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A compact system to extract topography information from scenes viewed by a miniaturized submersible explorer

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ABSTRACT

In images taken underwater, it is generally difficult to correctly extract distances and geometric information of objects. Different techniques, collectively referred to as photogrammetry, exist to measure features in images. One of these is to project a reference pattern onto an object in a scene viewed by a camera, and register the distortion of this pattern, to calculate the shape of, and distance to, that object. This method is implemented here on a miniaturized submersible explorer equipped with, among many other instruments, a camera. Diffractive optical elements (DOEs) have been designed and manufactured using microsystems technology, to, together with a laser diode, camera, and in-house developed software, provide a compact system for projecting reference patterns and analyzing their deformations. The system has been characterized by measuring the distances and angles of objects in a water tank, and attempting to reproduce their shapes. The range of operation of the system, verified to be at least one meter, is limited by the compact mounting in the small submersible and the cameras' performance. The system was found to work well under turbid conditions as well as in water containing larger particles. Together with a vehicle-mounted camera, the compact and low-power DOE laser projection system enables topographical measurement.

1. Introduction

The *Deeper Access, Deeper Understanding* (DADU) submersible is a cylinder-shaped vehicle, 20 cm long and 5 cm in diameter, under development with the main intention to explore harsh and constricted underwater habitats [1]. Despite its small size, the vehicle will maintain a high functionality by the use of miniaturization technologies, such as microelectromechanical systems (MEMS), for its sub-systems.

The main purpose of the vehicle is deployment through glacial boreholes to explore subglacial lakes, of the kind found, for example, underneath the up to 4 km thick ice sheets of Antarctica [2,3]. However, several other applications are anticipated, for instance: discovery of small cave systems, inspection of pipes, exploration of wrecks, and rescue missions.

Like many remotely operated vehicles, the DADU vehicle will have a camera. It will be forward looking, and thus placed in the bow assembly. This visual imaging system will complement the already developed side-scanning sonar [4], and capture high-resolution images and record videos, and relay these digitally in real-time to an onshore control station through a fiber optic cable connected to the submersible.

A common problem, however, with images taken in a subsurface environment, lacking the usual references with respect to light and shapes, is that they make a very flat impression. It is therefore difficult to estimate the depth, size and shape of the objects pictured, i.e. to perform photogrammetry. Of course, such geometrical information is vital to many scientists, for example, the size and shape of an animal to a marine biologist [5], that of an artifact to a marine archeologist [6], or the shape of geological features to a geologist [7]. In the field of engineering, for instance in underwater constructions [8], the accurate position of objects in 3-D space is also very important.

The already developed side-scanning sonar [4] can obtain the shapes and distances of objects – given high enough acoustical contrast, that is. However, it relies on the movement of the vehicle for imaging, and neither offers color images, nor optical resolution.

For the mere purpose of measuring the distance to an object, an ultrasonic wave distance measurement system [8] can be used. However, such devices exhibit low resolution, and only work for obtaining distances to larger objects. Hence, they will not provide sufficient topological information for smaller and irregular objects as needed in many applications.

Stereovision [9] can be used, but is computationally complex and requires at least two cameras mounted side-by-side and

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separated by a distance, preferably much larger than the diameter of the DADU vehicle and many other miniaturized submersibles.

Laser scanning systems have been developed to measure distances [10,11]. However, as with the stereovision, the system and the distance between camera and laser required to obtain a satisfying perspective are too large. Furthermore, a scanning system usually includes moving parts, increasing the complexity of the system, and maybe also its reliability, and makes it more difficult to integrate into the very limited space in the bow of the submersible.

Another common technique to help extract geometrical information in a scene is to project a known pattern onto objects. In its simples form, this could be accomplished with two parallel laser beams. Limited size estimations can thus be made in the camera view. To increase the number of data points, more lasers would be needed. However, since space is limited in many highly miniaturized ROVs, only a few closely placed light sources would fit, limiting the pattern's shape and coverage.

A system to complement, for instance, the DADU vehicle's visual imaging system with topographical measurements needs to be compact enough to fit with the camera in the nose cone. Furthermore, it should not add substantially to the limited power budget for the vehicle. Here, therefore, a solution using a diffractive optical element (DOE) and a single power-efficient laser diode, to project a pattern consisting of a large number of individual spots onto the scene, is presented. A similar solution has been implemented, for instance, to map the surface of the moon [12].

This paper describes the design, manufacturing, and evaluation of a compact optical pattern projection and measurement system developed for vehicles where size and power are limited, such as the DADU submersible.

2. Background

Generally, a DOE is a single lens through which a coherent light beam shifts its phase and/or amplitude and forms a desired projection pattern on the other side. A kinoform [13] is a DOE lens where the phase of the light is shifted locally by a discrete variation of the optical path length in a pixelized lens.

In this work, a kinoform solution based on sub-wavelength thickness variation of a glass member into pixels a few micrometers wide, is used. The structuring of a certain kinoform cell can be calculated using various algorithms. Here, the optimal-rotational-angle (ORA) algorithm [14], which is based on the simplified solutions of Maxwell's equations of the Fourier Scalar Diffraction Theory [15], was used.

An advantage with the ORA algorithm is that the light intensity of each pixel in the diffraction plane can be set individually. By this, the zero-order spot – the spot in the middle of the diffraction plane, which normally receives a large amount of light – can be weighted to all the other illuminated spots in the algorithm and suppressed by proper adjustment of the pattern. A disadvantage of using the ORA method is that it is slow, since a number of iterations have to be performed and each pixel has to be evaluated individually. The workload increases rapidly with each additional spot in the diffraction plane and with higher resolution in the aperture plane.

The ORA method is here implemented using the numerical computing software MATLAB (MathWorks Inc., USA), in a script henceforth referred to as DOECAD, which produces the required structure of the lens from a desired projection pattern.

For structuring of the DOE lens surface, MEMS-based processes [16] were used. To summarize, the pattern obtained from the DOECAD script was photolithographically transferred into a thin silicon dioxide layer deposited on a glass wafer using two mask layers and a two-step dry etching. Individual lenses of appropriate size were then diced out and mounted in front of a laser diode in the bow assembly of the submersible. With the exception for the projection of the pattern on a flat and perpendicular surface, there is a distortion, which is imaged by the camera and analyzed using in-house developed software to provide quantitative information on distances and topography, Fig. 1.

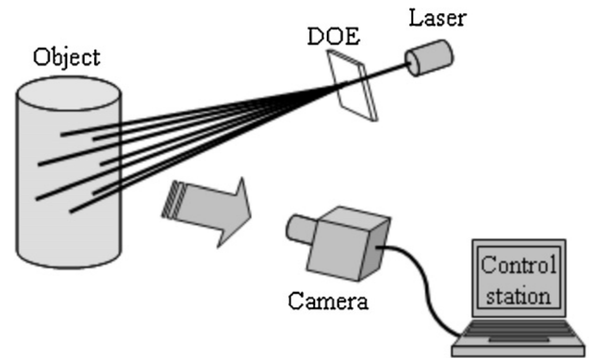

Fig. 1. Working principle of the optical pattern projection and measurement system. A laser and a DOE project a pattern onto an object, which the camera images. Software calculates the distances to each spot.

3. Design

3.1. Patterns

Although the main objective of this work is to investigate how topography can be measured from the quantification of the deformation of a known projected reference pattern, the same system should also be capable of projecting other patterns, e.g., a simple reference grid, a scale bar or a tag. To demonstrate this, 12 projection patterns ranging from regular arrangements of well separated laser spots to almost arbitrary shapes with straight and curved contours made up of relatively closely spaced pixels, were designed, Fig. 2.

With the simplifications of the solutions for Maxwell's equations [15] used by the ORA method [14], a number of restrictions apply to the operation of the DOE lenses. Firstly, a laser source must be used to ensure that the light is coherent and monochromatic. Secondly, the aperture, i.e. the DOE, should not have any features smaller than a few wavelengths in size, resulting in a minimum pixel size in the order of a micrometer or two, when using visible light. In addition, the projection pattern in the transmitted beam should not form closer than at a certain distance beyond the DOE lens, i.e. where the far-field region begins at a few wavelengths away. Lastly, the fan-out angle of the pattern exiting the DOE lens is governed by the wavelength of the light used, and the size of the DOE features, with a larger fan-out angle being obtainable with smaller features.

3.2. Lens design

Using the ORA algorithm, each pixel's contribution is calculated individually and its phase optimized to give as high and even amplitude as possible in the diffraction plane of each desired projected spot. This process is iterated until satisfactory quality of the projected pattern is reached as determined through a control step implemented in the DOECAD script, which enables visual inspection of the pattern. As input, the DOECAD script can use any kind of bitmap file with the desired pattern to be projected, such as those shown in Fig. 2. The output of the script consists of an AutoCAD DXF file (Autodesk, Inc.) with the required DOE designs.

The DOE lenses were designed to have a structure with four levels, corresponding to phase shifts of 0, $\pi/2$, π, and $3\pi/2$. More than two levels were needed in order to create asymmetrical patterns.