Energy-Sensitive Vision-Based Autonomous Tracking and Landing of a Quadrocopter on a Moving Platform

Georgios Zamanakos, Adam Seewald, Henrik Skov Midtiby, and Ulrik Pagh Schultz
SDU UAS Center, Mærsk Mc-Kinney Møller Institute
University of Southern Denmark
Email: {*}@mmmi.sdu.dk

***Abstract*—abstract abstract abstract abstract abstract abstract abstract abstract abstract abstract abstract abstract abstract abstract**

I. Introduction

Unmanned Aerial Vehicles (UAVs) are increasingly used for applications such as monitoring, surveillance, transportation of small payloads, and agricultural applications [1], [2]. One of the major constraints of such applications is their limited level of autonomy due to battery limitations. Extending the flying time of a UAV is normally done by having it land in order to replace or charge the battery before continuing the mission. Performing landings autonomously can however be challenging depending on the environment and whether the landing platform is stationary or mobile. Moreover, relying solely on the availability of a GPS signal for autonomous precision landing is not considered safe, since GPS signals can be temporarily lost or even tampered with. As an alternative, in this paper we investigate the use of a novel vision-based autonomous landing system, and evaluate its robustness towards environmental conditions such as visual disturbances and wind.

Extension of the flight time can be also achieved by using *energy-sensitive algorithms* that can reduce energy consumption by reducing the quality of service (QoS). With this approach, energy-costly computations such as computer vision are adapted by selecting the desired quality of service (QoS) to match the available energy [3]. By combining energy-sensitive algorithms with autonomous landing capabilities, we aim to increase the total availability of the UAV to perform operations, by extending the flight time and using autonomous recharging when needed.

The main contribution of this paper concerns the experimental study of a robust, energy-sensitive, vision-based algorithm for autonomous landing in varying environmental conditions. The algorithms are executed on an NVIDIA Jetson Nano companion computer controlling a simulated drone using a hardware-in-the-loop experimental setup. The vision-based landing algorithms provide novel capabilities in terms of tolerance to visual disturbance and varying environmental conditions such as wind. Our experiments are based on an agricultural use case where a quadrocopter UAV performs visual identification of ground-based hazards while tracking and landing on a moving tractor.

II. State of the Art

Vision-based autonomous landing on a marker has been extensively studied by many researchers. Key distinctions include whether the marker is on a moving platform, the type of the marker, the algorithms used to detect it, as well as the mounted sensors on-board of the UAV.

For stationary platforms, one of the first experiments with vision-based autonomous landing was conducted by Saripalli et al. [4]. Here, a helicopter with a color camera facing vertically towards the ground would land on an "H"-shape pattern (similar to ones found on a helipad) using a hierarchical behavior-based control architecture. In physical tests a marker of 122cm$\times$122cm size was detected for a maximum altitude of 10m. A landing marker inspired by a QR code but consisting of three artificial markers is demonstrated by Yuan et al. [5], and was shown to provide a 6-DOF pose over an altitude range of 0-20m. Our work is however focused on the ability to land on moving platforms.

Saripalli et al. [6] also demonstrated the use of a Kalman Filter to track a moving platform. However all the computations were performed offline. Similarly, an ArUco marker was used as a landing marker by Lee et al. [7] to detect a moving platform. The control of the UAV is performed based on the error provided by the vision algorithm but all the computations were performed off-board. Arrar, et al. [8] focus on extending the detection range by using an AprilTag [9] as a landing marker. Again all the computer vision algorithms were also executed off-board. A crucial aspect of our application is to perform all the computations on-board, and to evaluate them according to their energy efficiency as a function of QoS.

The design of the marker and choice of sensors can facilitate doing the computations on-board. Chen et al. [10] utilized a marker consisting of a circle and rectangles of different colors along with a LiDAR scanning range finder for height estimation. The marker was detected by performing color segmentation on the incoming image frame. By fusing the height measurement from the LiDAR into the vision measurement, a relative pose of the UAV from the moving platform was obtained. A color segmentation approach was also implemented by Lee et al. [11]. A red rectangle was used as a landing marker and a vertically facing camera with a fisheye lens was used to detect it, and a successful landing from an altitude of 70m was demonstrated. Both teams have used an on-board companion computer to perform all the computation on the UAV. However a color segmentation approach is not considered as a safe option for a realistic (outdoor) case it would be difficult, if not impossible, to ensure that the landing marker will be the only object of a specific color in the scene.

The use of a hybrid camera system consisting of a fisheye IR camera and a stereo camera was demonstrated by Yang et al. [12]. An ArUco marker was used to mark the moving platform and a convolutional neural network (CNN) Yolo v3 was trained specifically for marker detection. A similar approach concerning the detection of a landing marker was demonstrated by Nguyen et al. [13]. Here a specific landing marker was used and a specific CNN was used to detect it: successful detection of a 1m$\times$1m marker size was demonstrated from a distance of 50m. An AprilTag marker was used as a landing marker by Kyritsis et al. [14] for the purpose of "2016 DJI Developer Challenge". The identification of the AprilTag marker was performed through Graphics Processing Unit (GPU). The three teams have utilized the companion's computer GPU to detect the landing marker. In the agricultural use case addressed in this paper, the GPU is however needed for a CNN to detect ground hazards, and since the GPU cannot simultaneously run different algorithms, the CPU should be used for detecting the landing marker. By doing so, a different QoS could be chosen for each algorithm.

To account for the energy modeling of computer vision algorithms, we considered the work previously carried by Nardi et al. [15]. The authors present SLAMBench, a framework that investigates SLAM algorithms configuration alternatives for energy efficiency. Whereas, we use `powprofiler`, a generic energy modeling tool. The tool, presented at an earlier point in our work [16], accounts for measuring the energy impact of different configurations of the ROS based system featuring the agricultural use-case.

Some further energy modeling, such as mission-based energy models studied by Sadrpour et al. [17], [18], focus mostly on ground-based autonomous vehicles instead of the UAVs. Others investigated extensively the concept of motion, as the work presented by Morales et al. [19], but do not account further on the computation.

Energy modeling of mobile robots specifically, as the work carried by Mei et al. [20]–[22], has provided the ground for the concept of modeling computation for energy-sensitive algorithm design. The authors' approach has evolved from an energy-efficient motion planning technique in [22], a design strategy that allows accounting for motion and computations separately in [21], to an energy-efficient deployment algorithm in [20].

The battery in our system is considered in the context of a drone being able to perform its mission while accounting for the eventuality of a battery shortage; to this end, we investigated the approach presented by Berenz et al. [23], where a battery management mission-based dynamic recharge approach is presented. A set of recharge stations are used, along with self-docking capable robots. Our approach similarly allows landing on the platform, which is inherently in the proximity of the drone.

Taking into account varying environmental conditions and unpredictable movements of the platform to land on is relevant for the use of landing in outdoor, mobile scenarios. Regarading wind conditions, an AprilTag marker was used by Feng et al. [24] with a constant wind speed of 5 m/s as an external disturbance in a simulation environment. Nevertheless, a fluctuation in the wind's magnitude and direction is likely to happen in realistic cases. Concerning estimation of the moving platform's position and velocity, a Kalman Filter or Extended Kalman Filter has been used for the estimation [8], [24], [25], whereas Yang et al. [12] constructed a velocity observer algorithm by calculating the actual moving distance of the moving platform over a period of time.

III. Energy-Sensitive Control of Tracking and Landing

The energy-sensitive design is a mission-oriented concept that adjusts the computations to the mission being performed while taking into account energy requirements, such as the presence of a limited power source. Specifically, in the agricultural use-case, the concept is employed to level the computationally heavy algorithms: autonomous tracking, landing, and hazard detection, and is achieved in simulation iteratively in three steps.

First, the developer specifies the maximum and minimum QoS level per each algorithm the use-case is composed of. The levels are statically defined, an automatic generation during different phases of the mission is being currently investigated and is considered future work. The algorithms are wrapped using ROS middleware, requiring the developer to specify the current ROS configuration through a configuration file in a key-value pair format which is then interpreted by `powprofiler`.

Second, `powprofiler` evaluates the energy consumption empirically evaluating a number of possible combinations and inferring the others by the means of a multivariate linear interpolation. The First two steps are iterated in the simulated environment with different configurations. Namely, the autonomous tracking allows changing the QoS tracking step in ms, landing the QoS landing step also in ms, and hazard detection the QoS frames-per-second (FPS) rate the CNN runs at.

In the final step, the model is assessed and the QoS is adjusted to the desired granularity of the algorithms, along with the energy requirements.

IV. Vision-Based Autonomous Tracking and Landing

TODO: Georgios: your key contribution here

V. Evaluation

A. Use case: agricultural safety

Briefly describe the use case and simulation, including the use of CNN to detect

B. Experimental setup

How the experiment will be done concretely, i.e., time to land as a function of QoS and wind or whatever.

C. Results

Results of the experiments

D. Discussion

Discussion of the results

VI. Conclusion and Future Work

What we did, why it was exciting, and what we want to do.

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