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Attitude control strategy for a camera stabilization platform☆

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ABSTRACT

In this paper, an attitude control strategy for a 3-axis gimbaled platform used for the stabilization of film and broadcast cameras is presented. The attitude control strategy for the camera provides an alignment of the camera's line of sight with a desired attitude, independent of the movements of the platform base. This control objective is achieved by a combination of a feedforward compensation of the disturbances induced by the moving base (the operator) and a feedback control of the orientation of the camera. The required attitude information is obtained by an attitude estimation strategy presented in [1] that fuses the measurements of two inertial measurement units. The derivation of the proposed control law utilizes a number of approximations tailored to the considered application. This allows to obtain an efficient but yet accurate attitude control concept. The very good accuracy and the practical feasibility of the overall control strategy are demonstrated by simulation and measurement results of a prototype platform.

1. Introduction

Camera stabilization is applied in film and broadcast productions to avoid distractions of the line of sight of a dynamically moved camera. A growing use of camera stabilization systems can be observed that goes along with the demand for increasing accuracy and higher flexibility in operation [2,3]. The main requests are a small and light structure that can be applied in various settings and the capability to turn the camera in any desired direction independently from the motion of the carrier.

Basically, the various approaches for camera stabilization can be divided into passive and active systems. A state-of-the-art passive stabilization of the camera carried by an operator is the steadycam [4]. This system is composed of a pole that has a mount for the camera at the top and counterweights at the bottom. Due to the high inertia of the system and a spring-loaded link to a harness of the operator, the camera is decoupled from the (fast) movements of the operator. Another widespread method for passive camera stabilization is to mount fast rotating momentum wheels to the camera [5].

Active systems do not have the disadvantage of additionally attached masses and the limited work space due to mechanical constraints. In [6], inertially stabilized platforms (ISPs) are introduced that are typically assembled in the form of actuated gimbals. In the case of three nonparallel joints, the orientation of the camera mounted on an ISP is fully controllable. Since very lightweight constructions exist for these systems, they are often utilized in airborne applications. A system with a double-gimbal is described in [7], which is designed for aerial imaging and visual object tracking. In [8], an inertially stabilized double-gimbal airborne camera platform is presented that is applied to image based pointing and tracking.

Another field of application for ISPs is the stabilization of mobile antennas. Here, the task is to point a mobile vehicle based antenna to a satellite in order to establish a link for data transfer. In [9], a survey of stabilized satcom antenna systems is given and in [10], a ship-mounted satellite tracking antenna is presented.

The sensors used in ISP technology are typically gyroscopes measuring the angular rate in the inertial frame and encoders for position measurement of the joints angles [11]. With these measurements, a control loop for camera stabilization can be applied utilizing a control law of the form [12–14]

$$\boldsymbol{\tau} = \mathbf{K}_v \mathbf{J}^{-1} \Delta\boldsymbol{\omega}, \qquad (1)$$

with a positive definite matrix $\mathbf{K}_v$, the manipulator Jacobian $\mathbf{J}$ of the ISP and the error of the angular velocities $\Delta\boldsymbol{\omega}$. This approach can be found in numerous applications because of its simple structure. The drawback of (1) is that it does not provide absolute adjustment of the camera in the inertial frame and it is unfeasible if the manipulator Jacobian $\mathbf{J}$ becomes singular.

The control of the absolute orientation of a body is known as attitude control problem [15] in literature. It is primarily investigated in aerospace applications because of its importance to the

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navigation of aerial vehicles, see, e.g., [16]. In the attitude control problem, a feedback law of the form

$$\boldsymbol{\tau} = k_p \bar{\mathbf{r}} - k_v \Delta\boldsymbol{\omega}, \tag{2}$$

with the positive scalar controller parameters k_p, k_v, the vector part of a quaternion error $\bar{\mathbf{r}}$ and the error of the angular velocities $\Delta\boldsymbol{\omega}$, is typically utilized. For instance, this approach is applied to a quadcopter in [17]. In [18], a quaternion feedback law for attitude control of a micro satellite is obtained from integrator backstepping. In [19,20], it is shown how a quaternion feedback controller can be designed without measurements of the angular velocities.

In all contributions of the attitude control problem mentioned so far, the orientation of a single body is stabilized by assuming that the torques acting on the body can be directly applied. In a real stabilization platform, the inertia of the components of the gimbaled platform cannot be neglected such that this assumption is more or less violated. Including the inertia yields a multi-body control task. Up to the authors' knowledge, there is no systematic extension of the attitude control problem (2) to multi-body systems reported in literature and there does not seem to be an application of the attitude control problem to ISPs.

According to the classification of control strategies in [21], the control laws (1) and (2) are direct stabilization strategies, which are characterized by utilizing a measurement of the camera's actual movement. In contrast, the indirect stabilization approach achieves stabilization of an ISP by a feedforward compensation of the measured disturbance motion of the ISP base. In [22], the indirect control is applied for stabilizing a manipulator with a forced non-inertial base.

In this paper, a control strategy for the stabilization of a 3-axial ISP is introduced that combines a feedforward compensation of the disturbances with a feedback control of the camera's absolute orientation. The proposed controller constitutes a novel approach to ISP stabilization, which extends the well known position control using inverse dynamics (computed torque), see, e.g., [23,24].

In Section 2, the platform is introduced and models for the kinematics and dynamics are derived. Moreover, the attitude estimation strategy of [1] is briefly summarized. The derivation of the control strategy is given in Section 3. Section 4 shows the analysis of some specific features of the control strategy by means of simulations. Finally, the control accuracy and the practical feasibility of the overall control strategy is analyzed by measurements on a prototype platform in Section 5.

2. System description

In Fig. 1, a prototype of the platform under consideration is depicted. The sketch of this setup in Fig. 2 shows that the ISP comprises three gimbals p_1, p_2, p_3 and the platform base p_0. The camera is attached to p_3, while the base p_0 is carried by the operator. The bodies p_n, $n = 0, \ldots, 3$, are linked by three rotational joints which are actuated by direct-drive brushless dc (BLDC) motors. The joint angles $\mathbf{q} = [q_1, q_2, q_3]^T$ define the actuated degrees of freedom (dof) of the platform. In the experimental setup, the base p_0 of the ISP can be mounted on a suspension, which has the two rotational degrees of freedom ψ and ϕ, see Fig. 2. Each joint is equipped with a high-resolution encoder measuring the actuated dof $\mathbf{q}$ and the disturbance motion represented by ψ and ϕ.

In real application, the base p_0 is moved by the operator and thus has six dof. Two inertial measurement units (adis 16480 and adis 16485, see [25,26]) are used to measure the motion of the platform with respect to the inertial frame $(Ix_I y_I z_I)$. They provide inertial measurements of the angular velocity and the translational acceleration by means of their integrated 3-axial gyroscope and 3-axial accelerometer. In this paper, a combined feedforward disturbance rejection and feedback control strategy is derived in

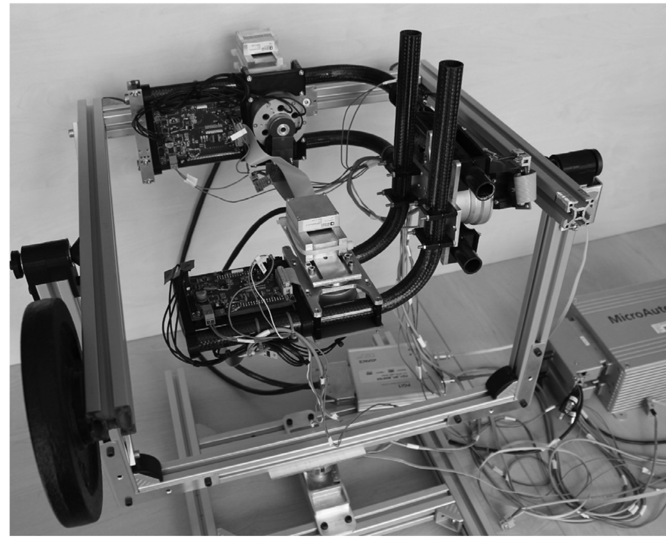

Fig. 1. Photo of the prototype platform.

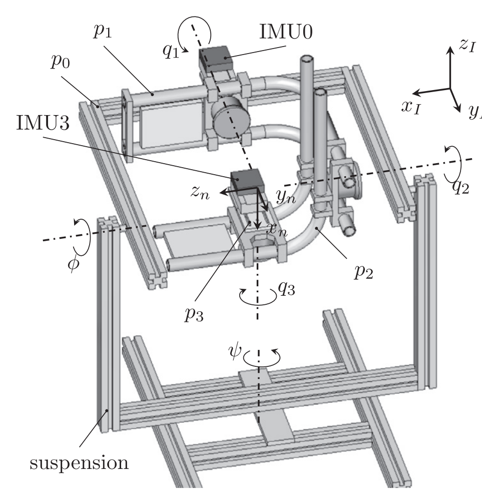

Fig. 2. Sketch of the prototype platform.

Section 3. For this task, it proves advantageous to mount an IMU on the base p_0 (IMU0) and one on the position of the camera p_3 (IMU3), see Fig. 2.

2.1. Platform kinematics

According to the model in [1], the inertial orientation of the camera $\mathbf{r}_I^3$ is described by the unit quaternion

$$\mathbf{r}_I^3 = \begin{bmatrix} r_{I,0}^3 \\ r_{I,1}^3 \\ r_{I,2}^3 \\ r_{I,3}^3 \end{bmatrix} = \begin{bmatrix} r_{I,0}^3 \\ \bar{\mathbf{r}}_I^3 \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{\alpha}{2}\right) \\ \mathbf{n}\sin\left(\frac{\alpha}{2}\right) \end{bmatrix}, \tag{3}$$

$\|\mathbf{r}_I^3\|_2 = 1$, which defines the rotation of the body-fixed frame $(3x_3y_3z_3)$ of p_3 with respect to the inertial frame $(Ix_I y_I z_I)$, see, e.g., [27,28] for the basics on quaternion notation. The quaternion $\mathbf{r}_I^3$ is defined by the orientation $\mathbf{r}_I^0$ of the body p_0 with respect to the inertial frame and the relative rotations of the body-fixed frames $(nx_n y_n z_n)$, $n = 1, \ldots, 3$, of the three gimbals.

$$\mathbf{r}_2^3 = \left[\cos\left(\frac{q_3}{2}\right), \quad \sin\left(\frac{q_3}{2}\right), \quad 0, \quad 0\right]^T \tag{4a}$$

$$\mathbf{r}_1^2 = \left[\cos\left(\frac{q_2}{2}\right), \quad 0, \quad 0, \quad \sin\left(\frac{q_2}{2}\right)\right]^T \tag{4b}$$