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Technical Note

Surface flow measurements from drones

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ABSTRACT

Drones are transforming the way we sense and interact with the environment. However, despite their increased capabilities, the use of drones in geophysical sciences usually focuses on image acquisition for generating high-resolution maps. Motivated by the increasing demand for innovative and high performance geophysical observational methodologies, we posit the integration of drone technology and optical sensing toward a quantitative characterization of surface flow phenomena. We demonstrate that a recreational drone can be used to yield accurate surface flow maps of sub-meter water bodies. Specifically, drone's vibrations do not hinder surface flow observations, and velocity measurements are in agreement with traditional techniques. This first instance of quantitative water flow sensing from a flying drone paves the way to novel observations of the environment.

1. Introduction

Surface waters influence the way the landscape evolves, ecosystems develop, environmental risks arise, and epidemics propagate (Tucker and Bras, 1998; Boulton et al., 1998; Chow et al., 1988; Mari et al., 2012). Due to the complexity of surface water processes, a unique observational method for identifying and quantitatively monitoring flows is yet to be found (Hrachowitz et al., 2013). Traditionally, surface flows are invasively monitored using current meters (Tazioli, 2011), tracing systems (Planchon et al., 2005), and acoustic doppler instrumentation (Yorke and Oberg, 2002). Water control structures, such as weirs and spillways, can also be used to estimate flow discharge (Chanson, 2004).

Even if the efficacy of such methods has been demonstrated in the technical literature (Leibundgut et al., 2009), their use is limited to easy-to-access environments. In addition, the measurement accuracy can be affected by the severity of natural rainfall events and by systematic errors associated with sensors interfering with the flow. To address some of these challenges, considerable efforts have been devoted toward the development and refinement of remote methods, including hand-held radars (Fulton and Ostrowski, 2008), microwave sensors (Plant et al., 2005), and satellites (Tarpanelli et al., 2013). These approaches have highly benefitted the realm of hydrological observations; however, most of them are only applicable to large scale channel flows, may be expensive, and may not be suitable to frequently monitor water bodies.

To mitigate such issues, several methods based on the remote acquisition and analysis of flow images have been proposed and implemented in the last two decades (Fujita et al., 1997). Specifically, in (Muste et al., 2008), images of large scale riverine ecosystems are analyzed through high-speed cross-correlation to obtain surface flow velocity maps. These surface flow velocity maps can be complemented with information on the bathymetry to allow for flow discharge estimations (Hauet et al., 2008). Such optical observational methods are challenged by practical difficulties, such as the need for collecting ground reference points GRPs (Tauro et al., 2014a), and, therefore, flow data are often not available at ungauged sites, such as extra-urban areas, large-scale lakes and glaciers, coasts, and river estuaries. Despite practical limitations, optical methods are inherently suited to enable continuous and remote observations over diverse water bodies, spanning from rills to large scale rivers. Notably, the potential of image-based methods has been assessed on a mountainous stream (Tauro et al., 2012a), a semi-natural hillslope (Tauro et al., 2012b), and a large scale river (Tauro et al., 2014a).

Here, we propose a novel, fully remote approach for surface flow observations that overcomes practical difficulties related to

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the implementation of optical methods in difficult-to-access environments. Specifically, we put forward the integration of optical observational techniques and drones for non-invasive quantitative flow measurement. With more than six billion dollars a year spent in research and development around the world (Palermo, 2014), drones have transformed our capacity to remotely sense and access the environment Clarke (2002), Cohen (2007), Eltner et al. (2015) and Pérez-Alberti and Trenhaile (2014). For instance, in the last decade, drones have empowered multiple fields of science by enabling data collection in hostile environments, such as volcanoes (McGonigle et al., 2008) and ice sheets (Shelley et al., 2014), and by providing footage over extended areas, such as forests (Cohen, 2007) and natural reserves (Schiffman, 2014). Just as aerial and satellite sensing have transformed scientific observations, allowing the resolution of large-scale physical processes (Jensen, 1983; Famiglietti et al., 2015), the pervasive use of drones is set to revolutionise geophysical sciences through the rapid and refined measurement of small to medium scale phenomena.

In the realm of hydrology, drones have the potential to enable remote and distributed flow measurements in difficult-to-access water environments during adverse hydro-meteorological events. In our vision, a drone is deployed in natural environments and is remotely piloted (or, alternatively, guided through GPS waypoint trajectory) above the water body of interest upon request/need of the operator. An onboard camera oriented with its axis perpendicular to the water surface captures videos of the flow, whereby a ground user identifies a region of interest through a wireless monitor in real time. Once the ground user selects an area of interest, the drone is set to the hovering mode, and the platform station-keeps above the region while taking high-resolution videos of the water surface. Pictures extracted from the drone footage can be processed off-line through several optical-based algorithms to estimate the surface velocity field.

To demonstrate the potential of our approach, we present the design and preliminary assessment of a novel aerial sensing platform. The platform features a low-cost recreational drone equipped with a miniature camera and a system of lasers to remotely assign metric dimensions to images (remote photometric calibration in the rest of the note) without the acquisition of GRPs. To assess the feasibility of the hovering capability of the drone for reliable flow velocimetry, we execute preliminary experiments on an ad hoc developed outdoor controlled facility at University of Tuscia. Finally, we perform surface flow observations in a small scale stream (less than 1 m wide and a few centimeters deep) in the Italian Alps. Interestingly, few noninvasive techniques are currently available to monitor small scale surface flows in natural environments. We remotely capture and calibrate videos of the stream from the drone and apply the Large Scale Particle Image Velocimetry (LSPIV) high-speed cross-correlation algorithm (Hauet et al., 2008) that extracts usable flow velocity maps from the motion of stream floaters. Such drone-based surface flow velocity estimates are compared to benchmark values from a current meter to demonstrate the validity of airborne flow velocimetry.

Our method is expected to help in hydrological monitoring in ungauged areas by providing information on the kinematics of surface waters. Differently from standard drone-based monitoring where image mosaicing techniques are used to assemble maps (Immerzeel et al., 2014), our approach treats captured videos as quantitative data and analyzes them to measure the surface flow velocity. These observations could leverage current knowledge on the contribution of surface flows to the overall hydrological response of natural systems. Further, continuous technological advancements in battery life and camera storage capacity may foster observations at the catchment scale and in large scale and yet ungauged water systems, thus opening novel research avenues in hydrology.

The rest of the technical note is organized as follows. In Section 2, the aerial sensing platform, experimental settings, and image-based procedures are presented. In Section 3, we report experimental findings for the hovering assessment and the airborne flow velocimetry. In Section 4, we discuss the advancements of the proposed approach. Section 5 is left for conclusions.

2. Materials and methods

Here, we present the aerial sensing platform utilized in the experiments. Further, we provide details for the hovering assessment and the airborne flow velocimetry experiments.

2.1. Aerial sensing platform

The aerial sensing platform features a DJI Phantom 2 quadrotor (http://www.dji.com/) mounting a Zenmuse H3-2D gimbal and a GoPro Hero 3 camera oriented with its axis along the perpendicular. This configuration allows for compensating the drone vibrations about the pitch and roll axes, while minimizing distortions in video capture due to the inclination of the camera axis with respect to the field of view (FOV). Remote photometric calibration is enabled through four green lasers (532 nm in wavelength and less than 5 mW in power) installed at the four corners of the fuselage along the drone's yaw axis. The platform is less than 1.5 kg in weight and its overall cost is €1300.

The relative distances of the laser pointers are measured upon assembly of the sensing platform with a precision caliper. This system of lasers has the twofold objective of: (i) focusing points at known distances in the FOV for remote image calibration and (ii) indicating possible elevation and attitude changes during hovering from the relative distance of the laser traces in the images (Tauro et al., 2014a). With respect to (i), the traces of the lasers in captured videos are used to estimate pixel dimensions in metric units. With respect to (ii), inaccurate hovering leads to images that depict slightly different FOVs. However, high-speed cross-correlation should be applied on images displaying consistent regions of the fluid domain (Raffel et al., 2007). To this aim, lasers can be instrumental to automatically identify portions of footage captured while the drone is hovering at a given location. In fact, the traces that lasers determine on the ground vary, based on the elevation and attitude of the drone; therefore, sequences of images displaying similar traces can be directly processed for surface flow velocity estimation.

2.2. Hovering assessment

A preliminary experiment assessment is conducted to assess the feasibility of using a commercial low-cost platform for airborne flow velocimetry. The aerial sensing platform presents limited hovering capability (vertical: ± 0.8 m and horizontal: ± 2.5 m (http://www.dji.com/)). Therefore, airframe changes in attitude and elevation may lead to variable image FOVs (Fujita and Hino, 2003; Fujita and Kunita, 2011). To evaluate such FOV variations, we fly the platform in the hovering mode above a large scale grid in an outdoor facility at the University of Tuscia, Italy. We perform a 22 s flight, whereby the onboard GoPro frame rate is set to 60 Hz and the FOV to medium (focal length equal to 21 mm). The experiment is conducted at dusk and during light air wind conditions (2.19 km/h wind speed) (http://www.wmo.int).

Hovering capability is assessed by estimating the relative variations in the pixel area of the grid cells captured by the drone during the flight. Slight variations in the pixel areas of the grid cells during the flight would suggest that changes in the drone's elevation and attitude can be mitigated with minimal image processing,