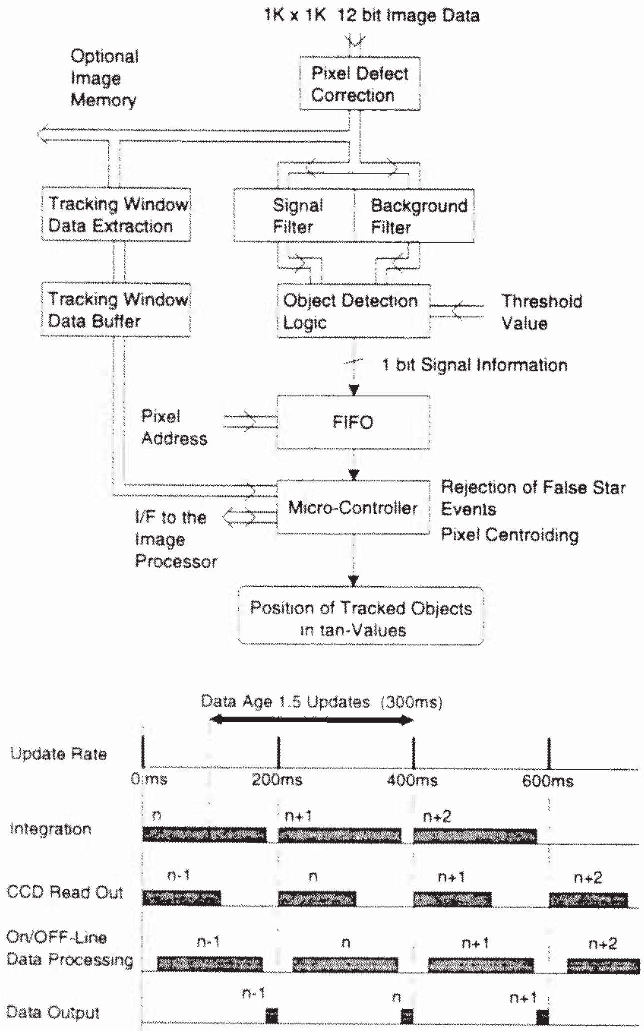

Fig. 3: hard-wired digital data processing flow and timing diagram

The data processing flow shown in Fig. 3 is completely realised within an rad-hard ASIC design which is described with VHDL tools.
At first the 12bit parallel image data will pass a pixel defect correction. A defect pixel can be replaced in 3 modes:

1. by the pixel value of the preceding pixel,
2. by the value of the following pixel or
3. by the mean value of the preceding pixel and the following pixel.

The reason of this pixel defect correction unit is that white defects shall not generate an object. Hence, the hard-wired processing flow will not be overloaded which such events. However, the positional accuracy of a single star will be influenced when a star image crosses such a corrected pixel. The microcontroller holds the address list of defect pixels in order to flag out such events.
After the pixel correction logic the 12bit image data flow will be split in a filter logic, a tracking window generator and a frame memory interface which provides the image data to the optional image processor module. The frame memory interface covers in maximum a 1k x 1k image. Therefore the image processor module can be equipped with such a full frame memory e.g. for on-board image data processing (landmark tracking) in a navigation camera application. The current application of an autonomous attitude determination sensor, however, does not need such a frame memory within the image processor module.
The digital on-line signal filtering performs an adaptive background estimation using an IIR filter and an FIR low pass signal filter. The outputs of both filters will be compared to each other including a threshold value which will be added to the estimated background value before the comparison. All filter parameters (coefficients) as well as the threshold value are controlled by the microcontroller.
One of the most difficult problems in on-line object detection chains is a proper estimation of the background value as an assumption for a defined threshold setting. An optimum solution for the background estimation and threshold setting could be to calculate the histogram over the whole image. However, this is a post-processing task and therefore not suitable for an on-line object detection algorithm. So we have to analyse the star tracker related requirements for a fast object detection. Objects to be tracked by a star tracker are point objects sized in a 3x3 up to 5x5 pixel environment. Such objects have to be detected with a specified threshold above the object surrounding background which can differ between the objects caused by stray light, low frequency noise and low spatial frequency dark signal non-uniformity's. That means an on-line background estimation is necessary. The CCD image read out is a sequential data flow line by line. Any digital processing of this data stream without the use of line buffers is a one-dimensional procedure. Now, the idea is to process in a first step only one-dimensional objects, so called line objects. Therefore the on-line background estimation can be performed using an IIR digital filter.

Applying this IIR filter on a CCD line the output value will follow the low frequency profile of the line in dependence on the smooth factor. The output value will not follow fast signal changes like star image profiles. Therefore the output signal of the IIR filter corresponds to a usable adaptive background value. Especially the robust detection of faint stars with the limiting threshold just above the background requires the local background estimation. Figures 4 and 5 show a CCD line sector containing two star object profiles with some high and low frequency noise. In Fig. 4 a fixed background value was used for the faint star detection. The low frequency noise within the background leads to a pixel noise detection. The comparator output (0/1 line in the top of the figures 4 and 5) indicates beside the star objects also false events.

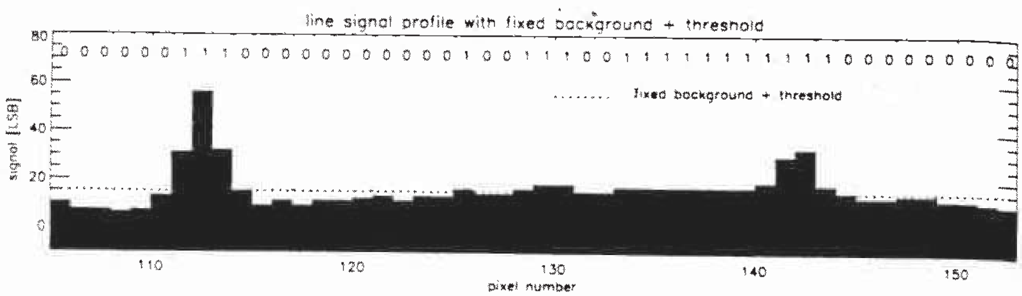

Fig. 4 detection of two faint star profiles with a fixed background+threshold value

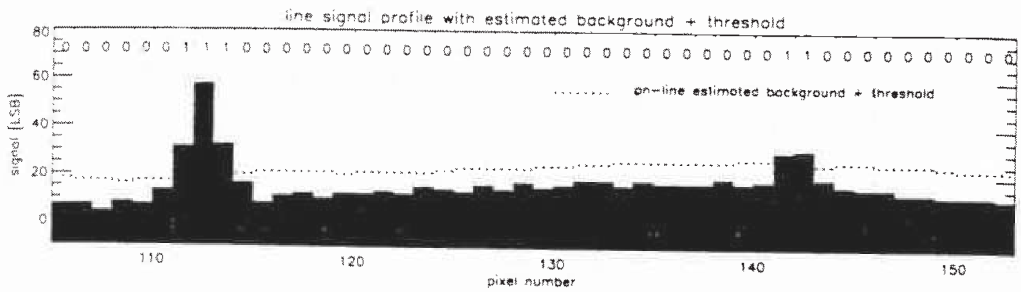

Fig. 5 detection of two faint star profiles with the on-line estimated background+threshold value

Fig. 5 shows the faint star detection using the IIR filter background estimator. It can be seen that the background+threshold value follows the low frequency part of the background noise. The comparator output indicates a proper faint star detection.
It is quite clear that the IIR filter background estimator always tends to follow the signal profile in dependence on the configured smooth factor. Star images on the CCD plane are very well-defined objects. As a function of the used defocus position and the star brightness a star will appear as a point image in a field of 3x3 up to 5x5 pixels. Therefore the difference between the low signal changes within the background and the sharp star signal profiles is always high so that the IIR background filter approach is a good solution for a faint star detection.
However, the intelligent modular star and target tracker shall also process extended targets. Some precautions have to be done referring to the extended target processing within this filter structure. For example, in case an extended target appears within the FOV with an area of 10%FOV the adaptive background filter value shall not be adapted to the extended target grey levels, otherwise the extended target would not be proper extracted from the background. For this reason some additional logic was included into the digital filter.

As mentioned above the estimated background+threshold value will be compared with the FIR filtered signal value. The output of the comparator indicates only a binary information;

0 - the pixel signal is less or equal than the detection threshold;
1 - the pixel signal is higher than the detection threshold.

This binary information will be used to generate line object entries in the digital hardware which will be stored in a FIFO (see Fig. 3). One line object entry looks like a run length code with the following information:

- x- and y-address of the first pixel above the detection threshold
- length of coherent pixels above the detection threshold

Figures 6 and 7 show an example for the object detection processing flow. Fig. 6 shows the comparator output binary information indicated as line objects. There are 3 stars, 1 extended object and 1 false event.

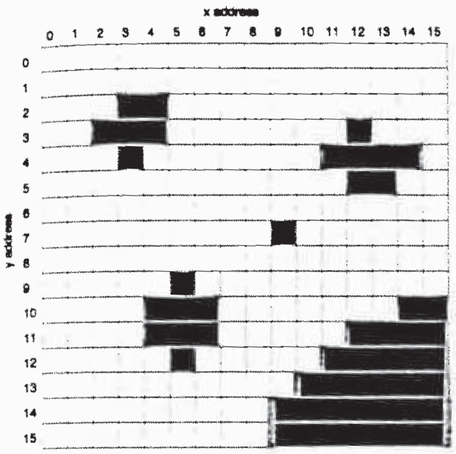

Fig.6 Binary image with 3 stars, 1 extended object and 1 false event

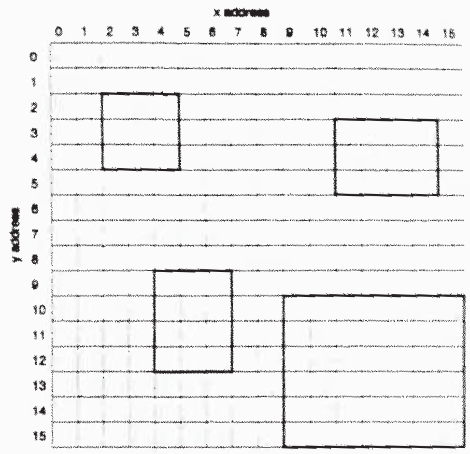

Fig.7 Surrrounding rectangles for trackable objects

The microcontroller (see Fig. 3) collects the line object entries from the FIFO and builds up two-dimensional objects by the arrangement of coherent line objects. Now it is possible to separate single pixel events from valid objects. A star is properly detected when more than 1 coherent pixels appear above the detection threshold. An extended object will be recognised if the extension of the object exceeds a predetermined level.
The microcontroller calculates the surrounding rectangles around the trackable objects. In dependence on the slew rate of the spacecraft the size of the track windows will be determined. The track window generator (see Fig. 3) will be programmed with the window co-ordinates. A tracking window data buffer holds the image data necessary for the pixel centroiding algorithm. The centroided position of up to 8 stars can be processed simultaneously meanwhile up to 64 objects can be monitored (acquired) with pixel accuracy. That means, a separation in an acquisition mode and a tracking mode as usual in some other star tracker designs is not further necessary. Now, the search and track function will be performed simultaneously. New stars appearing in the FOV and disappearing stars are monitored during each update period. The microcontroller starts its tasks (false star rejection, centroiding) when a certain number of object entries are in the FIFO. Therefore the microcontroller is able to process image data during the image read-out. Only a short off-line processing will be necessary.

The principle of the on-line object detection allows the acquisition of any objects (stars and extended objects) above the detection threshold during one frame. Therefore it is also possible to detect streaks caused by smeared stars at high slew rates. Figures 8 and 9 show the measured 3d-profiles of the track window of a 4.2m, F2 star at 195ms exposure time and different slew rates.

This capability of the hard-wired object detection can be used for a slew rate estimation in the pitch and yaw component. The length of the streak provides the estimated rate value and the start and end points give the direction. In order to avoid a 180deg mistake two successive streaks have to be considered. It is quite clear that the position accuracy of such streak objects decreases because of the lower signal to noise ratio and the object shape. Nevertheless a rough position information can be given in pixel resolution.

Using the described hard-wired signal pre-processing the sensor output information can be provided at the end of the same frame in which the image was read out. Therefore the data age for the star tracker related output amounts to 1.5 updates, starting in the middle of the preceding integration period (see also Fig. 3).

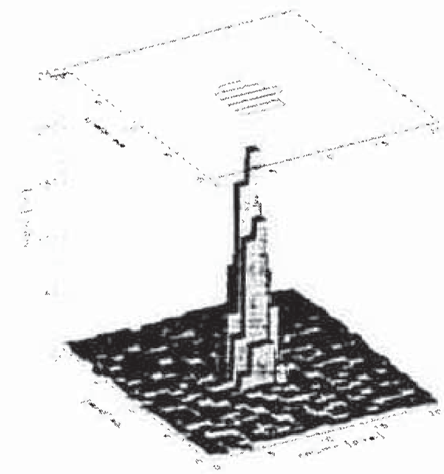

Fig. 8 measured star profile and corresponding line objects at a pitch velocity of 0.1deg/sec and a yaw velocity of 0.1deg/sec

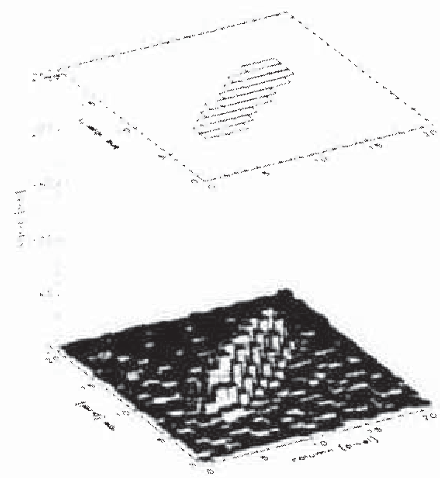

Fig. 9 measured star profile and corresponding line objects at a pitch velocity of 1.5deg/sec and a yaw velocity of 1.1deg/sec

4 - TEST RESULTS

4.1 - SETIS Bread Board - Real Sky Experiment Referring to the CCD Electronics Dynamic Range

Some experiments on bread board level carried out both in the laboratory and on the real star sky have shown the proper function of the digital pre-processing chain. The data generated by this experiment were processed with the VHDL model of the digital electronics and with a bread board FPGA design. Figure 10 shows an image acquired on April 8th 1997 22:10 MESZ (european summer time) at Jena. The comet Hale Bopp provided a suitable stellar extended object for the verification of the detection electronics and extended target tracking algorithms.

Acquired on:	April 8th 1997, 22:10 MESZ
Location:	Jena (FRG)
Acquired objects:	63
Stars:	59
Extended objects:	1
Single pixel events:	3
Exposure time:	495ms
Field of view:	16.2° x 16.2°
Optics aperture:	∅50.0mm
Ext.objects tracked:	1
Stars tracked:	7
Guide stars:	13
Brightest object:	0.9m (comet)

Faintest object: (star)	7.2m
CCD temperature:	10°C
I/F temperature:	18°C
Threshold above adaptive background:	10 LSB

Guide star catalogue: 2000stars (derived from SKYMAP)

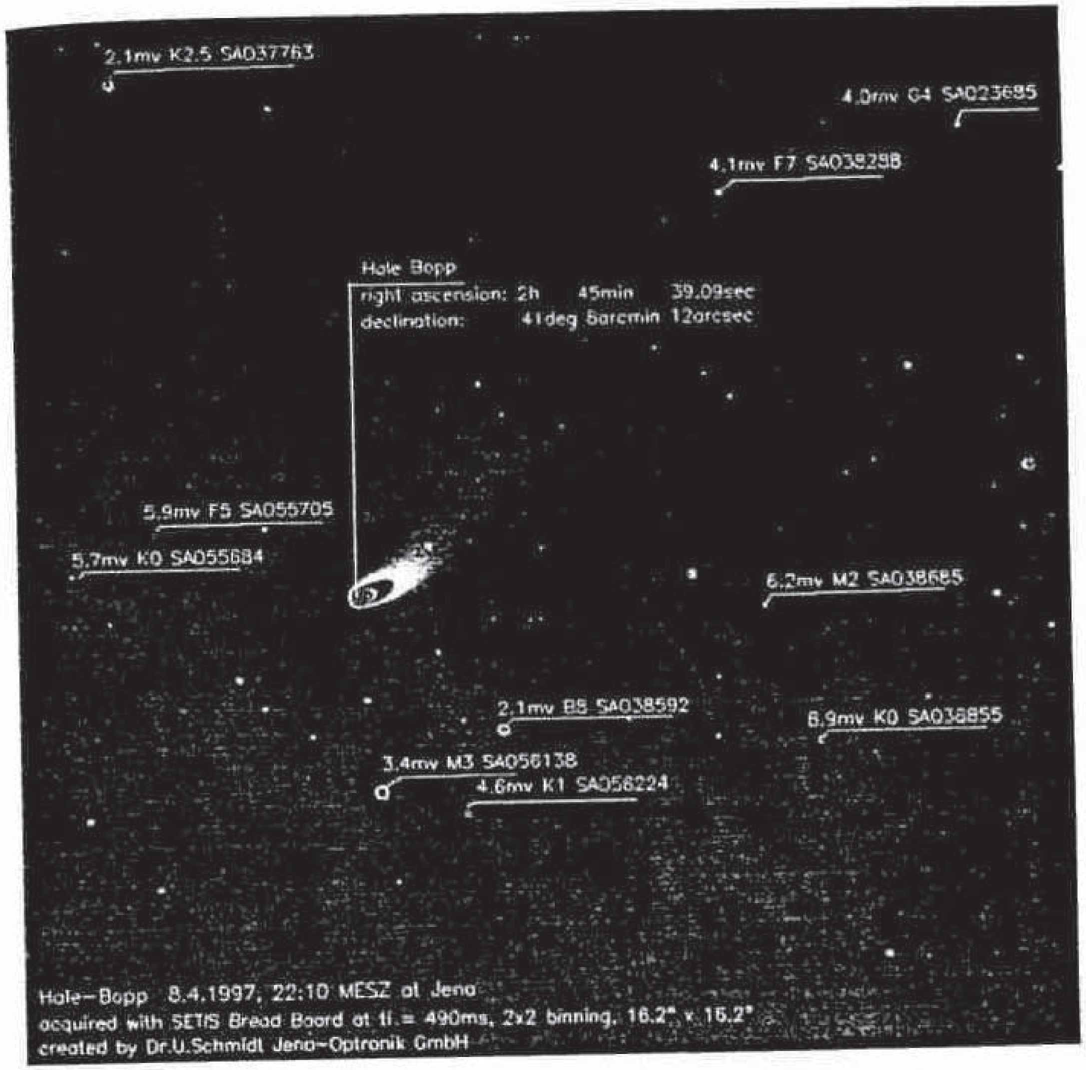

Fig.10 1k x 1k image acquired with the SETIS bread board

#	m	m	Spectral Class	Stars Tracked	Stars Identified
0	1.9	2.1	K2.5	*	*
1	2.0	1.8	F5	*	*
2	2.4	3.4	M3	*	*
3	2.4	2.1	B8	*	*
4	3.7	3.8	K0	*	*
5	3.9	4.0	G4		*
6	4.0	4.3	K3	.	*
7	4.0	3.8	F5	.	*
8	4.1	4.1	G0	*	*
9	4.2	4.1	F7		*
10	4.2	4.5	K5	.	*
11	4.3	4.2	F2	*	*
12	4.4	4.6	K1	.	.
58					

The dynamic range of the detected objects (7.2m up to 0.9m) covers the whole range of the 12bit AD-converter digital number output.
The 13 detected guide stars within the FOV indicate the robust and redundant on-board guide star catalogue.

4.2 - SETIS EM - Tracking and Attitude Determination on the Real Sky

Figure 11 shows on the left hand side a real sky tracking sequence performed with the SETIS EM at a slew rate of 0.3deg/sec. On the right hand side the smeared star profiles are shown. The SETIS EM was commanded to an update rate of 5Hz. The CCD exposure time was 195ms. The red coloured tracking windows indicate identified stars.

Figure 12 shows the x co-ordinate error of a tracked star without using any calibration data (neither pixel FOV nor entire measurement FOV calibration). These error statistics indicates a very good single star accuracy performance within the wide field of view. The correlation within this data set is caused by the systematic error of the centroiding algorithm, the so called „S-characteristic". After the calibration of this systematic error a BOL single star accuracy of < 1.0arcsec can be expected.

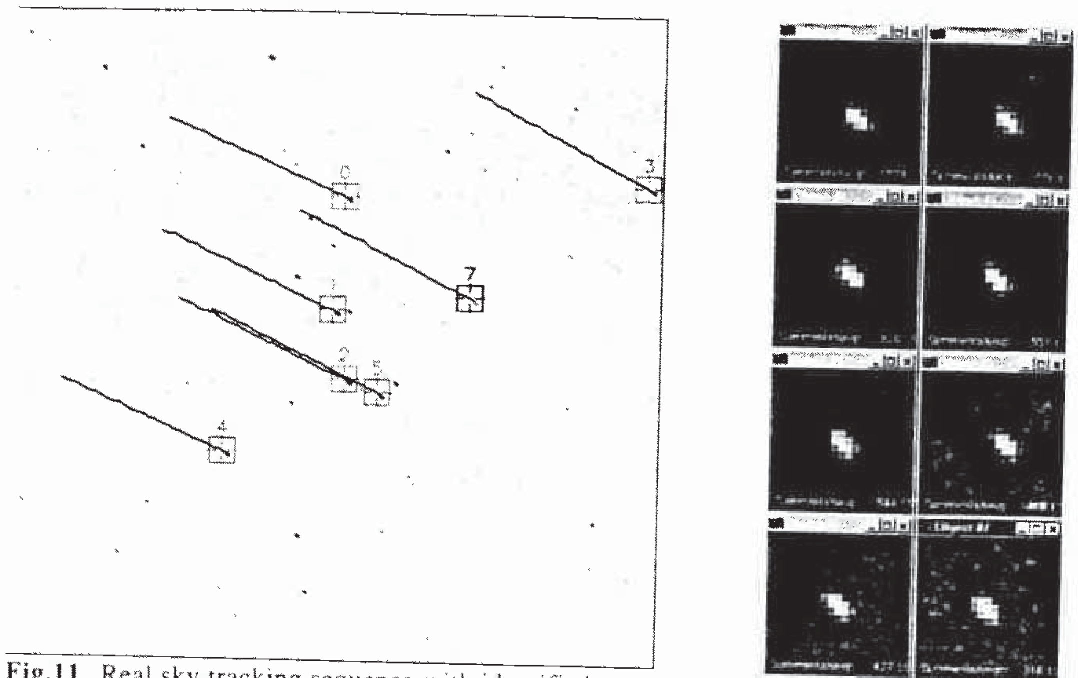

Fig.11 Real sky tracking sequence with identified guide stars

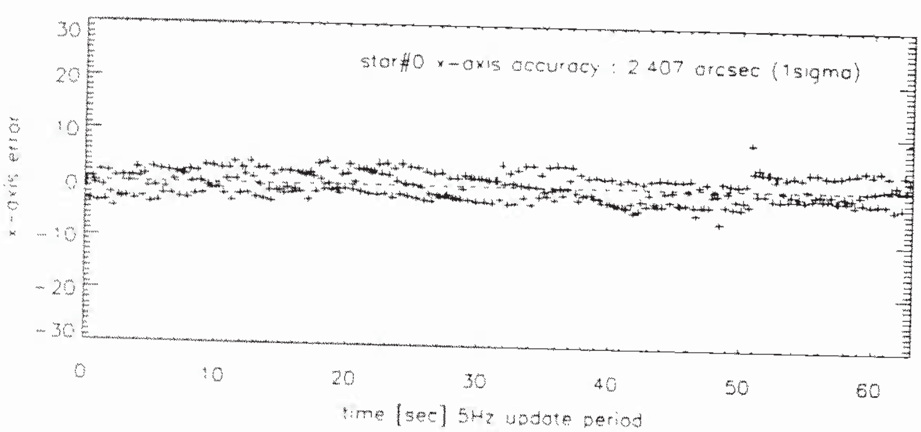

Fig. 12 Single star error statistics along a 60sec track at 5Hz update rate

4 - CONCLUSION

A digital hard-wired object detection chain applied within a modular star and target tracker has been presented. An engineering model of this star tracker will be functionally and performance tested up to the end of 1997. The presented principle of a real-time object extraction during the CCD image read-out allows a simultaneous track and search function within one frame. Only a small data buffer memory is necessary in order to hold the content of the track windows. A complete CCD frame memory can be omitted. Therefore, the reliability will increase and the power and volume budgets will decrease.
The object detection based on an FIR signal filter and an IIR background filter provide a proper detection of faint objects with the limiting threshold value. Low spatial frequencies in the CCD dark signal will have no influence during faint star detection because of the adaptive characteristics of the background filter.
Some experiment results show the proper and robust function of the presented design solution. Stars as well as any extended targets can be recognised and processed simultaneously. Streaks caused by bright stars at high slew rates can also be tracked so that a rate estimation can be performed. SETIS has no slew rate limit at the acquisition mode, any object which appears above the adaptive detection threshold can be acquired by the co-ordinates of its surrounding rectangle. The tracking mode allows a slew rate of 0.3deg/sec and the attitude mode allows up to 1.0deg/sec.
Due to the extended object tracking capabilities the device can be used not only as star sensor but also as a navigation camera for faint object approaches. Some long exposure experiments have shown that a proper 9.5mv G0-star detection at 10sec exposure time is possible.

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