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Biomimetics in Photonic Systems

Mable P. Fok
Photonics and Soft Robotics Lab, School of Electrical and Computer Engineering, College of Engineering
University of Georgia, Athens GA 30602, USA
mfok@uga.edu

Abstract: By learning and mimicking strategies of living organisms, effective photonics systems can be designed to tackle technology challenges. Biomimetics in microwave photonic systems and fiber-optic sensing systems for soft robotics will be discussed. © 2024 The Author(s)

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1. Introduction

After evolving over billions of years, living organisms have developed effective strategies and algorithms to ensure their species' survival. Comparatively, human-made technologies have a very short history for advancement leading to a lot of critical challenges that have not been solved yet. Examining biological algorithms and strategies can lead to inspiration and ideas for improving human lives.

Biomimetics has played an important role in the development of novel photonics structure and materials [1]. However, the use of biomimetic techniques for photonics systems has not been intensively explored. This paper will discuss a few examples of recent developments where biomimetic photonics systems were used for stealth transmission, frequency measurement, and sensing in soft robotics.

2. Marine Hatchetfish Inspired Stealth Transmission

Marine Hatchetfish effectively hide from predators and hunt prey thanks to their underwater camouflage strategies, as illustrated in Fig. 1(a). First, they employ silvering, where the hatchetfish undergoes destructive interference. Next, they undergo counterillumination, where the hatchetfish illuminates the bottom part of their body to the same brightness and color as their surrounding so that their prey will not notice their presence. Inspired by these camouflage strategies, a destructive stealth transmission scheme is designed and demonstrated [2] using optical interference to self-destroy a signal in case of interception. While still allowing legitimate users to retrieve the stealth signal at the designated location through constructive interference. This steganography approach has a major advantage over other approaches - its ability to self-destroy a signal instead of just hiding the signal in plain sight. To achieve this, a photonic based finite impulse response is used to achieve silvering while a wideband optical comb carrier is used to achieve counterillumination. Fig. 1(b) illustrates that the constructive interference condition is at a very high frequency (blue and purple) during transmission causing the secret signal (red arrow) to undergo destructive interference if interception occurs. Once the signal reaches the legitimate receiver, constructive interference is observed at the signal frequency, allowing the reconstruction of the stealth signal. Fig. 1(c) shows the experimental results of the constructive interference (bright red) condition and the retrieved stealth signal (dark red) at the receiver. While the blue curves show the destructive interference (blue) at the stealth signal frequency, such that the stealth signal is self-destroyed and cannot be obtained by the attacker. The results resemble the camouflage behaviour of marine hatchetfish.

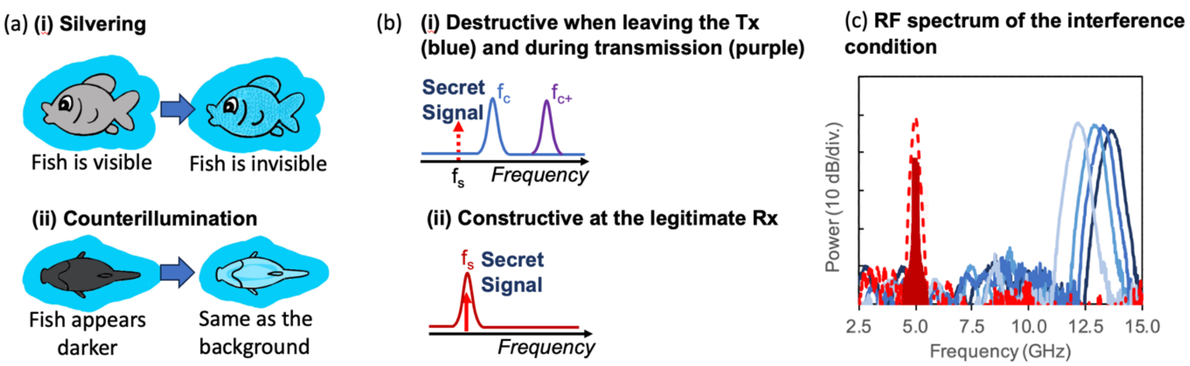

Fig. 1. (a) Illustration of camouflage strategies in marine hatchetfish; (b) Illustration of interference condition of the stealth transmission scheme; (c) RF spectrum of the stealth transmission system.

3. Learn to Hunt – Data Argumentation for Deep Learning in Instantaneous Frequency Measurement

Animals, like tigers, learn hunting through recreating these scenarios. For example, cubs stalk, pounce on, and wrestle with their siblings while playing. Additionally, mother tigers intentionally create opportunities for cubs

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to practice hunting by leaving injured prey for cubs to chase and capture. Inspired by how a tiger learns to hunt without actually hunting, we proposed and demonstrated data argumentation techniques that can be used in machine learning assisted microwave photonics systems. One challenge hindering the use of machine learning for hardware-based microwave photonics systems is the need to capture massive amount of experimental data for training neural networks. We introduce using a generative adversarial network (GAN) in photonic based instantaneous frequency measurement for augmenting data. Allowing deep learning to be practically used in microwave photonic systems [3]. In our experiment, only 75 sets of experimental data are required for data augmentation which then results in 5000 sets of data for training the deep learning model. By employing data argumentation, frequency measurement error has improved as shown by the comparison between Fig. 2(a) and (b). Which represents absolute frequency error of training, validation, and testing of the deep neural network without and with GAN. Data argumentation reduces the amount of experimental data needed by 98.75%, allowing for the effective use of machine learning in microwave photonic systems (Fig. 2(c)). Similar to how tigers become effective predators through artificial hunting scenario.

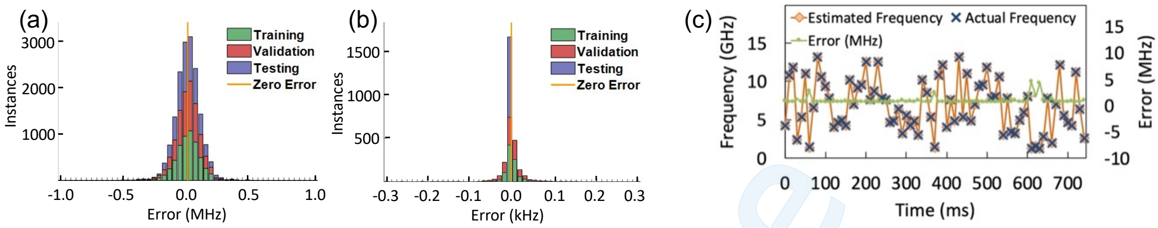

Fig. 2. (a) Absolute frequency error without GAN; (b) Absolute frequency error with GAN; (c) Prediction of frequency and the corresponding error using real data.

4. Twining Plant Inspired Fiber Optics Sensing in Soft Robotics

Twining plants wrap around long objects to support leaf and fruit growth. The twining motion is due to a unique growth hormone in the plant – the tendril's growth rate is slower on the side that touches an object. Due to the discrete multi- points of contacts used as an anchor, a secure grip can be achieved. Inspired by twining plants, high-birefringence (HB) fiber in a Sagnac loop is used as a sensor and is embedded in a pneumatic soft robotic spiral gripper for sensing an object being gripped. The spiral gripper can distinguish the target objects diameter, motion of spiralling, and any external perturbations. Below, Fig. 3(a) shows the soft spiral gripper's design. The gripper when actuated is shown in Fig. 3(b), where it is gently and securely holding a flower. Contact between the object and soft robot is precisely sensed by the embedded fiber optic sensor as shown in Fig. 3(c). Objects with different diameters would result in spectral shifting of the HB Sagnac loop, leading to a change in optical power at a particular wavelength. The fluctuation seen at time = 400s indicates an external perturbation detected by the sensor.

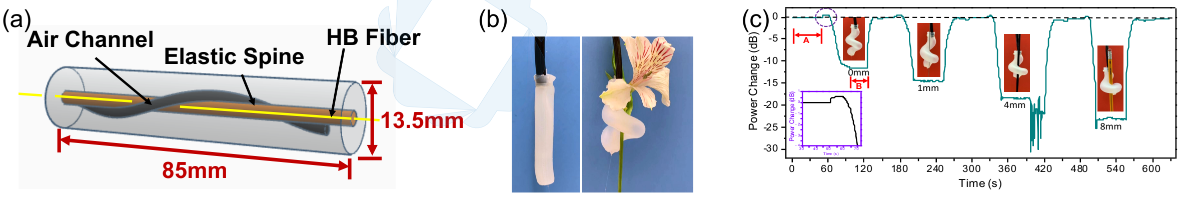

Fig. 3. (a) Design of the soft robotic spiral gripper; (b) Actuation of the spiral gripper; (c) Twining plant inspired sensing ability of the gripper.

5. Summary

In summary, we have discussed several interesting biological algorithms that inspired various photonic systems. We have observed performance enhancements when bioinspired techniques are employed; resulting in a more secure stealth transmission, more accurate and practical frequency measurement system, and a soft spiral gripper with accurate sensing capabilities. There is still a lot of room for us to learn from nature through mimicking biological strategies to improve human-made technologies.

3. References

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