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Visual-adaptation-mechanism based underwater object extraction

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ABSTRACT

Due to the major obstacles originating from the strong light absorption and scattering in a dynamic underwater environment, underwater optical information acquisition and processing suffer from effects such as limited range, non-uniform lighting, low contrast, and diminished colors, causing it to become the bottleneck for marine scientific research and projects. After studying and generalizing the underwater biological visual mechanism, we explore its advantages in light adaption which helps animals to precisely sense the underwater scene and recognize their prey or enemies. Then, aiming to transform the significant advantage of the visual adaptation mechanism into underwater computer vision tasks, a novel knowledge-based information weighting fusion model is established for underwater object extraction. With this bionic model, the dynamical adaptability is given to the underwater object extraction task, making them more robust to the variability of the optical properties in different environments. The capability of the proposed method to adapt to the underwater optical environments is shown, and its outperformance for the object extraction is demonstrated by comparison experiments.

1. Introduction

Since the exploration of the underwater realm has been of interest, a series of underwater observation and research projects have been carried out (e.g., [1–3]). In these tasks, underwater object extraction has been commonly included among the key components of the object tracking or recognition systems. However, the extreme attenuating and scattering properties of the water medium seriously limit underwater visibility, and the degree of this effect is not static but varies with water quality, depth, and sight distance [1–6]. Generally, the underwater image is not only generated by the original light radiated from the object but the accumulation of the imaging light and the hazing light.

$$I_\lambda(x) = J_\lambda(x)\rho_\lambda(x)\exp[-\alpha_\lambda r(x)] + B_\lambda(1-\exp[-\alpha_\lambda r(x)]) \quad (1)$$

where, λ is the color channel,$I_\lambda(x)$ is the acquired photons at point x, $J_\lambda(x)$ is ambient light, $\rho_\lambda(x)$ is the reflectivity of the object, α_λ is the wave-selective attenuation factor, $r(x)$ is the depth and the background light is represented as B_λ. For the additional haze and decayed information in underwater images, the underwater object extraction is more difficult than the ground-based tasks. Moreover, none of these parameters in this model is constant and can be easily estimated in any waters. For example, $J_\lambda(x)$, B_λ are changed with the depth, sky light and the artificial light injected into the water.α_λ is determined by the concentrate of the particles and nutrient in the special water medium. $r(x)$ varies with points in the three-dimensional world. Hence, it is very difficult to completely and truly restore the original information in underwater images. In existing works, the underwater object extraction is either achieved by the state-of-art ground-based methods or based on the image preprocessing. For example, the visual attention model is operated on the underwater image, producing the saliency map for the object detection [7,8]. In [9], a homomorphic filtering is used as a preprocessor to enhance the visibility of underwater images. Moreover, a self-tuning image restoration filter is applied in [10], but the illumination is considered to be uniform, which is a restrictive hypothesis. In [11] the constant background features are estimated for each frame by computing the sliding average over the ten preceding frames, and the average is subtracted from the frame.The ground-based method, for the lack of any knowledge about the special underwater optical environments, cannot gracefully handle the underwater images. Many background regions are possibly mistaken as the object region. By contrast, the image preprocessing method has more sound theoretical foundation. However, many vexing problems in practice remain unsolved. For example, since a sound restoration function is hard to establish and computationally expensive, the most popular algorithms often take advantage of empirically or semiempirically simplified versions [12–14] which however may be partially inaccurate, deteriorating the result of the underwater image restoration and the following object extraction.

Hence, an object extraction method, which is capable to adapt to the underwater optical environment and easy to operate, is required. To this issue, the underwater biological visual mechanism presents us with an available model. Through a long history of evolution, organisms living underwater have developed from a universal common ancestor to a vast diversity of species inhabiting environments with various optical properties [15]. Accordingly, their eyes actively change to adapt to special environments; this

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process results in the variability of the visual mechanism across species [16]. Furthermore, the self-adaption mechanism has also been discovered to allow animals' eyes to adapt to varying levels of light, catering to the need to act diurnally or nocturnally [17]. Modern biological studies have discovered that differs from the mechanism underlying the image restoration: the adaptation ability of the mantis shrimps' visual system originate from the organic metamorphosis which adapt their optical sensitivity to match the most visible and reliable information of the available light when the ambient light changes [16,17]. In this way, only the information which can clearly identify objects is enhanced, while the other information is weakened or even ignored completely. Inspirited by this biological finding, an alternative ideal is given that for underwater object extraction we should completely consider multiple information described various characteristics of objects and try to adaptively extract the most reliable one in the special scene, while not to blindly specialize to any single information. In order to achieve this ideal and practically imitate the biological visual adaptation mechanism, the machine learning approach is employed, denoting which optical information is stable and reliable for the underwater task. Further a prior-knowledge-based multiple information weighting fusion method is developed. The resulting significant improvement in accuracy and adapability has been proved by a series of real-world underwater object extraction experiments. The major novelty of our approach lies in the way to adapt the underwater object extraction to the special underwater environment. Instead of computing the restored or enhanced images by the complicated model, we achieve robustness by imitating to the visual adaptation mechanism which is of outperformance and computationally economical. This paper is organized as follows. Section 2 describes the underwater ambient light adaptation mechanisms reflected in the visual system of mantis shrimps, which is further analyzed through the task of underwater image processing and object extraction. Further the basic bionic model is given in the same section. The key processes, including the adaptive weight estimation and the initial object extraction are respectively presented in Sections 3 and 4. Section 5 is devoted to the brief description of the complete algorithm. Experiments and the obtained results are presented and discussed in Section 6. Finally, the conclusions are sketched in Section 7.

2. Underwater visual adaptation mechanism

Mantis shrimps live at all ocean depths, from brightly lit tropical surface waters to the bathypelagic zones, and at all latitudes. Research on biological systems discovered that the visual system of mantis shrimps is characterized not only by a complicated organ but also by the active adaptation mechanism. This discovery has aroused much interest in the eyes of mantis shrimps. Continual new findings in this field have contributed many constructive suggestions to the task of underwater optical sensing.

2.1. Evolutionary adaptation mechanism

As the research has progressed, scientists have realized that the acute vision of mantis shrimps not only derives from the complicated organ but also benefits from the capability to adapt to the optical environment of the habitat. This ability makes the visually guided predator's sensitivity precisely match the optical properties of the ambient light and helps them to sense the underwater world with a sort of selective light absorption and adaptive fusion mechanism. To show the evolutionary adaptation mechanism, six species are sampled for analysis, as follows: *Bathysquilla crassispinosa*, *Echinosquilla guerini*, *Squilla mantis*, *Hemisquilla mantis*, *Gonodactylus* spp., and *Pesudosquilla ciliate*. These species live at ocean depths of >500 m, 100 m, 100 m, 20 m, shallow, and shallow respectively. The group at the University of Torino reported anatomical results for these species in 1986 [18]. From these data, we can observe that properties including the ommatidium structure, the acceptance angle, the overlap degree of visual fields, and the amount of the ommatidia, typically differ for species that inhabit different depths but share the same characteristics among animals living in similar environments. The close relation between the optical environment and the intra- and extra-structure of mantis shrimps' eyes has been demonstrated. Generally, the shallower environment with its stronger light intensity and wider spectrum band is consistent with more complicated eyes characterized by complete middle-bands, a narrow acceptance angle, increased ommatidia, and a reduced degree of overlap, and vice versa. Applying computer vision theory reveals that these modifications have a strong relationship with the modulation in light sensitivity and visual imaging. In general the resolution and the spectral sensitivity of mantis shrimps' vision decreased with depth, but the light intensity sensitivity increased simultaneously. From this previous study on underwater optics, we find that this trend closely matches the variation in which kind of optical information is dominant and reliable. For example, in the deep ocean, the colors almost decay to vacancy, and the light intensity is weak but relatively dominant over other optical properties. Correspondingly, the middle bands of compound eyes degenerate while the aperture of the single ommatidia increases. According to this modification, we have full confidence in the assumption that in the deep ocean, at the cost of resolution and color information, the light intensity information is enhanced and collected by mantis shrimps as the key cue to sense the surrounding. However, the converse occurs in the shallow water.

2.2. Self-adaptation mechanism

Apart from the variety of visual systems between species, modifications also occur in individuals, and these are driven by the self-adaptation mechanism [17]. Throughout the lives of mantis shrimps, they encounter a variety of light environments. A self-adaptation mechanism in the compound eye and its corresponding neural network allows adaptation to extreme optical conditions. This mechanism also endows mantis shrimps with the ability to modify their visual system to accommodate the daily bright-dark alternation. Anatomical research has discovered that this ability is enabled by the contractile myofibrils in the veils. In a dim environment, myofibrils contract and cones become shorter which make the aperture and the visual field wider. More light enters the cone and transmits to the longer rhabdome. However with the increased overlap degree of the visual field, the resolution of the vision is reduced. The opposite happens in a bright environment.

2.3. Visual adaptation model

During the adaptation process, the task of visual information fusion is essentially optimized.

Combined with the underwater visual imaging and computer vision, the influence of visual adaptation on underwater scene sensing can be deduced (Table 1). It is concluded that the enhanced visual features are varied with optical environments, and closely in line with the changes in the dominant feature of the underwater objects. This adaptation mechanism according to the information fusion theory can be modeled by the linear weighting summation equation mathematically.

$$R = w_C r_C + w_I r_I + w_S r_S \qquad (2)$$

where w_C, w_I and w_S respectively define the reliance of the visual response on the color, light intensity and spatial feature of the