Proc. 2001 Australian Conference on Robotics and Automation
Sydney, 14-15 November 2001

A Camera as a Polarized Light Compass: Preliminary Experiments *

Kane Usher, Peter Ridley
School of Mechanical, Manufacturing & Medical Engineering
Queensland University of Technology, Brisbane 4001
{k.usher, p.ridley}@qut.edu.au

Peter Corke
CSIRO Division of Manufacturing Science & Technology
PO Box 883, Kenmore 4069
peter.corke@csiro.au

Abstract

Sunlight entering the Earth's atmosphere is scattered by atmospheric molecules producing a polarization pattern that is symmetrical about a line defined by the zenith and the current Sun position. This pattern can be observed and used to establish a reference direction for navigation. This paper reviews the topic and presents preliminary experimental results in which the polarization pattern is detected using a colour video camera.

1 Introduction

In its oldest sense, navigation referred to the process of plotting a ship's course and position. One tool developed to aid navigation was the magnetic compass which provides a reference bearing and a means of determining heading. Other sources used for reference bearings were the Sun and celestial information.

Today, although the methods of sensing the Earth's magnetic field have become more sophisticated (see e.g. [Everett, 1995] or [Borenstein *et al.*, 1996] for a comprehensive summary of magnetic compasses and other sensors), the magnetic compass remains the sensor of choice for a reference bearing. This method of sensing does have a drawback — it is susceptible to error from local variations of the Earth's magnetic field (e.g. due to the presence of metal structures in the environment) [Dudek and Jenkin, 2000].

In our course of research, we are aiming to develop a mobile robot capable of navigating on a building site; clearly metal structures will abound in such an environment. An alternative source for a reference bearing is to use the polarization pattern produced by the atmospheric scattering of sunlight. Lambrinos et al. [Lambrinos *et al.*, 2000] have presented methods of using photosensitive diodes to perceive the polarization pattern and thus derive a reference heading.

A similar approach was taken in this experimental study — instead using a digital video camera to successfully observe the pattern. A camera is an expensive alternative to photo-diodes, it was used for two reasons: (1) convenience; (2) the richness of information provided by a digital image.

The paper is organised as follows: Section 2 provides general background material on polarization, the use of the pattern by animals, and a discussion of related work. Section 3 presents the preliminary experimental results followed by a discussion. Finally, Section 4 concludes the paper and outlines future work.

2 Background

2.1 How is sunlight polarized?

Light incident on any material can be absorbed and partially re-radiated. On entering the Earth's atmosphere, unpolarized sunlight hits atmospheric particles setting them into vibration with a horizontal and vertical component. Light is re-radiated from the particle by this vibration, with the vertical component emitted tangential to the Earth and the horizontal component emitted towards the Earth's surface [Serway, 1996]. In the literature, this horizontal component is known as an e-vector. The phenomena is known as *partial polarization by scattering* and it produces a regular pattern over the entire sky.

Throughout the day, the polarization pattern rotates with the Sun about the zenith. Whilst rotating, the pattern retains two important properties:

1. It has mirror symmetry about the solar meridian (i.e. the line passing through the zenith and the Sun — the pattern is also symmetrical about the anti-solar meridian, the line at 180° to the solar meridian).
2. E-vectors are always perpendicular to the solar meridian [Lambrinos *et al.*, 2000].

Figure 1 shows a pictorial representation of the pattern for a particular time of day. The e-vector pattern is very strong overhead at sunrise, rotating and weakening towards midday, then growing to be very strong at sunset.

2.2 Animals and polarization

Several species of insects are known to use the sky polarization pattern to establish a reference direction for navigational purposes. This was first observed in bees in the 1940s

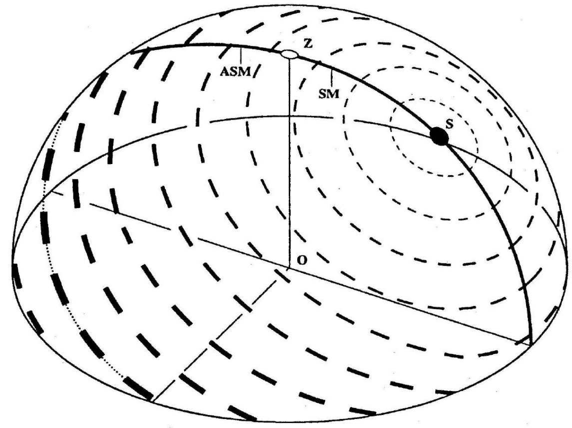

Figure 1: The polarization pattern produced by atmospheric scattering of sunlight. Z denotes the zenith, S is the Sun, O is the observers position, SM is the solar meridian and ASM is the anti-solar meridian. Orientation and width of the bars represent direction and degree of polarization respectively (diagram courtesy of [Lambrinos *et al.*, 2000]).

by Von Frisch [von Frisch, 1970]. More recent research has found that polarized light is used by various species of fish, amphibians, reptiles, and primates — including subliminal detection of the pattern by humans. In 1967, Ramskou [Ramskou, 1967] proposed a theory that polarized light was used by the Vikings in their epic voyages. However, this has since been disputed for lack of evidence (see e.g. [Roslund and Beckman, 1994]).

A simple way to see the pattern is to hold a pair of polarizing sunglasses to the sky and rotate them until a dark band appears. Insects are able to use this pattern for a reference direction with as little as 10% of blue sky visible.

In insects, particular neurons sensitive to polarization have been identified. These neurons receive signals from receptors in the insect eye which are tuned to perceive orthogonal e-vectors (i.e. similar to holding two sheets of polarizing film at 90° to each other towards the sky). Three of these neuron-receptor sets are used, each with maximum sensitivity in particular directions (in crickets 10°, 60°, and 110°). The receptors come in pairs to enhance e-vector contrast sensitivity and to reduce the effect of changes in light intensity [Lambrinos *et al.*, 1997]. One hypothesis as to how insects use the pattern is that they rotate their bodies until there is even stimulation of the pattern and thus their body is aligned with the solar meridian [Rossel and Wehner, 1986].

2.3 Related work

Lambrinos et al. modelled the polarized light sensitive receptors in the desert ant *Cataglyphis* by mounting photosensitive sensors with blue and polarizing filters to the mobile robot Sahabot [Lambrinos *et al.*, 1997] and later Sahabot 2 [Lambrinos *et al.*, 2000]. A sensor consisted of a pair of photosensitive diodes arranged to receive orthogonal e-vectors, i.e each diode in a pair had its polarizing filter rotated at 90° to the other diode, mimicking the receptors in insects. Signals from each diode in a pair were fed into a log ratio amplifier, with the sensor output being the logarithmised difference in a pair of diode readings. This step helped reduce the effects of changes in light intensity throughout the day.

In the earlier paper [Lambrinos *et al.*, 1997], a scanning method of locating the polarization pattern was presented. The robot was rotated 360° recording the output of one sensor (i.e a photo-diode pair) for use in a lookup table. A lookup table is, of course, only valid for a relatively short period of time due to the westward rotation of the Sun about the zenith.

Another problem that arises with this method is the fact that the pattern is symmetrical about the solar and anti-solar meridian so there is a need to distinguish between these two directions (i.e. there is an ambiguity of 180°). Their method of overcoming this problem was to use a set of directional light intensity sensors which detect the light intensity gradient of the environment, identifying which side of the robot the Sun is on.

In [Lambrinos *et al.*, 2000], Lambrinos et al. presented an analytical method of determining robot orientation based upon the polarized light neuron-receptor geometry of the cricket. Sensors whose maximum sensitivity occurred at orientations of 0°, 60°, and 120° were placed on Sahabot 2 and analytical expressions for orientation were derived based on models of sensor output.

Although the method was proven to be successful in their paper, such a setup with three pairs of cameras would prove unnecessarily expensive for a directional sensor and this method was only superficially explored in the present work.

3 Polarization pattern vision with a video camera

The camera used in this experimental investigation was a Sony colour charge couple device (CCD) video camera. The blue component of the camera's RGB output was used for analysis, as polarization of sunlight is most apparent at ultraviolet and blue wavelengths (350 - 450nm). To extract polarised images, linear polarising film was used as a filter. All images were smoothed with a two dimensional Gaussian function, particularly important for the blue output of a CCD camera due to the relatively poor response at these shorter wavelengths.

3.1 Initial tests

Initial investigations attempted to extract a reference bearing from an arbitrary orientation. Two images were taken at a time, with the second image having its polarizing filter axis orthogonal to the first. Some example images follow.

Figure 2 shows a plot of image intensity with the polarizing film transmission axis at 90° to the solar/anti-solar meridian, corresponding to maximum transmission of the e-vector. This position is defined as an orientation of 0° and signifies the position of the solar meridian.

Figure 4 is an image without the polarizing filter. Note its similarity to the image of Figure 2.

Analysis of image sets taken hourly with the same experimental setup (i.e. same filter orientations and camera locations) found some general patterns but extracting useful data has so far proved fruitless. This was, in part, due to a lack of understanding of what we were looking for in the images. Hence, a more fundamental approach was sought.

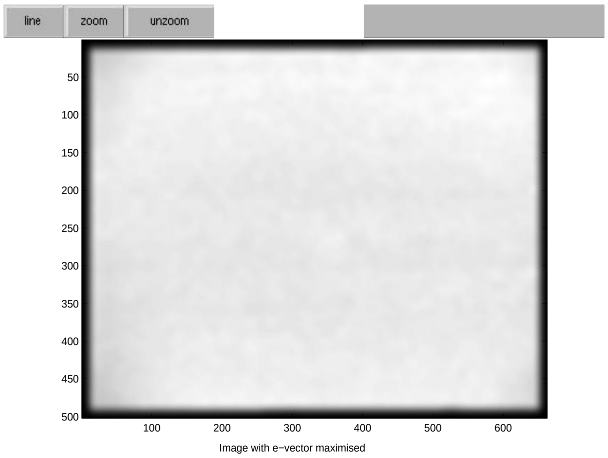

Figure 2: Intensity plot taken with polarizing film aligned with e-vector pattern, i.e. polarizing film transmission axis is at 90° to the solar meridian and transmission of the e-vector is a maximum. Note the relatively uniform intensity in the image.

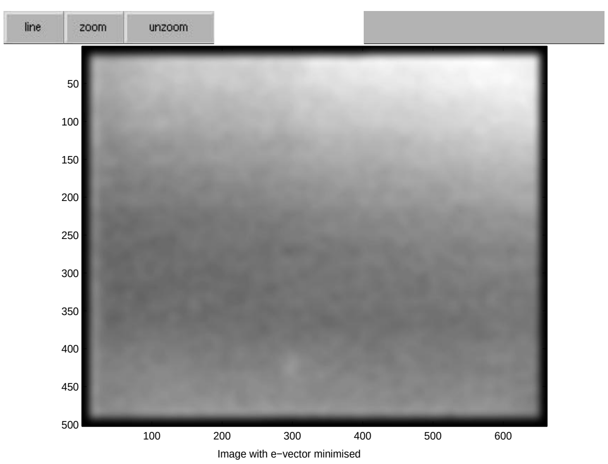

Figure 3: Intensity plot taken with polarizing film rotated 90° anti-clockwise from the solar/anti-solar meridian. Note the band across the middle of the image

Figure 3 shows a plot of image intensity with the filter rotated 90° with respect to the image of Figure 2. This position allows a minimum of e-vector transmission, as the polarising axis is orthogonal to the majority of e-vectors in the field of view.

3.2 Sky scanning

In experiments emulating the scanning method of Lambrinos et al. the camera was rotated 180° in 10° increments.

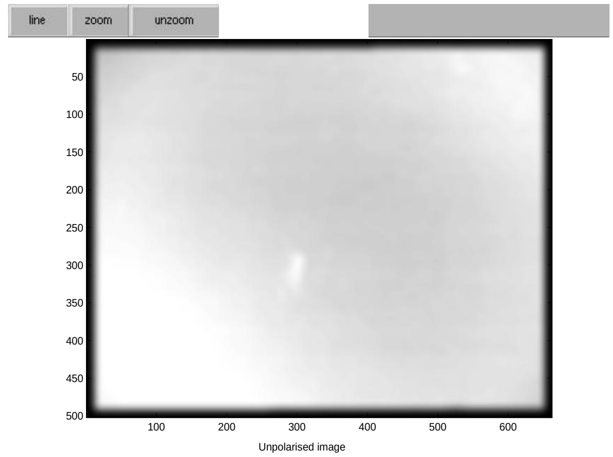

Figure 4: Intensity plot without a polarizing filter.

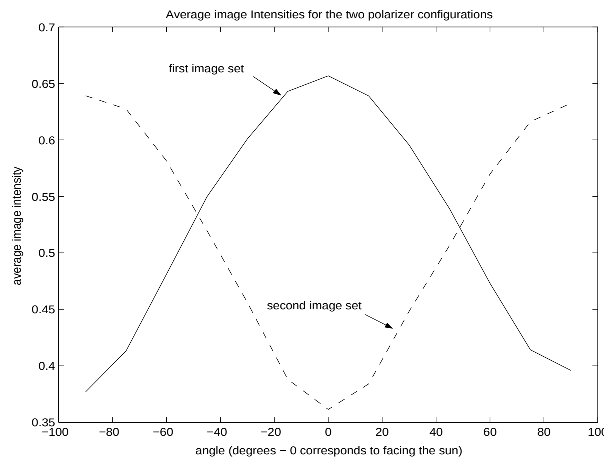

Figure 5: Variation of image intensity with orientation. Images were taken at 16:00 at which time the polarization band is almost overhead so the e-vectors are relatively large. Image set 1 is aligned with the e-vectors at an orientation of 0° which is defined as facing the Sun directly.

Two images were taken at each increment, with the polarizing axis of the first image orthogonal to the second. Zero degrees is again defined to be aligned with the solar meridian and anti-clockwise rotation is positive.

Figure 5 shows the average intensity of two sets of images with orientation. At an orientation of 0°, the average intensity of the first image set peaks. This indicates that the polarising axis of the filter at this orientation is aligned with the e-vector, i.e its transmission axis is perpendicular to the solar meridian. At the same orientation, the intensity of image 2 is a minimum indicating that the polarising filter is orthogonal to the e-vector.

In Figure 5 a mean image intensity is plotted. This is because the camera's orientation could be controlled more accurately than rotating the filter itself. Rotating the camera also rotates the Sun's position in each image and anything other than an average intensity does not have a lot of meaning (the relative position of the Sun would change in each image). Also, this is an easy way of discriminating bright-

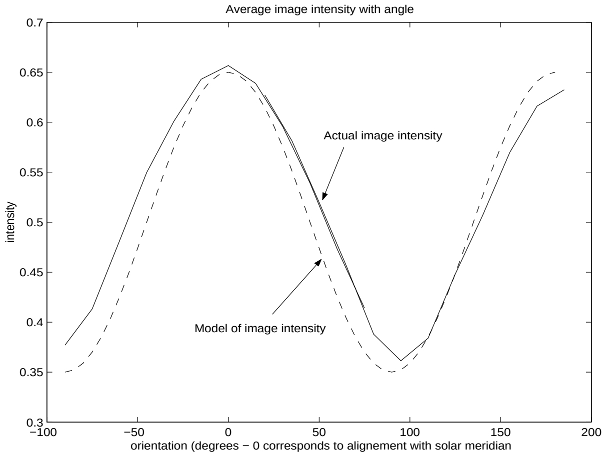

Figure 6: Plot of average image intensity variation with orientation. The sensor model is shown as a dotted curve while real data is plotted as a solid line.

ness differences in the thirteen images of each image set.

3.3 Response model

From the data of Figure 5, a model of the mean intensity as a function of orientation can be obtained. Figure 6 shows a plot of this model which is

$$f(\phi) = K[1 + d\cos(2\phi)] \quad (1)$$

where K is a scaling factor dependent on camera shutter settings and ambient conditions; d is degree of polarization, ϕ is orientation with respect to the solar meridian and $f(\phi)$ is the mean intensity of an image. For the plot of Figure 6, $K = 0.5$ and $d = 0.3$. This model is of the same form as that presented by Lambrinos et al. for their photosensitive diodes of [Lambrinos *et al.*, 2000].

3.4 Initial analysis

In the sensor model of above, there are three unknowns in the equation when an image is taken, K, d, and ϕ. Hence, as an initial test, three images with three different polarizer maximum transmission angles (0°, 45°, and 90°) were taken. By rearranging equation 1 and accounting for the different orientations of the polarizer allows solution of the resulting three simultaneous equations:

$$f(\phi) = K[1 + d\cos(2\phi)] \quad (2)$$

$$f(\phi) = K\left[1 + d\cos(2\phi - 2\cdot\frac{\pi}{4})\right] \quad (3)$$

$$f(\phi) = K\left[1 + d\cos(2\phi - 2\cdot\frac{\pi}{2})\right] \quad (4)$$

These equations were developed for an average image intensity. In this instance, the equations are solved at each pixel in the three images. The results for a set of images taken at 4pm are presented in Figure 7 as a contour plot. The convergence of the contour lines in the lower right hand

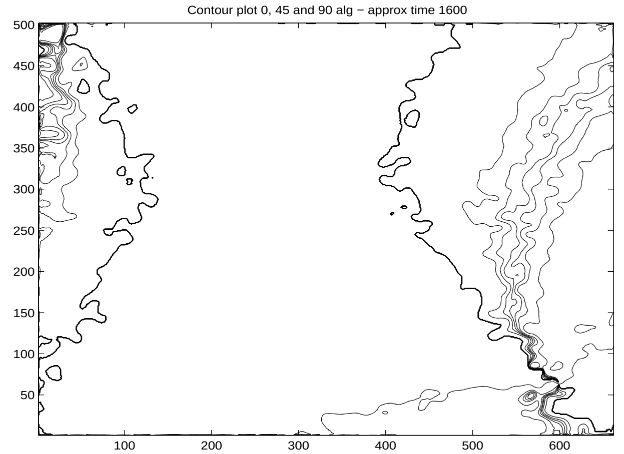

Figure 7: Contour plot of the solution for ϕ. The convergence point at the lower right points towards the Sun's actual position. Images taken at approximately 4pm.

corner of Figure 7 points towards the Sun's position. However, the contour pattern of Figure 7 holds only for early-morning/ late-afternoon, a different pattern starts to emerge between 11am and 2pm.

3.5 Discussion

As shown in the previous section, the scanning method can be used in combination with a digital camera to locate the solar meridian and hence establish a reference bearing. If this method was to be used on a mobile robot, a lookup table could be established before commencing a navigation task. This table would have to be regularly updated throughout the day as the solar meridian used for a reference bearing rotates with the Sun. Solving the ambiguity between the solar and anti-solar meridian should not be too difficult given the amount of data in an intensity plot of a camera image.

The model of mean intensity variation as a function of the orientation of the polarising filter will be important in developing an analytical method of extracting orientation information. The precise meaning of the results plotted in Figure 7 is as yet unclear but the convergence point at the lower right corner appears to shift throughout the day. Future work will focus on how to track this point and to extract it from an image.

4 Conclusion

Clearly a camera is an expensive alternative to the photodiodes used by Lambrinos et al.. However, use of the scanning method with a digital camera was proven possible and it is emphasised that the results presented here are preliminary. Given the richness of information of a camera image compared to the photo-diodes used by Lambrinos et al., it is hoped that further experimentation and analysis can reveal a method of analytically determining orientation suitable for use with either a single camera or a camera pair.

Acknowledgements

Thanks are due to the CSIRO Division of Manufacturing Science and Technology - Automation Group for funding the research.

References

[Borenstein *et al.*, 1996] J. Borenstein, H. R. Everett, and L. Feng. Where am I? Technical report, University of Michigan, April 1996. Edited by J. Borenstein.

[Dudek and Jenkin, 2000] Gregory Dudek and Michael Jenkin. *Computational principles of mobile robotics*. Cambridge University Press, 2000.

[Everett, 1995] H. R. Everett. *Robot Motion Planning - Sensors for Mobile Robots - Theory and Application*. A.K. Peters Ltd, 1995.

[Lambrinos *et al.*, 1997] Dimitrios Lambrinos, Marinus Maris, Hiroshi Kobayashi, Thomas Labhart, Rolf Pfeifer, and Rudiger Wehner. An autonomous agent navigating with a polarized light compass. *Adaptive Behaviour*, 6(1):131–161, 1997.

[Lambrinos *et al.*, 2000] Dimitrios Lambrinos, Ralf Moller, Thomas Labhart, Rolf Pfiefer, and Rudiger Wehner. A mobile robot employing insect strategies for navigation. *Robotics and Autonomous Systems*, 30:39–64, 2000.

[Ramskou, 1967] T. Ramskou. Solstenen. *Skalk*, 2(6), 1967.

[Roslund and Beckman, 1994] Curt Roslund and Claus Beckman. Disputing viking navigation by polarized skylight. *Applied Optics*, 33(21):4754, July 1994.

[Rossel and Wehner, 1986] S. Rossel and R. Wehner. Polarization vision in bees. *Nature*, 323:128–131, 1986.

[Serway, 1996] Raymond A. Serway. *Physics for scientists and engineers (with modern physics)*. Saunders College Publishing, fourth edition, 1996.

[von Frisch, 1970] Karl von Frisch. *The dancing bees: an account of the life and senses of the honey bee*. Springer Verlag, second edition, 1970. Translated by Dora Isle and Norman Walker.