곤충신경망 원심성복사 기반 방향제어 알고리즘

Angel Canelo[1], 김안모[1,2*]

한양대학교 융합전자공학과[1], 전기생체공학부[2]

An insect vision-inspired, auto-tuned efference copy-based flight control algorithm for changing visual environments

Angel Canelo[1], Anmo Kim[1,2*]

[1]Department of Electronic Engineering, Hanyang University

[2]Department of Electrical and Biomedical Engineering, Hanyang University

*anmokim@hanyang.ac.kr

Abstract

Flying insects can process multiple visual features in parallel neural circuits and generate an appropriate action. Neural processing of singly presented visual patterns has been studied intensively in *Drosophila* for the past few decades. How do parallel visual circuits responding to different features presented concurrently are integrated to control a shared motor circuit? An influential theory proposed for combining multiple sensorimotor circuits is an efference copy mechanism, in which an intended action offsets other sensory circuits to prevent them from responding to reafferent sensory inputs caused by the action. Recent studies in *Drosophila* have identified efference copy-like signals in an array of motion-sensitive visual neurons that mediate visual stability reflexes. Using a dynamical systems approach, we implemented two computational models that combine the stability reflex with spontaneous or other visually evoked flight controls such as object tracking and avoidance. The model demonstrates that the visual stability reflex dampens spontaneous as well as visual object-induced flight turns when combined additively and that the modulation of the stability reflex by an efference copy permits undamped, concurrent operation of multiple visual behaviors. Finally, we show that a simple multi-layered perceptron (MLP) can be used to auto-tune its efference copy to match variations in sensory feedback associated with changes in internal or environmental variables. Our study provides an integrative model of vision-based flight control when multiple visual features are presented simultaneously and may be extended to an adaptive flight control mechanism for artificial flying agents such as drones.

1. 연구 배경

Flying autonomous systems, whether artificial or biological, continually run a strong stability reflex loop against wind perturbations to stabilize their flight course. When the system responds to an external object (e.g., avoiding a collision or tracking a target) or turns intentionally, however, these maneuvers put the system off the track, potentially inducing stability reflex via reafferent inputs. Recently, it has been found in Drosophila that the stability loop is briefly suppressed by an internal feedback signal called an efference copy when a fly executes spontaneous or visually evoked flight turns [1, 2]. In this study, we provide a visuomotor flight control model of flying Drosophila that predicts the response of the fly to simple visual patterns. This model reproduces visually evoked flight turns and visual stabilization-like behaviors. Additionally, we also provide an integrative model for complex visual scenes, where multiple visual patterns can take place simultaneously. In this model, we introduce an efference copy, which is used to set priorities between multiple visuomotor pathways and helps to eliminate impediments between them. We further introduce a multi-layered perceptron to auto-tune the efference copy strength depending on the visual feedback, a mechanism that permits the adaptive flight control to changing visual environments.

2.연구 방법

We first developed flight control models based on a classical approach for simple visual patterns [3]. In this approach, the torque response of an animal is modeled as a sum of two independent visual components: one defined

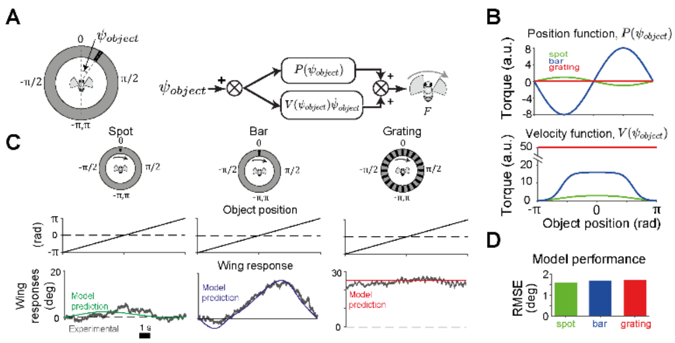

Figure 1. A simple model predicts the torque response of the fly. A. Experimental setup (left) and a model for visual behaviors. **B**. Position and velocity functions were derived from experimental data. **C**. The model predicts fly's wing responses to rotating spot, bar, and grating. **D**. Model performance measured by root mean squared error (RMSE).

by the position of the object (position function), and the other by the velocity of the object (velocity function) (Figure 1A). We calculated the position and velocity functions experimentally from wing responses of tethered, flying *Drosophila* to rotating visual patterns such as a bar, a grating, and a spot (Figure 1B). These models closely predicted the experimental data for each visual pattern when they are presented separately (Figure 1C, D). Natural visual scenes, however, typically comprise multiple visual features, which may activate multiple visual reflexes conflicting with each other. For example, when a fly tracks a bar in an environment with a vertical grating, both the bar and the grating responses are activated, which will oppose each other and slow the bar tracking [4]. We tested this prediction by simply adding the outputs of the bar and the grating models and indeed found a significant reduction in the tracking speed. Moreover, changes in the visual environment (Figure 2A), require the animals to adapt their efference copy accordingly [5]. We developed a simple auto-tuning algorithm in which a multi-layer perceptron adjusts the amplitude of the efference copy to match the reafferent visual input (Figure 2B), and we found that the fly was not interfered with by the grating, permitting flies to respond rapidly to visual objects in distinct visual environments (Figure 3A, B).

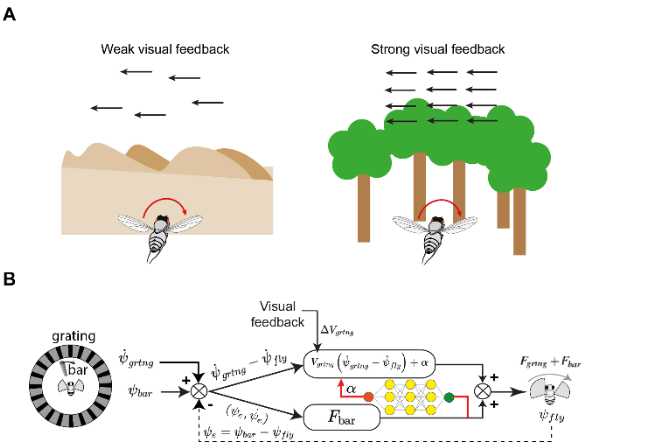

Figure 2. MLP-based auto-tuning of an efference copy for changing visual environments. **A**. Different visual environments change the amplitude of the visual feedback during self-generated turns. **B**. Schematic of an experimental setup where a bar rotates over a grating background. Model diagram of the combination of models for bar and grating including efference copy (α) auto-tuned by the multi-layer perceptron.

3. 연구 결과

We simulated the auto-tuned efference copy model for moving bar and static grating for 3500 episodes, starting from a weak visual feedback environment, and ending in a strong visual feedback environment (Figure 2A). We observed that the response to the bar pattern is slowed down during some episodes (Figure 3Ai) until the efference copy value is updated properly (Figure 3Aii) being in the early and last episodes more synchronized with the visual feedback. The multi-layer perceptron predicts the strength of the current visual feedback and allows the efference copy to be updated after each episode depending on the value of the mean squared error with respect to the bar pattern. We show the mean error over episodes with respect to both, the bar pattern, and the ideal response (when there is no change in the visual feedback) (Figure 3Aiii). The error is minimal in the

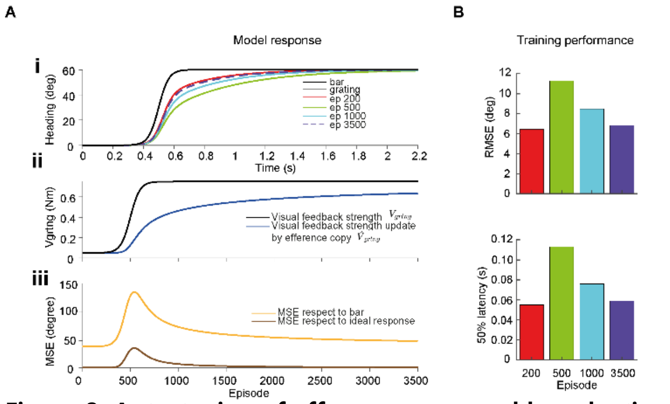

Figure 3. Auto-tuning of efference copy enables adaptive responses in changing visual environments. **Ai**. Responses to a moving bar over static grating background for different episodes. **Aii.** Strength of the visual feedback and the value updated by the efference copy over episodes. **Aiii.** MSE over episodes respect to bar pattern and respect to ideal response. **B.** Training performance in terms of RMSE and 50-% latency.

early episodes but increases when the visual feedback changes. After that, it steadily decreases thanks to the auto-tuning of the efference copy by the MLP. Consequently, the error is smaller in episodes 200 and 3500 than in intermediate episodes (Figure 3B). Similarly, in terms of latency, the response is faster in episodes 200 and 3500 than in intermediate episodes.

We have shown by including the efference copy in our model (Figure 2B) that the response to the bar visual pattern was no longer impeded by the presence of a grating. However, the adaptation of efference copy to different visual feedback strengths in changing visual environments remains to be tested. Our MLP-based model supports the hypothesis that an efference copy can be auto-tuned as the fly gets adapted to a new visual environment (Figure 3Aii).

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5.참고 문헌

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