Choosing the Resolution in AD Conversion of Biomedical Signals

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Abstract

The resolution and number of bits needed for AD conversion in the presence of noise is computed for a number of biomedical signals. Some other factors influencing these choices are discussed.

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Introduction

For instrumentation there are guidelines for the sample frequency [1, 2] but guidelines for choosing the resolution are not always present[2]. Also in many publications the resolution is indicated by the number of bits used, without clear indication of the dynamic range. Thus it is impossible to calculate the signal input step corresponding to the least significant bit (lsb). Another measure often specified in papers is the amplification. If the signal is sampled then the only relevant figure is the input step per lsb, because this figure determines the quantization noise added by the sampling process.

This paper tries to give a summary of various aspects that influence the choice of a V_{lsb} and the number of bits needed for a particular application.

Noise added by sampling

Sampling adds noise to the signal. In contrast to most other sources of noise which can be approximated by a gaussian noise, the quantization noise is uniformly distributed. The noise in a signal is distributed in accordance to the (propability) density function. Any density function satisfies the conditions: $\epsilon(t) \geq 0$ and $\int_{-\infty}^{\infty} \epsilon(t) = 1$

The total noise as a result of two noise sources has a density that is the convolution of the constituing densities. In general for n sources of noise one has

$$\epsilon(t) = \epsilon_1(t) * \epsilon_2(t) * \cdots * \epsilon_n(t)$$

with $\epsilon(t)$ the total noise distribution and $\epsilon_i(t)$ the noise components. The function $\epsilon(t)$ is itself a density and, more importantly, one has for the standard deviation of this density, irrespective of the noise distributions [3, p 226]

$$\sigma_\epsilon{}^2 = \sum_{i=1}^{n} \sigma_{\epsilon_i}{}^2.$$

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The standard deviation of a uniformly distributed noise with a width of V_{lsb} is $\sigma_{e_q}{}^2 = \frac{1}{12} V_{lsb}{}^2$. Thus a bitstep of V_{lsb} introduces a *rms* noise of $0.3V_{lsb}$ (approximately the same as gaussian noise with a $1.8V_{lsb}$ peak-peak value).

Discretization

When designing biomedical instrumentation using AD conversion one can either try to keep the signal to noise ratio above a specified value or try to minimize the addition of noise to the signal. Given the wide range of currently available convertors a suitable AD convertor for the latter approach can nearly always be found. Because the signal quality for the latter approach is better and the circuitry is more simple (only a fixed gain) this is the preferred approach.

Choosing the discretization level is a design choice. On the one hand one does not want to sample too coarse because that would add too much noise to the signal. On the other hand there is no point in the sampling of noise with a high precision. If we choose the quantization such that the *rms* of the introduced noise is one third of the other noise sources the total noise is only 5% larger. This seems to be a reasonal lower bound. A good upperbound is to make both noise sources equal. As a rule of thumb sampling should be done such that the following equation holds:

$$\frac{1}{3} V_{noise,rms} < \frac{1}{\sqrt{12}} V_{lsb} < V_{noise,rms}$$

Or in terms of the bitstep:

The sampling resolution should be chosen between one and three times the rms noise value.

Accordingly the number of bits needed is given by:

$$\log_2\left(\frac{V_{range}}{V_{noise,rms}}\right) + 1 \geq N_{bits} \geq \log_2\left(\frac{V_{range}}{3 \cdot V_{noise,rms}}\right)$$

For a number of biomedical signals the required resolution and number of bits for AD conversion is presented in table 1.

There are of course exceptions to this rule. In those cases where the noise itself is the subject of study it is better to use a higher resolution. An important example of this are EEG recordings that are used to determine brain death.

Two other aspects that could influence the final choice of the V_{lsb} are the desire to make the system useable for other signals, and wanting an integral value for the V_{lsb}.

Being able to use a system both for endocardial (catheter) recordings and body surface recordings would increase the useability of such a system. It is common to select an integral value (e.g. 500 or 1000) for the amplification resulting in a non-integral value of the V_{lsb} (e.g. $0.73\,\mu V$). Choosing an integral value for the V_{lsb} might mean that the computation of voltage levels could be handled in fixed point arithmetic.

Signal averaging

During signal averaging uniformly distributed noise is reduced the same amount as gaussian noise. The number of beats required to reduce the noise to the same level is increased if a larger V_{lsb} is used because of the added noise. Compared to the number of beats needed if sampling does not introduce noise the required number will be larger by a factor $\frac{V^2_{noise,rms}+V^2_{lsb,rms}}{V^2_{noise,rms}}$. If we sample at a resolution such that the noise from sampling equals the other noise sources, twice as many beats have to be acquired. Sampling with a quantization noise one third the other noise requires 10% more beats to acquire, to compensate for the 5% extra noise. Signal averaging is often performed in situations where it is hard to acquire more beats. In those situations a smaller V_{lsb} could be chosen.

Body surface ECG recordings

For the Body Surface Mapping system we built[4], we arrive at the following figures:

- The amplifier noise is $0.4\ \mu V_{rms}$. Assuming a totally resistive impedance for the electrodes of $50k\Omega$ the thermal noise in the electrodes would be $0.3\ \mu V$ (assuming a bandwidth of $0.1 \cdots 100Hz$). This gives a total noise before sampling of $0.5\ \mu V_{rms}$.
- For surface recordings the maximum amplitude for any lead is below $5\ mV_{pp}$. A total range of $-5 \cdots 5\ mV$ should therefore be sufficient.
- Using the rule above we would need between 15 and 13 bits for an ECG recording ($\log_2(10000/0.5) \approx 14.3$ and $\log_2(10000/1.5) \approx 12.7$).

At the time we were making the decisions for the hardware no 15 or 16 bit AD convertors were available that had sufficiently low power consumption ($\leq 100mW$). We chose to use a 14 bit AD convertor (Analog Devices 7872). This AD convertor has an input range of $-3 \cdots 3\ V$ and by having a gain of 2000, we obtained a total input range of $12\ mV$. The resolution V_{lsb} for this system is $0.73\ \mu V$ ($12\ mV/2^{14}$), this corresponds to $0.21\ \mu V_{rms}$ quantization noise.

signal	range* mV	noise p-p μV	V_{lsb} μV	N_{bits}
surface ECG	10	25	4–12	10–12
endocardial	100	50	8–25	12–14
μ-electrodes	200	60	10–30	13–15
ongoing EEG	1	60	10–30	5–7
VEP	0.1	1000	150–500	1

Table 1 Some typical values for biomedical signals, recommended quantization levels and required number of bits.
* Based on an estimate of the largest expected signal.

Discussion

In the computation above we deliberately used only the electrical and thermal noise because in our laboratory we are interested in the mechanisms that are responsible for the noise in surface leads. Noise generated by other sources (e.g. the skin and muscles) were not taken into account. In practice the noise for the isoelectrical interval during ECG recording is of the order of $25\ \mu V_{pp} \approx 4\ \mu V_{rms}$. If one is not interested in the noise but only in the ECG 10–12 bits would be enough.

There is reason to assume that the noise recorded by neighbouring electrodes is correlated, because at least part of the noise is due to muscle activity close to the electrodes. This correlation could be exploited to reduce the noise in single electrodes, given a good model of muscle artifacts. In multilead recordings one might therefore choose a somewhat smaller bitstep. In unipolar ECG recordings the noise of the Wilson Central Terminal is present in all channels and if this noise could be estimated the bitstep could be reduced by $1/\sqrt{2}$.

Conclusions

- The magnitude of the V_{lsb} should be present in publications.
- The V_{lsb} should be chosen as one to three times the *rms* noise value. The number of bits can then be computed from the dynamic range.
- The use of automatic gain control or other forms of selectable gain in preamplifiers can and should be avoided.

References

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