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FOLDED OPTICAL SYSTEM FOR SIMULTANEOUS ATTITUDE MEASUREMENT AND GROUND IMAGING - A PROPOSAL

Pal Greguss , *Edith Greguss*

Dept. of Manufacturing Engineering, Budapest University of Technology and Economics, Budapest, Hungary

Abstract – ***Panoramic Annular Lens based Attitude Measurement sensor combined with Ground Imager (PALAMGI)*** for satellites. There is a need of miniaturized platform elements of spacecrafts, especially for nano and micro satellites programs. A single unit is proposed instead of two separate ones using the newly developed Humanoid PAL vision system.

Keywords PAL-optic, attitude measurement, ground imager

1. INTRODUCTION

The optical attitude measurement system PALADS of the micro-satellite SEDSAT-1, successfully launched on orbit on October 24, 1998, used an omnidirectional imaging (ODI) module based on centric-minded imaging (CMI). It was a catadioptric optic, the *Panoramic Annular Lens* (PAL), which is a single-element imaging block with spherical surfaces, a combination of refraction and reflection for imaging [1].

2. PRELIMINARIES

2.1. Attitude Determination Methodology

A number of conventional attitude sensors are known, including sun sensors, earth horizon sensors, and magnetometers. However, sun sensors and horizon sensors must be used in combination with other sensors to achieve *three-axis attitude determination*, and have limited capabilities beyond attitude determination. Magnetometers can provide three-axis attitude, but they only achieve accuracies from 0.5-3.0 degrees, unless used in combination with other sensors. Star sensors have high accuracies (0.0003-0.01 degrees), but are very sensitive to random tumbles, oscillations, and make it problematic to ensure the sensor be pointed toward a given star.

2.2. Omnidirectional imaging and PAL optics

Omnidirectional imaging modules are based on centric-minded imaging using catadioptric optics such as the Panoramic Annular Lens (PAL) a single-element lens with spherical surfaces, a combination of refraction and reflection for imaging.

One of its first space-related applications was the *radial profilometer*, which is capable of contouring or measuring deflections on the inner surface of a cavity in 360° without the need for turning the optic around its axis. This is achieved by illuminating the internal surface of the cavity in such a way that the illuminating beam traces out a circular ring on the inside surface of the cavity. This light trace is captured by the PAL, and any deviation from the circular shape indicates inclusions, i.e., the profile of the inner surface of the given cavity is visualized. Please note that the resulting ring shaped image is not a *cross* section; it is a two-dimensional skeleton of the three-dimensional cavity volume, i.e., it contains information also on the direction perpendicular to the image surface. This technique was developed together with a team of the *Department of Mechanical Engineering of the University of Alabama in Huntsville.*

2.3. Imaging philosophy of PAL

The imaging philosophy of PAL assumes that the geometric structure of space encircling us is cylindrical, rather than spherical, thus, it follows the strategy of *centric minded imaging* (CMI). CMI means that points in 3D object space located on the inside surface of the imaginary cylinder are transformed into points in the 2D image space along the surface of a plane. Therefore, a point's true location in the 3D object space may be derived from its location on the image plane by referencing a cylindrical coordinate system. If now it is assumed that the radius of the circumscribed cylinder is equal to the *vision distance*, a panoramic view of the image volume shows up on the wall of this imaginary cylinder. However, the result of this course of thoughts is only a 360° panoramic *view*, but not an omnidirectional panoramic *image* in the sense of image definition, since it is not an intensity pattern displayed on an *Euclidean flat surface* yet.

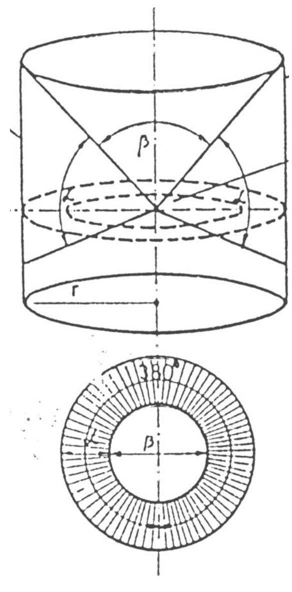

Fig. 1. Philosophy of CMI

It can be shown that by using special stretching maneuvers one can transform this panoramic view *image projection* onto a plane surface perpendicular to the axis of the imaginary cylinder. (The procedure is somewhat similar to, but not identical with, the Mercator projection.) As a result, a panoramic annular image of the three-dimensional environment is formed, where points in the cylindrical space seen at constant field angles perpendicular to the axis of the cylinder of vision are located on concentric rings in the image plane. (Fig. 1) The geometric relation of the three-dimensional environment remains represented in polar coordinates and provides an image in which the points retain the same 1:1 relation to each others as in reality. This allows a distortion-free omnidirectional display of the imaged scene.

Thus, CMI means that points in 3D object space located on the inside surface of the imaginary cylinder are transformed into points in the 2D image space along the surface of a plane. Therefore, a point's true locations in the 3D object space may be derived from its location on the image plane by referencing a cylindrical coordinate system.

Further analyzing the annular image one can find that this optical imprint displays the 2D skeleton of the encircling 3D environment in such a way that one may get data on the *place* and *time* position of object points, since the *width* of the ring shaped image corresponds to the *viewing angle* (α) in the direction of the axis of the cylinder of vision.

As a result, the depth of focus of such an imaging block extends from its surface out to infinity, consequently, systems based on this principle require no focusing during operation. [2]

2.4. Development of PALADS – Panoramic Annular Lens Attitude Determination System

The limitations of conventional attitude sensors led us to the development of an omnidirectional optical imaging subsystem for the determination of SEDSAT-1's attitude.

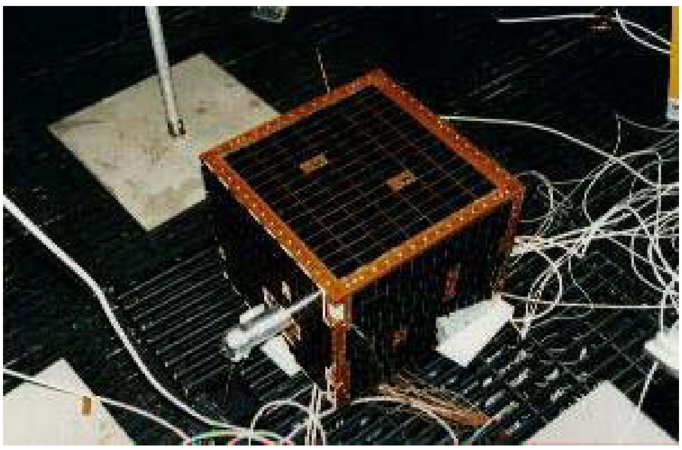

Fig. 2. SEDSAT-1 in the test chamber, with PALADS sticking out

The PAL of diameter of ~38 mm used in PALADS covered a 45º field of view of the entire 360º surrounding the optical axis, and sticked out from SEDSAT-1 (Fig. 2) in such a way that a virtual image of the earth limb and a star was formed in the PAL and projected, via an imaging lens, onto a target of a CCD camera and delivered data on the position of the sun and on the points where the earth limb crossed PAL's horizon. Exploiting the basic property of PAL imaging, namely, that each point in the image plane corresponds to a unique set of angles in the ring shaped reference plane, as a consequence of the relation between the two-dimensional skeleton displayed in the annular image and the geometric relation of the three-dimensional environment, the position and attitude of the satellite can be computed relatively easily.

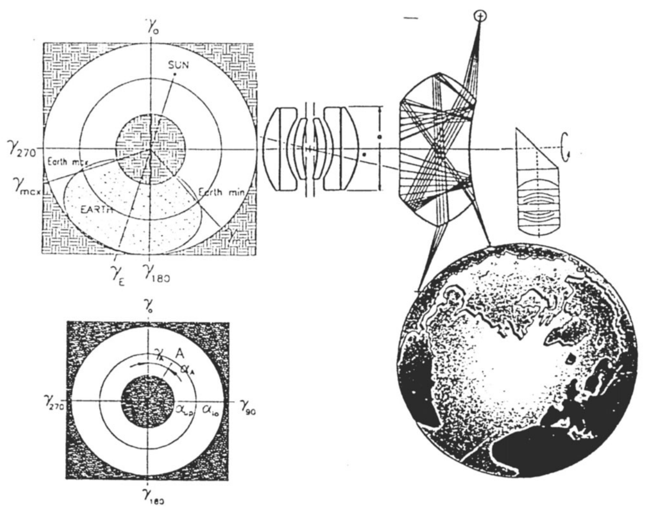

Fig.. 3. Functional block diagram of PALADS

The principal coordinate system used for PALADS was the celestial sphere coordinate system. This means that the spacecraft's altitude above the earth and position on the celestial sphere, as well as the positions of the reference sources on the celestial sphere have served as inputs to PALADS. The PALADS solution provides the attitude of a single spacecraft axis (the PAL optical axis) plus the phase angle about this axis, which corresponds to full three-axis attitude determination. These data are used to compute the formal attitude matrix in the form of a 3-2-1 Euler angle rotational sequence. The first Euler angle corresponds to the right ascension of the attitude vector (rotation about the reference frames' Z- or 3-axis); the second Euler angle corresponds to the declination of the attitude vector (a rotation about the reference frame's rotated Y- or 2-axis); the third Euler angle corresponds to the phase angle about the attitude axis (a rotation about the reference frame's rotated X- or 1-axis). Since each element of the 3X3 attitude matrix gives the cosine of the angle between a given spacecraft axis and a reference frame axis, as shown below, computing the attitude matrix fully describes the orientation of the spacecraft with respect to the reference frame.

Spacecraft Attitude Matrix

$X_{ref} \cdot X_{spc}$ $X_{ref} \cdot Y_{spc} X_{ref} \cdot Z_{spc}$

A(3x3) = $Y_{ref} \cdot X_{spc} Y_{ref} \cdot Y_{spc}$ $Y_{ref} \cdot Z_{spc}$

$Z_{ref} \cdot X_{spc} Z_{ref} \cdot Y_{spc}$ $R_{ef} \cdot Z_{spc}$

2.5. Ray tracing analysis of PAL imaging block

Ray tracing analyses show that a restricted cylindrical volume around the optical axis of PAL does not take part in forming the panoramic annular image; it serves only to ensure undisturbed passing through for the image forming rays[3]. This fact led to development a series combined vision system: combination of panoramic vision system with traditional image making systems. Examples are: straitforward-looking system, foveated PAL system, humanoid machine vision system.

Among others we have designed a new type of PAL, called *HPAL*, where a well-defined portion of the obstruction is removed. As a result, one can look through the imaging block without loosing its panoramic imaging capability, the basic factor in PAL-based attitude determination.

If now an imaging lens, called *foveal lens,* is put in front of the so designed optic in such a manner that its image plane coincides with the annular image plane of the PAL, the resulting image appearing in the center of the annulus will cover the missing viewing angle in the direction of the optical axis.

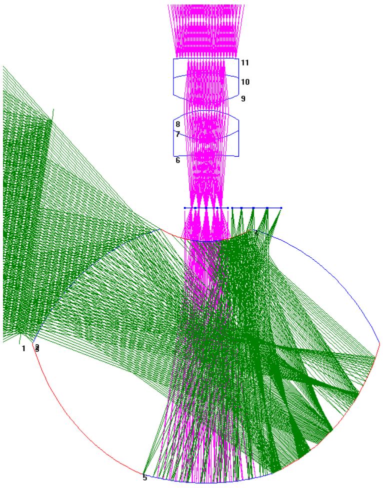

Fig. 4. Straithforward-looking system

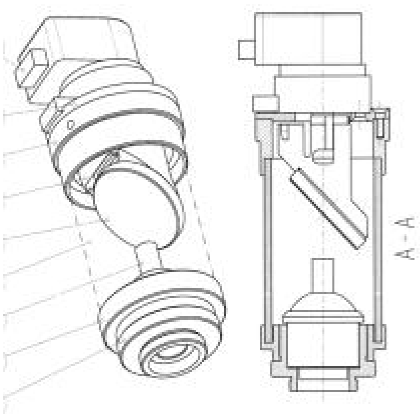

Fig. 5. Foveated PAL system

Fig.6. Foveated image shows a four times magnification of a selected part of the 360º panoramic image

3. DESIGN CONCEPT

Placing a front-surface mirror with a predetermined inclination to the optical axis of HPAL, or a beam splitter (reflecting prism), as shown on the right side of the functional block diagram of PALADS (Fig. 3), one can create a *folded optical system* with high performance and compact attitude measurement capability.

This is the ***essential part of our proposal to combine attitude determination with ground imager***, i.e., to create a basically new, PAL-based *folded* optical system for *simultaneous* attitude measurement and ground imaging.

4. FOLDED OPTICAL SYSTEM

Although PALADS forms a panoramic image of the stars and the earth limb, it cannot really function as a ground imager: the area it covers is too large. The scope of this proposal is to present a *folded optical system,* which does both jobs and uses a single imager.

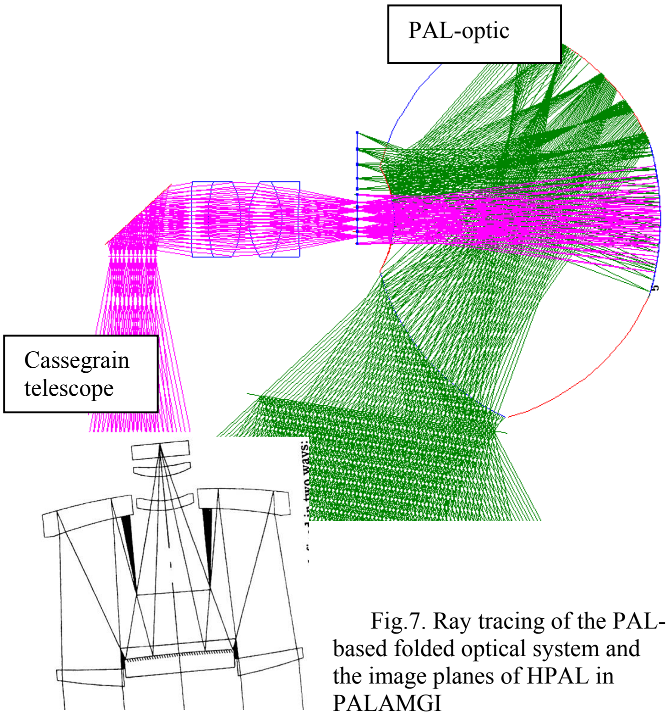

Fig.7. Ray tracing of the PAL-based folded optical system and the image planes of HPAL in PALAMGI

If now a ground imaging system combined with a front-surface mirror having a predetermined inclination to the optical axis is put in front of the so designed PAL in such a manner that its image plane coincides with the annular image plane of the PAL, the picture of the ground imager can fill out that part of the ring-shaped PAL-image, where otherwise no optical information is present.

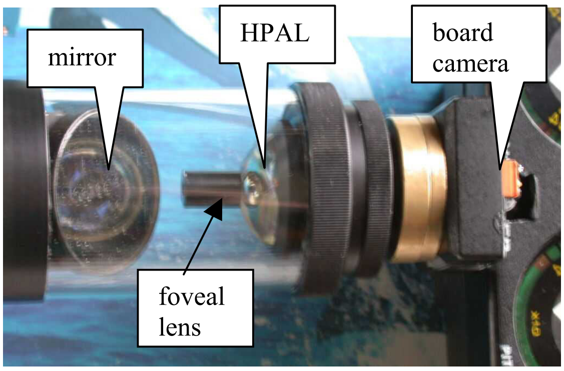

Fig.8. PALAMGI Mock-up

To test the validity of this idea a mock-up of PALAMGI was made in such a way that its foveal lens delivered an approx. 4x magnified view of the area selected at will from the panoramic image via a tilted mirror that could be rotated.

A color board camera recorded both the omnidirectional 360º panoramic picture of a viewing angle of 80º along the optical axis, and the ground image. The experiments showed that no re-focussing was necessary: the two image planes coincided as expected.

5. CRITERIA FOR TECHNICAL REALISATION

When we tried to put into practice the above proposed idea, we wanted to get a HPAL with a viewing angle that is bigger than the viewing angle of PAL formerly used in PALADS

Choosing a glass material with higher refractive index and developing a new optical design program, we have achieved an improved shape that allowed us to get an optimized total viewing angle of 80º, instead of the viewing angle of 45º of the PAL that was used in PALADS

The main problem in designing and realizing PALAMGI is to find out how the picture of the ground imager that is acting as a foveal lens can fill out that part of the ringshaped PAL-image, where otherwise no optical information is present.

If, namely, the two image planes do not coincide, one or both displayed images will be out of focus. In this case, one would loose just that feature of PAL that the depth of focus extends from its surface out to infinity and, as a consequence, requires no focusing during operation. Ray tracing of Fig. 4 shows how we have solved this problem

Since the intention with the folded optical arrangement is to use a *single* image sensor for capturing both the 360º panoramic image and the selected ground image we have to know the pixel area ratio of these two picture areas

The surface area of the image sensor covered by the panoramic image is about 3.37 times bigger than that of the foveal image. One should always keep this fact in mind when a camera is chosen for a given task.As for an example in the case we choose an IBIS5 *Mpixel CMOS Image Sensor,* where the resolution and pixel size result in a 2/3" optical format, the 360º panoramic image will cover about 535,753 pixels *of* 6.7 μm x 6.7 μm size, while the foveal image will occupy around 226,056 pixels of the same size. This folded optical system aims to be used, among others, for Earth observation, planetary, Mars or Lunar mission, since its lightness and compactness will be a valuable asset for tight payload mass and volume budgets. Additional requirements for such a CCD with low storage and operation temperatures are resistance to vibrations, low power consumption, etc.

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Authors: =Prof. (Emeritus) Pal Greguss Ph.D., and Edith M. Greguss; Dept. of Manufacturing Engineering, Budapest University of Technology and Economics/OPTOPAL Panoramic Metrology Service; Rona u. 226., H-1145 Budapest, Hungary. Phone/Fax: +36.1.363-1593; e-mail: greguss@manuf.bme.hu, greguss.edit@freemail.hu. – Prof. Greguss died on 26th February, 2003, in the 82nd year of his life, due to a tragic accident, just before he could have finished his paper, which then was put into its final form by his son, Pal Greguss, Jr, physicist, and is presented by his wife Edith, his closest co-worker and research mate for almost six decades.