Chapter 8
Conclusions

8.1 Summary of the Book

With the aim of advancing in the control and motion planning for aerial robots interacting with the environment, in this book we extensively studied*tethered aerial vehicles*. These consists of unidirectional-thrust aerial vehicles connected to a moving or fixed point on the ground by a link whose length can be changed by a link actuator. For this general system, we produced a complete theoretical analysis of its dynamics and intrinsic properties, the controllability and the observability with a minimal set of standard sensors.

Starting with the investigation of the differential flatness of the systems, a very useful and powerful property of dynamical systems, we proved the existence of two flat outputs. The first, $\mathbf{y}^a$, is directly linked to physical interaction. It contains the position of the vehicle with respect to the anchoring point, the rotation along the thrust vector (standard flat output for an unidirectional-thrust vehicle in free-flight) and the *internal force* along the link. This tells us that the position of the aerial vehicle and the interaction force between the robot, the link and the system at the other end, can be controlled independently. Thanks to the generality of the computed dynamic model, the internal force can be tension and/or compression accordingly to the specific implementation. The second flat output, $\mathbf{y}^b$, contains the position of the vehicle with respect to the anchoring point, the rotation along the thrust vector and the angle ϑ_A that is related to the *attitude of the vehicle* with respect to the link. The latter output entry is unusual for unidirectional-thrust aerial vehicles because, in the free-flight configuration, the attitude is (in terms of differential flatness) a by-product of the translational motion. This adds new potential capabilities to the system.

Aiming to control those outputs and not only the position of the vehicle like in the majority of the state of the art, we designed and experimentally validated two first *hierarchical controllers*. Those are based on the separation principle between translational and rotational dynamics and exploit the flatness to compute the feed-

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forward terms. The conducted experimental tests proven the validity of the method in quasi-static conditions but also shown its limitations when asked to track highly dynamic trajectories. For the goal of precisely tracking any sufficiently smooth time-varying trajectory (not only stabilization like in the state of art), we used the dynamic feedback linearization method to design a second pair of controllers. Parts of those control results were also extended to the particular case of a passive link actuator, which is an interesting case thanks to its simplicity. However, in this case, the internal force along the link is not controllable anymore, and neither the attitude-related variable.

All controllers require the full knowledge of the state of the system in order to compute the control action. Though, in practice it is difficult or even impossible to directly measure the full state of the system. Thus, motivated by the practical and theoretical relevance of the problem, we investigated which is the minimal set of standard sensors that make the system observable. Assuming that the motion of the anchoring platform is known, we proved that the standard onboard IMU together with three encoders measuring the attitude and the length of the link, are enough to obtain an estimation of the full dynamic state (including, e.g., the generalized velocities of the system). Differently from the state of the art in which an observer based on a quasi-static assumption was proposed, we aimed to design an almost globally convergent state estimator. For this purpose, we found some nonlinear transformations of the measurements that bring the system in the canonical controllability form. This allowed us applying a high gain observer. The case in which the link has a constant length and the vehicle is constrained on a vertical 2D plane is of particular interest. Under these assumptions, we proved that only onboard IMU alone is enough to retrieve an estimation of the full state (including position, attitude and generalized velocities). Such a surprising result is rather unique in the panorama of state estimation for aerial vehicles, indeed a positional measurement is typically always needed. Also in this case, we found some nonlinear transformations of the measurements and of the state such that to apply a high gain observer.

From the theoretical study, we passed to a more applicative and practical problem: *landing and takeoff of an unidirectional-thrust aerial vehicle on/from a sloped surface*. This problem is normally very challenging in a free-flight configuration due to the underactuation and the consequential need of a precise motion planning and tracking. On the other hand, we proved that the use of the tether makes those maneuvers much more safe, reliable and robust to model uncertainties and tracking errors. For the practical execution, we successfully employed the hierarchical controller for $\mathbf{y}^b$. A motion planner based on an optimal control method was also designed to improve the reliability and smoothness of the landing and takeoff.

Finally, we considered a multi-robot extension composed of two aerial vehicles tethered by two links to the ground and to each other, forming a chain-like system. The system is of particular interest for its similarity with a planar two-link manipulator, where the actuators are aerial vehicles. For this system, we extended the flatness and the dynamic feedback linearizability with respect to $\mathbf{y}_2^a$ (containing the position and internal link force for both couples vehicle/link). Also in this case, we designed a high gain observer based on IMU and encoders measurements.

8.2 Future Works

We presented a complete theoretical analysis of tethered aerial vehicles. Nevertheless, some additional works could be done, e.g., formally proving the stability of the proposed hierarchical controller, proven only experimentally. Other interesting extensions could be done toward an automatic identification of the system parameters and an adaptive controller, or toward a cooperative control with the moving platform. Another work could be to consider the problem of landing (and takeoff) on a surface with variable attitude, like a ship in a rough see. From the control and motion planning point of view, an interesting problem could be the one of using a tethered robot for the exploration of unknown and cluttered environments. On the other hand, given the level of maturity of the theoretical part, many are works that could be done form the practical and engineering point of view. Firstly, we plan to experimentally test the proposed dynamic feedback linearizing controller and the observers. Those could be then employed to enhance the performance during the landing and takeoff maneuvers in highly dynamic cases. However, for the real application, some improvements of the system have to be considered. For example a small winch could be added to unroll and roll-up the cable immediately before and after the tethered maneuvers. A more suitable anchoring mechanism can be designed according to the type of landing surface. Finally, the robot could be equipped with an onboard vision system to identify the position of the anchoring and landing points, as well as the landing surface attitude.