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Drogue detection for autonomous aerial refueling based on convolutional neural networks

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Abstract Drogue detection is a fundamental issue during the close docking phase of autonomous aerial refueling (AAR). To cope with this issue, a novel and effective method based on deep learning with convolutional neural networks (CNNs) is proposed. In order to ensure its robustness and wide application, a deep learning dataset of images was prepared by utilizing real data of "Probe and Drogue" aerial refueling, which contains diverse drogues in various environmental conditions without artificial features placed on the drogues. By employing deep learning ideas and graphics processing units (GPUs), a model for drogue detection using a Caffe deep learning framework with CNNs was designed to ensure the method's accuracy and real-time performance. Experiments were conducted to demonstrate the effectiveness of the proposed method, and results based on real AAR data compare its performance to other methods, validating the accuracy, speed, and robustness of its drogue detection ability.

1. Introduction

Autonomous aerial refueling (AAR) can greatly expand the effectiveness of unmanned aerial vehicles (UAVs) but is still a challenging task for UAVs.[1] Consequently, AAR has gained much attention due to its vital importance in extending operational range.[2–8] One AAR method, "Probe and Drogue" refueling, is especially preferred for UAVs due to its economy and flexibility. Therefore, more and more researchers are engaged in the development of "Probe and Drogue" UAV autonomous aerial refueling (PD-UAV-AAR).[9,10] PD-UAV-AAR is the exclusive AAR method considered in this research.

Drogue detection, which is vitally important for estimating the relative position and attitude of the refueling drogue, is a fundamental issue during the docking phase of PD-UAV-AAR.[11–21] Vision-based AAR technologies have been utilized to cope with this issue due to their high accuracy and independence. Though there are several vision-based methods employed in the docking phase of PD-UAV-AAR, it is still challenging to develop a robust drogue detection method in

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real-time because of the diversity of drogues available and the various environmental conditions in which AAR takes place. Most of the existing vision-based AAR approaches depend on utilizing artificial features such as light emitting diodes (LEDs)[11–14] and painted marks,[15–17] which require installation and also are susceptible to problems caused by occlusion. In Refs. 11–14, LEDs were placed on a drogue as features to measure the position by visual detection. This does not avoid information loss in image projection and also increases the number of power-supplied wires on the drogue, which creates a potential hazard for PD-UAV-AAR. In Refs. 15,16, a red-ring-shape feature using special materials with highly reflective properties was utilized for effective drogue detection requiring certain modifications be made to the drogue in advance. In Ref. 17, a 3D Flash LIDAR camera was used to conduct AAR ground test demonstrations by detecting strong signals returning from highly reflective materials of the drogue without considering conditions of air turbulence. Therefore, it would be advantageous to directly detect drogues from AAR images during the docking phase of PD-UAV-AAR without utilizing such artificial features.[18–21] Based on the gray value and shape of the inner drogue, Ref. 18 utilized template matching and threshold segmentation to detect the drogue in real AAR data under fair environmental conditions without using artificial features. However, the templates cannot address all drogue conditions, and the experience threshold is hard to define due to drogue and environmental variation. Ref. 19 presents a monocular vision-based approach for AAR based on direct image registration using a complex robotic testbed and estimated drogue position under medium turbulence conditions, also without utilizing artificial features. However, Ref.19 cannot avoid susceptibility to problems of drogue occlusion. Refs. 20,21 proposed a direct drogue detection strategy based on multi-scale, low-rank and sparse decomposition through use of drogue images, and estimated drogue position under fair environmental conditions without features. However, Refs. 20,21 reported that this method cannot detect drogues effectively in complex environmental situations such as in cloud, fog and light-interference conditions.

Fortunately, in recent years, deep learning with convolutional neural networks (CNNs) have surprisingly provided satisfactory solutions to many problems such as image recognition and object detection.[22–24] The region-based convolutional neural networks (R-CNN)[25] can achieve high object detection accuracy. However, the training of R-CNN is expensive in both time and space, and the detection speed is slow. Also, the networks of R-CNN, and its faster versions,[26,27] tend to be very large and have a high number of parameters, leading to low detection speed and the need for a large amount of labeled data to re-train the network after being pre-trained by ImageNet. The research in this paper aims to combine CNNs and a specific domain. The drogue detection for AAR based on CNNs can improve speed to meet the operational requirements of AAR. Many researchers have also been using Caffe, a deep learning framework utilizing GPUs for the advantages of expressive architecture, extensible code and high speed.[28] Thus, technologies utilizing a Caffe deep learning framework with CNNs have received much more attention by many research facilities.

Motivated by the above discussion, we propose a novel and effective method based on the Caffe deep learning framework with CNNs for real-time drogue detection during the docking phase of PD-UAV-AAR without artificial features, which both avoids being susceptible to problems caused by the occlusion of the drogue and realizes effective drogue detection under complex environmental situations. Firstly, in order to ensure the robustness of drogue diversity under changing environmental conditions, achieve optimal performance of drogue detection and avoid the potential dangers mentioned above, the proposed method directly uses real AAR images with the drogue extracted from "Probe and Drogue" aerial refueling videos not utilizing LEDs or other manually-made features. The "Probe and Drogue" aerial refueling videos contain diverse shape, size and occlusion of drogues under various conditions such as fair, cloudy, foggy and light-interference. An experiment is then conducted on the Caffe deep learning framework with CNNs by use of GPUs to test our proposed method on real "Probe and Drogue" aerial refueling data. Finally, the results of drogue detection and its accuracy analysis are discussed together with a comparison between the proposed method and competing methods. Reported competitive results for drogue detection are compared by using the deep learning idea. The experimental results on real AAR data show that the proposed method is effective in drogue detection in various situations, adding to the list of successful applications of deep learning methods. Our contributions can be summarized as follows.

(1) A novel framework for real-time drogue detection during the docking phase of PD-UAV-AAR that utilizes CNNs with GPUs without using manually-made artificial features.
(2) A robust drogue detection method that can not only avoid being susceptible to problems caused by the occlusion of the drogue, but also performs effectively under complex environmental situations such as in cloud, fog and light-interference conditions.
(3) An efficient drogue detection method that can ensure highly accurate, robust and speedy performance.

2. System design

We present a method for drogue detection during the docking phase of PD-UAV-AAR based on a Caffe deep learning framework with CNNs that performs well without the need for setting artificial features on the drogue. A deep learning dataset of images for drogue detection, fundamental for the robustness and accurate performance of the system, was prepared in advance that contained diverse drogues with various environmental conditions. By use of deep learning and GPUs, an experiment was conducted on real data from "Probe and

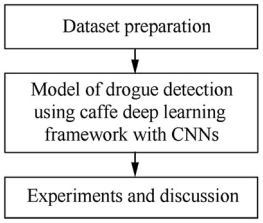

Fig. 1 Drogue detection for PD-UAV-AAR based on CNNs.