Optical Flow for Attitude Estimation of a Quadrotor Helicopter

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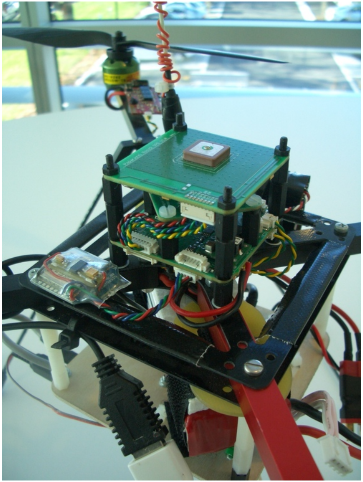
Outline

Introduction

- Quadrotor MAV, 700 g flying weight
- Mikrokopter style frame, custom electronics and controlled, based on Paparazzi system
- Autonomous hover, stability augmented manual flight
- Interested in measuring attitude of the MAV using visual means
- Consider hovering, not translating, flight with small-moderate motion
- This technique gives the yaw rate, r and velocity V_z of the MAV using visual means

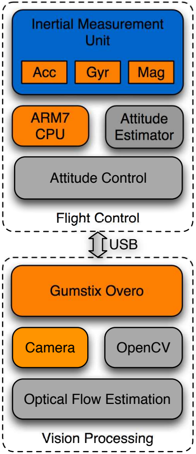


Motivation

- Use of MAVs close to the ground and in complex environments
- Many opportunities to investigate new methods of sensing and control using computer vision
- Good models for such methods are found in the world of flying insects
- Do the processing on the MAV, **real experimentation, not just simulation**
- Maximal utilisation of the vision system

Hardware

- Flight Control: 32bit LPC2148 ARM7 micro-controller running at 60 MHz
- Solid state inertial measurement unit
- Vision Processing: Gumstix Overo Earth single board computer (SBC). TI OMAP3503 processor, 600 MHz, 256 MB of flash and RAM.
- Runs linux-rt 2.6.29
- State and command messages passed over USB.



Imaging

- Downward facing image sensor
- Fitted with a miniature fisheye lens, an effective focal length of 1.8 mm
- Mated with a 1/3" image sensor delivering a 160° horizontal field of view image

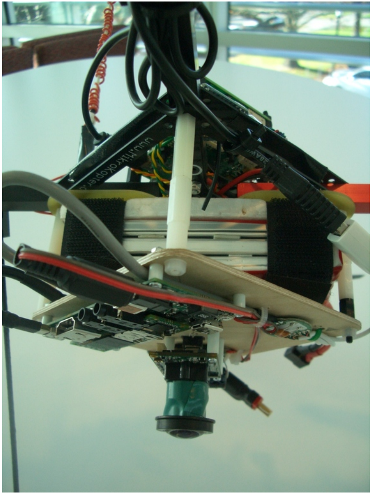
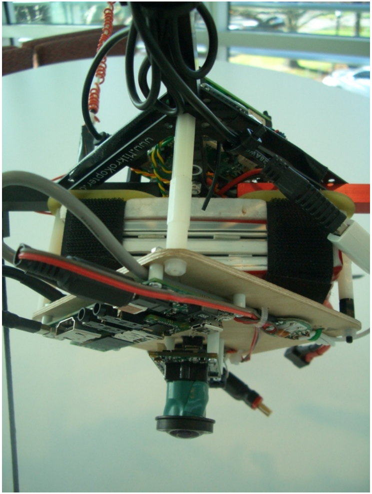


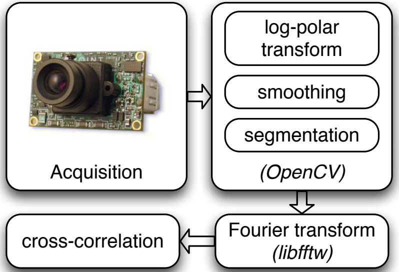
Image Processing Overview

- Capture omnidirectional images from down facing camera
- Transformation into log-polar domain
- Calculate optical flow using phase-correlation
- Derive estimation of yaw-rate, r and V_z



Vision Pipeline

- USB Point Grey Firefly camera
- Acquire images at 15 FPS, processing at 10 Hz on the SBC



Omnidirectional Vision

- Wide angle image sensors are advantageous for navigation, object avoidance, etc
- Omnidirectional vision systems usually applied to wheeled robots
- Usually as a means of obtaining a wide FOV scene for object recognition, or as a substitute for short range distance sensors.
- Objects stay in the image frame longer - generally smoother variation of the scene, can make optical flow calculation easier

Omnidirectional Vision

Optical Flow

- Optical flow is the approximation of the motion field which can be computed from time-varying image sequences
- Image changes due to motion during a time interval Δt

Optical Flow Estimation Methods

- Differential Techniques (dense motion field): Spatial and temporal variations of the image brightness at all pixels
- Phase Methods: Response of filters to energy signals
- Matching Techniques (sparse motion field): Estimate the disparity of special image points (features) between frames

Phase Correlation

- Phase is an intrinsic property of the image, from its luminance
- Unlike the BM method, which searches the blocks from luminance matches, the phase-correlation method measures the movement between the two fields directly from their phases

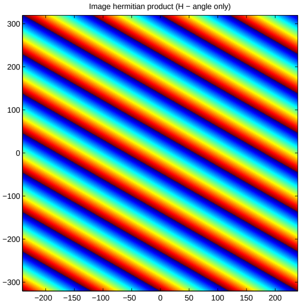
Why Phase Correlation

- Previous work showed phase correlation performed best, when considering computational requirements and the operational environment
- Resilience to global changes in illumination
- Optimized implementations of key components available for target platform, including the fftw3 library for the SBC, and numerous optimized implementations for the C64 series DSP also present on the Omap processor.

Process

The phase correlation method for determining optical flow estimates the relative shift between two image blocks by means of a normalized cross-correlation function computed in the 2D spatial Fourier domain

$$\bar{C}_{k,k+1}(u,v) = \frac{\mathcal{F}_{k+1}(u,v)\mathcal{F}_k^*(u,v)}{|\mathcal{F}_{k+1}(u,v)\mathcal{F}_k^*(u,v)|}, \tag{1}$$



(a) Hermitian product of image spectra, non-normalized, angle-only

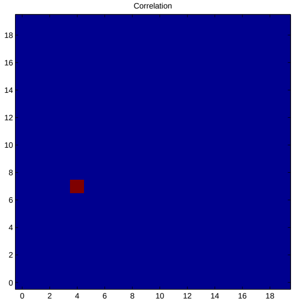
If we assume that $I_k(x, y)$ undergoes a linear translational motion of (v_x, v_y) and normalising the time between frames $(\Delta t = 1)$ then we are able to compute the displacement (x_0, y_0) of the brightness pattern captured on image sensor, such that $I_{k+1}(x, y) = I_k(x - x_0, y - y_0)$. The Fourier images will be related by a simple linear phase translation, i.e.,

$$\mathcal{F}_{k+1}(u, v) = \exp\left(-j2\pi(ux_0 + vy_0)\right) \mathcal{F}_k(u, v), \qquad (2)$$

and in this case the cross-correlation function can be stated as,

$$\bar{c}_{k,k+1}(x,y) = \delta(x - x_0, y - y_0), \tag{3}$$

where the location of the impulse in the cross-correlation space gives the optical flow estimate.



(b) Phase correlation of successive images

Optical Flow Computation in Log-polar Space

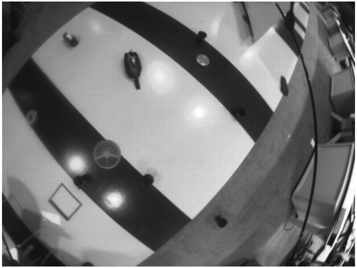
- 3D motion in the direction of the optical axis leads to a dilation or contraction (constant scaling) of the optical flow field
- Rotational 3D motion about the optical axis leads to a circular optical flow field
- In the Cartesian coordinate system this gives an optical flow field which is the vector sum of a rotational vector field and a dilation vector field

- Consider the polar coordinate system

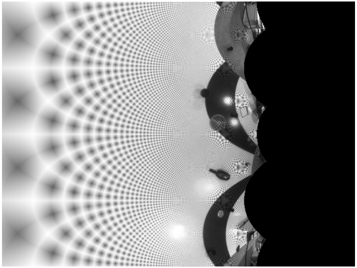
$$r = \sqrt{(x - x_c)^2 + (y - y_c)^2}, \tag{4}$$

$$\alpha = \tan^{-1} \frac{(y - y_c)}{(x - x_c)}. \tag{5}$$

- Thus, a change in heading is proportional to $\Delta\alpha$ and a change in altitude is proportional to $\log \Delta r$

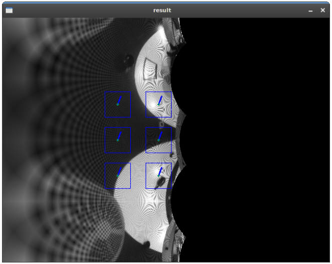


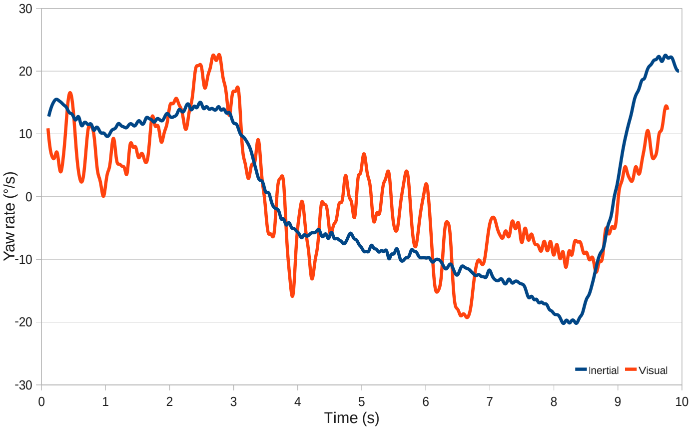
(c) Original image



(d) After log-polar transformation

- Correlation is computed for multiple small sub-regions of the transformed images
- Size and position of sub-regions is chosen according to FFT, and egomotion





(e) Estimated yaw rate

Results

- Visual estimate of yaw rate corresponds with the inertial result accross multiple flights
- Integration of yaw rate to heading was achieved, although fusion with additional sensors was necessary to minimize errors
- Direct integration of rate information into rate based controller was tested
- Similar results for V_z were acheived, although with less accuracy

Future Work

- Improving efficiency of phase correlation, estimation in the spectral domain (no IFFT)
- Combining the log-polar transformation step into the FFT, Fourier-Melin transform
- Renconciliation of the altitude estimate
- Use of optical flow estimates in other control layers
- Improvement of state estimation using visual yaw-rate r and V_z information

Questions