

Final Report
of the Project SPC 01-4009, Contract Order No. F 61775-01 WE009
entitled
“CNN-coupled Humanoid Panoramic Annular Lens (PAL) optical
system for military applications”

Introduction

The scope of this feasibility study was to find out how the unique properties of the Cellular Neural Network (CNN) focal-plane-array processor chip, which uses analogic algorithm for following continuously moving objects, could improve the performance of PAL-based vision systems described in the project *SPC-994065* (Contract Order No. F61775-99-WE065). Therefore, OPTOPAL started collaboration with AnaLogic Computers Ltd., who were on the way of developing special algorithms for CNN-UM focal plane array processors.

Being aware of the fact that the currently existing 64 by 64 CNN-UM focal plane array processor chip, - and even the 128 by 128 version under construction, - cannot handle moderately complex images with high spatial frequency, and the processing results will become poor if a low-resolution chip is used, we planned to develop a system where we get two images at the same time: one from the existing 64 by 64 CNN-UM focal plane array processor chip, while another from a camera which provides so-called Humanoid PAL images of high resolution. This means, it renders a "360° peripheral view" and, in addition, a "foveal view of "about 20°. Comparing the data delivered by a CNN-UM focal plane array and those presented by the Humanoid PAL, the performance of some military video systems such as

1. azimuth determination system (ADS)
2. sniper fire location display (SFLD)
3. helicopter blade tracking system (HBTS)

could be improved.

The research was conducted on various levels:

1. A Humanoid PAL with increased peripheral viewing angle was designed, resulting in workshop drawings suitable for manufacturing.
2. A foveal lens with viewing angle of about 20° was designed, resulting in workshop drawings suitable for manufacturing.
3. A mount system was designed which allows the use of off-the-shelf lens systems as relay lenses, resulting in workshop drawings suitable for manufacturing.
4. A software for color images was developed, which allows a quasi-real-time processing speed, about 15 images per second, capable to unwrap the panoramic ring-shaped image, and it can also perform various filtering procedures, fine edge detection, major edge extraction, summation, subtraction, etc.; further, it can also handle the foveal view, including creation of histograms in any selected direction.

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14. ABSTRACT This report results from a contract tasking OPTOPAL Panoramic Metrology Consulting as follows: This investigation will consist of adaptation of a Hungarian-developed single-piece imaging block, the Panoramic Annular Lens (PAL) and the CNN chip for a few military applications. A polar beam splitter will be placed immediately after the relay lens to obtain two image planes, one will be used by the existing 64X64 CNN-UM focal plane array processor chip. The other image plane will be projected on the space-variant CMOS retina-like digital camera GIOTTO. Using this configuration enables us to compensate for the relatively low pixel number of the CNN-UM array processor; further it will allow a real time switching from log-polar imaging to regular imaging and allow for the design of the humanoid PAL optical system.					
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Increasing the viewing angle of PAL

PAL, as an imaging block is a single glass piece with two refractive and two reflective surfaces, each of which could be plane, concave or convex. Therefore, the possible shapes of such an optical element amount to the number of iterative variations of the fourth class that can be formed of three elements, i.e., to 81. Fig. 1 shows five forms that are all suitable of forming 360° panoramic images, however, not necessarily of the same optical quality.

Until recently, our PAL designs started from the shape seen in the middle of the first row, mainly because its plane surface. It helps namely a lot in designing appropriate mounts for a given application task.

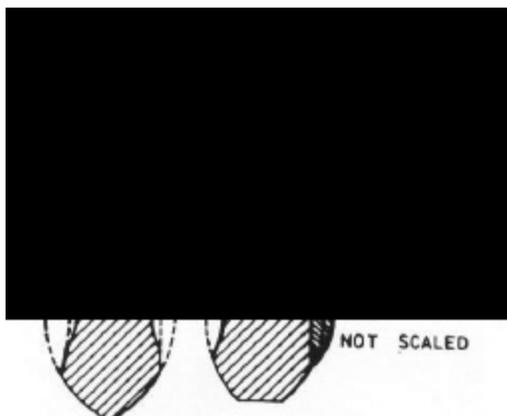


Fig. 1 Shape variations for PAL

Because of this shape a virtual 360° panoramic image – better to say, a panoramic image *volume* – of the 3D surroundings is formed *inside* the glass block, which represents the 2D skeleton of the 3D space.

The viewing angle of the PALs with the mentioned shape had approximately a viewing angle of about 40° above and 15° below the optical horizon of the PAL. (Optical horizon (OH) is the plane, where the curved surfaces intersect, it is perpendicular to the optical axis.)

Shortly after we began to design a new PAL with a total viewing angle of around 80° and suitable for foveal vision, it turned out that the optical design program ZEMAX EE we intended to use was not capable for optimization. The reason was that ZEMAX-EE and all present optical design programs are based on see-through-window (STW) principle. This means that they operate in Cartesian coordinates, and not in polar coordinates, thus, they do not "understand" centric-minded imaging (CMI).

A common feature of the axis-symmetrical imaging optics is that the *entire* optic is involved in imaging the object points. With other words, all optical rays issuing from an object point pass through the optic and meet in a single point at the image plane. This is the reason why an entire image of the object is formed even when a portion of the optic is blocked; the speed of the lens, however, may decrease and/or the image quality may change. Thus, optimization of such a so-called see-through-window (STW) imaging system means that each object point when imaged should provide the possibly smallest spot at the image plane, the limit of which is defined by diffraction. Therefore, high quality optics are diffraction limited at a given wavelength interval and viewing angle. Appropriate variation of the radii, the distances between optical elements, and the refractive index of the optical material achieve this, so that all image points will produce a spot in the image plane, the diameter of which is smaller than the Airy-diameter. In Fig. 2, one can see the ray tracing of two triplets of the same focal length: in the first row without optimization, in the second row, diffraction limited.

The green column shows the distance of the image points from the image plane, the blue column the diameter of the produced spot, and the percentage of the spot diameter with respect to the Airy-diameter. It well demonstrates that optimization of conventional STW imaging optics is not a simple task since too many variables have to be considered; in the case of triplets, three glass materials, six radii, and five distances.

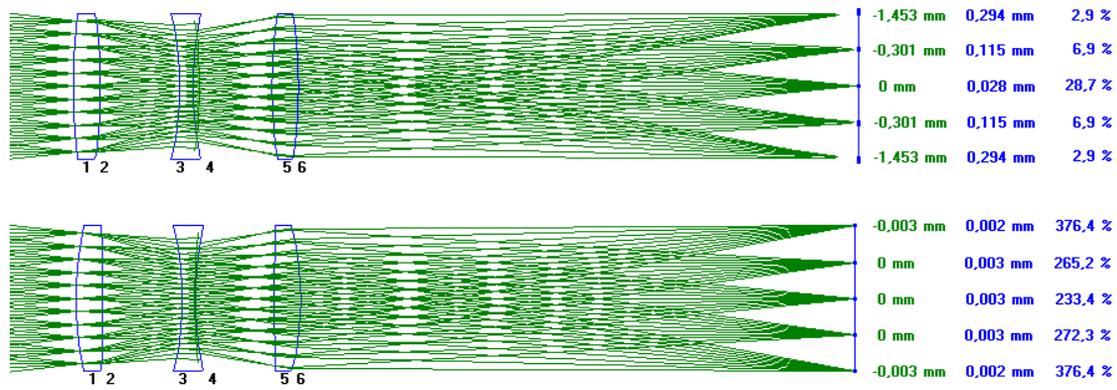


Fig. 2 Ray tracing of two triplets of the same focal length: non-optimized (upper row), diffraction-limited ((bottom row)

In designing a PAL, a *single* centric minded imaging block, we are faced with the problem that optical definitions used in traditional STW imaging loose their meaning and validity. Further, only a portion of the rays emerging from the object points in space and reaching the optical surface are taking part in image forming.

PAL can be thought to be built up from several small units, each of which produce, from a part of the 3D space, an image on the image plane.

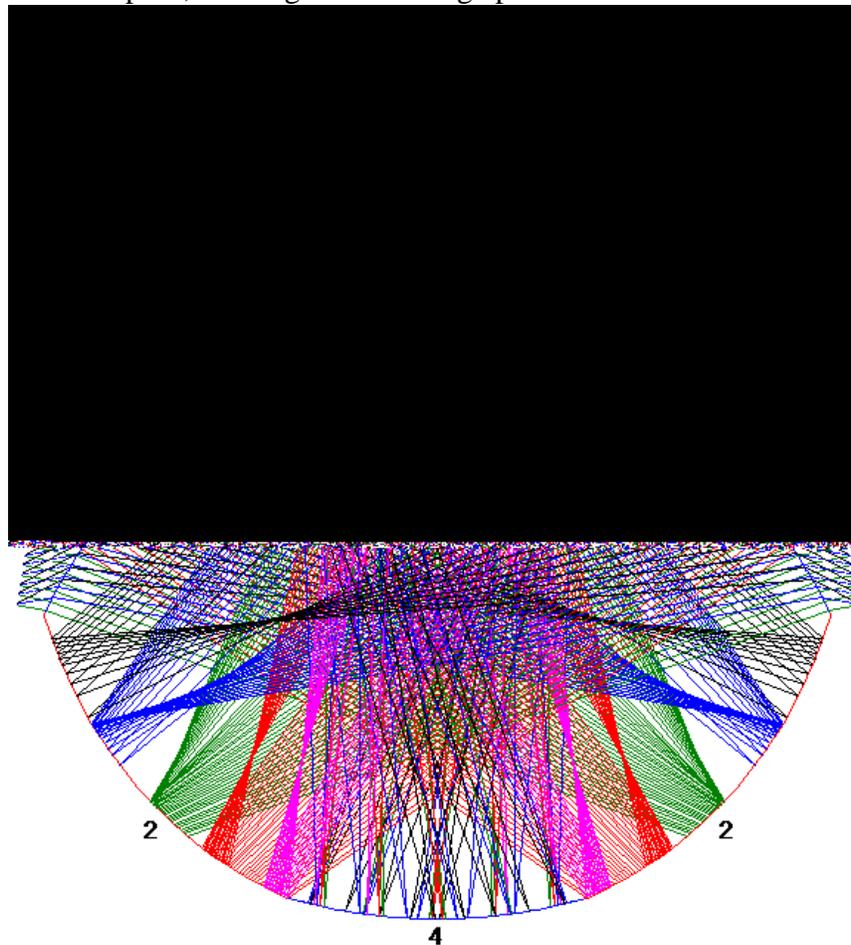


Fig. 3 Ray tracing of our new PAL design

This way of thinking is backed up by the findings that when blocking a part of the PAL not only the speed of the lens decreases, but a part of the image has been lost. Thus based on this idea we developed an optical software, one result of which is shown in the ray tracing diagram of Fig.3. The rays originating from different object points are displayed on the image plane by different sections of the optical surface in the sequence 1-2-3-4. The software takes this into account automatically. Please note that from manufacturing point of view these surfaces are well defined.

Another pleasant feature of this design is that the virtual ringshaped panoramic image shows up *outside* the glass block, thus, it is suitable for designing a foveal lens system which, when properly coupled to the PAL, renders the same image quality as the PAL itself.

Choosing a glass material with refractive index 1.80518 we have achieved a shape that allowed us to optimize the upper viewing angle to 41° and the lower viewing angle to 39° . This means that the total viewing angle in this case is 80° . Fig. 2 shows the ray tracing of this design. One can clearly see that the first reflecting surface is defined by two different radii, (2,4) instead of just one.

In the past PALs having a diameter of about 40 mm seemed to be adequate for most tasks, but now we choose 25 mm to decrease weight and to have better exploitation of light.

Foveal lens with viewing angle of about 20°

The first problem in designing a foveal lens, - i.e., a lens which conveys the optical information collected in cartesian coordinates from a viewing angle of about 20° , - is that the image has to fill out that part of the ringshaped image where otherwise no optical information is present. (In ordinary PAL-images, namely, one can see in the center only a black spot.)

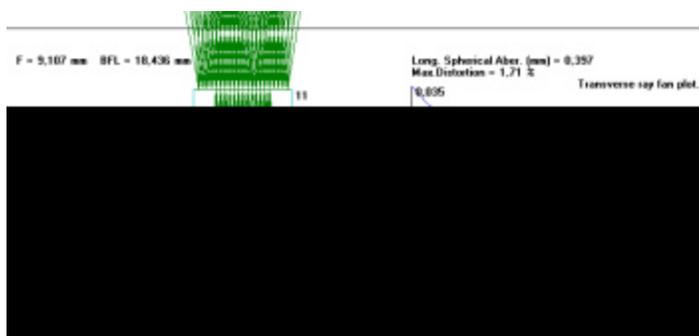


Fig.4.. Ray tracing of the foveal lens

The second problem arises from the fact that if the image plane of the foveal lens and the virtual image plane of the PAL do not coincide, one or both of the displayed images will be out of focus. The ray tracing of Fig.4. clearly shows that we succeeded to overcome this difficulty in our present development.

The ray tracing of Fig. 5. shows how this idea was realized when the foveal lens was put in front of the newly designed PAL, so that their optical axes coincided.

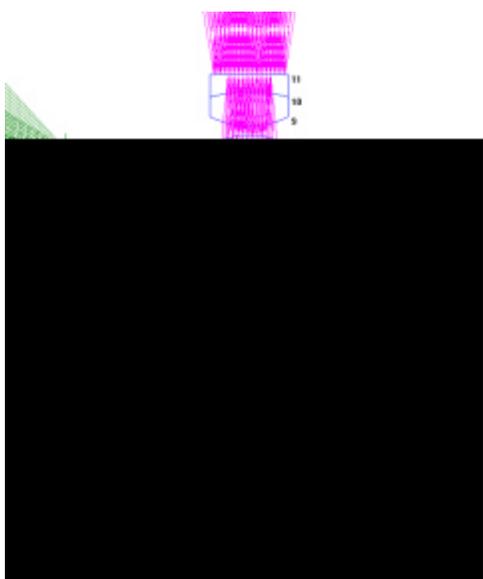


Fig. 5. Ray tracing in Humanoid PAL (HPAL) vision module

Placing a rotatable and inclinable mirror in the optical axis of the HPAL a vision system can be designed, which is capable of displaying any predetermined portion of the 360° ringshaped panoramic image of the 3D space surrounding the vision module, in that part of the ringshaped image where otherwise no optical information is present.

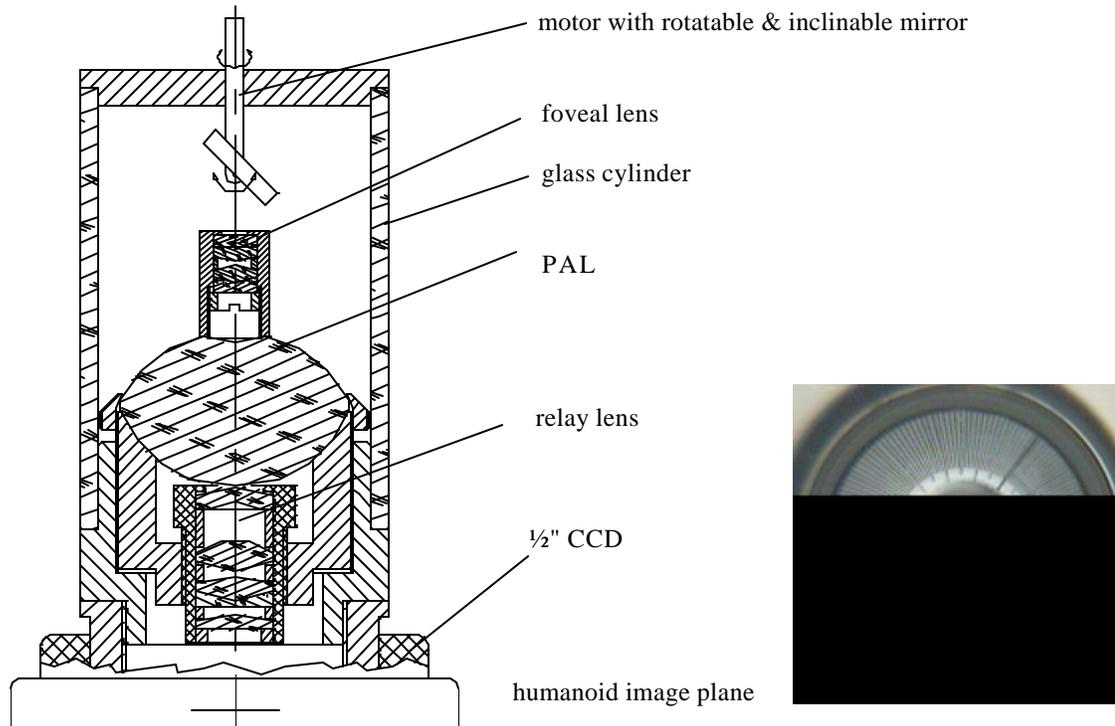


Fig. 5. HPAL vision module

This means that such a vision module will act similarly to the human vision (this is the reason why it is referred to as *Humanoid PAL*, HPAL) since it extracts the information really relevant to the given task.

Technical realization of the designs

When starting the technical realization of the PAL with increased viewing angle, we were facing two problems compared to the PALs where the virtual ringshaped image was inside of the glass block. One, the less severe, was connected to the grinding procedure of the optic, namely, that the first reflecting surface had two different radii. The second one issued from the fact that some portions of the concave surfaces had to be coated with high reflective mirroring layer, while other portions with broad band antireflective layers. Further, an aperture allowing the appropriate image forming of the foveal lens was required.

The tool that makes it possible to perform the above-mentioned procedures was designed with the intention that it could be used again and again. It consisted of three main parts. The sketch of Fig. 6 shows that part of the tool that is used during antireflection coating.

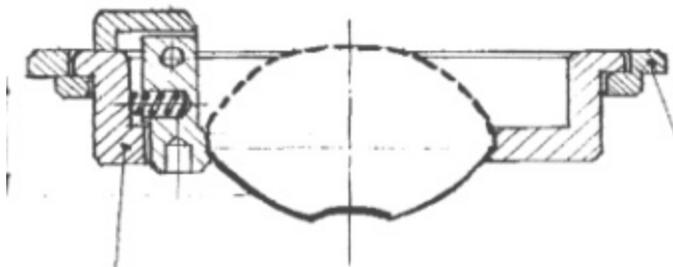


Fig. 6. Position of PAL during antireflective coating

In Fig. 7 one can see how the PAL is inserted into that part of the tool that is used during mirroring coating of the first reflecting surface, while Fig. 8 shows that part of the tool that is used when the aperture for the foveal lens is being produced during coating.

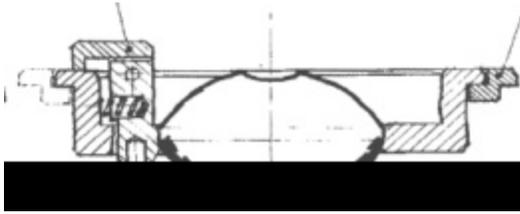


Fig. 7 Position of PAL during mirroring coating

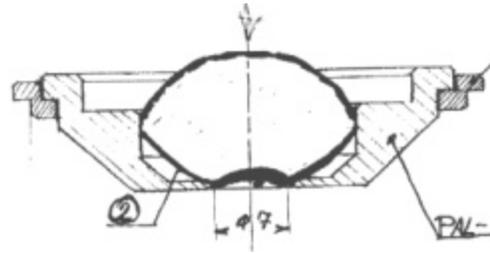


Fig. 8 Position of PAL forming the foveal aperture

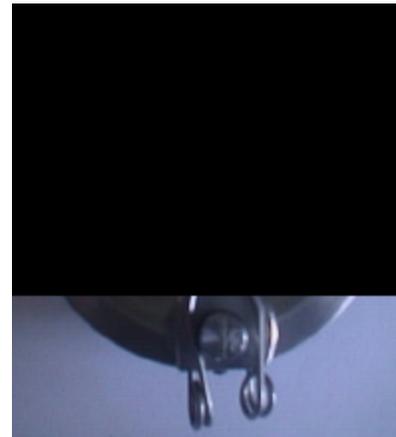


Fig. 9 Technical realization of the tools used in the coating procedures

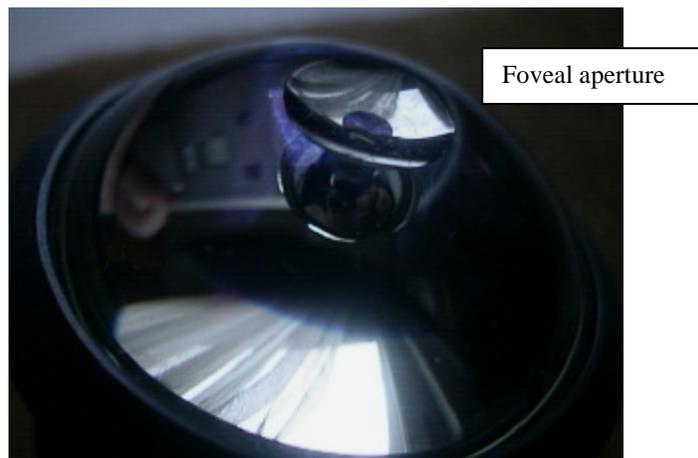


Fig. 10 Result of the coating procedure: HPAL. Observe the foveal aperture in the center of the concave surface

Motor for rotating the foveal mirror

We have set the requirements for the motor to be used for rotating the foveal mirror that can be tilted at will as follows:

1. It should be simple and lightweight structure with a diameter of less than 40 mm.
2. It should allow direct drive.
3. It should not require an electromagnetic brake.
4. Speed control should be possible in stepless regulation.
5. I should allow high precision speed control and position control.

Thus, we have selected an *ultrasonic motor*; a motor based on a new concept, which does not use magnetic force as its driving source. With other words, it does not use coils of magnets. They use ultrasonic vibration (20 kHz or above) as their driving source. They are built up of a stator made of piezoelectric ceramic, and a rotor that are pressed against each other with strong pressure to create tight adhesion. A progressive ultrasonic wave travels along the surface of the stator while undulating (Fig. 11). Only the vertexes of the progressive wave contact the rotor surface, and, as a result, an elliptical rotary motion is generated at each vertex. Since comb-tooth-shaped grooves are on the stator surface that adheres to the motor, the shaft of the motor will rotate clockwise or counterclockwise, depending upon the direction of the progressive wave's travelling (Fig. 12).

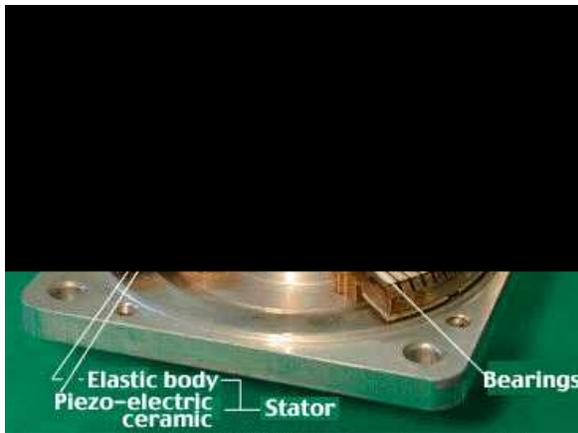


Fig. 11 Inside view of a US motor

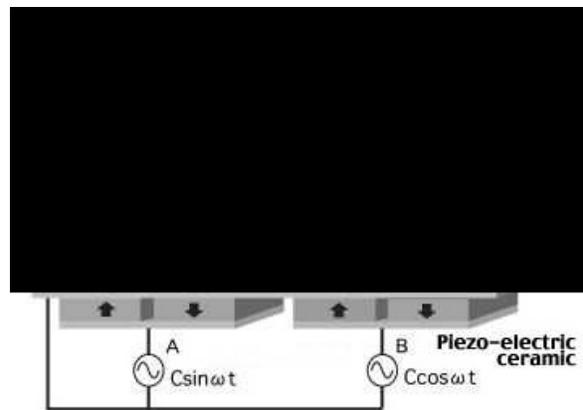


Fig. 12 Explanatory diagram of functioning

For rotating the tiltable mirror in the humanoid vision system we have chosen an ultrasonic motor Type USR30-B3 from Shinsei Corporation, which is coupled to an encoder. (Fig. 13) It has also a factory-adjusted driver with dimensions of 71 by 61 by 22 millimeters. (Fig. 14) The total weight of the system is only 125 gram; therefore, it seems to be rather suitable for HPAL-based portative instruments.



Fig. 13 USR30-B3 (Ø36 mm) motor with encoder

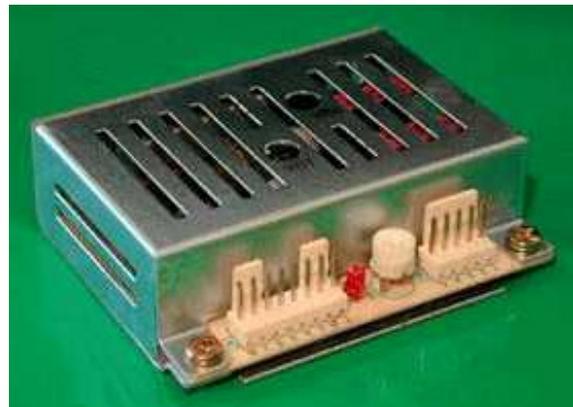


Fig. 14 Factory-adjusted US motor drive

The mount system of HPAL

The mount consisting of several parts was designed in such a way that off-the-shelf lens systems can be used as relay lens. So, e.g., the finite conjugate micro video imaging lenses of EDMUNDS Industrial Optics.

This is achieved by having three positioning options:

- a) The optical distances between the HPAL and the relay lens,
- b) between the relay lens and the camera mount,
- c) between the camera mount and the CCD target,

can be set independently.

Fig. 15 shows the various parts of the mount system.



Fig. 15 Various parts of the mount system

Please note that the foveal lens is *integrated* with HPAL into one single unit

We integrated the HPAL, the mirror and the US-motor via a glass cylinder into a single vision module suitable for designing and realizing ADS and SFDS.

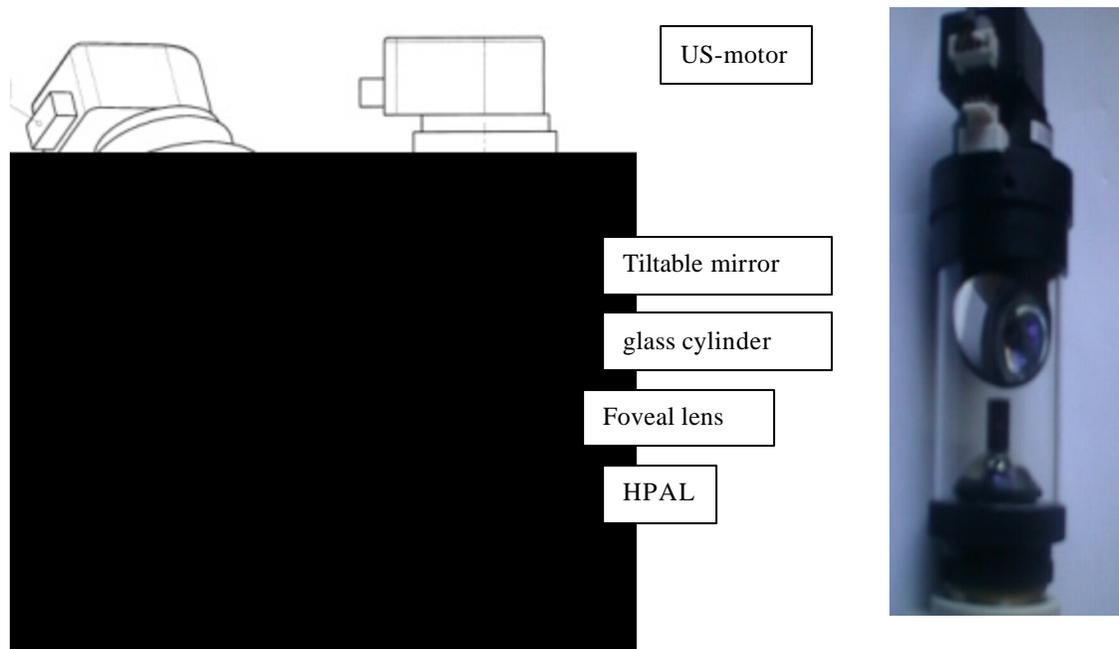


Fig.16. Workshop drawing and realization of HPAL based vision module

Fig.17.demonstrates well that the foveal vision displayed in STW is about 3.5 times larger than that parts of the panoramic peripheral view which it represents.

Theoretically it is possible to design a zoom foveal lens and our new optical design program is capable to this.

Naturally the manufacturing of a zoom foveal lens is rather expensive. Therefore we designed a fix focus foveal lens the viewing angel of which well corresponds with the viewing angel not covered by PAL.

(Video demonstration)

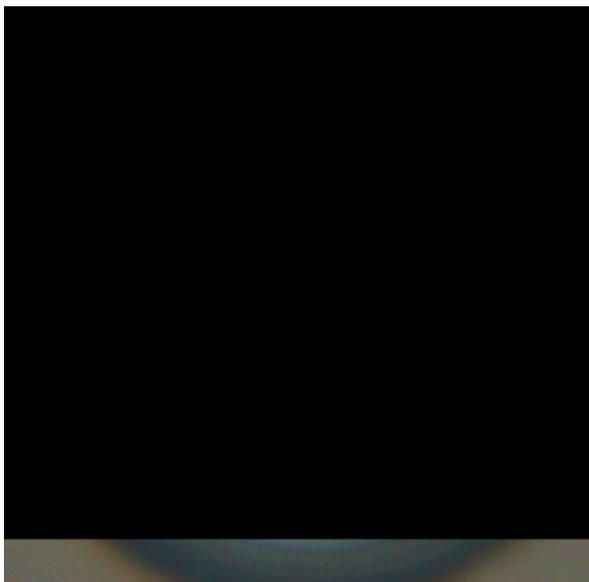


Fig.17. Enlarged foveal view of a selected peripheral site.

Software SATELLITE III

During our collaboration with AnaLogic Computers Ltd. it has turned out that the ACE4k chip available was not only of very low resolution but it was not really designed to have dedicated direct optical input. Thus, the light sensitivity of the chip was quite low, and to eliminate the consequence of noise effects rather sophisticated methods had to be used to filter out regular and stochastic errors. This experience has only strengthened our previously emphasized standpoint, namely, that one should back up the ACE4k chip with another chip.

Our first choice for the secondary chip was a space-variant CMOS retina-like digital chip used in the digital camera known as GIOTTO, developed by Prof. Guilio Sandini of the University of Genova, Italy. It would have been ideal for PAL, since it has an increasing resolution of the periphery up to the center; further, it allows real-time switching from log polar imaging to STW imaging.

Although it is not on the market yet, we had the promise we could buy one from the University. Unfortunately, this could not be realized, therefore, we decided to continue our investigations with a commercially available color camera that uses a 1/2" chip at least. We thought it was necessary to improve the image processing capability of software programs SATELLITE I and II, respectively, we reported on previously. To be able to operate these in quasi real-time, (about 15 images per second), we developed SATELLITE III, which is capable to unwrap the panoramic ringshaped image continuously. It can also perform various filtering procedures, fine edge detection, major edge extraction, summation, subtraction, etc.; further; it can provide a histogram from any direction of the foveal view.

On Fig. 18 on can see the monitor screen showing various options for processing the PAL-image display. The first icon button on the left of the top row of the Dialog Box indicates whether or not the camera equipped with the PAL is connected and ready for processing. The next four buttons serve to calibrate (set angles, upper angle position, lower angle position, center point position). If once calibrated, there is no need to re-calibrate the system again and again, except only after the camera and/or the PAL was changed. The next button with inscription AVI can be used to record real-time happenings the length of which is limited only by the capacity of the computer memory. The remaining buttons activate various filtering operations. *(Video demonstration)*



Fig. 18. Dialog box of software SATELLITE III as displayed on the monitor screen

Clicking on the key **Connection** one connects the CCD camera, which can be picked out from more than 50 brands, to the computer. We used in our experiments a PAL CCIR (Fig. 19)

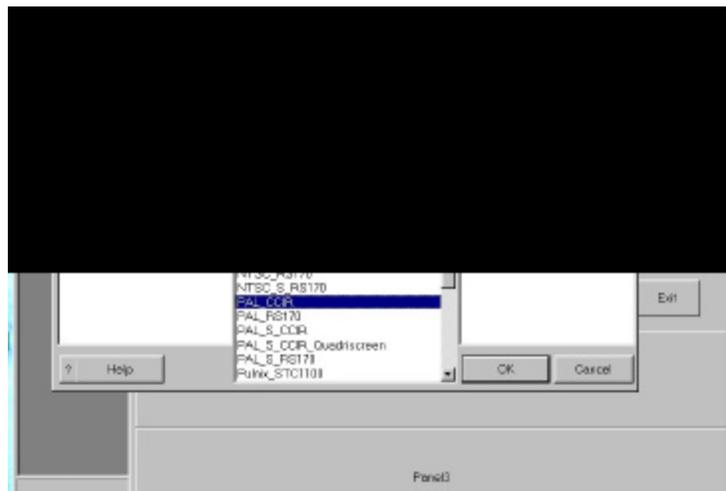


Fig. 19 Menu of selectable CCD cameras

Clicking on the key **Pan start**, the unwrapped version of the PAL image will be displayed on **Panel2** in real time. (Fig. 20) Activating the key **Stop**, and clicking on the key

Split start, - after choosing the direction East (E), North (N), West (W) or South (S) - the unwrapped image will appear on Panel2 and Panel3, each covering a viewing angle of 180°. (Fig. 21)

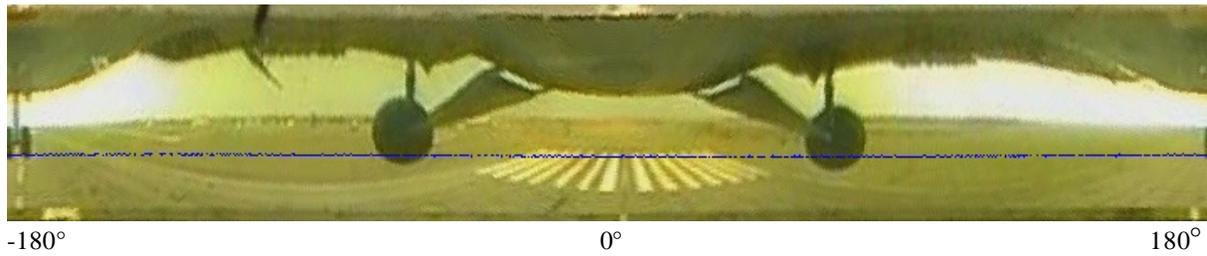


Fig. 20. Unwrapped version of a PAL image. Blue line indicates the OH of the PAL

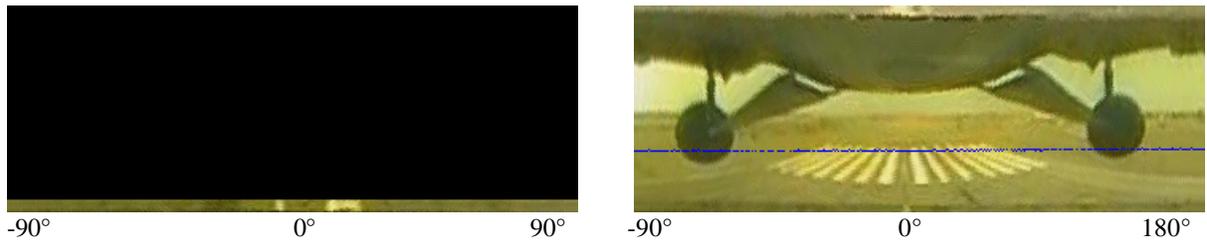


Fig. 21. Peripheral view in the direction of flight (left), and backwards (right) at a given moment

Azimuth Determination System (ADS) & Sniper Fire Location Display (SFLD)

From the point of view of real time image processing there is practically no difference between the software to be used in ADS and/or SFLD. In both cases the well known characteristics of PAL is exploited, namely that the annular image represents the 2D skeleton of the 3D surrounding, and is a function of the viewing angle α of the PAL, as well as of HPAL. It is a function of the viewing angle of the Pal that can be described as the sum of the viewing angles below (α_1) and above (α_2) the plane of the horizon of the optic.

When the panoramic annular image formed by the optic is projected onto the mosaic target of a chip, each pixel along the radii of the projected annular image displays not only intensity values but also a vector value. The reason for this is that radial lines mean lines in space parallel to the axis of PAL, which, however, is always perpendicular to the horizon plane of the optic.

Thus, if an object point is at a distance R from the optical axis and at a distance h_1 below the plane of the horizon, one can write:

$$R = h_1 / \tan \alpha_1$$

If it is above the plane of the horizon, at a distance h_2 :

$$R = h_2 / \tan \alpha_2$$

If now the distance (height) H of the plane of the optical horizon from a well defined location is known, and its inclination from the actual horizon d is also given, the *absolute* distance of the object point (target) from the PAL-based vision module can immediately be calculated. The value H can be obtained, e.g., via GPS. The flowchart of this procedure is shown in Fig.22.

The main difference between the vision modules of ADS and SFLD is that in the first case only PAL is used while SFLD needs HPAL, since its task is not only to detect but also to pinpoint the target, e.g., in such a way that it can be used for missile guidance.

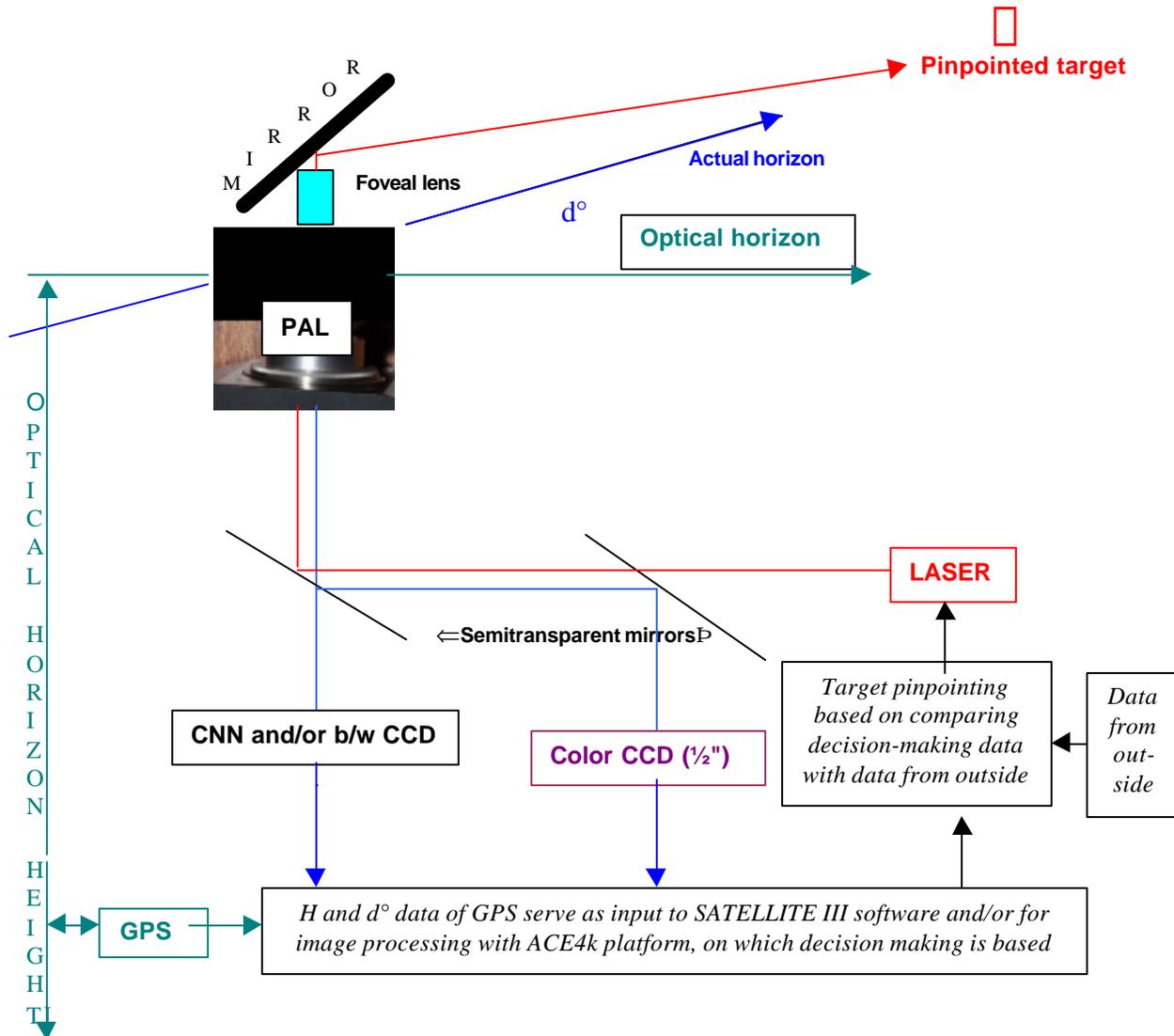


Fig. 22. Flowchart of absolute target distance measurement and pinpointing

Helicopter blade-tracking system (HBTS)

In the Final Report of the Project SPC-99-4065, Contract Order No. F61775-99-WE065, I indicated that a PAL-based measuring system could perhaps be developed for helicopter blade tracking. The proposed system is based on the fact that all rotating blades are of the same length, thus, if they are balanced correctly, their tips will run on the same circle. Placing a PAL-equipped CCD camera, the optical axis of which coincides with the center of this main rotor drive shaft, on the top of the dome protecting the rotating main shaft, the PAL image will not only show the blades being out of track or not, but it will give also a *numerical* measure of being out of track.

I have approached the *87th Bakony Combat Helicopter Regiment's Base* in Szentkiralyzabadja, Hungary, and asked them to help me to check how this idea may work in reality. As a first step, I received the drawings of the main rotary shaft and that of the protective dome (Fig. 23), in order that I design the structure holding a CCD camera equipped with PAL of a diameter of about 38 mm.

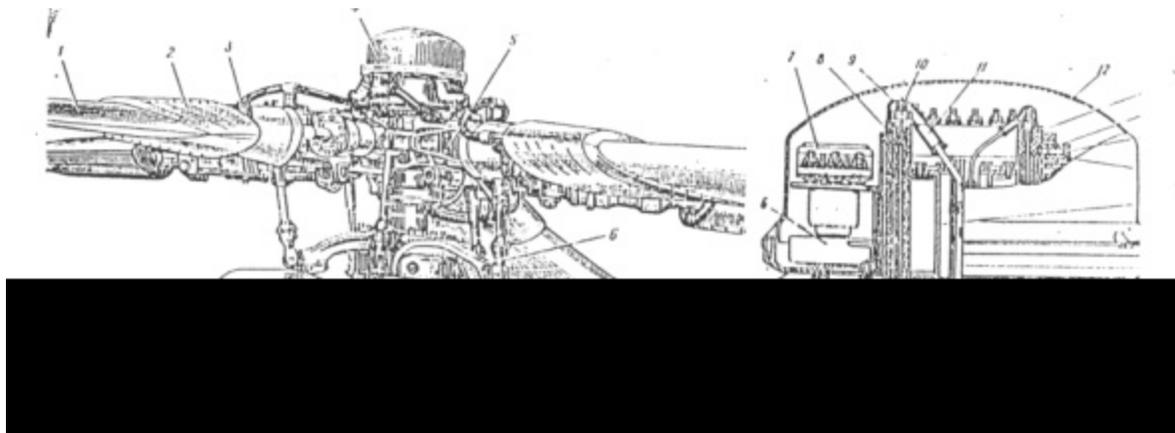


Fig. 23 Main rotary shaft (left) and its protective dome (right)

The workshop of the Base was as kind as to build this system, named ROTOPAL, which can be seen in Fig. 24.

Unfortunately, as a consequence of the re-organization of the Hungarian Air Force, the experiments had to be stopped, the new staff showed no interest in continuing these investigations, thus, we had no opportunity to mount ROTOPAL on a helicopter and to conduct field tests.

Thus, only to get a feeling how ROTOPAL may function, we tested the working of the idea with rotary blades of a ceiling fan, instead of helicopter rotary blades. Using the software SATELLITE III we were able to visualize the tracking behavior of the fan's rotating blades. We have chosen a fan with a diameter of about 1200 mm, which had four shovel-form blades. Their rotating speed could be varied between 1 to 20 rotations per minute.

Fig. 25 shows the panoramic image of the four blades.



Fig. 24 ROTOPAL mounted on the top of the protective dome

More informative is the picture of Fig. 26, which shows the unwrapped version of the PAL image. The undulation of the tips of the blades around the unwrapped optical horizon circle clearly indicates that the blades are out of track.

Perhaps even more information can be extracted from its filtered version, shown in Fig. 27.

As already often pointed out, the width of the annulus of the PAL picture represents the viewing angle of the PAL in its optical axis. Thus, each pixel along a given radius of the panoramic image indicates the direction of an image point in space. (*Video demonstration*)

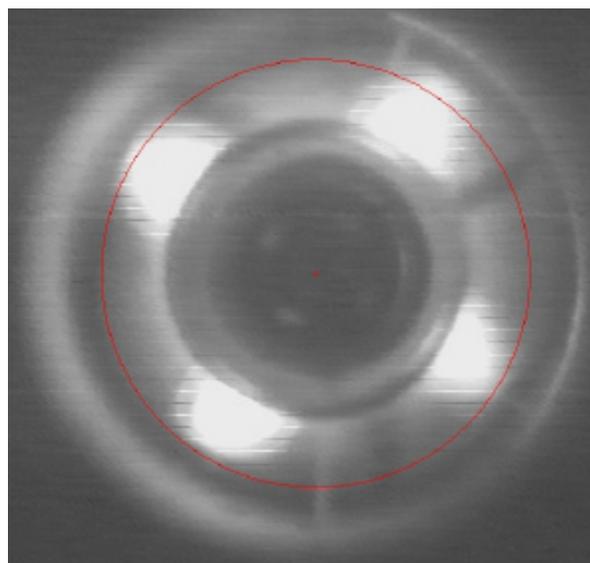


Fig. 25 PAL image of rotating blades



Fig. 26 Unwrapped version of the PAL image of Fig. 22

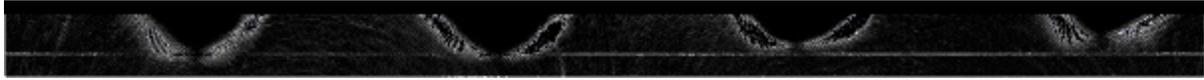


Fig. 27 Filtered version of the unwrapped PAL image of Fig. 23

In our case, the positions of the blade tips are shown in a given moment. Based on the above mentioned knowledge provided that the calibration of both, that of the ROTOPAL and of the software, was accurate, and the length of the rotating blades is known, the amplitude of the oscillation of the blade tips can be calculated and expressed in degrees.

CONCLUSIONS

1. A new humanoid PAL (HPAL) has been designed and optimized with a vertical viewing angle of about 80° .
2. A foveal lens with a viewing angle of about 20° has been designed and optimized.
3. Mount system for HPAL-based vision module has been designed.
4. Based on the designs 1, 2, and 3 a working model of a HPAL vision module using US motor for mirror rotating has been constructed for field-testing.
5. The software SATELLITE-III for real-time image processing has been developed and tested in part during helicopter flight.
6. A satisfying cooperation with AnaLogic Computers Ltd. has been worked out.

Suggestions on how to proceed to exploit the presented results

1. Since a working vision module of HPAL using US motor for mirror rotating is now available, it should be combined with GPS and directly used for military applications such as tracking and pinpointing missiles, independently from which points of the compass they are coming from.
2. Since our simple experiments simulating rotor blade tracking with a practically ready-to-mount ROTOPAL were very encouraging, and having a working vision module of HPAL I suggest that a system should be worked out which is capable of blade tracking during flight maneuvers.
3. In the preliminary design concepts of Reports of the Project SPC-99-4065, Contract Order No. F61775-99-WE065, I already emphasized that PAL imaging considers its surroundings to be cylindrical, then, if one places a mirror cylinder vertically on the center of the annular picture delivered by the PAL, and looking at the cylinder one can not only see the panoramic image rectified but one can also walk around.

This gives me the idea to propose a 360° panoramic projection system for training of helicopter pilot personnel, based on those PAL video recordings, which were shot during flight with a vision module based on HPAL.

We tested this idea by using a monitor having its screen horizontally and projecting on it in real time the pictures recorded by a PAL vision module.

Placing a mirror cylinder in the center of the projected image, which is usually black, one can see in the rectified panoramic image all movements that happened during recording.

Such a pilot system can be seen in Fig. 28.



Fig. 28 Ring-shaped PAL image that was recorded with a PAL-equipped video camera and is displayed on a flat monitor lying horizontally shows the happenings in the surrounding space and is simultaneously being “rectified” with a mirror cylinder placed in the central black spot.

A working model of such a system, called *anamorphic panoramic video*, can be seen till the end of the year 2002 at the one-year exhibition of the Millennium Park, Budapest.