A Vision-Based Algorithm for a Path Following Problem

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***Abstract* — A novel prize-winner algorithm designed for a path following problem within the Unmanned Aerial Vehicle (UAV) field is presented in this paper. The proposed approach exploits the advantages offered by the pure pursuing algorithm to set up an intuitive and simple control framework. A path for a quad-rotor UAV is obtained by using downward facing camera images implementing an Image-Based Visual Servoing (IBVS) approach. Numerical simulations in MATLAB® together with the MathWorks™ Virtual Reality (VR) toolbox demonstrate the validity and the effectiveness of the proposed solution. The code is released as open-source making it possible to go through any part of the system and to replicate the obtained results.**

***Index Terms* — Path following, UAV, multi-rotor, virtual reality, image processing.**

1 Introduction

Path following is a relevant application problem within the Unmanned Aerial Vehicle (UAV) field. For instance, in precision agriculture scenarios having good path following algorithms is a fundamental requirement to preserve high productivity rates and plant growth [**?**]. In civilian applications, monitoring of power lines can be encoded as a path following problem between several target regions that need to be inspected [**?**]. Whatever the field of application is, drones have to follow a path to accomplish the mission specifications safely and successfully.

Looking at the path following problem, it can be divided into two parts: *detection* and *path following* [**?**, **?**]. As regards the *path detection*, Hough transform [**?**] and its further developments [**?**, **?**] are considered the most valuable solutions in the literature to cope with the task. However, such a transformation demands a high computational effort making it hard to run on-board the aircraft when battery and processing constraints are tight. These requirements are increasingly stringent when considering Micro Aerial Vehicles (MAVs), where the sensor equipment and the vehicle dimensions are minimal. On the other hand, when the computational burden is at minimum, e.g., lightweight machine learning solutions have been recently proposed to tackle the problem [**?**, **?**], the time required to set up the algorithms makes them difficult to apply in real world applications. For all such reasons, it is of interest to have low computational intensity algorithms, possibly without any prior knowledge of the surrounding environment, able to provide references to the *path following* in a given time window.

Figure 1: Parrot Mambo quad-rotor [**?**].

Moving at the *path following* level, much of the state-of-the-art solutions [**?**, **?**] rely on the use of nonlinear guidance law [**?**], vector field [**?**], and pure pursuit [**?**] algorithms due to their simple implementation and ease of use. Although the choice of path planner is application sensitive, general considerations can be provided. The performance of nonlinear guidance law degrades as the target acceleration changes rapidly introducing a not negligible delay in the trajectory generation. An adequate knowledge of the target velocity and acceleration is required to avoid instability issues [**?**]. On the other hand, a vector field solution prevents from such oscillations problems, but it is inherently characterized by a high computational effort [**?**]. Besides, a pure pursuit approach is a suitable solution when tracking error and computational effort are critical. The position of a look-ahead point is set up at the beginning of the mission, and then updated at each step following some tracking criteria [**?**, **?**, **?**]. The objective is to reduce the distance between the current position and the look-ahead position.

In this paper, we propose a novel winner-prize algorithm designed to deal with the path following problem in the context of the IFAC2020 MathWorks Minidrone competition [**?**]. The framework combines the advantages provided by the pure pursuit algorithm and some simple image processing to detect and to track a pre-established path. The lightweight and ease of implementation of the proposed so-

*This project was partially funded by the ECSEL Joint Undertaking (JU) research and innovation programme AFarCloud and COMP4DRONES under grant agreement no. 783221 and no. 826610, respectively, and by the European Union's Horizon 2020 research and innovation programme AERIAL-CORE under grant agreement no. 871479. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Spain, Germany, Austria, Portugal, Sweden, Finland, Czech Republic, Poland, Italy, Latvia, Greece, and Norway.

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Figure 2: Snapshot extracted from the virtual scenario. A dashed circle is used to indicated the drone position.

lution allow the deployment on low computational capacity MAVs, such as the Parrot Mambo [**?**] (see, Figure **??**) considered as a testbed for the application. Numerical simulations carried out in MATLAB together with the MathWorks Virtual Reality (VR) toolbox [**?**] show the validity and the effectiveness of the proposed approach. Moreover, the code is provided as open-source [**?**] making it possible to go through any part of system and to replicate the obtained results.

The paper is organized as follows. Section **??** presents the problem, while in Sec. **??** the vision-based path following algorithm is described. Numerical simulations are reported in Sec. **??**. Finally, conclusions are drawn in Sec. **??**.

2 Problem Description

The work presented here finds an application within the IFAC2020 MathWorks Minidrone competition [**?**], where the use of a model-based design approach is the aim of the specific contest. Path error and mission time are used as evaluation metrics for the algorithm. The whole process is the following: a quad-rotor UAV follows a pre-established red path by using its downward facing camera to get feedback from the environment. Images are updated according to the position and orientation of the vehicle simulated in the MATLAB VR world. No prior knowledge on the path and the surrounding scenario is given. The drone takes off and starts its motion looking at the path, and the mission stops with the recognition of an end-marker. At that time, the drone lands staying within the delimited area. Figure **??** shows the considered scenario.

3 Vision-Based Path Following Algorithm

The vision-based path following algorithm combines the advantages offered by the pure pursuit algorithm [**?**] with that of an easy image processing system to cope with the task. The algorithm starts selecting a target position ahead of the vehicle and that has to be reached, typically on a path. The framework is based on the following operations: (i) given the actual position $\mathbf{d} = (x_d, y_d)^\top \in \mathbb{R}^2$ where the UAV is located, a Virtual Target Point (VTP) is set over the track

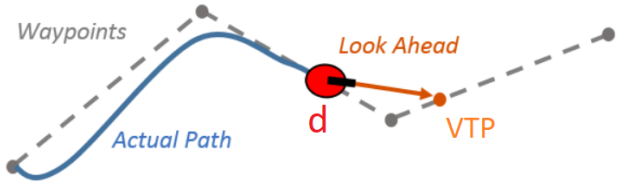

Figure 3: An illustrative example of the proposed vision-based path following algorithm works. The red point $\mathbf{d}$ represents the drone position, while the orange point $\mathbf{w}$ depicts the VTP.

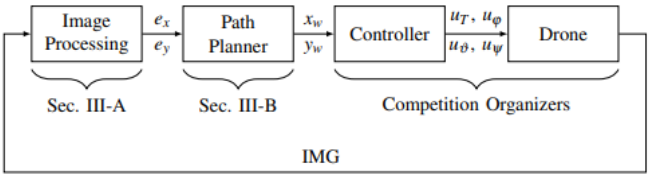

Figure 4: Control system architecture. From left to right: the image processing, path planner, controller, and drone blocks.

at $\mathbf{w} = (x_w, y_w)^\top \in \mathbb{R}^2$; then, (ii) the quad-rotor is commanded to reach the VTP along a straight line (essentially it is the pure pursuit algorithm with a curvature of infinite radius) [**?**], i.e., moving the vehicle from its current position to the goal position[1]. In Figure **??** an illustrative example of how the algorithm works is depicted.

Contrary to the pure pursuit algorithm, the proposed approach exploits the intrinsic characteristics of the multi-rotor UAV motion: differently from ground vehicles with steering wheels, drones can follow a path without modifying their heading. Such an assumption allows reducing the time to accomplish the task by removing the control of the heading from the purposes of the path follower.

In Figure **??** the whole control scheme architecture is reported. The algorithm is mainly divided into two parts: (i) the Image Processing System (IPS) deals with extracting the red path from the camera images, providing the errors along the x- and y-axis of the camera frame between the current drone position and the VTP point, and recognizing the End-Marker for the landing operations; while, (ii) the Path Planner (PP) figures out the path following problem by computing the new position $\mathbf{w}$ of the drone in the world frame [**?**, Sec. V] implementing an Image-Based Visual Servoing (IBVS) scheme. The control algorithm computes the commands u_T, u_φ, u_ϑ, and u_ψ that should be given to the drone in order to update its position and orientation in accordance to the PP references.

The overall mission is divided into four parts: *Take off*, *Following*, *End-Marker*, and *Landing*. A decision-making process has been implemented to achieve the competition objectives triggering the system from a state to another, as depicted in Figure **??**. For each frame, the IPS accesses the system status and plan the next action (i.e., landing, follow-

[1]The quad-rotor is assumed to fly at a fixed height along the entire mission.

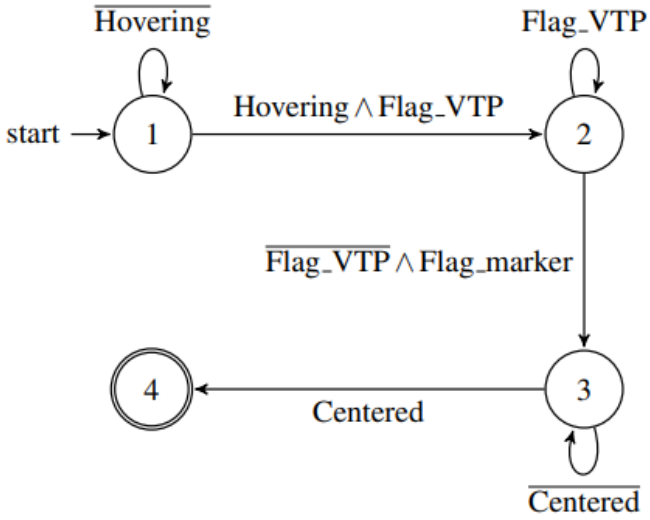

Figure 5: State machine implemented. State 1: *Take-off*. State 2: *Following*. State 3: *End-Marker*. State 4: *Landing*.

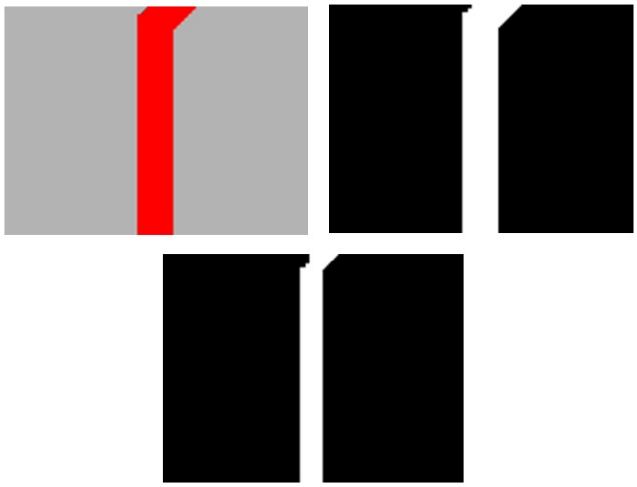

Figure 6: Original frame (upper left), converted and binarized frame (upper right), and eroded frame (lower).

ing, etc.). The drone starts taking off from its initial position looking at the path. Once the vehicle reaches the hovering position, the IPS detects the path and the state machine enters in the *Following* state, hence the path following starts. As soon as the IPS detects the End-Marker, the state machine exits from the *Following* state and goes into the *End-Marker* state. At this stage the mission stops, and the drone starts the landing. In the following subsections the implementation of the image processing system and path planner modules are detailed.

3.1 Image processing system

Starting from the camera frames, the Image Processing System takes care of separating the features of the pre-established path from that of the environment. The IPS receives frames of width W and height H from the camera sensor at each $T_{\text{IPS}} = 0.2$s, i.e., the camera sampling time. The image format is RGB with 8 bits for each color channel. The path is 0.01 m in width, while the landing marker is circular with a diameter of 0.02 m. The path color is red, and this information is taken into consideration in all the elaborations to filter out the background scenario. The procedure consists of the following steps: first, the RGB frame is converted into an intensity level frame representation as follows

$$F(n,m) = f_R(n,m) - \frac{f_G(n,m)}{GG} - \frac{f_B(n,m)}{GB}, \qquad (1)$$

where the pair (n,m) represents the pixel located at row $n \in \{1,2,\ldots,H\}$ and column $m \in \{1,2,\ldots,W\}$ of the image frame and f_i, with $i \in \{R,G,B\}$, provides the intensity level representation of the corresponding red, green and blue channels. An heuristic approach was used to tune the GG, $GB \geq 1$ parameter values. These parameters help to detect the pixels belonging to the path. Further, a binarization process based on a K_T threshold value refines the process removing artifacts from the elaboration. The binarized frame can be described by the binary function $F_{\text{bin}}\colon (n,m) \to \{0,1\}$ whose output is one when the pixel belongs to the path and zero otherwise. Finally, an erosion operation is performed through a square kernel to shrink and regularize the binarized frame. In Figure **??** the overall process is reported for a single sample frame.

Then, the obtained reference path is used in a twofold way: (i) to identify a new VTP belonging to the track; (ii) to detect the landing marker. The two tasks are described in the pseudocode reported in Algorithm **??**.

Looking at the algorithm, the first three functions (i.e., `channelConv`, `binarization`, and `erosion`) take care of extracting the path information from the frame. Then, the `detectTrack` and `detectMarker` functions deal with raising a flag when the path (`Flag_VTP`) or the End-Marker (`Flag_marker`) are detected. The path following algorithm starts with the IPS that computes the errors (e_x and e_y) between the drone position and the VTP point for the PP by using a circular arc mask centered in the drone Center of Mass (CoM)[2] with thickness $R_{\max} - R_{\min}$ [3].

In Figure **??**, the arc mask considering the VTP position at time $\mathbf{t}_k$ is depicted, where $\mathbf{t}_k$ denotes the k-element of the time interval vector defined as $\mathbf{t} = (0, T_{\text{IPS}}, \ldots, NT_{\text{IPS}})^\top \in \mathbb{R}^{N+1}$, with $k \in \mathbb{N}_0$. The orientation angle $\vartheta = \arctan2(x_{\text{VTP}}, y_{\text{VTP}})$ is calculated with respect to the frame coordinates, where the $\arctan2$ function is the four-quadrant inverse of the tangent function. A portion Θ of the arc mask is established by taking into account the previous VTP's orientation. In particular, we set up two semi-arcs with width $\frac{\Theta}{2}$, namely Field of View (FoV), in counter-clockwise and clockwise directions from ϑ. Then, the arc mask is applied to the eroded image obtaining the VTP point at $\mathbf{t}_{k+1}$. The function TP calculates x_{VTP}, y_{VTP}, and ϑ which represent the frame coordinates and angle ori-

[2]The assumption that the CoM being in the center of the reference frame, i.e., $x_{\text{CoM}} = \frac{H}{2}$ and $y_{\text{CoM}} = \frac{W}{2}$, is taken into consideration.

[3]$R_{\max}$ and $R_{\min}$ are the outer and inner radius, respectively.

IMG ← channelConv(IMG),
IMG ← binarization(IMG),
IMG ← erosion(IMG),
Flag_VTP ← detectTrack(IMG),
Flag_marker ← detectMarker(IMG)
if *Flag_VTP* **then**

end

$x_{\mathrm{VTP}}, y_{\mathrm{VTP}} \leftarrow$ vtp(frame)
$e_x \leftarrow x_{\mathrm{VTP}} - x_{\mathrm{CoM}}$
$e_y \leftarrow y_{\mathrm{VTP}} - y_{\mathrm{CoM}}$
Flag_marker

$x_{\mathrm{MARK}}, y_{\mathrm{MARK}} \leftarrow$ cgMarker(frame)
$e_x \leftarrow x_{\mathrm{MARK}} - x_{\mathrm{CoM}}$
$e_y \leftarrow y_{\mathrm{MARK}} - y_{\mathrm{CoM}}$

return e_x, e_y, Flag_VTP, Flag_marker

Algorithm 1: Image Processing System

Figure 7: Frame after the application of the Arc mask (left). Extracted pixels belonging to the path (right).

entation of the VTP at $\mathbf{t}_{k+1}$, respectively. Subsequently the corresponding errors with respect to the center of mass, i.e., e_x and e_y, are computed inside the frame coordinates. Finally, the `Flag_VTP` and the e_x and e_y values are provided as input to the PP at each T_{IPS}. Figure **??** shows the result of the entire process setup.

It is worth noticing that when the landing marker is detected and no other VTP point is found in the frame, the IPS triggers the state machine in the `End-Marker` state. Here, the new main task of the IPS is to obtain the position of the End-Marker within the frame coordinates. An additional erosion process is performed by using a circular kernel, as depicted in Figure **??**.

Figure 8: Original (left) and eroded frames (right) of the End-Marker are reported.

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