Electrical and Human Feedback

(Invited Paper)

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***Abstract*—In this paper, the difference between simple and complex research projects is explained and shown with two technical examples. One example is an analog pad driver for a microelectrode array in which as little feedback as possible was used in order to make it possible that one designer could design, layout and characterize it in two weeks, getting it first time right. Another example is a MEMS accelerometer that uses feedback around the full system to reach extraordinary performance: 19-bit SDNR over 300-Hz bandwidth with suffcient long-time offset stability for inertial navigation. Achieving this required special care in the project set-up. The main conclusions of this paper are philosophical rather than technical: There is a fundamental difference between simple and complex projects. Complex electrical feedback structures cause complex human feedback structures. Faced with complexity, designers should choose intuitively rather than rationally or analytically. And finally, the main determinant for the success of a complex project is the experience of the team members and the level of trust in the project team.**

I. Introduction

This paper — and the NORCHIP 2012 plenary talk for which I wrote it — explores a few simple relationships in research projects and in product development:

- A system with more feedback is more complex to design.
- A more complex system requires a more complex research or development project.
- Developing a system with more feedback requires more human feedback in the research team.
- The more complex a research project is, the less it is possible to tackle it rationally and analytically.
- A complex project can best be done by relying on the individual and collective intuition of the project teams.
- The main determinants for the ability of a team to use collective intuition are experience and trust.
- It is better to search for a good solution than to search for the best solution.

This topic is itself a very complex one, so I will not even try to tackle it analytically. What I will do is: show some effects of complexity in electrical and human systems, formulate a few conjectures, and back them up with electronics theory, psychology research, and anecdotal evidence.

In Section II-A, a simple OpAmp with resistive feedback and a small number of non-idealities is presented. It is shown that, even in this extremely simplified system, closing the feedback loop also connects all main performance parameters. Changing the width of the input stage transistors will change *all* main performance parameters, which leads to the typical simulate – change – simulate – change cycles known from design projects.

Section II-B then looks at feedback, complexity, choice and intuition from a psychological and philosophical point of view. In this section, six conjectures are made about complex projects that are backed up by the rest of the paper.

Two technical examples are given: Sec. III presents an analog pad driver that had to be designed in an extremely short time, and describes how and why omitting feedback in the circuit had a direct and massive impact on the necessary design time and on the quality of the project outcome. To show the other side of complexity, Sec. IV gives a closed-loop MEMS accelerometer as an example, shows how the closed feedback loop connected everything technical as well as human, and discusses why the main determinant for reaching the really extraordinary performance — 19-bit SDNR over 300-Hz bandwidth with sufficient long-time offset stability for inertial navigation — was intuition and trust rather than explicit technical knowledge.

Section V elaborates on the importance of trust as a facilitating factor in team cooperation, and how to build and maintain trust in teams. Finally, in the Conclusions, a few unorthodox rules for project management of complex projects are outlined; they are intended as a Dirac impulse for the reader's mind rather than a set of rules to follow blindly.

II. Theoretical basis

A. Feedback in Electronics

Figure 1 shows a simple inverting amplifier using two resistors with conductances G_1 and G_2 and an OpAmp with gain A. This stage gives a closed-loop gain of

$$\frac{V_3}{V_1} = -\frac{G_1}{G_2} \quad \text{for } A \to \infty \ . \tag{1}$$

The voltage $V_2 \approx 0$ because of feedback; it is often called virtual ground. And now we add to this the three main non-idealities of this circuit: (1) The OpAmp-Gain is frequency dependent; neglecting the low-frequency pole it is $A \approx \omega_1/s$ for some unity-gain frequency ω_1. (2) The open-loop output has a finite conductance G_o. (3) The input pins behave capacitively with capacitance C_i. This makes the closed-loop gain much more complicated:

$$\frac{V_3}{V_1} = -\frac{\omega_1 G_o G_1}{\Delta} \ , \tag{2}$$
$$\Delta = s^2 C_i (G_o + G_2) + s(G_1 + G_2)(G_o + G_2) + \omega_1 G_o G_2 \ .$$

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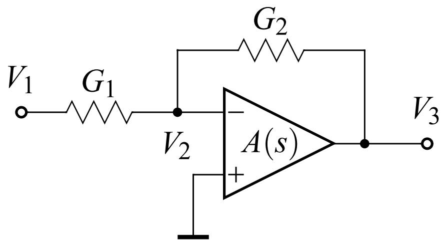

Fig. 1. Simple inverting amplifier with an OpAmp.

It is apparent that (1) and (2) are the same for $\omega_1 \to \infty$. What is also apparent, though less obvious, is that the pole quality factor q_p of this second-order function is proportional to $\sqrt{C_i}$. This means, even for this very simple model: if C_i becomes too large, the closed-loop transfer function will show over-peaking at the pass-band edge, and the amplifier's step response may overshoot or even ring.

The output impedance of this circuit is

$$Z_{\text{out}} = \frac{s(G_1 + G_2 + sC_i)}{\Delta} \approx \frac{s(G_1 + G_2)}{\omega_1 G_o G_2}\,, \tag{3}$$

where the approximation is valid for low frequencies. This output impedance increases linearly with frequency; the behaviour observed is *inductive*. If such an amplifier is loaded with too much capacitance, it also starts to ring, because its inductive output then forms an LC tank together with the capacitive load.

It is now also possible to calculate the transfer function from V_1 to V_2 as well as the ratio of V_2 and V_3 for a given input voltage V_1:

$$\left.\frac{V_2}{V_3}\right|_{V_1} = \frac{V_2/V_1}{V_3/V_1} = -\frac{s(G_0 + G_2)}{\omega_1 G_0}\,. \tag{4}$$

This means that, for a given output voltage, the magnitude of the input voltage *increases* with frequency. For low frequencies, V_2 varies very little, but the variation increases by $20\,\text{dB}$ per decade.

If the input stage of the amplifier has some second- and third-order non-linearity, this means that there is very little harmonic distortion for low frequencies, but the second- and third-order distortion products increase with $40\,\text{dB}$ and $60\,\text{dB}$ per decade, respectively.

Now imagine that the input stage of the amplifier causes too much flicker noise. This noise can be lowered by making the input transistors wider, which (if the transistors are in strong inversion) increases both ω_1 and C_i. Through this we change white noise, ringing, bandwidth, harmonic distortion, and output impedance. One small alteration, and *everything* we have discussed changes, has to be re-checked, and may make another change in the circuit necessary.

And this is a *very simple* example; it is not even a comprehensive description of a single analog cell on an ASIC. How complex do things become, then, if one uses feedback in a larger system?

By the way, if such a simple electronic system becomes unstable, for example due to parasitic poles and zeros that we have not even discussed yet, then it will oscillate, or its output will stick to one of the supply rails. If a complex system has a second feedback loop coupled to the first one, and sufficient non-linearity, then it can become chaotically unstable: it may behave well for most of the time, but occasionally it will show very extreme reactions. This also implies that the term *complex*, as used in this paper, is not at all a quantitative measure. A small system with two interconnected feedback loops is more complex than a huge system with hundreds of parts that have well-defined interfaces and no feedback.

B. What psychology and philosophy says about complexity

Human systems are not much different: if there is little feedback, all is nice and stable, but if there is a lot of feedback, the situation may get chaotic. This has been discussed in detail for the field of economics in [1]. In that book, Taleb presents economy as a field in which everything is interconnected with virtually everything else, giving a very tight web of interrelated feedback loops, and in the resulting system it is big successes and complete failures that dominate the picture, not the average behaviour of the system. Therefore, he states, the best recipe for success is to do your trading such that you can profit from extreme positive excitations of the system, but are not destroyed by the extreme negative excitations, both of which are, by the way, more frequent *by several orders of magnitude* than predicted by standard models of the market

The same holds for engineering projects: the more feedback loops there are in the research team and process, the more the research process will behave chaotically. The main conjecture in this paper is:

■ **Conjecture 1: There is a direct relation between how much feedback (or interrelations) a technical systems has and the necessary amount of feedback and interrelations in the design team.** ■

If feedback (and therefore research complexity) is reduced as much as possible in a project, it will start to behave like a sufficiently linear system that can be held in a stable state by simple methods. It will then go towards its end without any massive negative excitation, and a tight time schedule can be kept in such a project, with high probability of reaching the goal on time.

Many time management and project management methods try to simplify projects so that they dissolve into a discrete set of subsystems that do not behave chaotically. If the methods actually simplify the technical aspects (as opposed to ignoring the complexity), this even works occasionally — and when it does, there will also not be any massive positive excitations. Such projects will not give extraordinary results. (In the words of André Gide: The direct path will only lead to the goal.)

■ **Conjecture 2: The more complex a research project, the bigger the risk that it fails, and the bigger the chance that something extraordinary is created.** ■

If a research project should result in a something extraordinary, then it must be allowed to be complex, with all disadvantages this entails. How to reduce the risk of failure will be discussed in depth in Section V. Here we stay with complexity for a little longer, with a very important reminder: complexity is *not* a quantitative measure. Leaving as many options as possible open in a project will *not* make it complex in a beneficial way, just unmanageable.

In many research (and development) projects, I have seen a tendency towards making systems highly configurable. You do not yet know the necessary gain range of your amplifier? Make it configurable! You do not yet know how much supply current you should give your OpAmps such that your switched-capacitor circuits settle properly? Make it configurable! You do not yet know whether your sensor system has offset problems? Make it configurable!

This sounds very convenient, but what then happens is simply that having a configurable system, you will actually have to configure it! And this is where the problems start, because of three simple reasons. (1) There can be such a thing as too much choice. In this respect, less *is* indeed often more. (2) As soon as a problem is too complicated in the sense that it has too many parameters, the conscious mind cannot deal with it analytically anymore. Too much configurability is very hard to handle. (3) Most obvious: making everything configurable gives the impression that it is certain that the specs will be met, but this is not so. It merely puts peoples' minds at ease and lures them into not thinking about some very important decisions that one should normally make early in a project. We will now briefly discuss the first two concerns.

(1) There can be such a thing as too much choice: Schwartz made a very good point in [2] that having too many options to choose from makes the choice more difficult, and less satisfying. People are most satisfied with their choices if they only have few options to choose from, and then choose irreversibly. On the other hand, if there is too much choice, or choices can be reversed easily, people will be less satisfied with the choices they make, or will even refuse to choose. Schwartz underlines this with anecdotes from daily life, but I have seen this happening again and again in research and development, up to the point where projects went into a deadlock because nobody wanted to (or indeed could) make choices anymore. These projects got up and running again only when somebody made a choice by force, seemingly arbitrary, and irreversible.

■ **Conjecture 3: One of the most important tasks in a complex research project is to limit options to choose from, and do this as early as possible in the project.** ■

This goes directly against common sense. How can you optimize a system if you limit the parameter space early in the project? Don't you risk that the optimum solution is then outside that space? The truth is: yes, you risk this! However, you cannot guarantee anyway that the optimum is within your parameter space. In fact you *should* not even attempt to find the optimum. Searching for the best solution will very seldom give satisfactory results. Only searching for a good solution will do so. After all, "the best" may be the best of several bad possibilities, where "a good one" will be good according to *your* set of values. Therefore, a parameter space (and with that possibilities to configure a system) should be chosen such that there is a high probability that it comprises a good solution.

■ **Conjecture 4: Find a good solution. Then stop. Do not go for "the best".** ■

As Schwartz points out, the difference between those who want something good and those who want the best is: the former will be satisfied once they have something good; the latter will never be satisfied because there could always be something better.

Funnily, the people who pitch for "good" often find the better solution than those who try for "best". One reason for this may be that trying to find the "best," you become a slave to other people's opinions and value systems, and you also make the whole optimization procedure much more complicated.

(2) This brings us to Dijksterhuis [3]. All this complexity might still be tangible if people allowed their subconscious to decide. However, people who want "the best" cannot really allow subconscious decisions, because they would then not *know* that they have the best. Therefore, the attempt to get the best directly leads to the rejection of a very efficient way to deal with complexity. The power of subconscious decisions is tremendous, as shown in [3]:

There Dijksterhuis tested the "deliberation-without-attention" hypothesis that simple choices (such as between different towels or different sets of oven mitts) indeed produce better results after conscious thought (pro/con lists, etc.), but that choices in complex matters (such as between different houses or different cars) should be left to unconscious thought.

The reason for this is that conscious thought is rule-based and very precise, but it suffers from the low capacity of consciousness, making it less suitable for complex issues. Unconscious thought can only conform to rules in that it detects recurring patterns, but it does not suffer from low capacity. Indeed, it has been shown that during unconscious thought, huge amounts of information can be integrated into an evaluative summary judgement. The process is one of pattern recognition, which means that a team that works with complex projects needs more than one experienced team member.

In practice, "deliberation without attention" can mean for a single person: carefully collect information about something, then do other things and sleep over it, then decide intuitively. And it can mean for a team: do the same, discuss it in depth, and then, after the weekend, let the team have a short time-limited meeting in which they adjust their intuition and just make the decision without more ado.

Subconsciously, we can tackle hundreds of criteria, but the conscious mind can only deal with four to five criteria. Note that this number was already exceeded by the simple circuit discussion from Sec. II-A. Therefore we arrive at

■ **Conjecture 5: In the majority of research projects, most of the momentous decisions should be made by deliberation without attention (intuitively) by experienced people.** ■

The most illuminating part of Dijksterhuis's work is the quality criterion for decisions he uses: it is how *satisfied* the people who made a decision were when they looked back on their own decision after a sufficiently long time. This is the same criterion Schwartz used in [2]. Surprisingly, neither is it efficient to decide rationally in complex projects, nor is the quality measure for a good decision rational.

So far so good, but how does this work out in our modern environment where everything should be analysed and explained rationally? Here we find insight with Gebser [4] who pointed out that every mode of thinking has an efficient and a deficient side. For the mental mode, as Gebser called it, its efficient side is to put things into perspective and to create structures, theories and hierarchies that serve as guides for further thinking. Its deficient side would be the rational, analytic side; if used for its own sake, it will cut into pieces what can only be understood as a whole. So complexity drives us to a point where rational thinking stops being a universal remedy and turns out to be just one tool among others that may or may not be appropriate in a certain situation. The use of these tools must be guided by a mode of thinking that goes far beyond the rational. Gebser called it "aperspectivic", Wilber, "integral", but there is as yet no standard expression for such a way of thinking.[1]

■ **Conjecture 6: The most efficient way to write and talk about a design or a research process is to show how it fits into perspectives, structures, and theories. Presenting an analysis only is destructive.** ■

So much about theories. The topic of this paper is complexity and how to deal with it, so in the remainder of the paper, I will present and discuss one example of a system that was simplified on purpose to make the design time as short as possible (Sec. III), and one very complex example in which the team was built such that it could survive the extreme negative excitations of their project and profit from the extreme positive excitations (Sec. IV).

III. One example with just a little feedback: Analog pad driver

The first example is an analog pad driver for the microelectrode array shown in Fig. 2. The task was to create an array of 16 single-input differential-output pad drivers that could bring the analog signals from the pixels of a microelectrode array off chip to be processed by 16 ADCs. The amplifiers needed to settle to 12-bit precision within 280 ns.

A switched-capacitor (SC) amplifier from an earlier chip already existed, so two weeks for one designer (the author of this paper) were assigned in the project for a small redesign. The new specs did not seem much different from the old specs, the main differences were that the new driver should have more gain (4 instead of 2), and should also do a voltage level shift from the voltage domain of the electrode array to the 3.3 V supply of the ADCs. It was the latter "small change" that rattled the project plan: with the existing SC amplifier, it was not possible to do a higher gain as well as correlated double sampling and on top of that a voltage level shift.

[1]This paper can serve as an example as it is an attempt at writing in an aperspectivic style. The measure of aperspectivic thinking is not "true/false" as for rational thinking, but "transparent/non-transparent" [4]. This paper has succeeded if the topic becomes transparent (clear) to the readers.

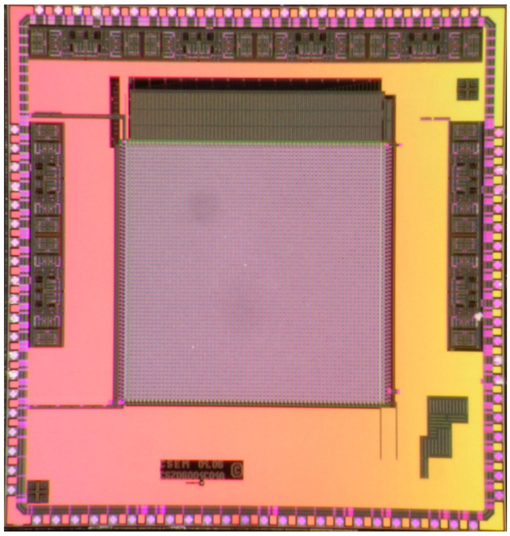

Fig. 2. Chip photo of the first implementation of a micro-electrode array with analog pad drivers. The array chip was designed by Yue-Li Schrag and Simon Neukom, CSEM Zürich; the drivers were designed by Hanspeter Schmid. They have not been published elsewhere for reasons explained in Sec. III-B.

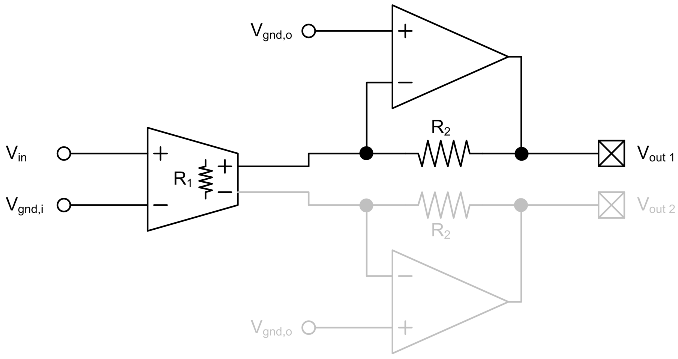

Fig. 3. Open-loop pad driver without offset compensation.

A different topology needed to be selected, designed, layouted, and verified, and this is normally not feasible by one person in two weeks. So we removed as many electrical feedback loops as possible, therefore also removing most of the human feedback that, when only one designer works at it, would manifest itself as the typical simulate – change – simulate – change cycles that bring reality in sync with the simplified theoretical models.

A. System description

Such an open-loop driver is shown in Fig. 3. The driver is typical for low-feedback systems that were often used within the current-mode circuit community [5]. Its first stage is a transconductance amplifier with transconductance $1/R_1$ that compares the input voltage to the microelectrode array reference voltage $V_{\mathrm{gnd,i}}$ and produces two currents proportional to the difference, with different directions. Each of these currents flows into a transresistance amplifier that converts it back into

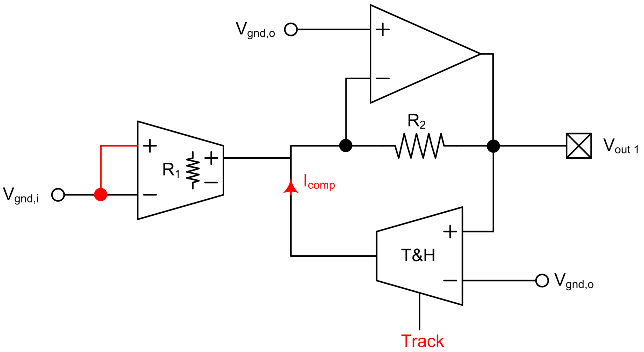

Fig. 4. Upper half of Fig. 3 including the offset compensation circuit.

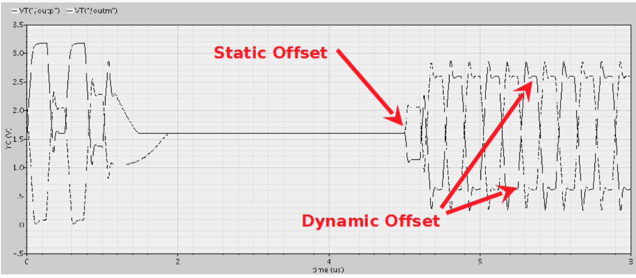

Fig. 5. Offset compensation cycle: two balanced outputs are shown before and after offset compensation.

a voltage, but this time relative to the output reference voltage $V_{\mathrm{gnd,o}}$. Therefore we have two output voltages

$$V_{\mathrm{out},i} = V_{\mathrm{gnd,o}} \pm \frac{R_2}{R_1} \left(V_{\mathrm{in}} - V_{\mathrm{gnd,i}}\right) \ . \qquad (5)$$

In this circuit all three amplifiers contribute to offset. A conventional SC amplifier would now apply correlated double sampling; for every sample to process it would first sample the offset and then subtract it from the signal. Therefore it could not use the comparatively long time available for offset compensation between the read-out of two frames of the microelectrode array.

Figure 4 shows the upper output path together with a track-and-hold transconductor. During the 4 µs pause between reading out two frames, this transconductor is switched to 'track' while the input of the driver is connected to $V_{\mathrm{gnd,i}}$. The resulting feedback loop will cause a current I_{comp} to flow that compensates all offsets except the offset of the T&H amplifier itself. That offset can be designed to be quite small as the T&H amplifier can be more than an order of magnitude slower than the other amplifiers.

When evaluating how well the offset compensation works, it is necessary to differ between static and dynamic offset. Static offset would be what remains at the end of the offset compensation phase, while dynamic offset would be how far the average of the settled values for minimum and maximum input would deviate from the reference voltage. Static and dynamic offset correlate very well in Monte-Carlo simulations; the offsets of two balanced outputs do however not correlate at all. This is clear, of course, as each output has its dedicated T&H amplifier.

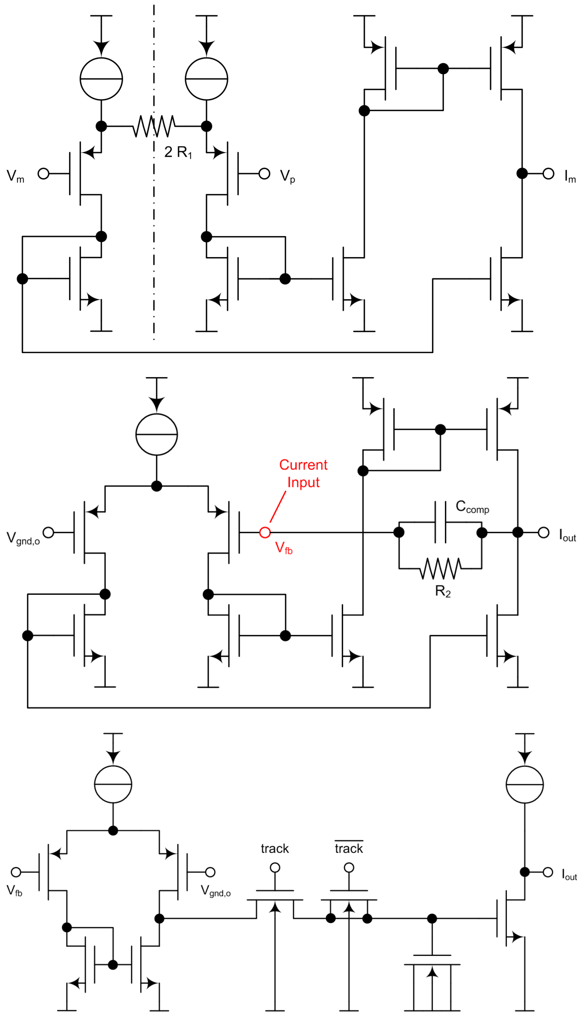

Fig. 6. Transconductance amplifier, transresistance amplifier, and T&H circuit used in the pad driver.

The transistor circuits used to implement these blocks are shown in Fig. 6, without transistor dimensions. They are standard circuits, almost trivial to design, which is really the point of the design strategy discussed here.

This circuit has no global feedback, and therefore the design space becomes almost orthogonal: even-order distortion is dominated by the transconductor; odd-order distortion by the transresistance amplifier; gain errors by the matching of the two resistors; offset by the T&H amplifier. All amplifiers contribute to the noise budget, but then the microelectrode array itself is more noisy, so noise is by far not the toughest constraint.

In addition to the blocks described above, the 16-channel system also contains reference voltage generators and filters to reduce cross-talk; the layout is made with light shields on the top metal layer.

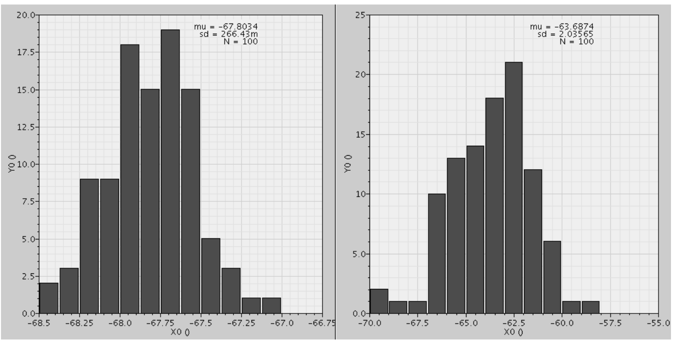

Fig. 7. Example for Monte-Carlo distortion simulation; HD2 on the left and HD3 on the right.

Parameter	min	typ	max	
Linearity	57.5	63.5		dB
	9.6	10.6		bit
Offset 3σ			3.3	mV
Gain	3.86	3.96	4.06	
Supply voltage	3.0	3.3	3.6	V
Supply current (trimmed)	0.92	0.94	0.96	mA
Current swing max signal			180	µA
12-bit settling time			280	ns
Crosstalk			-64.6	dB
Slew rate		22.4		V/µs
Area per driver		0.3		mm^2
Hold time for 12-bit offset precision	10			s

TABLE I
PERFORMANCE OF THE PAD DRIVER IMPLEMENTED IN A 0.35 µM TECHNOLOGY WITH SPECIAL OPTIONS FOR OPTICS.

B. Discussion

The design of such a circuit is straightforward: (1) choose the resistor ratio and size from the gain and gain accuracy specs; (2) design a transconductor with a sufficiently large R_1 and g_m of the differential pair such that it does not cause too much even-order distortion and is fast enough; (3) design a transresistance amplifier for odd-order distortion and speed; (4) design the T&H for offset; (5) verify.

During verification of the full system it may occur that one of the specifications is not yet met. For example, if even-order distortion is not good enough, something has to be changed in the transconductance amplifier. This will then have *almost no influence* on odd-order distortion, gain accuracy, or offset. So there will be very few design cycles until all specs are met.

In addition to this, global layout parasitics will not give bad surprises. There is no global feedback loop whose gain might amplify the detrimental effect of parasitic capacitors or resistors. Furthermore, the longest lines with the largest parasitics have current signals on them. Therefore there will be no critical surprises when the circuit is simulated with extracted layout parasitics.

Figure 7 shows HD2 and HD3 histograms from Monte-Carlo simulations; a correlation analysis shows that, indeed, the two are almost uncorrelated. Monte-Carlo distortion simulations of discrete-time circuits can be very time consuming, so we used a method suitable for massively speeding up such simulations that works for low and medium distortion levels: it allows to simulate one set of dynamic offset, gain, HD2 and HD3 by simulating only five discrete-time input values [6].

The design was a full success: all electrical design, verification and layout could be finished in two weeks. The circuit worked first time right, and was used on three consecutive microelectrode arrays without any re-design. Later it was re-designed for a new process technology; the new designer did not even see the need to ask for feedback from the original designer. Because of the very straightforward design process, the documentation could be written so clearly that it left few questions open.

Table I shows the performance of the pad driver. It might have been possible to improve it with another design cycle, but neither was there time to do this, nor was there a need: this amplifier uses only 22 % of the power than the SC amplifier on a previous IC used. The reason is that it can be made considerably slower, because the offset compensation is not done per sample, but per frame. The original SC amplifier had to settle within half the time available in our case. A second reason for the massive power saving is that noise was not an important issue, and with such an open-loop system it is very simple to make a noise-vs-power trade-off without compromising other aspects of performance.

This amplifier has not been published before,[2] and not for lack of trying: the paper was rejected by the reviewers because the circuit is trivial. In an academic context, design time is seldom a striking argument. However, in the context of industry research or development it always is; even when a company wants to develop something fundamentally better than the state of the art.

IV. ONE EXAMPLE WITH LOTS OF FEEDBACK: MEMS ACCELEROMETER

This was the plan with a project in which a MEMS accelerometer with 300 Hz bandwidth, 19 bits dynamic range and sufficient offset stability for inertial navigation applications was to be designed. This was way beyond the state of the art when the project was started in 2004, and remained so until it was published in 2009 and 2010 [7], [8]. As the system description shows, this is a system with a feedback loop through everything, so the project team also needed a lot of human feedback.

Unfortunately, the project was first set up in the traditional, rational "divide and conquer" approach, identifying subsystems, defining interfaces, and assigning subtasks to the different groups. In 2005 it had all but failed. We will discuss this after a brief description of the system.

A. System description

The system published in [7], [8] is a closed-loop MEMS accelerometer. It uses a sensor whose cross section is shown in Fig. 8. The sensor consists of a small mass on a spring

[2] It was, however, presented at two ISCAS tutorials in 2007 and 2009.

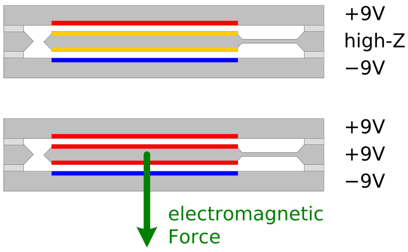

Fig. 8. Cross section through a MEMS acceleration sensor: sensing (top) and actiation (bottom).

ASIC Chip Area	9.7	mm^2
Analog supply	3.3	V
Sensor supply	± 9	V
Power consumption	12	mW
Signal bandwidth	300	Hz
Full scale (FS)	11	g
Input noise (no signal)	1.15	$\mu g/\sqrt{Hz}$
Input noise (FS signal)	7.1	$\mu g/\sqrt{Hz}$
Dynamic range (300-Hz BW)	19	bits
Peak SNDR (300-Hz BW)	16	bits

TABLE II
PERFORMANCE OF THE MEMS ACCELEROMETER SYSTEM USING A SENSOR ELEMENT SUITABLE FOR INERTIAL NAVIGATION.

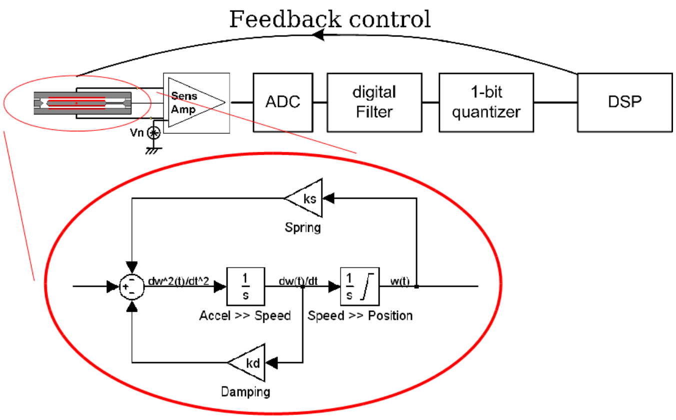

Fig. 9. Closed-Loop MEMS accelerometer.

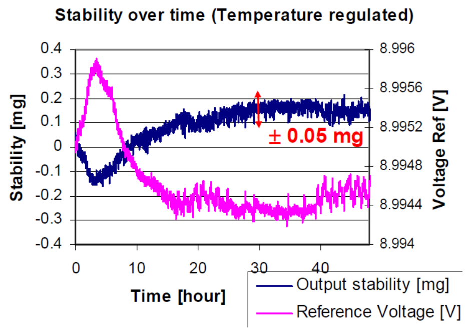

Fig. 10. Offset stability over time, plotted together with the reference voltage, from [8].

that bends when an acceleration is applied. The mass is sandwitched between two rigid electrodes. In an open-loop system, the acceleration force is proportional to the mass displacement (the proportionality factor is the spring constant), and that displacement can be measured by applying opposite voltages to the rigid electrodes and measuring the voltage on the mass (Fig. 8 top).

The spring is not linear enough for inertial navigation, but the whole system can be linearised by applying feedback: if voltages are applied to the electrodes as shown in Fig. 8 bottom, then the mass accelerates downwards. Negative feedback becomes possible, and if the feedback loop gain is very high, the feedback signal and the input signal become almost identical. The mass displacement becomes much smaller, linearity is improved, and the spring constant only determines system stability, but loses its direct relation to the mechanical acceleration force.

In principle any number of voltages can be applied to make the electric field accelerate the mass, but that feedback signal will need to be as precise as one wants to measure the input signal, and building $\pm 9\,\mathrm{V}$ relative to ground with 19-bit precision is already difficult enough. It is also clear that measurement and electrostatic acceleration cannot be done simultaneously, so a sampled system is needed.

Now if the loop is closed, as shown in Fig. 9, and the feedback signal can only be one of two distinct levels (full acceleration up or full acceleration down), then the resulting system is actually a 1-bit Sigma-Delta ADC that converts from the acceleration domain into the digital domain. The input and feedback signals are accelerations, but the capacitive read-out explained above determines the position of the mass. Between acceleration and position are two mechanical integrations, as shown in Fig. 9. So this is a Sigma-Delta ADC that does the subtraction as well as two integrations in the mechanical domain, in continuous time.

Then the system described in [7], [8] goes into the digital domain through an externally linear flash ADC with 2^6 non-linearly distributed quantization levels and a 16-bit output described in [9], and into digital filters. The point of this is that the same ASIC can then be used to operate different types of acceleration sensors. The ASIC containing the actuation switches, amplifiers and ADC was implemented in a $0.6\,\mu\mathrm{m}$ technology, and the digital part runs on a small FPGA. For the right choice of coefficients in the digital filter, and for a good MEMS sensor element, the system performs extremely well, as shown in Table II and in [7], [8].

Long-term offset stability is also very important for inertial navigation systems; this has been measured in [8] and is shown in Fig. 10. The proportionality of the reference voltage to the measured signal can be seen clearly, but it is also clear that the reference voltage is not the only part of the system that is important for long-term stability.

Finally, Fig. 11 shows a noise simulation of the full system for one type of sensor. To give an impression of the noise levels: The sensor shown in Fig. 8 is in a vacuum package; what is called “sensor noise” in the plot is the noise caused by the remaining gas molecules in the package which impinge

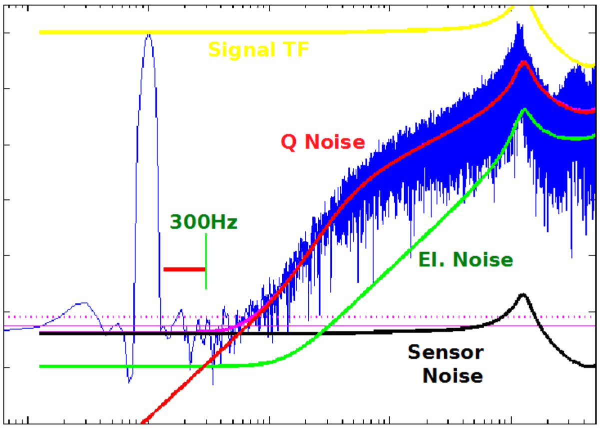

Fig. 11. Simulated noise power spectral density, plotted together with calculated values of the sensor noise, the electronic noise, and the $\Sigma\Delta$ quantization noise (from a slide of the talk at ESSCIRC 2009 [7]).

onto the sensor mass due to Brownian motion. The curve for electrical noise also contains kT/C noise coming from sampling the sensor. One reason for the high loop frequency of $1\ \mathrm{MHz}$ is to keep the kT/C noise below the sensor noise. Flicker noise is removed by correlated double sampling or chopping (both are configurable; the choice is made depending on how well the offset capacitance can be controlled through other means in a specific product); the noise corner of the remaining flicker noise is so low that it is not visible in the spectra anymore. It does, however, contribute to long-term stability.

The slope of the $\Sigma\Delta$ quantization noise is $100\ \mathrm{dB/dec}$; it is a fifth-order $\Sigma\Delta$ converter that is quite hard to get stable in all process and temperature corners, because $\Sigma\Delta$ stability now depends on *everything* from physical sensor parameters over digital filter coefficients straight to the timing properties of the electrical force feedback. Analytically, every part of the system is trivial to understand, but the full system is very complex.

The performance of this system is extraordinary, and the reason that our team could do this where others could not is *not* only that we had explicit knowledge others did not have. We found a way to deal with this very complex project such that we could profit from the extreme positive excitations (having great ideas and holding on to them) while not being thrown off the path by extreme negative excitations (finding something that at first and second sight looks like making a success impossible).

B. Discussion

Many different experts had to cooperate in this project. There were difficult tasks in many fields, essentially in sensor design and manufacturing; analog circuit design (sensor amplifier and ADC); digital circuit design (FPGA); system and digital filter design; PCB and power supply design.

The feedback loop in this system really goes through all of this, so (as in Sec. II-A) if anything is changed anywhere, it has an influence on noise, stability, distortion, and so on.

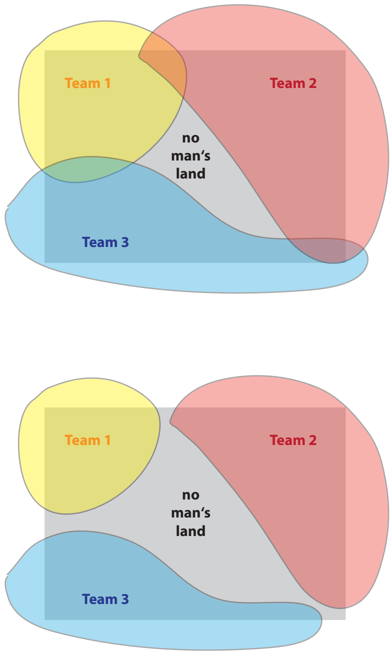

Fig. 12. No man's land in a project (top) and when people are put under pressure (bottom).

Therefore all people involved are affected by any change, even if it looks small.

The main problem in such a project is illustrated in Fig. 12. It is virtually impossible that one person can grasp all aspects of the project. The project can only succeed through team cooperation, and if team communication works well enough. Unfortunately, a "no man's land" comes into existence as soon as the work is partitioned into work packages and assigned to teams (or individuals). There will always be many aspects for which somebody must be responsible for the project to succeed, but that are not mentioned in any of the work packages, and are not explicitly assigned to anybody.

A well-functioning team will recognize these aspects during their research and development work, and then assign the responsibility to somebody. However, if the rational "work package & requirement specification" approach is the dominating project management technique, then the people in the team will rapidly become blind towards the no man's land. After all, their responsibilities are clear, and the rational-analytic approach has seen to it that work packages are independent of each other, so there is no need to reflect on the other teams' responsibilities.

It will then not take long until the complex, chaotic research process makes a massive negative excitation, or in plain English, until a problem pops up for which no-one is responsible and which, if it cannot solved, is a show stopper. It then becomes apparent that the carefully crafted project time plan has just turned into waste-paper. The normal reaction of the project leader's boss is then to put pressure on the project, but what happens to a project team under pressure? The teams will *concentrate* more on their tasks, which *increases* the area of no man's land, as illustrated in Fig. 12 bottom. This will increase the vulnerability of the project teams against the next negative excitation in the project flow.

Funnily, in many projects I have seen, "overall system performance" is actually in the no man's land. It is supposed to become correct by design, by the means of proper analysis. The whole idea behind system analysis is, after all, that if the parts are identified correctly and if the parts work according to the parts' specs, then the whole system will work according to the system's specs. That idea, however, is thoroughly incorrect if applied to complex systems (this is one example for the deficiency of analysis mentioned in Sec. II-B). *The whole is more than the sum of the parts*, an over-used sentence, but I hope it has by now become apparent why this is really so in complex systems.

And what is complex? According to the discussion in Sec. I, "complex" is any system with feedback whose performance is judged according to more than four or five criteria. Which means: the vast majority of research and development projects are complex.

Although the past few paragraphs are formulated in a quite abstract way, they tell the story of the project out of which the MEMS accelerometer came, a story that is extremely interesting, but not publishable in detail, for obvious reasons: the project almost failed 15 months after it had started; the no man's land had grown so much that the teams did no *trust* each other anymore to take on responsibility for the full system. And this is what it really comes down to: trust.

■ **Conjecture 7: Trust is by far the most important factor for team cooperation in complex projects.** ■

V. Complexity and Trust

If trust is the most important factor, how then would one build trust in a virtual team? According to [10], it is different behavioural factors that facilitate trust early in a project and once it is fully up and running.

Building trust in a team early in a project mainly requires *social* communication and *social* exchanges: it is much easier to trust a person when you have seen her or him laugh about a joke, swear when a beer glass topples over, or lose in a card or board game. It will instil trust if people are enthusiastic about the project and show that they can cope with task uncertainty. One very important point here is whether people are perceived as hopeful or naive: the difference between the two is that naive enthusiasm conveys a general "all will be well" feeling, but hope includes the conviction that there is a concrete way to reach the goal.

If this now gives the reader the impression that it might be a good idea to bring a whole project team into a two-day retreat somewhere away from daily business and combine short and intensive technical sessions with long lunches, walks, and a game tournament night ... then the main idea of the previous paragraph has become crystal clear: doing such a retreat with lots of social interaction is *very* effective. In the project described above, when I came in as an outsider, I was asked to take over the project and manage the conflict. I used classical conflict moderation techniques until people were willing to trust each other again, and then we really went into a two-day mountain retreat. This retreat, where team members from different groups got to know each other through social exchanges, was the turning point of the whole project. With more trust came better technical understanding.

Trust will, however, evaporate unless people maintain it actively. Things that help there are predictable communication, a regular pattern of communication, warning of absences, and also substantive and timely responses to e-mails.

Writing an e-mail to someone and not receiving any reply within a reasonable time gives rise to the question whether the e-mail was received, whether it was read, whether it was understood, and when the same person repeatedly responds slowly, whether he is helpful, whether he cares, and so on. Paul Watzlawick's story about the hammer, reprinted in the Appendix, gives a very accurate (and funny) impression of how the absence of communication erodes trust.

This is why warning people of absences and giving substantive and giving timely responses to e-mail messages are very important. The point here is not that the response contains the expected substance, just real substance. For example, a reply like "I am very busy now, but I will look at this next week, and you will get a reply on Friday afternoon" has a lots of substance. And even if the plan fails and your Friday e-mail says "I am sorry, I need two more days, you will get your reply on Wednesday", trust is still maintained.[3] Even if this happens very often, trust can still be hold by discussing the situation that one project member is under a heavy load, for example from other projects, and dealing with the situation by team decision.

This is also why a regular pattern of communication (both technical and social) is necessary — for example regular team meetings with a following long lunch — it gives a forum to have such discussions before the problems get so big that a project team member decides to take it up in a formal meeting with a written agenda.

All this is valid for virtual teams, but what is a virtual team? There are formal definitions [10], of course, but for all practical purposes, this simple

■ **Definition** will do**: A virtual team is a team whose members do not have their coffee and lunch breaks together.** ■

VI. Conclusions

In this paper I have shown with some theory and anecdotal evidence that there is a direct relationship between electrical (or, more generally, technical) and human feedback.

In order to make choices, one either has to keep a project simple and then make a rule-based choice, or create an

[3]Just as a side remark: the worst thing you can do is to give a timely response without substance that is not followed up by a comparatively timely response with substance. Automatic responses sent by e-mail tools when an e-mail is opened can be extremely destructive.

atmosphere in which the subconscious (be it the individual or collective subconscious) can choose intuitively.

So problems to solve are either simple, then the project outcome is predictable; or complex, then you can only provide for the present to let the (collective) unconscious lead to a good solution, if possible capture one of the positive extremes, and ensure robustness against negative extremes. The outcome of a complex project is not well predictable (nor is the project time), but the chances for a great success are indeed very high. In plain English: you may then not get what you wanted, nor when you wanted it, but you will get something that you can use. Therefore there can be complex *research* projects, but a product *development* project should better not be complex.

There is a lot of literature on project and time management methods that promise to make a complex project more simple, such that a specific goal can be reached within a specific time. Unfortunately, many of these methods were developed for small to medium projects with low feedback complexity and were then successfully extrapolated to huge projects with low feedback complexity. None of them will work properly with complex projects, small or large.

If what I wrote in this paper is sufficiently close to reality, then project leader of a complex project should observe the following points:

- Build a team with mutual trust, and trust them on technical matters as well as project management matters.
- Lead (instead of manage) the team.
- Protect the team from pressure coming from above. All pressure should be made by you. (This is again related to trust; anonymised pressure erodes trust.)
- Use project management methods when appropriate, but only as tool. Drop them when they become ineffective, as you would do with technical design strategies.
- Do not let the minds of the team get at ease (compare to (3) above). Whenever the project team members only see one side of a situation, help them see the other side too. Try to balance the project.
- Most important example: when people focus too much on time plans, relax them. When people focus too little on time plans, let the team discuss it in a meeting, and encourage team members' initiatives to take responsibility for good time planning.
- Accept that it is more important to have *good* results as quickly as it is possible instead of *the best* results achievable until the deadline of the original time plan.
- Hold on to the believe that a team managed like this *will* get good results as quickly as it is possible.
- Apply the same thinking style to all other aspects of the project.
- Last, but not least, if your team cannot make choices, then facilitate choosing, or choose yourself, and see to it that the choice is made irreversibly.

Finally, please remember the footnote in Section II-B and do not ask "is all of this true?" Rather ask yourself "has electrical and human feedback become more transparent to me?"

VII. Acknowledgements

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Appendix: The Hammer

Here follows my own translation (from the German original) of Paul Watzlawick's short story about a hammer [11]. I told this story in the plenary talk at Norchip 2012.

A man wants to hang a picture on the wall. He's got a nail, but no hammer. His neighbour has one, so our guy decides to go over and borrow the hammer. But then he has doubts.

What if the neighbour does not want to give me his hammer? Yesterday I only got a hasty greeting from him. Maybe he was in a hurry? Or did he just pretend to be in a hurry because he doesn't like me? And why doesn't he like me? I never did anything to him, he must imagine something there. You know, if anyone wanted to borrow my hammer, I'd immediately give it to him. Why won't he? How can he just refuse such a small favour? People like that guy poison one's life! And then this guy thinks I depend on him just because he's got a hammer and I haven't! Well, enough is enough!

And so he runs across the street, rings the bell, the neighbour opens, but before he can say "hello" our guy shouts "Keep your fucking hammer!!!!"

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