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Using natural features for vision based navigation of an indoor-VTOL MAV

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ABSTRACT

The use of natural features for vision based navigation of an indoor Vertical-Take-Off-and-Landing (VTOL) Micro Aerial Vehicle (MAV) named Air-Quad is presented. Air-Quad is a small four-rotor helicopter developed at the ITE.

Such a helicopter needs reliable attitude information. The measurements of the used MEMS gyroscopes and accelerometers are corrupted by strong noise. To be useful, the MEMS sensors have to be part of an integrated navigation system with aiding through complementary sensors like GPS or the computer vision module presented here.

In the computer vision module, feature points are detected and tracked through the image sequence. The relative rotation and translation of the camera are estimated using the two-dimensional motion of the feature points.

The three-dimensional points in the scene are modeled with the image coordinates of their first sighting and their inverse depths. Only these inverse depths are estimated for the feature points. An efficient sparse bundle adjustment algorithm is used to improve the estimation of the scene structure and the navigation solution.

It is shown that the use of the computer vision module greatly improves the navigation solution compared to a solution based only on MEMS sensors.

1. Introduction

In the last years, small Unmanned Aerial Vehicles (UAV) called Micro Aerial Vehicles (MAV) were developed to be used in surveillance and reconnaissance tasks.

Especially for the control of helicopters accurate attitude information is necessary. The used cheap Micro-Electro-Mechanical Systems (MEMS) gyroscopes and accelerometers are noisy and need additional aiding sensor information to supply reliable navigation information. Such an additional sensor could be GPS. GPS provides accurate position information, but fails in indoor environments, cannot aid the yaw angle estimation during hovering, or can be jammed. Therefore, the use of a computer vision module for the aiding of the navigation system is an interesting option.

Due to the increased availability of computer power, computer vision systems are more and more used for MAV in the last few years: A simulation of a GPS/INS system for a fixed wing aircraft with horizon detection is shown in [15]. In [2], the speed over ground is calculated using a stereo camera. In [1], a camera based control of a four-rotor helicopter using colored markers is shown. Artificial markers to determine the position and attitude are presented in [11].

In [12], a stereo vision odometry system using sparse bundle adjustment for unstructured outdoor environments is presented. A self-tracker using an IMU and artificial fiducials is shown in [5].

In this contribution, the possibility to use a computer vision module to aid the position and attitude estimation using non-artificial features is shown with real data.

This paper is divided in the following parts: In the next section, the used airframe Air-Quad is presented, after that a description of the integrated navigation system follows. In Section 4, the developed computer vision module is described in great detail. After that, the experimental results are presented. Finally, conclusions are drawn.

2. Airframe Air-Quad

A four-rotor helicopter named Air-Quad (see Fig. 1) was designed at the ITE to develop and verify navigation algorithms. Its advantages are the simple mechanical design without swash plates and the high agility. The control of the position, velocity, and attitude is achieved using different rotational speeds of the rotors. For example, a roll to the left is made by reducing the speed of the left rotor and increasing the speed of the right rotor.

Due to the lack of a tail-rotor, which would only compensate the yaw-movement and not increase the lifting power, Air-Quad is

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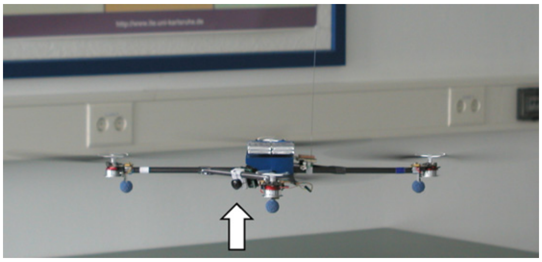

Fig. 1. Flying Air-Quad with mounted camera looking outwards (marked by the arrow).

very energy-efficient and can fly with one set of lithium polymer batteries up to 25 minutes.

Reliable navigation information provided by an integrated navigation system is required to control the helicopter using cascaded PID controllers.

3. Integrated navigation system

An integrated navigation system (see Fig. 2) integrates the measured accelerations $\tilde{\boldsymbol{f}}^{\mathrm{b}}$ and angular rates $\tilde{\boldsymbol{\omega}}^{\mathrm{b}}$ using the strapdown algorithm [13] to gain attitude $\boldsymbol{R}_{\mathrm{b}}^{\mathrm{w}}$, position $\boldsymbol{p}^{\mathrm{w}}$, and velocity $\boldsymbol{v}^{\mathrm{w}}$ information. Because of the noise of the used MEMS sensors (standard derivation of the accelerometer $\sigma_a = 0.029267\ \mathrm{m/s^2}$ and the gyroscope $\sigma_\omega = 0.025867$ rad/s at 70 Hz) aiding with complementary sensors like GPS [14] or the here presented computer vision module is essential.

In the following sections, the used strapdown algorithm, the Kalman filter for the data fusion, and the experimental setup are introduced.

3.1. Strapdown algorithm

The used inertial sensors are fixed with respect to the body of the UAV. The strapdown algorithm (using the inertial frame mechanization [13]) transfers the measurements from the body frame to the inertial frame. They are integrated to provide attitude, velocity, and position of the UAV. The measurements of the inertial sensors are modeled as data with an additional constant bias and superimposed white noise. The bias is estimated with a Kalman filter. The used navigation equations neglect the effects of earth rotating (Coriolis force). This is justified by the slow speed of the vehicle and the limited flying range in indoor environments.

3.1.1. Notation

The following notation is used: The vector $\boldsymbol{p}_{\mathrm{wb},k}^{\mathrm{w}}$ is the position of the body frame b (right lower index) given in the world frame w (upper index) with respect to the world frame (left lower index) at the time t_k.

The direction cosine matrix $\boldsymbol{R}_{\mathrm{b}}^{\mathrm{w}}$ transforms the vector $\boldsymbol{x}^{\mathrm{b}}$ from body frame to world frame representation.

The matrix $[\boldsymbol{t}]_\times$ is the skew-symmetric matrix of the vector $\boldsymbol{t}$. Therefore, the cross product is $[\boldsymbol{t}]_\times \cdot \boldsymbol{a} = \boldsymbol{t} \times \boldsymbol{a}$.

3.1.2. Position and velocity computation

After the time step ΔT, the new velocity $\boldsymbol{v}_{\mathrm{wb},k+1}^{\mathrm{w}}$ and position $\boldsymbol{p}_{\mathrm{wb},k+1}^{\mathrm{w}}$ are calculated using

$$\boldsymbol{a}_{\mathrm{wb}}^{\mathrm{w}} = \boldsymbol{R}_{\mathrm{b}}^{\mathrm{w}}\big(\tilde{\boldsymbol{f}}^{\mathrm{b}} - \hat{\boldsymbol{b}}_a\big) + \boldsymbol{g}, \tag{1}$$

$$\boldsymbol{p}_{\mathrm{wb},k+1}^{\mathrm{w}} = \boldsymbol{p}_{\mathrm{wb},k}^{\mathrm{w}} + \boldsymbol{v}_{\mathrm{wb},k}^{\mathrm{w}}\Delta T + \frac{1}{2}\boldsymbol{a}_{\mathrm{wb}}^{\mathrm{w}}(\Delta T)^2, \tag{2}$$

$$\boldsymbol{v}_{\mathrm{wb},k+1}^{\mathrm{w}} = \boldsymbol{v}_{\mathrm{wb},k}^{\mathrm{w}} + \boldsymbol{a}_{\mathrm{wb}}^{\mathrm{w}}\Delta T \tag{3}$$

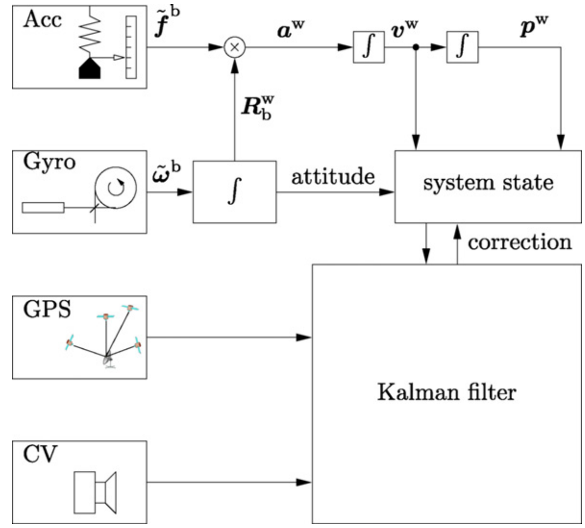

Fig. 2. Integrated navigation system.

with the estimated bias $\hat{\boldsymbol{b}}_a$, the gravity vector $\boldsymbol{g}$, and

$$\boldsymbol{R}_{\mathrm{b}}^{\mathrm{w}} = (\,\boldsymbol{c}_1 \quad \boldsymbol{c}_2 \quad \boldsymbol{c}_3\,) \tag{4}$$

with

$$\boldsymbol{c}_1 = \begin{pmatrix} a^2+b^2-c^2-d^2 \\ 2(bc+ad) \\ 2(bd-ac) \end{pmatrix}, \tag{5}$$

$$\boldsymbol{c}_2 = \begin{pmatrix} 2(bc-ad) \\ a^2-b^2+c^2-d^2 \\ 2(cd+ab) \end{pmatrix}, \tag{6}$$

$$\boldsymbol{c}_3 = \begin{pmatrix} 2(bd+ac) \\ 2(cd-ab) \\ a^2-b^2-c^2+d^2 \end{pmatrix}, \tag{7}$$

and the current attitude quaternion $\mathbf{q}_k = (a, b, c, d)$.

3.1.3. Attitude computation

To update the attitude information stored in the quaternion $\mathbf{q}$, the angular rates $\tilde{\boldsymbol{\omega}}_{\mathrm{wb}}^{\mathrm{b}}$ are integrated over the time ΔT resulting in the rotation $\boldsymbol{\sigma}$. The angular rates are considered to be constant during this integration:

$$\boldsymbol{\sigma} = \int_{t_k}^{t_{k+1}} \big(\tilde{\boldsymbol{\omega}}_{\mathrm{wb}}^{\mathrm{b}} - \hat{\boldsymbol{b}}_\omega\big)\,dt = \big(\tilde{\boldsymbol{\omega}}_{\mathrm{wb}}^{\mathrm{b}} - \hat{\boldsymbol{b}}_\omega\big)\Delta T. \tag{8}$$

The rotation $\boldsymbol{\sigma}$ is transformed into the quaternion $\mathbf{q}_c$. Using $\mathbf{q}_c$, the current attitude $\mathbf{q}_{k+1}$ can be calculated from the old attitude $\mathbf{q}_k$:

$$\mathbf{q}_{k+1} = \mathbf{q}_k \bullet \mathbf{q}_c \quad \text{with } \mathbf{q}_c = \begin{pmatrix} 1 - \frac{1}{2!}\big(\frac{|\sigma|}{2}\big)^2 + \frac{1}{4!}\big(\frac{|\sigma|}{2}\big)^4 \\ \frac{1}{2}\cdot\big(1 - \frac{1}{3!}\big(\frac{|\sigma|}{2}\big)^2 + \frac{1}{5!}\big(\frac{|\sigma|}{2}\big)^4\big)\cdot\boldsymbol{\sigma} \end{pmatrix}. \tag{9}$$

The symbol $\bullet$ is used for the quaternion multiplication.

With this strapdown algorithm a complete navigation is possible. This navigation is autonomous and cannot be jammed.

Even with a perfectly known starting position, velocity, and attitude, the navigation solution would drift away because of sensors errors like bias and noise. Therefore, aiding of the navigation with a complementary sensor is needed. For this purpose, stochastic filters like the here used Kalman filters are common.