SPACE MAPPING FOR ROBOTICS

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Abstract: In robotics, the need for space mapping means to acquire not only intensity-bound data from the optical signal, which then can be processed to become information, but also data bound to the phase of the signal carrier is of importance. The main objective of this paper is to introduce a new concept for mapping strategy, the so-called centric minded imaging (CMI) on one side, while, on the other side, to demonstrate how this concept has already been applied to robotics in a broad sense, further, which is the situation at present, and what can be expected in the future. Topics such as space robotics applications, machine vision systems for robocar guidance are discussed.

Keywords: centric minded imaging, flow measurement, mobile robot, panoramic metrology, robocar, seabed mapping, see-through-window imaging

1 INTRODUCTION

A robot is defined in general as a machine that performs functions ordinarily ascribed to human beings, or operate with what appears to be almost human intelligence, so, e.g., orientation in 3D space, which means ability of space mapping.

One has to emphasize that for space mapping not only intensity bound data from the optical signal are needed, which can be processed to become information, but also data bound to the phase of the signal carrier. However, according to Webster's Third New International Dictionary, **map** is "*a* ***drawing*** *or other representation that is usually made on a* ***flat surface*** *and that shows the whole or a part of an area and indicates the nature and relative position and size according to a chosen scale or projection of selected features or details.*"

After a thorough examination of this definition it turns out that, in several cases, this type of mapping comprehension is not really suitable to solve the design problems of a robot. A "*drawing"* namely means *recording* of a pattern of a 2D *intensity* distribution, the consequence of which is loss of the amplitude bound data, since intensity = amplitude^2. Further, the retina, and all optical sensor surfaces, natural or man-made, are by nature insensitive to phase-bound data, which means that they are also lost during the procedure of mapping. Thus, since the functioning of the target of a CCD is similar to that of the retina, it seems to be worthwhile to briefly investigate, how our vision system solves problems related to mapping.

Without going into details, one has to be aware of the fact that our vision system processes the information carried by optical signals from 3D space only in *fragments* as if "viewing through a window". [1] The instantaneously perceived view (the sense of sight, the gaze, the "frame") is an intensity pattern on an Euclidean two-dimensional surface, the retina. None of the depth lines carrying the phase information are appearing on the retina parallel with straight lines that can be laid on the retina. I.e., information related to phase differences seems to disappear with increasing distances, which is manifested in the so-called "*feeling of perspective*." However, this is only a *feeling,* an emotion, but not a map in a physical sense. If we wish to record, i.e., to code this feeling on a 2D surface, the lines carrying the information on depth would converge on a seemingly straight line, the horizon, the gathering loci of the so-called *vanishing points*.

Since the *entire* field of vision – meaning the totality of "seeing through a window" – has to be described as a sphere, and a sphere cannot be transformed onto a plane without tear or distortion, as it has been proven mathematically, one cannot map the entire 3D space surrounding the person or instrument that collects optical information from space *in a single shot*. This is the so-called "effect of frame", and the resulting problem can only be solved if one finds a mapping strategy resulting in a *single* vanishing point.

Starting from the observation that our vision system perceives parallax, the basics of spatial orientation, only horizontally, and we have no feeling of parallax vertically, one can assume that it considers the structure of the 3D space to be cylindrical, and therefore a mapping strategy can be found where the “effect of frame” is eliminated. According to this consideration, the mapping system is in the *center* of the 3D space and describes it in polar coordinates, and not on its periphery as in the case of imaging via “see-through-window” method. This concept is called Centric minded imaging (CMI).

In CMI one starts with projecting the cylindrical image volume onto an imaginary cylinder wall located at a distance equal to the *actual vision distance* [2]. By using mathematically well defined stretching maneuvers, this projection can be transformed onto a plane surface perpendicular to the axis of the imaginary cylinder. This procedure is somewhat similar to but not identical with the Mercator projection used in cartography. As long as Mercator projections are displayed in C*artesian* coordinates, in CMI, the geometric relations of the 3D environment are represented in *polar* coordinates. As a result, a new coding of the feeling of perspective in a *single* vanishing point is created, and it is called *Flat Cylinder Perspective* (FCP). In such a map, the points retain the same 1:1 relation to each other as in reality, allowing so a distortion-free omnidirectional mapping of the imaged scene. The width of the resulting ring shaped image corresponds to the viewing angle in the direction of the axis of the cylinder of vision, while concentric rings mean equal distances at a given vertical viewing angle.

2 TECHNICAL REALIZATION OF CMI

Since 1878, when the French astronomer, A. Mangin [3], created the first device for centric minded imaging, several patents have been filed all around the world, claiming better and better performing, non-scanning optics for CMI. They can be classified in two main groups: either they are based on multiplex element design using *several optical elements* such as lenses and/or cones and/or prisms and/or mirrors with coinciding optical axes, while the others use a single glass block with sophisticated shaped refracting and reflecting surfaces, i.e., they are of a *catadioptric* type design.

The most advanced design at present seems to be the *Panoramic Annular Lens* (PAL) [4], a single imaging block having two refractive and two reflective surfaces with the important features that:

a) a miniaturized image volume of the surrounding 3D space is formed *inside*,
b) the center region around the optical axis does not take part in forming the annular image volume, which feature is especially important when space mapping for robocars has to be considered,
c) objects to the front of the lens are projected to the interior of the annular image, and objects to the rear of the optic appear on the outer rim of the annulus,
d) it is almost afocal,
e) the plane perpendicular to the optical axis, where the first refracting and reflecting surfaces intersect, is considered to be the “*plane of horizon*” of the optic,
f) the resulting annular image not only contains data from objects in the horizon plane but it also renders a *two-dimensional skeleton* from the *three-dimensional space*, therefore, e.g., not only the top surfaces of the columns consisting of dices inside a cavity can be seen, but also their side surfaces.

Since, in general, optics for high quality imaging require aspheric surfaces, but the production of these is rather complicated and expensive, therefore it was decided not to use aspherics but to calculate the so-called nearest best-fit spheres. From the various possible approaches we defined – having in mind that the aspheric aperture increases rapidly with both diameter and inverse focal length – the maximum distance between the best-fit sphere and the aspheric in question. question, called aspheric departure, Δ, as approximately

$$D = D^4/4096f^3 \qquad (1)$$

where D is the diameter of the FCP imaging optic, and f the focal length of the aspheric.

Figure 1. Explanation of the phrase “*2D skeleton of the 3D space*”.

3 PANORAMIC MAPPING STRATEGIES

The main objective of this paper is to describe some of the possibilities inherent in panoramic mapping strategy when applied to robotics.

3.1 Panoramic metrology

Optical measurements of interior surfaces of cavities are important in many areas, and the instrument for this is called endoscope. The main disadvantage of conventional endoscopes is that they cannot collect 360º panoramic data without using some sort of scanning technique or rotation of the endoscope. PAL-optics being available changed the situation basically, and several omnidirectional mapping techniques have been developed:

a) **Radial profilometry** uses structured light for space mapping [5]. 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 of the cavity. This light trace is captured by the PAL, it shows the 360º panoramic profile of the inner surface of the given cavity. Any deviation from the perfect circle shows changes in the profile (Fig. 2), and may indicate inclusions, chemical depositions, corrosion, or where combination of thermal and mechanical stresses cause wear or produce cracks, etc. Fig. 3. Shows such a radial profilometer mounted on a robot arm.

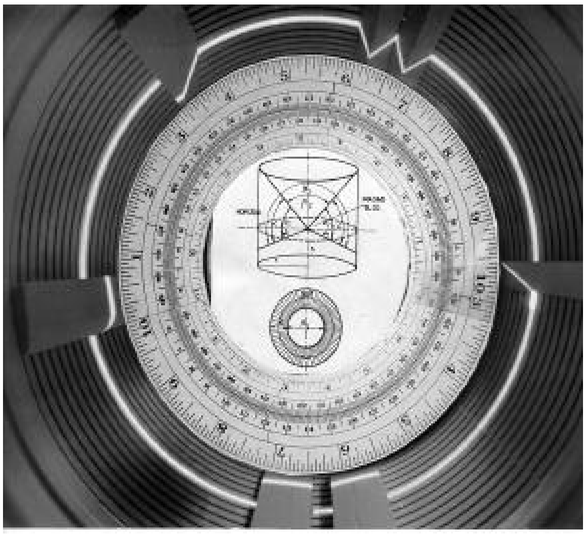

Figure 3. Radial profilometer on a robot arm. showing the 360º contour of a cavity.

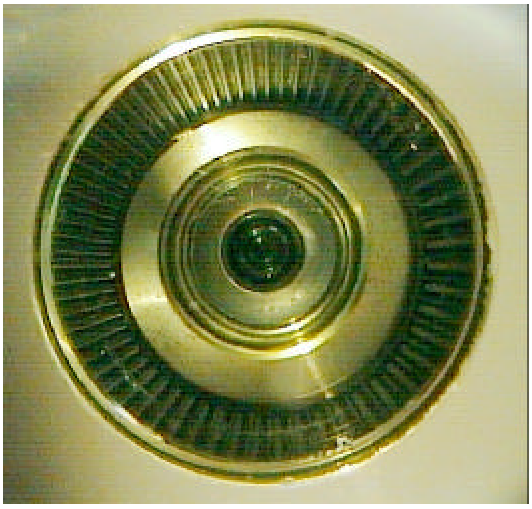

Figure 2. Basics of radial profilometry. Structured light

b) **Radial speckle interferometry**, instead of structured light, uses shadow speckle pattern projected onto the surface to be measured [6]. The resulting annular speckle pattern is digitally recorded and compared either with a reference standard or with another speckle pattern issuing from the deformation or displacement of the cavity. The apparent shift of the speckle pattern is computed by numerical correlation of small portions of each pattern, and used to compute the contour of the cavity with respect to the reference shape.

3.2 Long range mapping

A typical example for *robotic long-range mapping* is attitude determination during space flight. As long as conventional attitude determination systems are rather voluminous and complicated in structure, the attitude determination system based on PAL optic, the PALADS, can be miniaturized to fit into a microsatellite as small as 40 centimeters in diameter [7]. It is based on the idea that a virtual image of the Earth limb and a star is simultaneously formed inside the PAL, and is projected, via an imaging lens, onto the target of a CCD camera. Since the radius of curvature of the Earth is known, the position and attitude of the satellite could be computed relatively easily from the resulting annular PAL-picture. That this idea really works was proven on October 24, 1998, when the SEDSAT-1 microsatellite equipped with PALADS, was successfully launched to orbit from Cape Canaveral at 08:08 EDT (12:08 UTC), as a secondary payload within the Deep Space-1 Project.

3.3 Omnidirectional vector field mapping

Recognizing that the relation between a reflected structured light and its centric minded image delivered by a PAL can be regarded as a relation between an "*object wavefront*" and a "*reference background*", similar to but not identical with the reference background known in optical holography, a panoramic vector field mapping strategy can be developed [8].

The annular image namely – as mentioned earlier - represents the 2D skeleton of the 3D surrounding, and is a function of the viewing angle of the PAL that can be described as the sum of the viewing angles below and above the plane of the horizon of the optic. If now the annular image formed inside the optic itself is projected onto the mosaic target of a CCD, each pixel along the radii of the projected annular image displays not only an intensity value but also a vector value, since radial lines mean lines in space parallel to the optical axis. Therefore, one can write for an illuminated object point below the plane of horizon: $h_1 = R.tg\alpha_1$, and for an object point above the plane of horizon: $h_2 = R.tg\alpha_2$, where R is the distance of the object point illuminated by the structured light from the optical axis.

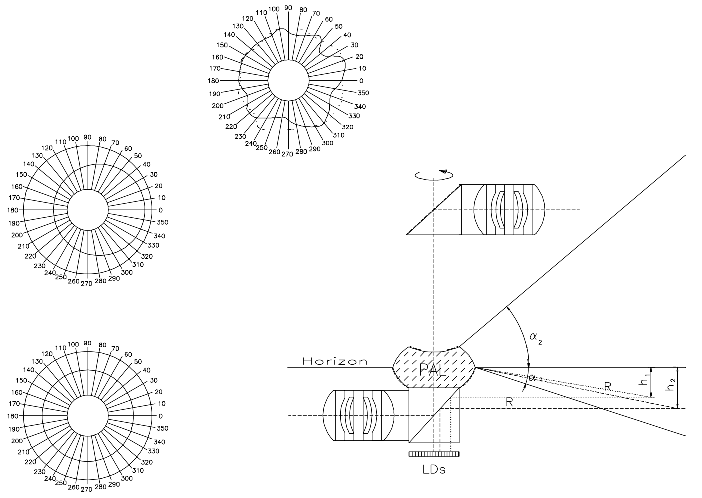

Figure 4. Omnidirectional vector field mapping strategy

The vector value of the object points illuminated by the structured light issues from the fact that each point of the image plane corresponds to a unique set of angles in the cylindrical reference plane as a consequence of the relation between the 2D skeleton displayed in the annular image and the geometric relation of the 3D surrounding

From the philosophy of this mapping strategy it follows that its robotics application capability could be extended by combining with a feature extraction operator (FEO), similar to but not identical with the *tripoid operators,* introduced by F.J. Pipitone [9] for recognizing objects in range images.

First of all, one has to define the "*range pixel*" as the representation of three points in space where three structured lights (probing light) hit the object. The shape recognition is based on pairing the range pixel with a model facet, which is in general in the form of computer representation of the rigid physical object, such as a surface interpolation of a range image, or a surface model of an object obtained from a computer aided design system, etc.

The "structured light hits" show up in the PAL image at a distance **p** from the center of this annular image. This center coincides with the optical axis of the omnidirectional mapping system, and is considered as a **position vector**, the numerical value of which is given by $\mathbf{p} = h \sin \alpha$.

Since the distances between the planes of the structured light emitting sources, and the plane of the horizon for a given mapping system are constant and known, the numerical value of the position vector **p** is available in real time**,** which then can be used to introduce a feature vector **f** of length n, - where n is the number of the scalar measurement made, **-** to facilitate object recognition. This feature vector **f** is an *intrinsic property* of the object, represented by the surface, and it depends on the shape of the object and where the structured lights hit the object.

Let us now suppose that h1, h2 and h3 are distances between the planes of the structured light sources S1, S2 and S3, respectively, and the position vectors belonging to these are **p**1, **p**2 and **p**3. Thus, one can compute the value of FEO

$$k = \{(\mathbf{p}2-\mathbf{p}1)x(\mathbf{p}3-\mathbf{p}1)\}/|(\mathbf{p}2-\mathbf{p}1)x(\mathbf{p}3-\mathbf{p}1)| \qquad (2)$$

Positive values mean local depressions in the surface, negative ones local "bumps". Further, if adequate algorithm is found, the FEOs can be linked together so that we can combine the information gotten from the feature values and use for object recognition and localization. As a consequence, this may provide a base for a variety of increasingly effective methods to extract shape information invariant under rotation and translation of the object with respect to the mapping system.

3.4 Omnidirectional mapping of pollutant concentration

The measurement of concentration distribution of air pollutants around models of buildings and features of terrain is of growing importance in air quality management. With the introduction of the Laser Sheet (LS) flow visualization technique (a structured light technique) a powerful tool for high-resolution tomographic mapping of the concentration field has recently been developed. At the Department of Fluid Mechanics of the Technical University of Budapest we combined this idea with CMI, which resulted in a new method, the PALLAS (PAL + LAser Sheet) for omnidirectional air pollutant concentration measurements. [10, 11]

Preliminary studies are very encouraging and indicate that a small-scale compact mobile measurement device could be designed which fully eliminates the disturbance of flow during measurement, further, the shading effect can also be avoided. As a consequence, complex transport phenomena in the vicinity of solid boundaries as well as immission parameters can be extensively studied.

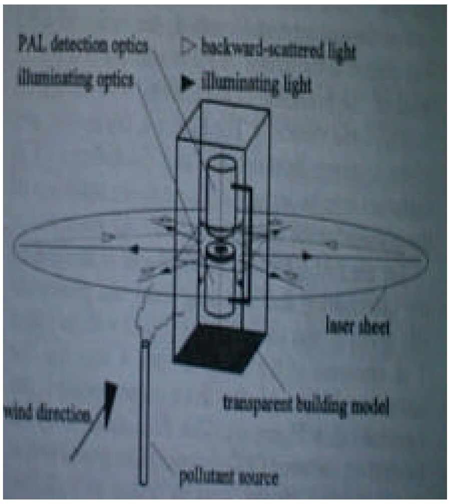

Figure 5. The PALLAS concept applied for studies on pollutant concentration distribution around enclosures.

3.5 One step further: humanoid mapping

The expression *humanoid mapping* indicates a mapping strategy which is somewhat similar to that of the human vision: one can “focus in” on the target of interest in the peripheral field of view, only, in this case, the peripheral view covers 360º, since it uses CMI, instead of about 40º of the human vision.

The technical realization of this idea is based on the recognition that the center region of the PAL around its optical axis does not take part in creating the ring shaped panoramic image, it serves only to transmit the image forming rays.

If an appropriately designed lens-mirror combination is set in front of the PAL in such a way that its image plane coincides with the annular image plane inside the PAL, a picture will emerge in the center of the annular image showing objects in a selected sector of the peripheral image. The target of interest in the peripheral image can be found by rotating the lens-mirror system. Since with this omnidirectional mapping technique one can get information from the target from two different viewing directions, stereoscopic range measurement becomes feasible. As a consequence, this mapping strategy may solve navigation problems of autonomous robocars in several ways. Fig. 6 shows an experimental model of an autonomous robocar under construction by M. Patko, Ph.D. student [12].

Figure 6. Robocar model using humanoid mapping.

The rotating mirror is seen in the extension of the optical axis of the PAL. One possible steering control software would be based on the computation of the panoramic peripheral image flow making comparison between image flow in the left and right peripheral regions. Larger flow on one side indicates that objects in the surrounding are closer on that side, thus, the robot should get commands to steer to the opposite direction. The presence of an obstacle directly in front of the robocar can be detected and the distance computed with the aid of the foveal image. Another possibility is to use the “potential-based guiding”, presented and disscussed in detail in the paper of P. Baranyi et al. [13].

3.6 SEA BED MAPPING

The idea to combine the mapping philosophy of the microsatellite SEDSAT-1 with that of the spherical remote visual inspection and environment sensing system of "*MicrOs*" of Daimler-Chrysler Aerospace inspired some students at our Department to investigate wether or not CMI, this new optical mapping technology, is applicable to underwater robotics. Such a system namely could function as an autonomous underwater vehicle which would display data from the sea surface and map the sea bed simultaneously.

The life-size breadboard model under development by the students was put into a spherical plastic housing having a diameter of 20 centimeters, as shown in Fig. 7. It is thought to serve as a tethered inspection device which would contain an underwater sun compass [14] based on CMI.

Figure 7. Breadboard model of the proposed under-water inspection and mapping device.

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