3

System Design

3.1 Preliminary Remarks

The NIRS instrument was developed in three major design steps (see fig 3.1):
First, an evaluation board was designed. Implementing main elements of the later NIRS instrument on a mid-scale PCB enabled easy testing and debugging. As a second step, prototypes were designed and produced. Findings from evaluation and testing were included in succeeding designs. Finally, a compact 4-layer final version was designed and then manufactured by a professional PCB manufacturer.

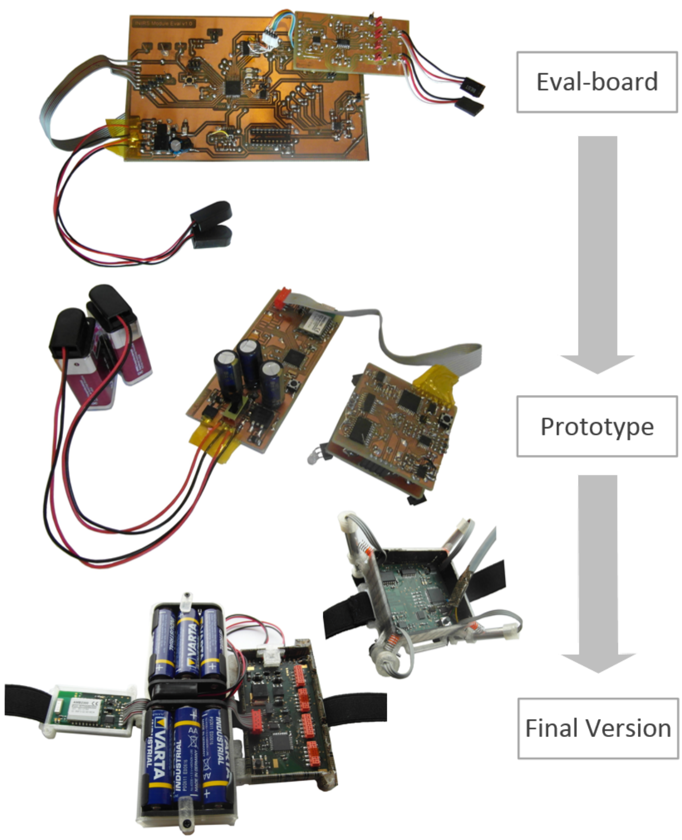

Figure 3.1: Instrument design process.

All evaluation and prototype versions were produced by hand with a standard UV exposure and etching process that is depicted in the Appendix (see fig. A.2).

The following sections of this chapter will provide a detailed description of the system design. For better clarity, the design process was subdivided into thematic sections. The first part revolves around noise, crosstalk and error sources that were taken into consideration during hardware design. Then, the overall system concept and instrument's basic functionality will be depicted. Based on this concept, the hardware design of the instrument is then subdivided into two modules and commented in detail, followed by a short section on user safety design aspects. Finally, the software and mechanical design will be explicated.

For explanation purposes, excerpts of the schematics will be given in the text. The whole schematics can be referred to in the Appendix. The basic software functionality will be described using flow charts and mechanical concepts will be illustrated with 3D renderings. The software code and mechanical drawings are partly depicted in the Appendix and fully supplied on the annexed data carrier.

3.2 Noise, Crosstalk and Error Sources

In this section, noise, crosstalk and other error sources will be examined as preparatory work for the system design.

3.2.1 Noise Errors

There are three main types of noise in photodetector systems:

- *shot noise*,
- *dark current*,
- *thermal noise.*

Shot noise is based on the quantum nature of the photons and cannot be avoided completely by technical means. Being quantized and discrete, the photons arrive independently of each other, resulting in random fluctuations in photon-to-electron conversion in the detector over time. Without internal amplification, the shot noise power is proportional to the square root of the average intensity (the number of incident photons) [11]. This results in the fact that the accuracy of the measurements increases with the intensity of the detected light in a constant time window. Shot noise can be minimized by shielding the detector from background radiation, e.g. with opaque covers [44], or NIR bandpass filters [11].
Dark current is the current flowing in the detector in completely dark conditions (no incident photons) and is highly influenced by the temperature of the material. To minimize dark current due to thermal generation, the device can be cooled.
Thermal noise is white noise resulting from Brownian motion of charge carriers in resistors internal and external to the detector, and is proportional to the resistor value

$$\bar{u^2} = 4k_B T R \Delta f, \tag{3.1}$$

where $\bar{u^2}$ is the mean square voltage variance, k_B is the Bolzmann's constant, T is the absolute temperature of the resistor in Kelvin, R is the resistor value in Ω and Δf is the

spectral bandwidth in Hz over which the noise is measured.
In detectors with internal gains (for instance PMTs or APDs), photonic shot noise and dark currents are amplified together with the signal. Thus, thermal noise is typically small compared to the signal and becomes negligible, requirements of the preamplifier components in terms of noise are therefore reduced [11]. In detectors without internal gains (e.g. SPDs), however, the preamplifier circuitry must be carefully designed to minimize noise pickup and enable a good SNR.

In the following, based on the work of Cope in 1991 [21], a brief mathematical description of the noise in a photodetector is derived:
For photon shot noise (the random arrival of photons at the detector), the probability of n photons arriving in a time interval τ is given by the Poisson distribution

$$P(n,\tau) = \frac{(\eta N_p \tau)^n}{n!} e^{-\eta N_p \tau}, \tag{3.2}$$

where N_p is the average photon arrival rate and η is the quantum efficiency of the detector. Mean μ_p and variance σ_p^2 of the Poisson distribution are given by

$$\mu_p = \eta N_p \tau \tag{3.3}$$

$$\sigma_p^2 = \mu_p \tag{3.4}$$

and thus the SNR of purely Poissonian noise is

$$\mathrm{SNR}_p = \frac{\mu_p}{\sigma_p} = \sqrt{\eta N_p \tau}. \tag{3.5}$$

Dark emission due to unwanted background light or thermal emission from the detector contributes additional noise [21]:

$$\sigma_d^2 = N_d \tau \tag{3.6}$$

Hence, the overall SNR of the detector is

$$\mathrm{SNR}_{\mathrm{detector}} = \frac{\eta N_p \tau}{\sqrt{\eta N_p \tau + N_d \tau}} \tag{3.7}$$

From eq. 3.7 it can be seen that for a high SNR

- the dark noise should be much lower than the optical signal,
- the quantum efficiency of the detector should be as high as possible (near unity),
- the photon arrival rate should be high (the interrogating light intensity as high as possible),
- the noise reduction is proportional to the square root of the total photon count and thereby to the measurement interval τ: noise reduction $\propto \sqrt{N_{\mathrm{photon}_{\mathrm{total}}}}$ [44].

The detector's collection efficiency is proportional to its active area and the square of its numerical aperture [21]. Together with careful design regarding thermal noise influences, these findings were considered for the system design approach.

3.2.2 Crosstalk

There are two main origins of optical crosstalk in NIRS systems:

- *Intrinsic crosstalk*: Change in HbR may mimic a change in HbO and vice versa. One source of this crosstalk is the *partial volume effect* [12] that results from estimates of the correct path length factors (DPFs) (using constant mean path lengths in the MBLL), which are wavelength-dependent [66]. These estimates often have systematic errors that can create crosstalk between species in the estimated concentration changes.
  The size of the intrinsic crosstalk is highly wavelength-pair-dependent and can be significantly reduced by the selection of an optimal wavelength pair [67] (see section 3.4.1).
- *Crosstalk between different sources* that illuminate one detector: When there are more active light sources than one at the same time, NIR light from one source can reach a detector of another active source. This can be minimized by using I-Q-/frequency modulation/demodulation or by time-sharing of the sources (Time-Division Multiplex).

Furthermore, as usual in system design of acquisition instruments, electrical crosstalk should be minimized, e.g. by shielding and large ground planes.

3.2.3 Other Error Sources

Finite bandwidth effect: As the MBLL is only valid for monochromatic light sources, finite bandwidth effects have to be taken into account. In practice, all light sources have a finite bandwidth, beginning with a few nm for laser diodes up to several $10\,nm$ for LEDs. The effect can be mathematically described as follows [21].
The measured transmission $\tilde{T}$ is given by

$$\tilde{T} = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda)S(\lambda)10^{-A(\lambda)}d\lambda}{\int_{\lambda_1}^{\lambda_2} I(\lambda)S(\lambda)d\lambda}, \tag{3.8}$$

where $I(\lambda)$ is the input light intensity, $S(\lambda)$ is detector sensitivity and $A(\lambda)$ is the monochromatic absorbance. The measured absorbance $\tilde{A}(\lambda)$ is then given by

$$\tilde{A} = \log_{10}(\frac{1}{\tilde{T}}). \tag{3.9}$$

As in the fNIRS context $A(\lambda)$ is not constant, the source and detector wavelength dependencies will have an effect: The measured attenuation is less than the theoretically expected value for the mean of $A(\lambda)$ between λ_1 and λ_2 [21].

Stray radiation: Other light sources such as sunlight or room light sources also emit light in the NIR range and thereby effect the detector signal. The acceptable amount of stray light is dependent on the maximum positive absorbance change observed [21]. Its influence can be reduced by opaque covers, frequency modulation techniques, and the subtraction of a dark current intensity baseline that is measured during inactive NIR emitter time slots.

System non-linearities and **system drift** must be avoided in system design and have to be assessed before the instrument is used for the collection of physiological data (see subsection 4.1.5).