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Controlling spacecraft landings with constantly and exponentially decreasing time-to-contact

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***Abstract*—Two bio-inspired landing strategies are studied. Both strategies enforce a constant ventral optic flow with, respectively, (1) constantly decreasing time-to-contact, or (2) exponentially decreasing time-to-contact. Until now these strategies have only been studied assuming the visual quantities to be known, i.e., without sensor noise and delay. In this study, the control laws executing the aforementioned landing strategies are studied both theoretically and empirically, taking into account the actual extraction of the visual cues from images.**

***Index Terms*—Optic flow, spacecraft landing, ventral flow, time-to-contact, vision-based landing.**

I. INTRODUCTION

RECENT studies on autonomous spacecraft landing combine laser / radar altimeters with computer vision in order to obtain highly accurate state estimates [1]–[4]. While the use of heavy altimeters makes sense for the main landing system of a large spacecraft, a backup emergency system or a system for much smaller spacecraft should be light-weight and energy efficient. In the quest for such a system, several studies have drawn inspiration from small flying animals [5]–[7], which land robustly relying only on proprioceptive and visual information. These studies have focused on the use of optic flow, a visual cue also studied for the control of Micro Air Vehicles (cf. [8]–[13]). Optic flow can be measured and processed with extremely light-weight and energy efficient neuromorphic sensors [14], [15].

In particular, previous bio-inspired spacecraft landing strategies were based on the *ventral flow*, which is a measure of the translational velocity divided by the height. Bees are known to employ a strategy of keeping the ventral flow constant during landing [16]. Valette et al. study a control law that implements this strategy and they simulate some landings on the moon [6].

The drawbacks of only using ventral flow for landing are two-fold. First, the lander's vertical dynamics are left free. The ventral flow can have the same constant value for a trajectory in which the lander ascends while accelerating and a trajectory in which the lander descends while decelerating. Thus, one has to directly or indirectly assume some type of descent profile, for example by introducing a pitch law for the spacecraft [6]. Without the use of additional exteroceptive information to compute an optimal pitch profile, this leads to a considerable expense of propellant [7] and to undefined final low-gate conditions. Second, in the case of a straight vertical landing the ventral flow is (close to) zero. In such a case, e.g. in an asteroid landing scenario, the ventral flow does not provide any information on how to land the spacecraft.

In order to amend the above drawbacks, two of the authors proposed to complement ventral flow with another biologically important visual observable [17]: the *time-to-contact* (TTC) [18], [19]. In the context of landing, the time-to-contact is a measure of the height divided by the vertical velocity[1]. It can be measured by the increasing expansion of imaged ground features (cf. [18], [20]–[23]). In [17] two landing strategies were introduced, both enforcing a constant ventral flow with either (1) constantly decreasing time-to-contact (cdTTC), or (2) exponentially decreasing time-to-contact (edTTC). The latter strategy was shown to result in a relatively small mass penalty with respect to a mass-optimal landing. However, in the study the visual observables were assumed to be known and sensor noise was not taken into account. This assumption is particularly strong, since both landing strategies rely on the time derivative of the time-to-contact.

The *main contribution* of this article is to show that constantly and eponentially decreasing time-to-contact landing strategies can be executed successfully on the basis of the noisy and delayed information extracted from images. A secondary contribution is the introduction of a computer vision algorithm that estimates the time-to-contact accurately enough for its time derivative to be used by the control laws. The estimates resulting from the vision algorithm are characterized with respect to measurement error and delay, and the control gains are tuned accordingly. Finally, experiments are performed in a simulated moon landing scenario. These experiments show that the use of real visual cues (with associated noise and delay) results in a reduction of mass efficiency in the order of only 1%. In the nominal landing, 14.8% more mass is spent than by a mass-optimal solution, in comparison with 13.7% with perfect measurements.

The outline of the study is as follows. In Section II the cdTTC and edTTC landing strategies are briefly revisited. Subsequently, in Section III, the vision algorithm measuring both the ventral flow and the time-to-contact is introduced. In addition, the measurements of the vision algorithm are characterized in terms of noise and delay. In Section IV the control laws and corresponding gains of the spacecraft are discussed. Then, in Section V simulation experiments are performed, testing the landing strategies under a broad range of circumstances. Finally, conclusions are drawn in Section VI.

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[1] Note that this measure is only equal to the actual time to contact if the velocity remains constant, which is typically not the case in landing scenarios.