Robotics and Autonomous Systems ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Evaluation of control strategies for fixed-wing drones following slow-moving ground agents

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HIGHLIGHTS

- We compare target tracking strategies on a large set of target motion patterns.
- We propose a new methodology that introduces energy expenditure as a new metric.
- Optimal parameters are set in each test and Pareto fronts are used for comparison.
- LGVF strategy shows superior performance both in simulation and field experiments.

ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form
2 June 2015
Accepted 15 June 2015
Available online xxxx

Keywords:
Target tracking
Fixed-wing UAVs

ABSTRACT

There are many situations where fixed-wing drones may be required to track ground moving agents, such as humans or cars, which are typically slower than drones. Some control strategies have been proposed and validated in simulations using the average distance between the target and the drone as a performance metric. However, besides the distance metric, energy expenditure of the flight also plays an important role in assessing the overall performance of the flight. In this paper, we propose a new methodology that introduces a new metric (energy expenditure), we compare existing methods on a large set of target motion patterns and present a comparison between the simulation and field experiments on proposed target motion patterns. Using this new methodology we examine the performance of three control strategies: the Lyapunov Guidance Vector Field strategy, the Bearing-only strategy and the Oscillatory strategy. Among the three strategies considered, we demonstrate that the Lyapunov Guidance Vector Field strategy has the best performance for all target motion patterns. Field experiments with fixed-wing drones provide additional insights into the benefits and shortcomings of each strategy in practice.

1. Introduction

Fixed wing drones have been extensively used to track moving targets on the ground Theodorakopoulos and Lacroix [1]; Ding et al. [2]; Rafi et al. [3]. Since the speed of the target is usually slower than the speed of the drone, drones have to perform maneuvers such as spiraling or sinusoidal motion along a target's trajectory to stay in the close vicinity of the target. When choosing the appropriate strategy, one is usually concerned with how well the drone tracks the target. In [4–6] authors used the distance between drone and ground agent positions as the performance metric they wished to optimize.

Energy performance of flight has not yet been included in any comparison of strategies, despite the fact that it plays a major role in determining flight duration. Energy performance is related to the type of trajectory that the drone performs while tracking a ground agent. While a fixed wing drone performs sinusoidal or spiral like motion, it has to change the bank angle to turn, which lowers the lift force. If we assume that the drone is performing level flight, to maintain the altitude the drone has to apply an additional thrust to counteract the reduction in the lift force. This additional thrust increases the energy consumption of the flight. Hence by measuring the turn rate of the robot while performing level flight, the additional energy required to perform a given maneuver is estimated.

Besides introducing a new metric, to improve the comparison of the strategies an experimental method should be carefully designed to capture most of the differences in performance. In the literature, strategies are usually compared in test cases where

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http://dx.doi.org/10.1016/j.robot.2015.06.003
0921-8890/

Please cite this article in press as: M. Varga, et al., Evaluation of control strategies for fixed-wing drones following slow-moving ground agents, Robotics and Autonomous Systems (2015), http://dx.doi.org/10.1016/j.robot.2015.06.003

the target performs a straight line motion pattern as in Wise and Rysdyk [7]. Such experimental design does not allow one to identify whether the performance of the strategies varies with the change in the target motion patterns. Furthermore, each control strategy that is being compared has different parameters that can be tuned in order to modify the performance of the strategy. In [7,8] authors set parameters to fixed values before the experiment and they do not tune these parameters to the same objectives. Lastly, comparisons proposed in the literature Wise and Rysdyk [7], Savkin and Teimoori [8], Beard [9] are conducted only in simulation. Usually simulation experiments cannot capture performance degradation due to sensing and actuation noise from their simplified mathematical models.

In this paper, we introduce a new measure: energy expenditure of the flight, and we propose a new methodology to compare target tracking strategies. We choose to compare three strategies following our experimental methodology. In the first strategy, the Lyapunov Guidance Vector Field (LGVF) strategy proposed by Frew et al. [10], the drone follows a ground agent by performing an orbital flight path. The second strategy, the Bearing-only strategy proposed by Savkin and Teimoori [8], relies only on the relative bearing between the drone and the ground agent and the drone performs a combination of circular and straight fight paths. In the third strategy, the oscillatory control strategy proposed by Lalish et al. [11], the drone follows a left–right (sinusoidal like) flight path while following the ground agent.

We design comparison experiments in low wind scenarios for three types of ground agent motion patterns, both in simulation and in field experiments. Each strategy has one or two control parameters that influence target tracking performance. In order to make a fair comparison between these strategies that have different parameters, we run a multi-objective optimization (MOO) experiment to find the optimal parameter configuration for each strategy in the comparison experiments. The objectives to be optimized are the average distance to the ground agent and the energy expenditure of the flight. Using this technique, we obtain Pareto fronts for each strategy and each comparison case, and use them to examine whether one strategy dominates the others when all strategies have optimal parameter settings. We choose two extreme sets of control parameters and conduct field experiments to compare to the simulation results.

This paper is organized as follows: Section 2 describes the target tracking strategies and experimental method, Section 3 provides simulation results and Section 4 provides results of field experiments. In the Appendix we show results of the comparison of the strategies based on the distance measure in low and high wind conditions.

2. Experimental method

In this section we describe the novel experimental methodology to evaluate the target tracking strategies. We briefly present each target tracking strategy and explain our choice of motion patterns and control parameters used to compare the strategies in simulation and in reality.

2.1. Lyapunov Guidance Vector Field (LGVF) strategy

The LGVF strategy, proposed by Frew et al. [10], determines a commanded turn rate of the drone based on the distance between the ground agent and the drone by constructing a circular vector field around the position of the ground agent. The field guides the drone to perform a circular loitering pattern with radius R_c if the ground agent is still. On the other hand, if the ground agent starts to move, the vector field also moves with the agent and guides the drone to perform an orbital motion along the trajectory of the ground agent, as shown in Fig. 1.

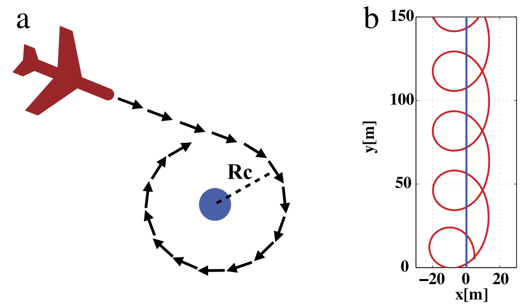

Fig. 1. Illustration of the LGVF strategy (a) graphical interpretation of the LGVF strategy and (b) the drone's trajectory while tracking the ground agent, $v_a = 0.3v_r$.

2.2. Bearing-only strategy

The *Bearing-only* strategy, proposed by Savkin and Teimoori [8], determines commanded turn rate of the drone using only the relative bearing between the ground agent and the drone. It utilizes a simple control strategy using sliding mode control. If drone is ahead of the ground agent, it turns back with the maximum turn rate. If the drone is behind the ground agent, it adjusts its heading vector to align to the distance vector between drone and ground agent. Formally, if we define a distance vector, **d** and a drone orientation vector as $\mathbf{p}_r$, then the control output (turn rate) is determined using the following function:

$$|u| = \begin{cases} \omega_{\max} f(\mathbf{d}, \mathbf{p}_r) & \text{if } |d| \neq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Generally, function $f(\mathbf{d}, \mathbf{p}_r)$, is defined as:

$$f(\mathbf{d}, \mathbf{p}_r) = \begin{cases} 0 & \beta = 0 \\ 1 & 0 < \beta < \pi \\ -1 & \pi < \beta < 2\pi \end{cases} \tag{2}$$

where β is the angle between the distance vector and the drone position vector, always measured counterclockwise from the distance vector. Graphical interpretation of the control strategy, together with resulting behavior of the drone is shown in Fig. 2.

2.3. Oscillatory control

The Oscillatory Control Strategy, introduced by Lalish et al. [11], generates a sinusoidal (left–right) motion of the flying robot along ground agent's trajectory. To generate sinusoidal motion of the drone along the ground agent's trajectory, the desired turn rate is defined as a sinusoidal function given by:

$$\begin{aligned} u(t) &= A\sin(\phi(t)) + B + C\sin(2\phi(t)) \\ \dot{\phi}(t) &= \omega_0 + k_\phi(\phi(t) - \phi_0). \end{aligned} \tag{3}$$

The task of the tracking controller is to determine the parameters A, B, C that will guide the drone to align its average speed and position with the ground agent speed and position.

$$\begin{aligned} A &= -k_e(e^* - e)\cos(\alpha) - k_v(v_{CO} - v_a) \\ B &= k_\alpha \alpha + v_{CO}\frac{\sin(\alpha)}{e} - v_a\frac{\sin(\theta)}{e} \\ C &= 0 \end{aligned} \tag{4}$$

where k_v is a speed gain of the control law and k_e is the distance gain. We found in preliminary simulation experiments that these two gains have a major influence on the performance and convergence of the oscillatory tracking strategy. The principles of the tracking law are depicted in Fig. 3.

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