ACOUSTIC APPLICATION OF PHOTOMETRIC STEREO

PF Dobbins SEA, Bristol, UK

1 INTRODUCTION

Optical Photometric Stereo (PS) is a technique that derives information about an object's surface by comparing co-registered images obtained from at least three different illumination sources[1-3]. The information obtained is used to isolate the object's surface normal from the 2D surface colour, and the surface normal can be used to derive the object's 3D shape. In this way, it is possible to make visible camouflaged threats, enhance the visibility of indistinct or concealed objects or, potentially, automatically recognise threatening objects.

Because PS operates on images rather than signals, it is in principle applicable to suitably co-registered images obtained with any imaging technology that uses scattered reflection – including acoustic. Enhancing the visibility of indistinct or concealed objects, or automatically recognising threatening objects would be of great benefit in minehunting where robust classification is an ongoing problem, especially when it comes to discriminating between mine-like objects (MLO) and non-mine bottom objects (NOMBO) of similar size and shape.

With this in mind, we are embarking on a study to evaluate the feasibility of an acoustic photometric stereo system – phonometric stereo – principally aimed at mine countermeasures (MCM) applications.

2 THE CONCEPT

Ignoring colour, a Lambertian surface element may be considered to posses three degrees of freedom, two describing attitude and a third specifying reflectance. Thus, the observed brightness at a given point is a function of both the reflectivity and the orientation of the surface at that point. Three independent images thus give three equations for each pixel with three unknowns. In principle, these can be solved to isolate both the shape and the reflectance of the surface.

2.1 Optical Implementations

A basic optical three-light photometric stereo setup is shown in Figure 1. In this arrangement, the three white light sources are illuminated sequentially (assuming temporal multiplexing – see §4) and three independent but co-located images obtained. Subject to a number of assumptions and limitations discussed below, it can be shown[3] that the surface reflectance, P, and the surface normal (N_x, N_y, N_z) at image location (x, y) can be found by solving an equation of the form

$$\begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix} = P \begin{bmatrix} S1_x & S1_y & S1_z \\ S2_x & S2_y & S2_z \\ S3_x & S3_y & S3_z \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} \qquad (1)$$

where $I1$, $I2$ and $I3$ are the measured image intensity values at location (x,y), and the locations of the three illuminates are described by the unit source vectors $S1$, $S2$ and $S3$.

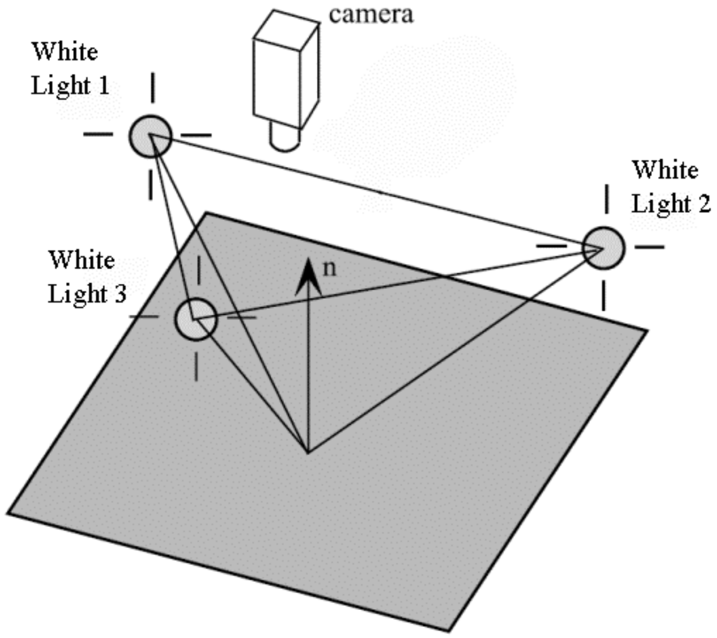


Figure 1 Basic lighting and camera configuration for optical photometric stereo (after Smith and Smith[3]).

It has been shown by Smith[4] that the concept of a surface 'bump map', a term borrowed from the computer graphics community, may be used to represent a photometrically captured detailed 3D surface topography or texture. Figure 2 shows a schematic representation of a surface bump map in cross section.

The bump map, composed of a dense array of surface normal vectors, in essence describing the surface topographic texture in isolation from surface colouring, may be subject to conventional graphical rendering algorithms to produce synthetically illuminated views of fine 3D surface features within artificially configured virtual environments[4]. In addition, it has been shown how the bump map description offers an opportunity for the characterisation of surface topographic features and textures by classifying the observed gradient distribution[5]. Such surface characterization may well be useful in seabed classification applications as well as potentially providing additional information for target recognition in minehunting and similar applications.

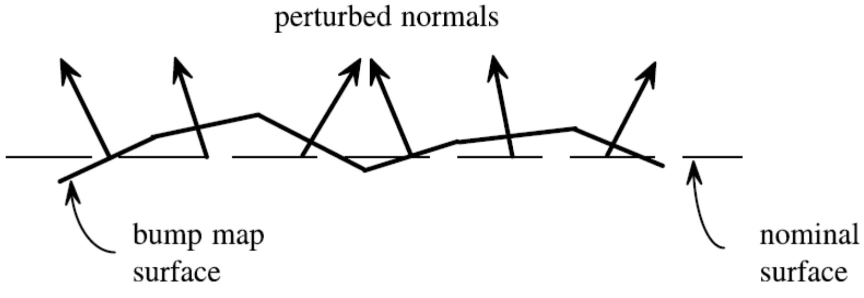
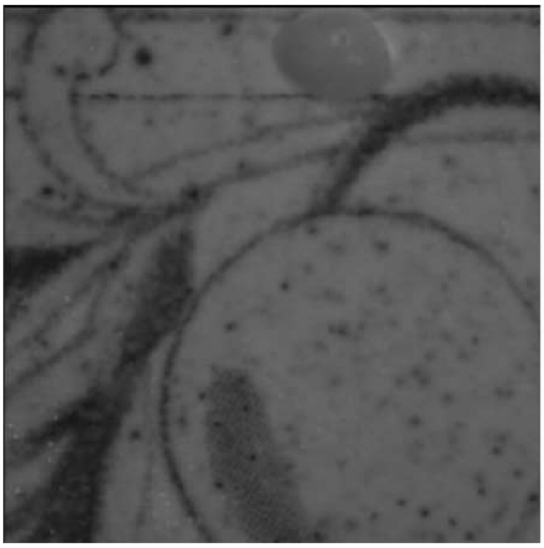
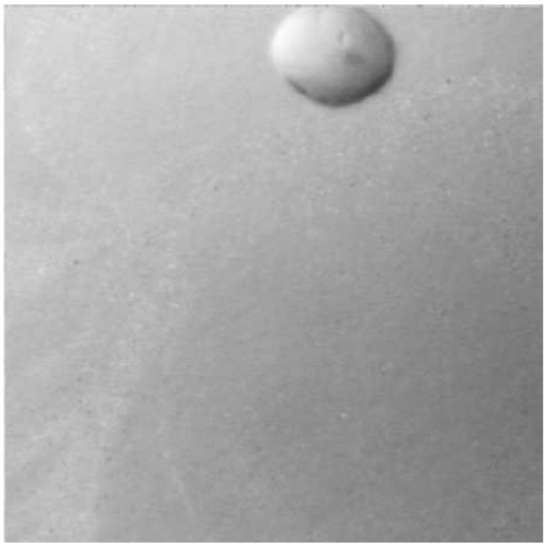


Figure 2 Section through a surface bump map (after Smith[4]).



Acquired image



Rendered bump map

Figure 3 Example of photometric stereo separation of surface pattern and 3D shape hidden by the pattern (after Smith and Smith[3]).

An example of the application of this process is shown in Figure 3. The surface includes a multi-coloured pattern and, at the top of the image, a three-dimensional feature. As can be seen, the surface topography has separated well in the rendered image on the right, whereas it is not easily distinguishable from the pattern in the original image on the left.

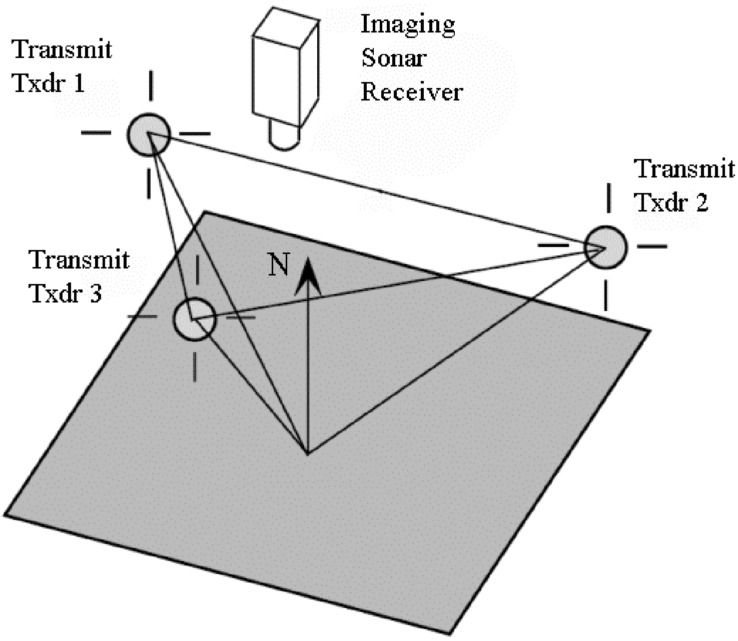


Figure 4 Phonometric analogue of the basic optical photometric stereo setup shown in Figure 1

2.2 Acoustic Implementation

We propose to design an experiment to assess the feasibility of phonometric stereo initially by setting up a direct acoustic analogue of the simplest optical setup as shown schematically in Figure 4, where the illuminating lights are replaced with acoustic transmitters and the camera by an imaging sonar receiver.

The sonar receiver will be derived from one of the many off the shelf high resolution imaging sonars currently available, such as

Tritech	http://www.tritech.co.uk/products/products-imaging_sonars.htm
DIDSON	http://www.soundmetrics.com/
BlueView	http://www.blueviewtech.com/

Such sonars operate at frequencies from a few hundred kilohertz to a few megahertz, and potentially achieve resolutions on the order of millimetres. However, it will be essential to determine which is most suitable for the proposed experiment after considering all the assumptions and limitations inherent in the theory, as described in §3 below.

The transmitting transducers will sequentially transmit broadband white noise, the analogue of incoherent white light, tailored to match the bandwidth of the chosen sonar. A sequence of measurements will be devised, using scaled down mine-like targets to test the system in a variety of configurations including:

- Air filled, flooded and sediment filled.
- Suspended above the seabed, sitting on the seabed, partially buried.

Subject to satisfactory results from the initial tests, we will go on, firstly to check that we understand how the assumptions and limitations applying to optical systems relate to the acoustical analogue, and then to assess methods of obtaining effectively simultaneous images from the three sources, which will be essential if a mobile system is to be developed.

3 ASSUMPTIONS AND LIMITATIONS

Conventional optical PS normally assumes that the viewing and lighting positions are 'distant', with the latter modelled as a collimated point source, and that the surface reflectance is Lambertian. At first these assumptions appear somewhat limiting in terms of achieving a practical application; however they can largely be accommodated in practice.

Although a distant viewing position allows orthographic projection to be assumed, moving the view position closer simply requires that a perspective model be introduced. Equally, the assumption of a Lambertian reflectance may also be reasonably well approximated, either by minimising specularities using polarising filters or by adapting the reflection model. Thus, in practical applications the assumption of a Lambertian reflectance function is not as restrictive as it might first appear.

In acoustics, most surfaces act both as diffuse scatterers (approximately following Lambert's law) and specular reflectors. Additionally, many of the targets of interest will have corners and other features acting as point scatterers. Thus, it is important to determine whether the Lambertian assumption, along with other assumptions and limitations embedded in the optical theory, will limit the applicability of the technique in the acoustic domain.

Overall, the main assumptions applying in the optical case likely to be significant in acoustical applications are as follows:

- Both the viewing and lighting source positions are ‘distant’ – i.e. far field.
- Lights are collimated point sources.
- Surface reflectance is Lambertian – i.e. no specularities.
- Images obtained from each source are independent – i.e. no cross-talk.

As suggested above, techniques for overcoming these limitations have been developed for practical optical systems, or it has been found that the limitations are not restrictive in practice, and we aim to confirm that it is also possible to overcome them in acoustic systems.

4 DYNAMIC OPERATION

Finally, the means of obtaining the multiple images must be considered. Two are sufficient to characterize a more-or-less planar surface, three are needed for a fully 3D capability, and four can eliminate errors due to specular reflections. Static systems could use time multiplexing – only one transmitter on at any point in time – and total channel separation is achieved by temporal separation. A mobile, dynamic system, however, requires concurrent images to ensure that the images can be co-registered even when there is relative movement between the imaging system and the surface under inspection. In the optical case this is generally achieved with either spatial or spectral multiplexing.

Spatial multiplexing involves awkward lighting and shielding arrangements to ensure channel separation and is unlikely to be useful in an acoustic context.

Spectral multiplexing allows multiple images to be captured at a single point in space and time. Channel separation is realized in terms of light frequency (colour) separation, and this would be applicable in the acoustic case. However, problems may arise if the surface reflectance varies with wavelength. This is overcome in optical systems by using closely spaced narrow band channels, and relies on appropriate high precision filters to achieve channel separation.

An alternative for acoustic applications might be a set of orthogonal signals such as different chirps that can be separated with appropriate matched filters, but without further investigation it is not clear whether such coherent signals will lead to image corruption by speckle and other degrading factors.

These various techniques will be reviewed carefully, but it seems likely that the most viable approach for acoustic systems would be spectral multiplexing. Further experiments will be included in the programme to test the feasibility of such techniques, and it will be of especial interest to determine the minimum bandwidth that gives satisfactory results. This is significant because, as described above, if the reflectance of a surface varies with frequency, using the narrowest possible frequency bands will minimise frequency dependent differences between the images.

5 CONCLUSIONS

In this paper, the optical technique known as photometric stereo has been described and the feasibility of an acoustic implementation, phonometric stereo, has been considered. The optical technique uses co-registered images obtained from at least three different light sources to isolate information about an objects shape from surface colour and reflectance. Potential applications of an underwater acoustical analogue are widespread, but enhancing the visibility of indistinct or concealed objects would clearly be of benefit in minehunting.

The various limitations and assumptions embedded in the optical theory have been discussed. However, techniques for overcoming these applications have been developed for practical optical systems, or they have not been found restrictive in practice, and it seems likely that the same would apply in acoustic systems.

An experiment is being planned to assess the feasibility of phonometric stereo, initially by setting up a direct acoustic analogue of the optical setup before proceeding to more general sonar applications. The results of this experiment will be reported in due course.

6 REFERENCES

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