Overactuation in UAVs for Enhanced Aerial Manipulation: A Novel Quadrotor Concept with Tilting Propellers

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Abstract—In this work we present a novel concept of a quadrotor UAV with tilting propellers. Standard quadrotors are limited in their mobility and ability to interact with the environment because of their intrinsic underactuation (only 4 independent control inputs vs. their 6-dof pose in space). The proposed quadrotor prototype, on the other hand, has the ability to also control the orientation of its 4 propellers, thus making it possible to overcome the aforementioned underactuation and behave as a fully-actuated flying vehicle. We first describe the control design of our actuated UAV, illustrate the hardware and software specification of our flying prototype, and finally show a future perspective for an interaction task between the UAV and the environment.

I. MOTIVATION

Common UAVs (Unmanned Aerial Vehicles) are underactuated robotic systems (this is for instance the case of helicopters or quadrotors) [1]. As a consequence, only their position and yaw angle can be independently controlled, and the behavior of their pitch and roll angles is completely determined by this choice. This underactuation does not only limit the flying ability of UAVs, but it further degrades the possibility of interacting with the environment when trying to exert desired and arbitrary forces in space. Motivated by these limitations, we developed a novel concept of a quadrotor UAV with tilting propellers (propellers which can be actively rotated along the arm axes [2]) that allows to gain full controllability of the quadrotor pose in 3D space.

Exploiting this novel design, our goal is to move quadrotors from pure flying vehicles to fully flying service robots with independent control over all 6-dof of the main body and the ability to exert forces in arbitrary directions.

II. CONCEPT

The overactuation of our novel quadrotor design (4 spinning velocities plus 4 tilting velocities for a total of 8 commands) allows to obtain full controllability over the main body pose in space [3]. As a first proof of concept, we built the prototype shown in Fig. 1 and derived its detailed dynamical model taking into account the actual properties of our prototype (e.g. mass, inertia, communication delays) [4]. In order to achieve asymptotic tracking of an arbitrary trajectory in $R^3 \times SO(3)$, we designed and implemented a control law based on dynamic feedback linearization. Because of its overactuation (8 inputs for 6 controlled dofs), we could also exploit the actuation redundancy of degree 2 for minimizing energy consumption during the maneuver execution. This was achieved by minimizing a cost function penalizing too large spinning velocities for the propellers.

Fig. 1: Picture of the quadrotor prototype with actuated tilting propellers

Fig. 2: Red - propeller spinning velocity; Green - rotor arm spinning velocity

We could then experimentally show that our prototype is able to track trajectories in $R^3 \times SO(3)$ thanks to this control action. It is interesting to note that, as long as the propellers keep on spinning, no singularities in the control action can occur for any propeller-body configurations as proven in [3]. By tracking several complex trajectories (with independent motions for the quadrotor position and orientation), the experiments have clearly demonstrated the potential of this
novel UAV design. One followed trajectory is a 8-shape lying on a horizontal plane. While tracking this shape in position we performed a sinusoidal rotation around the roll-axis. The position error $e_d$, rotation error $e_R$ and a snapshot of of this trajectory is reported in Fig. 3. After having obtained these promising results, confirming the validity of our design, our next step is to build an improved prototype with a better actuation system.

Fig. 3: Left: Video snapshot while performing an 8-shape trajectory with sinusoidal rotation around pitch-axis; Right top: Position error while tracking the trajectory; Right bottom: Rotation error while tracking the trajectory (both: x - blue, y - red, z - green)

III. PERSPECTIVE

We are currently completing the construction of a second prototype (see Fig. 4) with a new more precise actuation system for the tilting arms and a better IMU. For this next iteration, we expect several improvements (e.g. actuated propeller rotating around center of mass and exact knowledge of center of mass) based on the experience gained from the first prototype. This improved design will result in much higher tracking abilities and, additionally, in the possibility of implementing the planned interaction tasks with the environment (e.g., grasping an object or driving a screw into a hole).

Fig. 4: CAD model of 2nd prototype with improved actuation system, below transported screw for interaction with the environment

REFERENCES