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Energy based 3D trajectory tracking control of quadrotors with model-free based on-line disturbance compensation

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Abstract In this work, a Revisited form of the so-called Model-Free Control (R-MFC) is derived. Herein, the MFC principle is employed to deal with the unknown part of a plant only (i.e., unmodeled dynamics, disturbances, etc.) and occurs beside an Interconnection and Damping Assignment-Passivity Based Control (IDA-PBC) strategy. Using the proposed formulation, it is shown that we can significantly improve the performance of the control through the reshaping properties of the IDA-PBC technique. Moreover, the control robustness level is increased via a compensation of the time-varying disturbances and the unmodeled system dynamics. This on-line compensation capability is provided by the MFC principle. The problem is studied in the case of Multi-Input Multi-Output (MIMO) mechanical systems with an explicit application to a small Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) where a stability analysis is also provided. Numerical simulations have shown satisfactory results, in comparison with some other control strategies, where an in-depth discussion with respect to the control performance is highlighted by considering several scenarios and using several metrics.

1. Introduction

Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicles (UAVs) are very popular platforms of research, due to their maneuverability, hovering ability, and maintenance and construction simplicity. In Refs. [1,2], hexacoptors are used to build binocular vision based UAVs. A novel forest fire detection method using quadrotor motion features is detailed in Ref. [3] Moreover, quadrotors are considered as a good case study to design, analyze, and implement flight control strategies.

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It is necessary to design a controller so that a quadrotor will be able to efficiently follow a predefined trajectory, particularly in the presence of disturbances. For this reason, many studies have led to the development of sophisticated and robust nonlinear control laws. In Ref. [4], an H_∞ controller and backstepping approaches were proposed in order to stabilize the attitude and tackle the path-tracking problem of a quadrotor, respectively. The authors in Ref. [5] proceeded by considering two subsystems and applying two nested control strategies. The Internal Model Control (IMC) strategy was applied to the inner loop whilst the Immersion and Invariance (I&I) one was applied to the outer loop. In Ref. [6], a robust adaptive control was proposed for attitude stabilization under external disturbances and validated by real-time implementation. Refs. [7,8] presented a sliding mode control combined with the backstepping technique for the sake of stabilization, regulation, and trajectory tracking. Other approaches have been applied for an instance direct adaptive sliding mode controller[9] and an SMC-neural networks controller.[10]

However, some of the existing control strategies require an accurate modeling of a system in order to perform a good control, which is extremely difficult especially when the system is maneuvering in harsh environment. This is due to the lack of complete knowledge on the system and its surrounding phenomena. In this regards, a Model-Free control (MFC) technique has been developed (see for instance[11]). The main advantage of this control strategy is that it doesn't require the knowledge of system dynamics as it involves a continuous updating of the input–output of a very-local model. This anticipation property makes a control possible even with the presence of disturbances. It has been employed in many real cases such as a mobile robot[11] and quadrotors.[12]

In a certain point of view, assuming no available model is not totally a correct assumption due to the fact that most of systems, at least, may be approximated by mathematical models even with poorly known dynamics. Therefore, using available information about a system will bring a notable benefit and significantly improve the performance of control. In such a case, a nonlinear control auxiliary input should be used to deal with the nonlinear modeled dynamics of the system. Notice that the classic MFC control employs a PID controller as an auxiliary input. As in general, the tuning of PID parameters allows to meet the desired specifications of control, we propose the use of a reference model based nonlinear control technique that achieves a control with required specifications, by means of Interconnection and Damping Assignment- Passivity Based Control (IDA-PBC).

Quadrotors allow the development of advanced manipulation tasks (robot vision[13], flying sensors[14], etc.) where damping and inertial properties play a significant role. For this reason, the development of techniques that explicitly present these factors is of major impact. Therefore, in the last two decades, the use of the so-called Port-Controlled Hamiltonian (PCH) representation has attracted the attentions of researchers. Many control tools have been developed to deal with this compact representation. Passivity-Based Control (PBC) is well known especially in mechanical applications for controlling nonlinear systems. An improvement was developed through Interconnection and Damping Assignment (IDA) where the use of energy shaping was originated in Ref. [15] Recently, the IDA-PBC has become an efficient tool in nonlinear control applications (electrical, hydraulic, chemical, and mechanical) and has been illustrated in several real experimentations including electrical motors[16], robots with a parallel architecture[17], rotary inverted pendulum[18], etc.

1.1. Contribution

As stated above, the classic MFC is data-driven, i.e., only input and output data are used while the differential equations associated to the mathematical physical laws are ignored. Therefore, the MFC does not distinguish between system dynamics and disturbances.

Since control requires some mapping, taking system information, a controller is constructed in this paper through the use of the MFC principle to accommodate the unknown parts of a system and disturbances whilst an auxiliary input is used to ensure the asymptotic convergence of tracking errors toward the origin. Therefore, this paper involves the MFC algorithm, which requires only system measurements (not a system model) to deal with uncertainties and disturbances in order to ensure a good level of robustness.

In the literature, the use of MFC is always linked to a linear PID controller. Unlike this common case, this paper proposes an IDA-PBC approach to design the auxiliary input that enables the system to meet the desired specification of control.

This formulation is considered as a Revisited form of the classic Model-Free Control (R-MFC) strategy that combines both MFC and IDA-PBC approaches. Such an approach has potential advantages in control performance as well as its robustness level compared to classical controllers. This is due to the capability of MFC in estimating system uncertainties, modeling errors, and disturbances as well as the IDA-PBC's capability in meeting a fixed control performance.

By using this formulation, the asymptotic stability of the system is guaranteed, for which a detailed analysis is provided hereafter. It is applied to a small quadrotor where numerical simulations are also provided. Throughout this paper, a performance assessment is presented via results of several scenarios with complementary comments on the proposed revisited strategy of control with respect to other techniques (MFC and backstepping approaches). Particular attention is paid to the tracking accuracy and energy consumption of each control strategy considering some performance criteria, such as Integral Squared Error (ISE) and Integral Squared Control Input (ISCI).

1.2. Outlines

The remainder of this paper is organized as follows. In Section 2, some notations and concepts of energy based control are briefly recalled. Section 3 concerns the dynamics of a VTOL quadrotor and the control architecture. Sections 4 and 5 introduce the design of our nonlinear control approach. Simulation results are illustrated in Section 6. Finally, the paper is ended with some concluding remarks.

2. Background

2.1. Notations

We denote $\mathbf{R}, \mathbf{R}^n$, and $\mathbf{R}^{n\times n}$ the sets of real numbers, vectors, and matrices, respectively, and $\mathbf{R}^+$ denotes the non-negative