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Trajectory Tracking Control of an Aerial Robot with Obstacle Avoidance

Ícaro Bezerra Viana * Igor Afonso Acampora Prado *
Davi Antônio dos Santos * Luiz Carlos Sandoval Góes *

* *Technological Institute of Aeronautics, São José dos Campos, SP 12228-900 Brazil (e-mail: icaro,igorap,davists,goes@ita.br).*

Abstract: The present paper deals with the problem of position control of a flying robot type multirotor helicopter with obstacle avoidance. In order to solve the problem, an architecture with model predictive controller (MPC) minimize the tracking error, where are implemented the inclusion of convex constraints on the position vector, making it possible to avoid obstacles with a flexible trajectory. The proposed method is evaluated on the basis of computational simulations considering that the vehicles is subject to disturbance forces. Simulation results show the effectiveness of the method related to the tracking performance with focus on the treatment of obstacle avoidance constraints.

Keywords: Aerial robotics, Multirotor helicopter, Model predictive control, Tracking control, Obstacle avoidance.

1. INTRODUCTION

There is a tendency in using multirotors helicopters as robotics platforms for executing missions in urban areas, for example product delivering and traffic monitoring. In order to continue improving the flight safety and for completely autonomous operation, it is indispensable that the multirotors have incorporated in their control system the ability of avoiding obstacles. The main idea of this topic is to design algorithms able of recognizing the obstacle and recalculating the multirotor trajectory for achieving the final point with safety.

Applications using MPC strategy are expanding to robot control [Vivas and Mosquera, 2005], because this technique is suitable for control of multivariable systems governed by constrained dynamics. The multirotors have an under-actuated dynamics with six degrees of freedom (DOF) and four independent controls. Namely, they have three DOFs of translation and three DOFs of rotation and can be actuated by three torque components and the magnitude of the total thrust vector. To ensure avoidance requirements in the context of trajectory planning, several solutions have been proposed in the literature, such as potential fields [Chuang, 1998, Paul et al., 2008], A^* with visibility graphs [Hoffmann et al., 2008, Latombe, 1991] and mixed integer linear programming (MILP) [Richards and How, 2002]. In particular the latter shows how integer variables are added to the optimization process in order to deal with the constraints properly.

This paper presents a control system for flight of an autonomous multirotors in the presence of obstacles. In order to ensure, simultaneously, performance in the trajectory tracking and treating the obstacle avoidance constraints, a structure with a MPC controller is used for guiding the vehicle. In this, the design of a position controller consists of a linear state-space model predictive control (MPC) strategy. Thus, is used here the trajectory control proposed in [Prado and Santos, 2014], where the controller is designed taking into account a conical constraint on the total thrust vector, ie constraints on the inclination of the rotor plane and on the magnitude of the total thrust vector. This paper extends the problem treated in [Prado and Santos, 2014] and in [Santos et al., 2013] including integer constraints on the problem formulation using a quadratic cost function, resulting in a MIQP (mixed-integer quadratic program). The main contribution of this paper is the incorporation of a MIQP form in a predictive control scheme to treat the obstacle avoidance problem for multirotors helicopters.

Figure 1 shows the block diagram of a control system for controlling only the three-dimensional position $\mathbf{r} \in \mathbb{R}^3$ of a multirotor to follow a time-varying position command $\mathbf{r}_\mathrm{d} \in \mathbb{R}^3$. This system is organized in two loops: an inner loop for attitude control and an outer loop for position control. The Navigation System block is responsible for estimating the vehicle's attitude $\mathbf{D} \in \mathrm{SO}(3)$, angular velocity $\boldsymbol{\omega} \in \mathbb{R}^3$, position $\mathbf{r}$, and linear velocity $\dot{\mathbf{r}} \in \mathbb{R}^3$. The Attitude Control block receives an attitude command $\mathbf{D}_\mathrm{d} \in \mathrm{SO}(3)$ and produces the control torque $\boldsymbol{\tau} \in \mathbb{R}^3$ to incline the rotor plane with respect to the horizontal plane as desired. The Position Control block has the role of generating the throttle command (command for the total thrust magnitude) $f \in \mathbb{R}$ and the attitude command $\mathbf{D}_\mathrm{d}$ necessary to accelerate the multirotor in such a way to control its position as desired.

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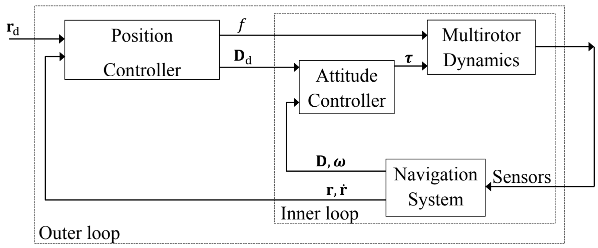

Fig. 1. Block diagram of a multirotor position tracking control system.

The rest of the body text is organized as follows: Section II presents the definition of the problem. Section III describes the problem solution. Section IV describes the evaluation based on computer simulations using MATLAB/SIMULINK and Section V contains the conclusions and suggestions for future work.

2. PROBLEM STATEMENT

Consider the multirotor vehicle and the three Cartesian coordinate systems (CCS). In Figure 2 is assumed that the vehicle has a rigid structure. The body CCS $S_\mathrm{B} \triangleq \{X_\mathrm{B}, Y_\mathrm{B}, Z_\mathrm{B}\}$ is fixed to the structure and its origin coincides with the center of mass (CM) of the vehicle. The reference CCS $S_\mathrm{R} \triangleq \{X_\mathrm{R}, Y_\mathrm{R}, Z_\mathrm{R}\}$ is Earth-fixed and its origin is at point O. Finally, the CCS $S_{\mathrm{R}'} \triangleq \{X_{\mathrm{R}'}, Y_{\mathrm{R}'}, Z_{\mathrm{R}'}\}$ is defined to be parallel to S_R, but its origin is shifted to CM. Assume that S_R is an inertial frame.

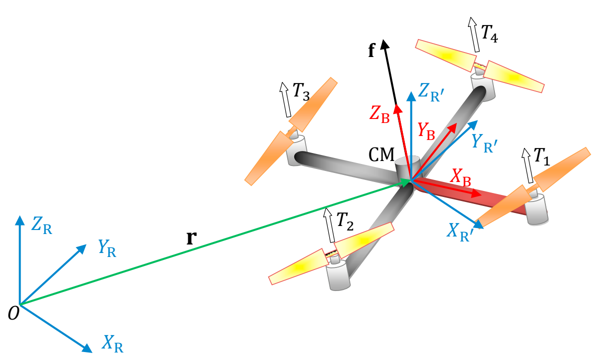

Fig. 2. The Cartesian coordinate systems.

Invoking the second Newton's law and neglecting disturbance forces, the translational dynamics of the multirotor illustrated in Figure 2 can be immediately described in S_R by the following second order differential equation:

$$\ddot{\mathbf{r}} = \frac{1}{m}\mathbf{f} + \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}, \tag{1}$$

where $\mathbf{r} \triangleq [r_\mathrm{x}\ r_\mathrm{y}\ r_\mathrm{z}]^\mathrm{T} \in \mathbb{R}^3$ is the position vector of CM, $\mathbf{f} \triangleq [f_\mathrm{x}\ f_\mathrm{y}\ f_\mathrm{z}]^\mathrm{T} \in \mathbb{R}^3$ is the total thrust vector, m is the mass of the vehicle, and g is the gravitational acceleration. As illustrated in Figure 2, $\mathbf{f}$ is perpendicular to the rotor plane.

Define the inclination angle $\phi \in \mathbb{R}$ of the rotor plane as the angle between Z_B and $Z_{\mathrm{R}'}$. The angle ϕ can thus be expressed by

$$\phi \triangleq \cos^{-1}\frac{f_\mathrm{z}}{f}, \tag{2}$$

where $f \triangleq \|\mathbf{f}\|$.

Define the position tracking error $\tilde{\mathbf{r}} \in \mathbb{R}^3$ as

$$\tilde{\mathbf{r}} \triangleq \mathbf{r} - \mathbf{r}_\mathrm{d}, \tag{3}$$

where $\mathbf{r}_\mathrm{d} \triangleq [r_{\mathrm{d,x}}\ r_{\mathrm{d,y}}\ r_{\mathrm{d,z}}]^\mathrm{T} \in \mathbb{R}^3$ is a position command.

Problem 1. Let $\phi_\mathrm{max} \in \mathbb{R}$ denote the maximum allowable value of ϕ, $f_\mathrm{min} \in \mathbb{R}$ and $f_\mathrm{max} \in \mathbb{R}$ denote, respectively, the minimum and maximum allowable values of f. The problem is to find a control law for $\mathbf{f}$ that minimizes $\tilde{\mathbf{r}}$, subject to the inclination constraint $\phi \leq \phi_\mathrm{max}$, and to the force magnitude constraint $f_\mathrm{min} \leq f \leq f_\mathrm{max}$.

Problem 2. Let $\mathbf{L}^l \in \mathbb{R}^3$ and $\mathbf{U}^l \in \mathbb{R}^3$ denote, respectively, the coordinates of the lower left-hand corner and the upper right-hand corner of a static obstacle l. The problem consists in include avoidance requirements so that a control action should calculate a command $\mathbf{f}^{(i)}$ by ensuring that the current position of the ith vehicle $\mathbf{r}^{(i)}$ lie outside the obstacle l, at each time step, as show in Figure 3.

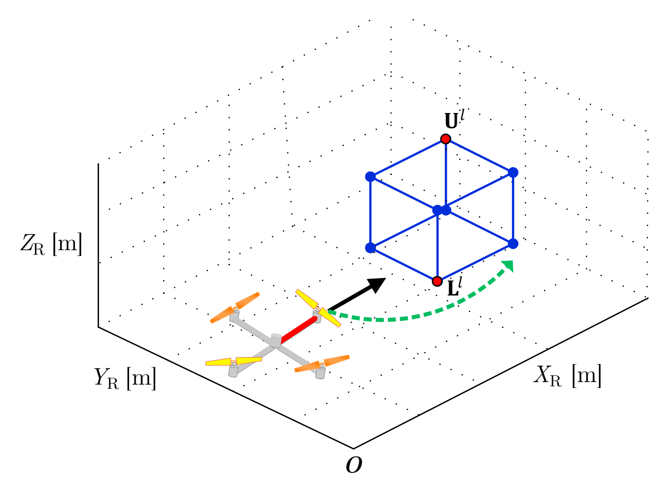

Fig. 3. Obstacle avoidance problem

The obstacles can be modeled in this framework as convex polygons of any number of sides, but, to simplify the presentation, the results in this paper only use a parallelepiped, as shows in Figure 3. It supposes that a laser range sensor is used for the detection of the obstacle.

It is assumed that the location of the parallelepiped obstacle defined by $\mathbf{L}^l$ and $\mathbf{U}^l$ are known. Thus, to achieve the obstacle avoidance and to attend the requirement proposed simply add the following set of linear inequality convex constraints in the problem formulation,