FINE TRACKING SYSTEM FOR AERONAUTICAL FSO LINKS

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Abstract

Free-space optical terminals on aeronautical platforms for A/C-Ground or A/C-Sat links are likely to suffer from pointing errors induced by e.g. carrier vibrations. These drawbacks can be overcome with an agile Fine Pointing Assembly (FPA). Such an FPA, based on a Fast Steering Mirror, has been implemented for an aeronautical free-space optical terminal. Background light is rejected by using a modulated beacon signal and digital filtering in the tracking processor. The system concept as well as simulation results are presented in this paper.

1 Introduction

Free-space optical communications become more and more popular in applications that require high data rates along with high power efficiencies. Especially for the high-rate downlink of image data taken by visible light cameras, FSO links are a good choice, as operation of the sensor is only possible under good visibility conditions what eliminates the probably largest FSO drawback: the link bloackage by clouds.

In the scope of German Aerospace Center's ARGOS project[1], such an image acquisition system has been developed. It is meant to serve as reconnaissance system for disaster management applications after catastrophic events, e.g. after floodings or earthquakes, but also for gathering real-time imagery during e.g. mass-events. Combined with e.g. smart vehicle detection algorithms[2], the system can be used to guide traffic flows, among many other applications. In all scenarios, a real-time downlink of the captured data to a transportable optical ground station at the operations center is foreseen.

The developed Airborne Optical Terminal has undergone the first tests at the end of 2008[3] and has been continuously advanced since then. One major goal of the developments was to increase the power efficiency, what involves decreasing the tx beam divergence. However, with small beam divergences ($<< 1$ mrad), the misspointing errors due to carrier vibrations gain a more and more remarkable influence on the stability of the link.

For the purpose of allowing the decrease in beam divergence while maintaining a stable link between the aircraft and the ground station, a Fine-Pointing Assembly (FPA) has been added in the latest stage of development. It essentially consists of a Fast-Steering-Mirror (FSM) as actuator, a Four-Quadrant Photodiode (4QD) as feedback sensor and a Digital Signal Processor (DSP) as controller. Furthermore, the beacon laser system has been modulated. This allows the rejection of background light influences by applying digital filters to the sampled signals in the DSP.

In order to achieve a high grade of eye-safety, the whole system has been developed for wavelengths in the 1550 nm range.

2 System Description

Figure 1 shows the Dornier 228 aircraft that is used for the In-Flight Validation Tests during the measurement campaign in December 2008. The optical bench and the control system is mounted inside the aircraft, while only the CPA - in the lower left corner - is visible outside. A more detailed description of the terminal design without Fine-Pointing Assembly is available in [3].

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Figure 1: Picture of the Do228 Aircraft with Installed Optical Terminal. Lower Left: Enlargement of Coarse Pointing Assembly

A block diagram indicating the implemented optical system is visible in Figure 2. The Coarse Pointing Assembly (CPA) is used to achieve a hemispherical Field of Regard. However, as its mass is comparably high, its agility is limited and thus it's not suitable for compensating high-frequency distortions of the carrier. For this purpose, a Fast-Steering Mirror (FSM) has been installed in the system.

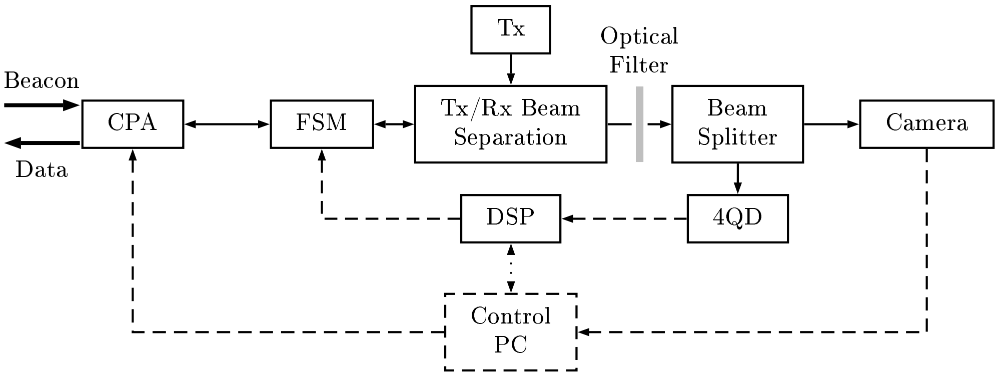

Figure 2: Blockdiagram of the Implemented Optical System

After the FSM, the Tx-Data- and Rx-Beacon-Light is seperated. Subsequently, the light is filtered by a narrow optical bandpass and splitted onto a tracking camera (InGaAs Focal Plane Array) and a Four Quadrant Photodiode (4QD, also InGaAs). The camera with its high detector size and Field-of-View (FoV) serves as acquisition sensor, while the 4QD with its narrow FoV is used as accurate and fast feedback device for closing the control loop to the FSM by means of a Digital Signal Processor (DSP).

The Control PC is used for processing the data of an GPS/IMU device in order to calculate proper pointing angles towards the ground station. Furthermore, it processes the signals of the camera during the acquisition process, and is also connected to the DSP for controlling the system with data from the 4QD sensor.

The electronical setup as visible in Figure 3 has been implemented. A transimpedance amplifier has been installed for the conversion of the 4QD's photocurrent to a reasonable electrical signal. A first order analog bessel high-pass has been placed before a second amplifier, that increases the signal to a suitable level for the A/D-Converter. Furthermore, the high-pass prevents the second amplifier from getting saturated, as a remarkable amount of the expected background light is supressed. The DSP executes a control loop and generates a proper signal for the mirror driver. Finally, the control loop is closed from the mirror to the 4QD. Anti-Aliasing and Reconstruction Filters have been implemented, but are not

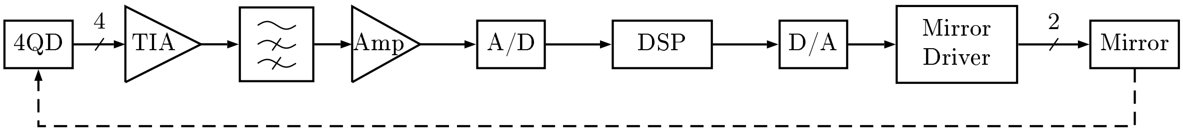

Figure 3: Blockdiagram of Implemented Electronical System

shown in the above block diagram.

3 Power-Budget and Tracking-Accuracy

A power budget including atmospheric attenuation has been calculated. The resulting Signal-to-Noise Ration (SNR) over the link distance is visible in Figure 4. The system has been specified for an operational distance of up to 100 km, resulting in an SNR of ≈ 15 dB. At this distance, the fading margin is approximately 12 dB. It will be shown that the remaining SNR of 3 dB is sufficient for an accurate tracking.

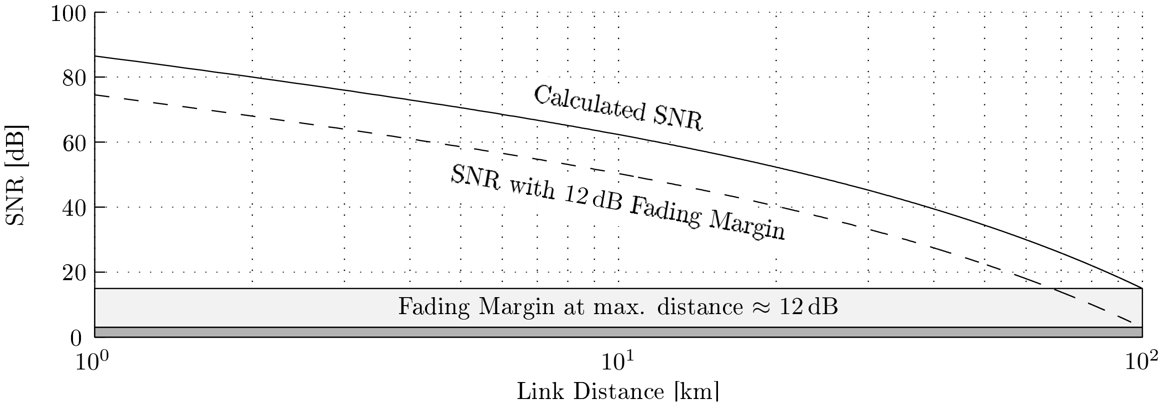

Figure 4: Signal to Noise Ratio at Amplifier Output vs. Link Distance

The actual expected tracking accuracy based on the obtained SNR figures can be estimated based on assumptions by Lambert and Casey[4]. Considering their definition of a *Slope Factor* for an airy pattern in the focus

$$\mathrm{SF} = \frac{4.14}{\theta_a} \tag{1}$$

with

SF	Slope Factor	[1/rad]
θ_A	Optical Spot Diamter	[rad]

and their definition of Root-Mean-Square Tracking Accuracy

$$\sigma_{\mathrm{rms}} = \frac{1}{\mathrm{SF} \cdot \sqrt{\mathrm{SNR}}} \tag{2}$$

with

SF	Slope Factor	[1/rad]
SNR	Signal to Noise Ratio	[1]

an estimation of the tracking accuracy can be calculated for a diffraction limited system.

In order to evaluate if a diffraction limited image can be expected in the focus, a worst case estimate of the Fried-Parameter r_0 has been calculated for the forseen link scenario. For the case that r_0 is remarkably larger than the Rx-Aperture, it can can be expected that no spot pertubances occur due to atmospheric influences. Furthmermore, as the link distances are comparably high, a plane wave at the rx aperture has been assumed for the following calculations.

Given the structural parameter C_n^2, that can be calculated with the *Huffnagel Valley Model*[5],

$$C_n^2(h) = 0.00594 \left(\frac{\nu}{27}\right)^2 (10^{-5}h)^{10} \cdot e^{(-h/1000)} + 2.7 \cdot 10^{-16} \cdot e^{-h/1500} + A \cdot e^{-h/100} \tag{3}$$

with

h	height above ground	[m]
ν	rms wind speed	[m/s]
A	nominal C_n^2 at ground	[$m^{-2/3}$]

and the coherence radius ρ_0 of a plane wave[5]

$$\rho_0 = \left(1.46 C_n^2 k^2 L\right)^{-3/5} \tag{4}$$

with

C_n^2	structural constant	[$m^{-2/3}$]
k	wave number	[1/m]
L	link distance	[m]

the Fried Parameter can be calculated with the estimation[6]

$$r_0 = 2.1\rho_0 \tag{5}$$

with

ρ_0	coherence radius	[m]

For a worst-case estimate, the maximum projected link-distance (100 km) and a rather high wind-speed (30 m/s) have been assumed. Given the known values for aircraft height (3 km) and wave number, an integration over Equation 3 could be carried out for the link path. This approach led to a Fried Parameter of

$$r_0 \approx 150\,\text{mm} \tag{6}$$

at the maximum link distance, what is remarkably larger than the aperture of the optical terminal (30 mm). Thus an airy pattern can be expected in the focus, and Equation 2 is valid for the calculation of the estimated tracking accuracy.

Given the results for the SNR over link distance from Figure 4, the expected tracking accuracy has been calculated and is shown in Figure 5. In order to evaluate the system performance under turbulent channel conditions, the tracking accuracy has been calculated considering 12 dB fading margin, leaving an SNR of 3 dB at the maximum link distance. In order to determine the system's behaviour with lower SNRs, the tracking accuracy for a hypothetical 15 dB fading margin has also been plotted, leaving a SNR of 0 dB at the maximum distance.

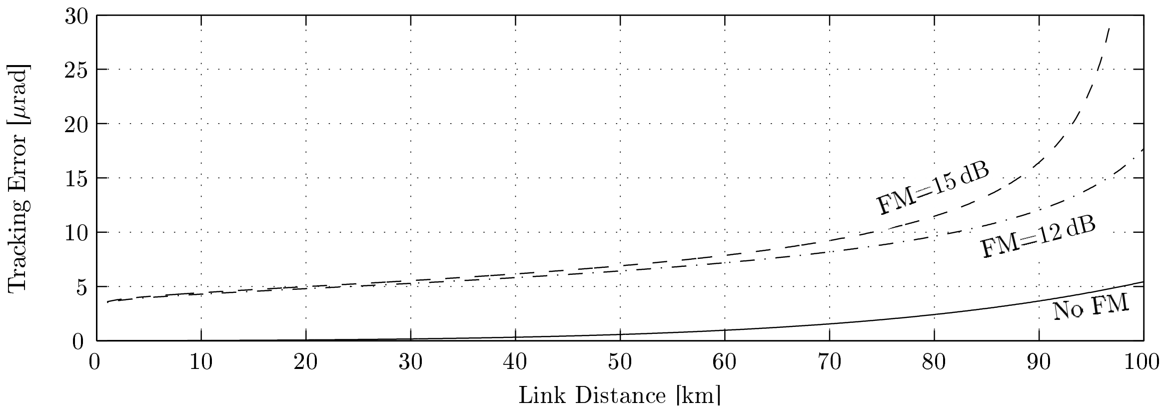

Figure 5: Expected Tracking Accuracy of the FPA vs. link distance for different Fading Margins (FM)

It is visible that the RMS-tracking-accuracy for a 12 dB fading margin is below 20 μrad. This is sufficient for the foreseen project goal of decreasing the laser beam divergence significantly below 1 mrad. However, with worse SNRs (as visible for a fading margin of 15 dB), the RMS tracking accuracy quickly increases to unacceptable values.

4 Background Light Rejection

Although narrow band optical filtering is accomplished before the tracking system, a remarkable amount of background light can still be expected to leak through. This effect might lead to errorneous illumination of the 4QD, resulting in significant misspointing angles or in saturation of the amplification stages. This effect is depicted in Figure 6.

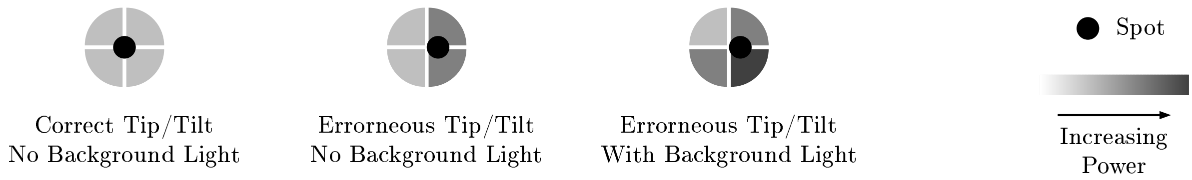

Figure 6: Influence of Background Light to Four Quadrant Tracking

In the picture on the left side, the laser spot created by the 4QD's focus lens falls into the middle of the 4QD, resulting in a uniform power distribution over all 4 Quadrants. In the middle, an errorneous tip/tilt angle of the inclining wavefront exists. Thus the power distribution on the 4QD is not uniform, and a control signal can be generated to correct the tip/tilt angle by moving the FSM. In the picture on the right side, however, the spot offset is equal to the case in the middle, but with additional background light illuminating several quadrants. In this case, an errorneous control signal would be generated, leading to misspointing of the system.

For the purpose of allowing proper tracking with existing background light, the beacon laser system has been modulated. Thus the modulated beacon signal can be extracted and the background light, which is expected to change only slowly, can be supressed. This is accomplished in two stages: First, the analog high-pass mentioned before removes the major part of the background light. However, as the filter characteristic is not very steep, distortions with a higher frequency are still available at the output.

For the purpose of supressing these remaining background light components and for obtaining an additional noise supression, the signal processing chain as visible in Figure 7 has been implemented on the DSP.

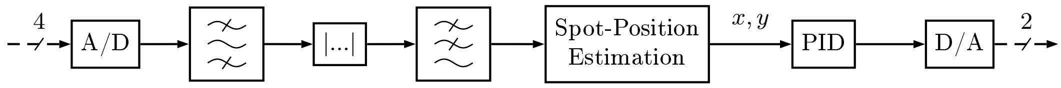

Figure 7: Digital Signal Processing Chain

After the quantization of the signals for the single quadrants with the A/D-Converter, they are fed through IIR butterworth bandpass filters, which are centered on the beacon laser's modulation frequency. Subsequently, the absolute values of the signals are calculated. Then the signals are guided through lowpass filters, which serve as smoothing filter to generate DC signals. Finally, a Spot-Position estimation algorithm calculates the position of the spot on the detector, and the PID-Controller for the tracking control loop is applied.

In order to evaluate and optimize the performance of the system, a step response of the signal processing chain has been simulated. Figure 8 shows the simulated rx signal at the 4QD. The modulation frequency of the beacon laser has been selected to 2 kHz and is limited by the current beacon laser system. The slow signal level fluctuations caused by the background light have been generated as low-pass filtered white noise and are also visible in the Figure as slow DC-offset drift. The dashed vertical lines are seperated by 1 ms and mark the beginning of the modulated sequence. The unit of the signal amplitude at this

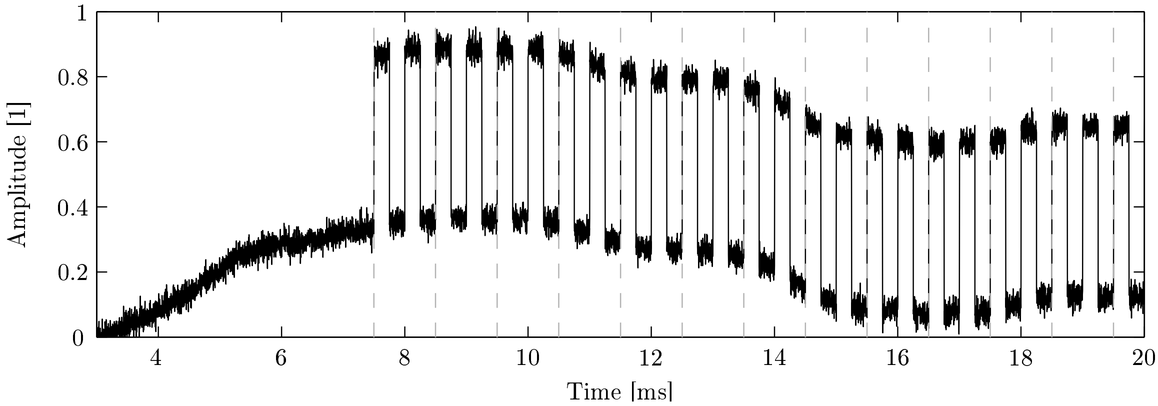

Figure 8: Simulated Rx-Signal with Background-Light Fluctuations

point in the system is AD-counts. However, as the real amplitude values are of no importance for the step response, a normalization to the intervall [0; 1] has been accomplished.

Figure 9 shows the step response of the digital signal processing chain for different bandpass-filter widths. It is visible that the low frequency signal fluctuations of the input signal visible in Figure 8 don't affect the output signal. Thus a rejection of the background light and a good tracking is possible. Unsurprisingly, the widths of the bandpass filters have a remarkable influence on the settlement speed, as the number of filter coefficients increases with smaller filter widths.

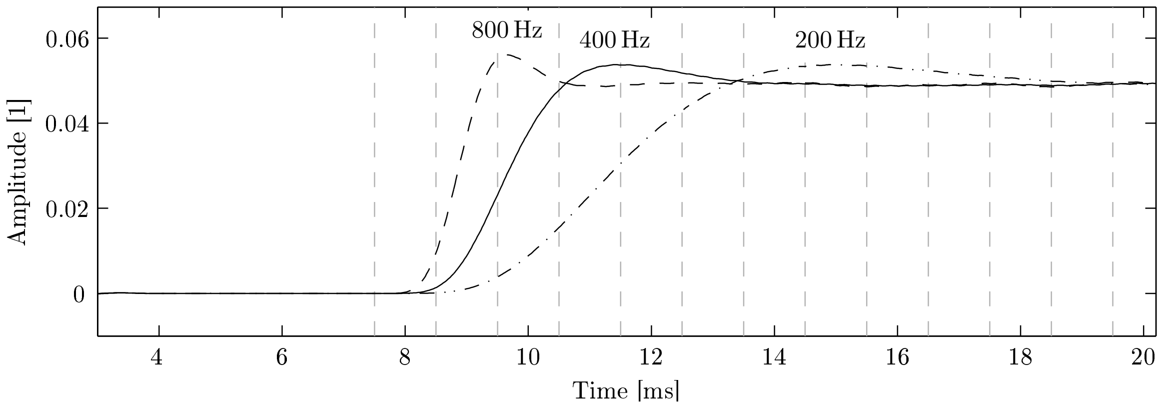

Figure 9: Simulated Step Response for different Bandpass Filter Widths

As a trade-off, 400 Hz of filter width has been chosen for the actual system. Although the settle time is rather high with 4 ms, it seems to be a good compromise between speed and the additional noise rejection that is obtained with a narrow filter. Further system improvements seem possible with an increase of the modulation frequency, resulting in a steeper step response and thus a more agile controller.

5 Measurements

The whole system will undergo further testing in summer and fall 2009. Unfortunately, at the date of paper submission, no measurement results from an airborne campaign have been available for evaluation. However, first lab tests showed promising results and it can be expected that the system will perform well in an airborne environment.

6 Conclusions and Outlook

A Fine-Pointing Assembly for aeronautical applications has been developed and implemented. An estimate for the tracking accuracy based on the expected Signal to Noise Ration for the foreseen scenario has been calculated. As a result, the expected RMS tracking accuracy is in the order of 20 μrad.

A measurement campaign of the optical terminal system will be carried out in summer/fall 2009. It will allow the evaluation of the FPA's impact on the overall system performance.

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