Visual-Inertial Navigation for a Camera-Equipped 25 g Nano-Quadrotor

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***Abstract*— We present a 25 g nano-quadrotor equipped with a micro PAL-camera and wireless video transmitter, with which we demonstrate autonomous hovering and figure flying using a visual-inertial SLAM system running on a ground-based laptop. To our knowledge this is the lightest quadrotor capable of visual-inertial navigation with off-board processing. Further we show autonomous flight with external pose-estimation, using both a motion capture system or an RGB-D camera. The hardware is low-cost, robust, easily accessible and has freely available detailed specifications. We release all code in the form of an open-source ROS package to stimulate and facilitate further research into using nano-quadrotors as visual-inertial based autonomous platforms.**

I. Introduction

Research interest in autonomous micro-aerial vehicles (MAVs) has grown rapidly in the recent years. On the one hand, we have seen aggressive flight manoeuvres using external tracking systems (e.g. Vicon), which are however limited to a lab environment. On the other hand, there have been significant advances regarding autonomous flight in GPS-denied environments using cameras as main sensors both with on-board [10], [8] and off-board processing [5].

A. Motivation & Related Work

Even though current mono-vision controlled MAVs are already much smaller than approaches based on RGB-D cameras, most models are still too large for indoor flight in a tightly constrained environment (e.g., a small office) or too dangerous to fly close to people. In particular the weight of the platform plays a critical role, as it directly correlates with danger the MAV poses: Even with a flight weight of only 500 g, a crash can do significant damage to both the MAV itself as well as its environment or in particular human bystanders. Furthermore, size and weight influence the transportability, the usability e.g. as a flying scout for a ground-based robot, the potential to be deployed in large swarms and – in particular if mass-produced – the per-unit cost. While most research regarding MAVs focuses on – in the context of this paper – relatively large platforms, there are some exceptions: In [6], a visual SLAM system is used on-board a quadrotor weighing around 100 g. In [9], [1], nano-MAVs (36 g and 46 g) are stabilized using optical flow. Most notably, in [2], a 20 g flapping-wing MAV is presented using on-board stereo vision for obstacle avoidance and navigation.

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Fig. 1: Crazyflie nano-quadrotor with attached camera. 25 g total weight, 3.5 minutes of flight time and 9 cm across.

B. Contribution

With this paper, we present a 25 g nano-quadrocopter based on the open-source, open-hardware Crazyflie by Bitcraze[1] equipped with analogue on-board camera and wireless video transmitter. Using this platform, we demonstrate (*1*) autonomous flight using external pose estimation (Vicon or Kinect), and (*2*) autonomous flight with only on-board sensors, using the on-board camera for visual-inertial pose estimation.

We released all code required to reproduce the presented results as open-source ROS package, including the visual-inertial SLAM system. In particular we provide a full fledged, easy to set up ROS driver with intuitive GUI, which exposes all the nano-quadrotor's functionality to ROS. With this we hope to encourage and ease further research into the field of autonomous nano-quadrotors. More information can be found in [4].

II. Hardware Platform

The platform consists of *(1)* the Crazyflie Quadrotor Kit, a mass produced, open source & open hardware €170 quadrotor, and *(2)* the camera system, consisting of a micro PAL-camera (720×576, 25 fps, interlaced) with fisheye lens, an analogue 2.4 Ghz video transmitter, a voltage regulator and a 3D printed camera mount, amounting to €80 total (Fig. 1).

The Flie features a programmable Cortex M3 MPU, is equipped with an IMU, barometer and magnetometer and communicates over a 2.4GHz bi-directional link with a

[1] `http://www.bitcraze.se/`

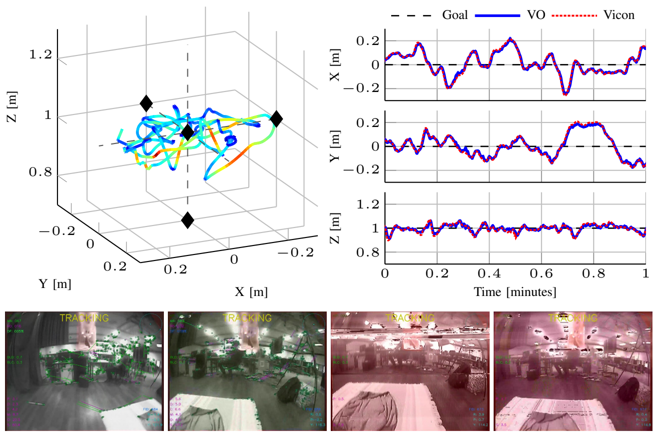

Fig. 2: Autonomous hovering for 60 s using only on-board sensors. The bottom row shows images used by the visual-inertial SLAM (left pair) and automatically dropped, corrupted ones (right pair). The nano-quadrotor stays within 22 cm of its set goal position.

ground-station. The flight time is around 7 minutes, after which it needs a 20 minutes recharge via USB. Particularly noteworthy is the extraordinary robustness of the platform: it survives most crashes, including drops from several meters altitude or flying into a wall at high speed. In fact – without camera and as long as it doesn't land upside down – it can typically directly take off again. Only the motors and propellers need to be replaced occasionally.

The added camera system is powered by the Flie's battery (reducing flight time to 3.5 minutes) and transmits a PAL video to the ground station where it is digitalized, amounting to a total delay of roughly 40 ms. The voltage regulator filters out most of the motor induced noise, but some frames are still corrupted and should be dropped (see Fig. 2). This, as well as deinterlacing, is done by the provided ROS driver. For details on the hardware and assembly, see [4].

III. ROS Software Integration

We provide all software as an open-source ROS package, which includes the following:

(1) The Crazyflie ROS driver, which exposes the entire Crazyflie functionality to a full fledged intuitive GUI and the ROS network, allowing for realtime telemetry (delay of around 8 ms), changing parameters on the Flie during runtime, as well as sending control commands.

(2) A camera processing node for efficiently detecting and dropping corrupted frames, de-interlacing images and rectifying them using the FOV [3] model.

(3) A Crazyflie detector, that uses a commodity RGB-D Camera combined with on-board attitude estimation to provide a 6 DOF pose estimate, effectively providing an easy to set up external tracking solution.

(4) A visual-inertial SLAM system loosely based on [7], specifically adapted for the Flie's sensor characteristics. In contrast to e.g. [10], [8], [5], IMU measurements are tightly integrated into the visual SLAM pipeline at an early stage, thus helping to compense for the comparatively poor image quality of the analogue camera.

(5) A PID controller to control the Flie with gain presets for use together with SLAM or external tracking based pose estimates.

IV. Flight with External Pose Estimation

Using a motion capture system and the PID controller, we evaluated the Flie's flight characteristics: The top speed reached with / without attached camera is $1.3\,{}^{m}/_{s}$ / $1.9\,{}^{m}/_{s}$ and typical RMSEs for hovering are around 6 cm.

V. Flight with On-Board Sensors

Further, we tested autonomous hovering and waypoint flying using the implemented visual-inertial SLAM system. The absolute scale of the world is set during initialization; either manually or using the barometer. The estimated pose is then directly used as input to a PID controller. Holding a position under disturbances is even possible without further filtering or delay compensation. Fig. 2 shows the ground truth position over a 60 s hover flight using visual-inertial control; the mean RMSE to the goal position is 15 cm.

VI. Conclusion

We presented an open-source and open-hardware 25 g nano-quadrotor with wireless video capability. In addition to manual flight, it can be controlled using external positioning systems such as Vicon or, to facilitate usage if such a set-up is not available, a Kinect. Furthermore, we demonstrated drift-free hovering capability by using the on-board camera for visual-inertial SLAM – to the best of our knowledge demonstrating the smallest and lightest quadrotor with such capability.

By providing open and user-friendly, ROS based access to the Crazyflie along with some tools to get started, we hope to encourage and ease further research into the field of autonomous nano-quadrotors.

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