Learning Dynamics for Agile Quadrotor State Estimation

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***Abstract*—In this extended abstract, we present our latest research on learning dynamics to improve quadrotor state estimation in agile flights. First, we present a hybrid, model- and learning-based, dynamics visual-inertial odometry (HDVIO) system that estimates the vehicle state and external disturbance (for example, wind) acting on the robot. Second, we present an odometry algorithm that relies on an inertial measurement unit (IMU) as the only sensor modality, no camera is needed, and leverages a learned dynamics component to estimate the state of a racing drone flying at high speeds.**

I. Introduction

Quadrotors are the most agile and maneuverable flying vehicles. These characteristics make them the best aerial robotic platform for time-critical applications including transportation, surveillance, and search and rescue. Yet, there is still a gap between the peak flight performance that autonomous quadrotors can achieve and how they are currently used. Closing this gap would clearly bring benefits in terms of profitability and robustness to industries that aspire to increase efficiency and productivity by leveraging automation. This consideration raises the question: What hinders the users from exploring and exploiting the full potential of autonomous drones, such as quadrotors?

The high agility of quadrotors poses several challenges to the development of accurate and robust state estimation algorithms using onboard sensing and computation. These algorithms are essential to achieve autonomous quadrotor flight in the wild. The most common solution for state estimation of flying vehicles is visual-inertial odometry (VIO) thanks to its low cost and low weight requirements. VIO systems use a camera and an IMU to estimate the state (position, orientation, and velocity) of the drone platform. However, the performance of VIO systems degrades in scenarios characterized by poor illumination conditions, textureless scenes, and motion blur. These scenarios are common in agile flight in the wild.

For these reasons, developing robust state estimators for agile quadrotor flights is challenging and still unsolved. This extended abstract presents our latest research on leveraging learned quadrotor dynamics to improve state estimation.

II. Hybrid Dynamics VIO

To improve the performance of the VIO pipeline, the drone dynamics can be used as additional constraints in the estimation process [1]. Including the system dynamics in the VIO formulation brings in new information, which allows the VIO system to distinguish between motion due to actuation and motion due to perturbations (external forces). This results in an increased accuracy of the state estimates and the possibility of estimating an external force acting on the robot.

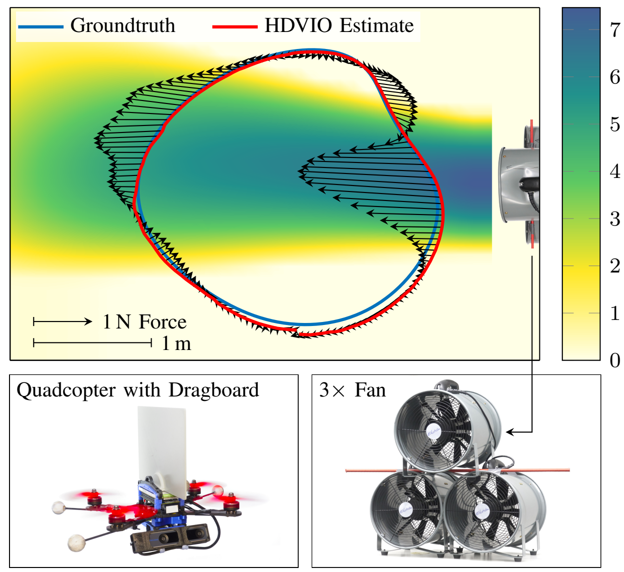

Fig. 1. A quadrotor with a dragboard attached is flown on a circular trajectory through a wind field generated with three industrial fans. Our method, HDVIO, is used to estimate the position of the drone (shown in red) and the external disturbance force (black arrows) acting on the vehicle.

Despite working well in many situations, the performance of state-of-the-art methods degrades drastically if the model mismatch is large (high speeds, systematic noise in the actuation inputs) or if continuous external disturbances are present (continuous wind). This is because their simplifying assumptions—no aerodynamic drag and zero-mean noise in the system dynamics—no longer hold.

Simply reusing state-of-the-art dynamics models [2] inside a VIO pipeline is difficult as these methods typically require knowledge of the full drone state, including velocity and attitude. However, the full state is part of the VIO output. Consequently, the prediction of the aerodynamic force would depend on the estimator state, introducing a feedback loop that can lead to a diverging estimator. We present HDVIO (Hybrid-Dynamics Visual-Inertial Odometry) [3], a VIO pipeline that uses a neural network to refine the drone dynamics model. In contrast to prior work focusing on drone modeling, our

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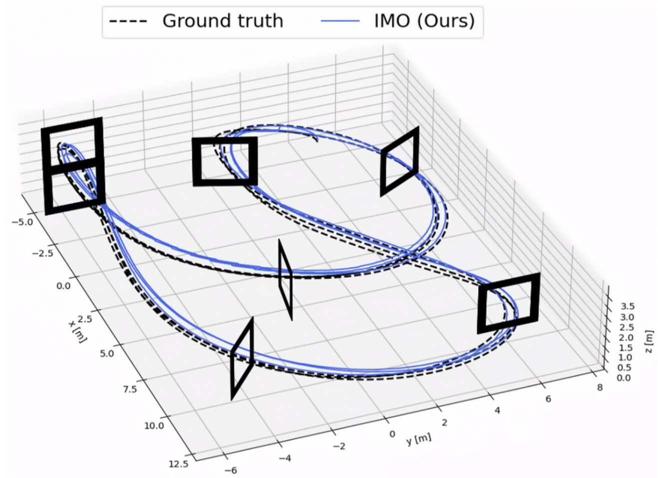

Fig. 2. Our method, IMO, is able to estimate the trajectory of an autonomous racing drone using an IMU as the only sensor modality.

learned dynamics model does not require knowledge of the full drone state. Instead, by using a temporal convolutional network (TCN), we only need thrust (commands or measurements) and angular velocities from a gyroscope to estimate the aerodynamic forces. We integrate our hybrid drone model into an optimization-based VIO system and leverage the preintegration theory to efficiently compute dynamics residuals between consecutive camera frames.

The goal of the learning-based component is to estimate a residual force that accounts for aerodynamic effects and model mismatches (systematic noise). The TCN takes a buffer of collective thrust and gyroscope measurements as input and predicts the residual force. The residual force is added to the thrust inputs. These forces are then used to predict relative velocity and position changes of the quadrotor platform. The training loss function minimizes the difference between the predicted relative velocity and position changes and the ground-truth values. Our training does not require force ground-truth data, which removes the need for a high-resolution motion-capture system. Instead, the training data could be collected using a SLAM pipeline.

We run several experiments using state-of-the-art datasets and real-world flights [3]. We show that HDVIO improves motion and external force estimation compared to the state-of-the-art methods. We show up to 33% reduction of the absolute trajectory error in fast flights, and that HDVIO, see Fig. 1, is able to accurately estimate the external disturbance due to continuous wind.

III. Learned Inertial Odometry

Inertial odometry is an attractive solution to the problem of state estimation for agile quadrotor flight. It is inexpensive, lightweight, and it is not affected by perceptual degradation. However, only relying on the integration of the inertial measurements for state estimation is infeasible. The errors and time-varying biases present in such measurements cause the accumulation of large drift in the pose estimates.

Recent research [4] has shown that neural networks can learn motion priors from the inertial measurements recorded by pedestrians leveraging the repetitive pattern of the human gait. However, these methods fail when the IMU follows arbitrary motions, such as the ones of drones.

We present IMO (IMU-Model Odometry) [5], a learning-based odometry algorithm that uses an off-the-shelf IMU as the only sensor modality.

Our algorithm combines a kinematic motion model—driven by the IMU measurements—with a learned dynamics motion prior—driven by the commanded collective thrust. Our neural network architecture is a TCN that takes as input a time window of commanded thrust and gyroscope measurements and outputs an estimate of the distance traveled by the quadrotor in this time window. These relative displacements are then used to update an Extended Kalman filter (EKF), which is propagated using a kinematic motion model based on the IMU.

We apply IMO to estimate the state of a racing drone. Drone racing requires flying a drone through a sequence of gates in minimum time and has now become a benchmark for the development of new drone technologies. What makes drone racing challenging is that the platform is flown at incredible speeds, over a hundred kilometers per hour, pushing the boundaries of the physics of the vehicle. Classical VIO systems fail in this scenario due to low light, low texture, high dynamic range, and motion blur.

We show [5], see Fig. 2, that IMO is able to accurately estimate the state of a racing drone.

IV. Conclusion

The results of our research show that including the learned dynamics in the state estimation pipeline improves state estimation in scenarios where state-of-the-art methods fail due to visual-degraded conditions. In addition, the learned dynamics enable to estimate external disturbance, for example, wind, acting on the vehicle.

Robust state estimation can increase the safety of autonomous flights in hazardous scenarios, such as fast flights and operations in windy conditions. In view of the increasing drone usage in our everyday life, such aspects are becoming more and more relevant and we believe that our work makes a valuable contribution towards this goal.

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