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IFAC-PapersOnLine 48-1 (2015) 904–909

Cascaded Nonlinear Control of a Duocopter with Disturbance Compensation by an Unscented Kalman Filter

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Abstract: A cascaded control strategy for an innovative Duocopter test rig – a helicopter with two rotors combined with a guiding mechanism – is presented in this paper. The guiding mechanism consists of a rocker arm with a sliding carriage that enforces a planar workspace of the Duocopter. The Duocopter is attached to the carriage by a rotary joint and offers 3 degrees of freedom. The derived system model has similarities with a PVTOL and a planar model of a quadrocopter but involves additional terms due to the guiding mechanism. In the paper, a model-based cascaded control strategy is proposed: in the outer MIMO control loop, sliding mode techniques are employed to control both the horizontal and the vertical Duocopter position. The rotation angle of the Duocopter is controlled in a linear inner control loop using flatness-based techniques. An additional feedforward control takes into account known parts of the coupling forces between the carriage and the rocker. The control structure is extended by an Unscented Kalman Filter (UKF) that provides estimates for the state vector and, moreover, estimates for remaining errors concerning the feedforward coupling forces. The sum of the feedforward part and the estimated part can be used to accurately compensate for the impact of the guiding mechanism on the motion of the Duocopter frame. Thereby, an excellent tracking performance in vertical and horizontal direction can be achieved. The efficiency of the proposed control strategy is demonstrated by experiments.

Keywords: Mechatronics, sliding mode control, unscented Kalman filter, disturbance compensation.

1. INTRODUCTION

In recent work, different approaches to controlling a quadrotor Unmanned Aerial Vehicle (UAV) have been investigated at the Chair of Mechatronics, University of Rostock, see Gerbert (2012); Meinlschmidt (2013); Gruening et al. (2012). Several feedforward and feedback control algorithms as well as combined state and disturbance observers could be successfully tested in simulations. The validation with a self-built quadrotor system, however, proved to be difficult due to 1) limited possibilities concerning a spatial position measurement and 2) an immanent risk of destroying the set-up during the experiments. In order to reduce the given complexity of a quadrotor with six degrees of freedom (DOFs) and, hence, to enable a comparison of alternative control algorithms in real experiments, the Duocopter test rig has been developed, see Meinlschmidt and Aschemann (2014). The main idea has been a practical realisation of an UAV that is able to fly in a plane with 2 translational DOFs and 1 rotational DOF. This realisation basically combines a helicopter with two rotors and a guiding mechanism as depicted in Fig. 1. The rocker arm can perform a limited rotation in a rotary joint and guides a carriage that can move freely along the rocker arm. The two rotors of the Duocopter are mounted at both ends of a metal rod that represents the frame of the Duocopter. This rod can rotate relative to a short shaft that is fixed rigidly to the carriage.

The test rig is equipped with 3 sensors: a contactless hall effect encoder for measuring the relative rotation angle α of the Duocopter frame w.r.t. the rocker, a contactless hall effect encoder for the rotation angle β of the rocker, and a laser sensor for the distance d between the lower rotational joint of the rocker and the moving carriage. In

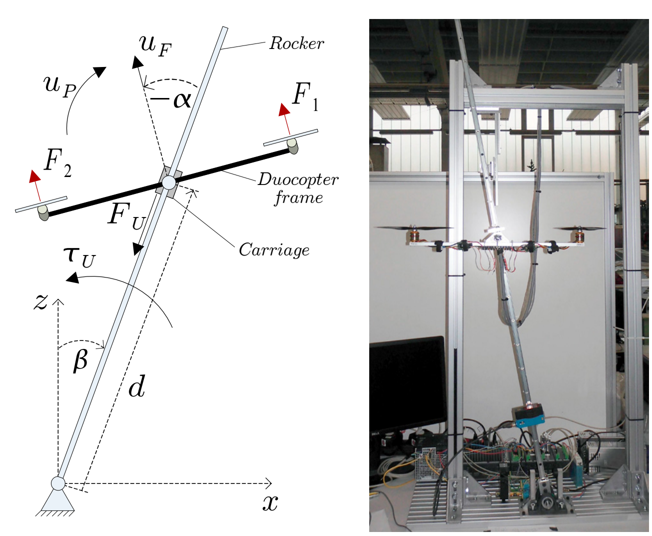

Fig. 1. Mechanical structure and corresponding test rig.

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10.1016/j.ifacol.2015.05.089

this paper, a dynamic model of the Duocopter is derived, and a nonlinear model-based control is designed. The cascaded feedback control structure consists of an outer loop with a sliding mode trajectory tracking control and an inner tracking control loop w.r.t. the rotation angle. It is extended by a feedforward control as well as an unscented Kalman filter (UKF) to take into account the given gravitational, inertial and friction forces acting on the rocker and to estimate the translational velocities. The UKF was proposed in Julier and Uhlmann (1997) and since then revisited in numerous articles including Julier and Uhlmann (2004); van der Merwe (2004). It was developed to overcome the weak spot of the extended Kalman filter (EKF) caused by a linearisation of the state equations during the covariance propagation. This step introduces inaccuracy as soon as the higher order terms of the Taylor series expansion become significant. The UKF employs the complete nonlinear system model and rather approximates the distribution of the state random variable by using a set of deterministically chosen sample points. In this contribution, the scaled unscented transformation proposed in van der Merwe (2004) is used as UKF algorithm.

The paper is structured as follows: In Section 2, both the modelling of the test rig – based on a rigid multibody system – and the derivation of a control-oriented model are presented. A cascaded control design using sliding mode techniques is proposed in Subsections 3.1 and 3.2. It involves an outer control loop for the tracking of desired trajectories in the x, z-plane, whereas an inner loop provides an accurate tracking control of the orientation angle. In Subsection 3.3, a discrete-time UKF is designed for a combined state and disturbance estimation. In Section 4, the discrete-time implementation of the tracking control structure in combination with the UKF is validated by experimental results from the test rig. The paper closes with conclusions given in Section 5.

2. DYNAMIC SYSTEM MODELLING

2.1 Test rig modelling

The Duocopter test rig offers 3 DOFs and can be described by a planar multibody system with three bodies: the rocker (index R, mass m_R, mass moment of inertia I_R), the carriage (index C, mass m_C, whereas the mass moment of inertia I_C is negligible) and the Duocopter frame with two propeller drive units (index F, mass m_F, mass moment of inertia I_F). The vector of generalised coordinates is chosen as

$$\mathbf{q} = \begin{bmatrix} d \\ \alpha \\ \beta \end{bmatrix} . \tag{1}$$

The distance of the carriage center of gravity to the hinge point of the rocker is denoted by d, the rocker angle w.r.t. the perpendicular line by β, and the relative rotation of the Duocopter frame w.r.t. the rocker by α. The control inputs are $u_F = F_1 + F_2$, representing the total thrust, and $u_P = (F_2 - F_1)l$, describing the torque around the upper rotational joint caused by the two rotors. The rotors are mounted in a distance of l w.r.t. the joint. As disturbance inputs, the unknown torque τ_U acting on the rocker – addressing nonlinear friction in the lower joint as well as a restoring torque due to the cable connection – and the unknown friction force F_U acting along the rocker arm are considered. The nonlinear equations of motion can be derived either by Lagrange's equations or, advantageously, by the Newton-Euler projection approach. For this purpose, position vectors to the corresponding centers of gravity are introduced: the position vector to the rocker $\boldsymbol{r}_R$, to the carriage $\boldsymbol{r}_C$ and the Duocopter frame $\boldsymbol{r}_F$ are given by

$$\boldsymbol{r}_R = \begin{bmatrix} d_R \sin(\beta) \\ d_R \cos(\beta) \end{bmatrix}, \ \boldsymbol{r}_C = \begin{bmatrix} d \sin(\beta) \\ d \cos(\beta) \end{bmatrix}, \ \boldsymbol{r}_F = \boldsymbol{r}_C \ , \tag{2}$$

where d_R denotes the distance to the center of gravity of the rocker. The corresponding Jacobians of translation can be computed as

$$\mathbf{J}_{Ti} = \frac{\partial \mathbf{r}_i}{\partial \mathbf{q}}, \ i = \{R, C, F\} \ , \tag{3}$$

for these vectors. Introducing the absolute angles $\varphi_R = \varphi_C = \beta$ and $\varphi_F = \alpha + \beta$, the Jacobians of rotation follow from

$$\mathbf{j}_{Rj} = \frac{\partial \varphi_j}{\partial \mathbf{q}}, \ j = \{R, F\}. \tag{4}$$

Given the Jacobians, the nonlinear equations of motion $\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{k}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{h}(\mathbf{q}, u_F, u_P, F_U, \tau_U)$ are stated as follows: the mass matrix becomes

$$\begin{aligned} \mathbf{M}(\mathbf{q}) =& m_R \mathbf{J}_{TR}^T \mathbf{J}_{TR} + m_C \mathbf{J}_{TC}^T \mathbf{J}_{TC} + m_F \mathbf{J}_{TF}^T \mathbf{J}_{TF} \\ &+ I_R \mathbf{j}_{RR} \mathbf{j}_{RR}^T + I_F \mathbf{j}_{RF} \mathbf{j}_{RF}^T \ , \end{aligned} \tag{5}$$

whereas the vector of Coriolis and centrifugal terms is given by

$$\begin{aligned} \mathbf{k}(\mathbf{q}, \dot{\mathbf{q}}) =& m_R \mathbf{J}_{TR}^T \dot{\mathbf{J}}_{TR} \dot{\mathbf{q}} + m_C \mathbf{J}_{TC}^T \dot{\mathbf{J}}_{TC} \dot{\mathbf{q}} \\ &+ m_F \mathbf{J}_{TF}^T \dot{\mathbf{J}}_{TF} \dot{\mathbf{q}} \ . \end{aligned} \tag{6}$$

Furthermore, the vector of non-conservative and conservative forces results in

$$\begin{aligned} \mathbf{h}(\mathbf{q}, u_F, u_P, F_U, \tau_U) =& \mathbf{J}_{TR}^T \begin{bmatrix} u_F \sin(\alpha + \beta) \\ u_F \cos(\alpha + \beta) \end{bmatrix} + \mathbf{j}_{RF} u_P \\ &- \frac{\partial U(\mathbf{q})}{\partial \mathbf{q}} + \begin{bmatrix} -F_U \\ 0 \\ -\tau_U \end{bmatrix} \ . \end{aligned} \tag{7}$$

The function $U(\mathbf{q}) = [m_R d_R + (m_C + m_F) d] g \cos(\beta)$ represents the potential energy with the gravitational acceleration is given by g. By solving for the second time derivatives of the vector of generalised coordinates

$$\ddot{\mathbf{q}} = \mathbf{M}^{-1}(\mathbf{q}) \left[-\mathbf{k}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{h}(\mathbf{q}, u_F, u_P, F_U, \tau_U) \right] \ , \tag{8}$$

the dynamics can be described by the following set of second-order differential equations

$$\ddot{d} = \frac{u_F \cos(\alpha)}{m_{Fr}} - g \cos(\beta) + \dot{\beta}^2 d - \frac{F_U}{m_{Fr}} \ , \tag{9}$$

$$\begin{aligned} \ddot{\alpha} =& \frac{u_P}{I_F} - \frac{u_F d \sin \alpha}{I_{Rr}} \\ &- \frac{[m_{Fr} d + m_R d_R] g \sin(\beta) - 2 m_{Fr} \dot{d} \dot{\beta} d - \tau_U}{I_{Rr}} \ , \end{aligned} \tag{10}$$

$$\begin{aligned} \ddot{\beta} =& \frac{u_F d \sin \alpha}{I_{Rr}} \\ &+ \frac{[m_{Fr} d + m_R d_R] g \sin(\beta) - 2 m_{Fr} \dot{d} \dot{\beta} d - \tau_U}{I_{Rr}} \ . \end{aligned} \tag{11}$$

Here, the abbreviations $m_{Fr} = m_C + m_F$, and $I_{Rr} = I_R + m_R d_R^2 + m_{Fr} d^2$ are introduced.