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Model effectiveness prediction and system adaptation for photometric stereo in murky water☆

C. Tsiotsios[a,*], T.K. Kim[a], A.J. Davison[b], S.G. Narasimhan[c]

[a] Department of Electrical and Electronic Engineering, Imperial College London, SW72AZ, UK
[b] Department of Computing, Imperial College London, SW72AZ, UK
[c] Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213, USA

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ABSTRACT

In murky water, the light interaction with the medium particles results in a complex image formation model that is hard to use effectively with a shape estimation framework like Photometric Stereo. All previous approaches have resorted to necessary model simplifications that were though used arbitrarily, without describing how their validity can be estimated in an unknown underwater situation. In this work, we evaluate the effectiveness of such simplified models and we show that this varies strongly with the imaging conditions. For this reason, we propose a novel framework that can predict the effectiveness of a photometric model when the scene is unknown. To achieve this we use a dynamic lighting framework where a robotic platform is able to probe the scene with varying light positions, and the respective change in estimated surface normals serves as a faithful proxy of the true reconstruction error. This creates important benefits over traditional Photometric Stereo frameworks, as our system can adapt some critical factors to an underwater scenario, such as the camera-scene distance and the light position or the photometric model, in order to minimize the reconstruction error. Our work is evaluated through both numerical simulations and real experiments for different distances, underwater visibilities and light source baselines.

1. Introduction

Consider a robotic platform operating in a murky sub-sea environment, equipped with light sources and a camera to illuminate and image the scene in front. Imaging and scene understanding in this scenario is challenging for two reasons: (a) light from the sources is backscattered toward the camera reducing image contrast severely, and (b) light reaching the scene and reflected back to the camera is weak and results in dark (and noisy) scene appearance.

Feature-based methods such as Structure-from-Motion are effective in mapping large areas in clear water [14]. However, they fail to perform reliably in murky maritime environments due to the strong image degradation that de-features the captured images and dictates special post-processing [28].

Photometric approaches on the other hand attempt to *model* the cause of image degradation and develop algorithms for scene reconstruction. However, the image formation model in murky water is complex and non-linear, making it hard to use effectively with a shape estimation approach such as Photometric Stereo (PS). For this reason all photometric approaches [15,21,23,38,39] have resorted to approximations to keep the problem tractable. For example, often the scene is assumed to be distant enough that inverse-square law can be ignored and that backscatter does not vary with distance, or the scene is assumed to be close enough that backscattering can be ignored.

The above photometric model simplifications are very effective when applied in the appropriate scenarios. But it is hard for a robotic platform exploring an unknown environment to know a priori which assumptions are valid. Blindly applying a model simplification is very likely to result in poor scene reconstruction. Fig. 1 shows the Photometric Stereo images of a barrel using an ROV in real murky port water, and the reconstruction results using the method of [38] as the vehicle was navigating toward the target. Being too far decreased the *SNR* severely as the backscatter dominated the dynamic range of the sensor and the reconstruction was poor. Being too close also yielded errors, since the photometric model neglected the strong non-uniform illumination on the scene. Since the scene was unknown, it was hard to predict which

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* Corresponding author.
E-mail address: c.tsiotsios@imperial.ac.uk, chtsiotsios@gmail.com (C. Tsiotsios).

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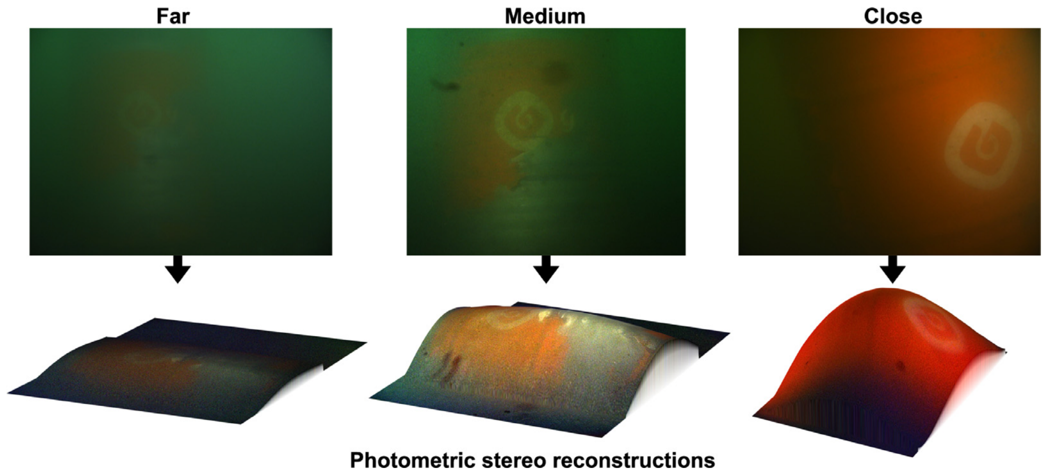

Fig. 1. The underwater images and the respective estimated Photometric Stereo reconstructions of a barrel object using an ROV in the port water of Leixões in Porto, Portugal. The reconstruction quality varied according to the distance. For large distances this was degraded due to the low camera *SNR* and for small distances it was also poor due to the photometric model invalidity [38]. Since the scene is unknown, it is hard to predict the optimal distance (middle reconstruction), or adopt automatically a more effective photometric model or light position.

distance was more effective, or if another photometric model or light source position could have been more successful.

In this work, we propose an effective approach for reasoning about the validity of such photometric models when the scene is unknown. To achieve this, we use a dynamic lighting framework where a robotic platform is able to probe the scene with varying light positions. This approach is based on a simple idea: if the photometric model is wrong for a particular scenario, the estimated surface normals will be erroneous and, more importantly, the error will vary significantly as the light source positions are varied with respect to the camera. On the other hand, if the photometric model is correct, the estimated surface normals will not vary as the source positions are varied.

In short, we obtain a faithful proxy for the true reconstruction error by estimating the change in surface normals under different light source positions. For example, when the source is close to the camera, backscatter is strong and any algorithm that ignores this produces worse shape estimates. But, as the source is moved away (even a short distance), the backscatter reduces [10] and the same algorithm produces better normal estimates. Our proposed dynamic lighting framework offers significant potentials to Photometric Stereo in murky water. The ability to approximate the reconstruction error can be used to adjust automatically: (a) the camera-scene distance, (b) the light position, and (c) the photometric model, in order to maximize the reconstruction quality.

We perform extensive numerical simulations where we mimic realistic scenarios underwater with different medium, distance, and system characteristics. Then, we present a real robotic platform in murky water navigating toward the scene of interest which can move the lighting fixtures along a mechanical arm. We demonstrate our system in the controlled environment of a big water tank, where the platform explores an unknown object for different distances, light positions and scattering levels, and we compare our results with the reconstruction from a depth sensor [24].

2. Related work

During the past years several approaches have shown how the effectiveness of Photometric Stereo can be extended by relaxing some of the limiting assumptions of the original method. [1,31] have shown how PS can be applied in uncontrolled environments where the scene is imaged by different cameras and variant outdoor conditions. Specifically, internet images taken in different weather conditions were used to reconstruct tourism sites. In [25] and [18] the distant-lighting and orthographic projection assumptions were relaxed by modeling the effects of near-field illumination and perspective projection.

Various works have studied PS for the underwater case. The seminal work of [11] derived the image formation model in murky water, and since then many approaches showed how this can be simplified and optimized for the unknown orientation and albedo [15,20,21,23,38,39]. However, the resulting photometric models were used arbitrarily without examining their validity in different conditions. In our work we evaluate the effectiveness of such models considering various distances, scattering levels, light positions and sensor noise, and we propose a novel framework for predicting their effectiveness when the scene is unknown.

Some works emphasized the importance of the imaging system for the quality of the captured images in murky water. The impact of the vertical or horizontal displacement of the sources on image quality was investigated in [11,27], the use of polarizing filters [35,36] or the fusion of two images [37] were proposed to reduce the impact of backscatter, and the optimal separation between the camera and the sources in terms of image quality was calculated in [10] assuming that the scene is planar and the imaging conditions are known. Our work differs significantly from these works. First, because it tackles the problem of shape and albedo estimation using Photometric Stereo and not the improvement of visibility in murky water. Second, our work comprises an automatic approach that requires no prior knowledge about the scene.

In a sense our dynamic lighting system comprises an active approach. However, it could not be compared with active approaches in pure-air [5–7,17]. In these works, a specific photometric model was employed without further investigation. Our work provides the framework for evaluating such models automatically in murky water.

Our work also proposes a way for estimating the optimal light configuration for Photometric Stereo in murky water. Some works have examined the problem of finding the light position that is more robust to gaussian noise in pure air [3,8,16,32,33]. However, once again these works adopted a specific model (distant-lighting) without examining its validity. In our work, we take into account both the model validity and sensor noise in murky water, and we show that the optimal light position varies according to the scenario.