Unconventional sensing: doing it unusual way in unusual settings

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The standard way of sensing implies a linear flow of information, from the object we wish to analyse towards the observer. The object of interest will be referred to as "the environment." The environment can be many things, a temperature in a room or the amount of cracks in the material. The usual sensor is like a factory line where the flow of information is well understood and every step is carefully engineered. Normally, a sensing instance is a one-time event. It can be, and often is, repeated, leaving the impression of continuity. We know exactly how every part of the sensor is supposed to behave. But it is a one-time event nevertheless and the execution of every sensing event is always nearly the same. But there are other ways of doing sensing, and over the course of the last few years we have explored a novel, somewhat unconventional way of sensing, to be referred to as the SWEET sensing approach. SWEET is more a template than it is an approach. The SWEET is an algorithmic template for building intelligent sensing substrates. The user is supposed to engineer different instances of it depending on the situation. The typical SWEET sensing process is very flexible, and is essentially a dynamic process, where the single time instance is irrelevant, but rather the behaviour over an extended time interval is of paramount importance. It is a sort of indirect sensing which happens through a proxy. There is an ongoing dialogue between the observer and the proxy, in which the observer accumulates small clues proxy provides about the system of interest. In turns, the proxy also accumulates information through a dialogue. This article summarizes how such an unconventional sensing setup can be realized and what its essential ingredients are. The main objective is to present the material in a pedagogical way so that colleagues from other disciplines can understand the method and use it to solve their problems.

The standard way of sensing implies a linear flow of information, from the object we wish to analyse, the environment, towards the observer. In sensing applications the "environment" can be many things, a temperature in the room, the amount of cracks in the material, or the amount of rare molecules in a unit volume of solvent. The usual sensor works according to well-understood principles which are carefully engineered. There are no surprises. The flow of information is linear. Further, a traditional sensing instance is a one-time event. Events like these are often repeated in time, which might give an impression of continuous sensing, even some sort of intelligence perhaps, but in reality such sensing events are discrete separate events. To gain a time perspective on the observed data, one needs to engineer an external intelligence that can gather information obtained from the sensor, and further process it. The typical time to execute the sensing event is much smaller than the times that separate these events. Sensing instances can occur at an equally spaced intervals, or when triggered by a control mechanism. Regardless of the engineering details, we are talking about a one-time event since the execution of the sensing event is always nearly the same, and we know exactly how every part of the sensor is supposed to behave. In fact failing to do so is considered to be a malfunction. The typical sensing setup is show in the figure below. However, there are other ways of doing sensing.

Over the course of the last few years we have explored a novel, somewhat unconventional way of sensing where irregularity and temporal aspects of the sensor's dynamics are of paramount importance, the SWEET sensing setup.[2] The SWEET sensing setup is an algorithmic template. The most important components are depicted in the figure below. Though the SWEET sensing setup has been developed with a particular application in mind, the analysis of time series data, it is very likely that the setup could be used to solve problems featuring in other disciplines, but more on that later. The details will of course differ depending on the implementation context. Our own work[3] covered some problems related to ionic sensing with ion sensitive electronic components, such as an organic transistor and a memristor. The SWEET sensing process is very flexible, and is essentially a dynamic process, where the single time instance is irrelevant, but rather the behaviour over an extended time interval is of paramount importance. It is a sort of indirect sensing which happens through proxy and it happens in a dialogue form. A similar indirect sensing idea has been suggested in 2006[4] but, surprisingly, has not been pursued rigorously. The authors have shown that by monitoring the changes in the structure of the feedback apparatus that controls the robot it is possible to infer about the environment that the robot resides in.

The SWEET approach is an algorithmic template for realizing the indirect sensing idea in the context of time-series data analysis where the notion of time and remembering history is treated as an opportunity rather than a problem. The notion of time is extremely important as there is an ongoing dialogue between the environment and the proxy. The proxy (sensing reservoir)[5] is an environment sensitive dynamical system. It is affected by the environment, but the details of the proxy interacts with the environment are not important from an engineering point of view. It might appear that this interaction is a one-way information channel where the information propagates from the environment into the proxy. To some extent this is true, as the proxy is not supposed to influence the environment. However, the proxy updates its state recurrently, where the state of the proxy at a particular time instance depends on its previous state and the information it has received from the environment.

Through the dialogue with an environment (cf. fig. 2, dialogue 1) the proxy is pushed towards a certain state, and the state of the proxy encodes all previous instances of environment-proxy interaction. Perhaps, one could think of it as a one-way dialogue, in the same way as a psychotherapist gets to know his patient. Through this dialogue, the proxy accumulates small clues about the environment of interest, which a traditional setup might simply miss. Again, it is important to realize that this would be impossible without a memory of the past, the system used as a proxy would "forget" every bit of information it has collected.

There is a second dialogue going on, the one between the observer and the proxy (indicated by dialogue 2 in fig. 2). This second dialogue happens through two mechanisms: (a) the fixed instructions in the form of a drive signal, and (b) through a feedback. In many instances, this feedback can greatly improve the performance of a device. The feedback mechanism

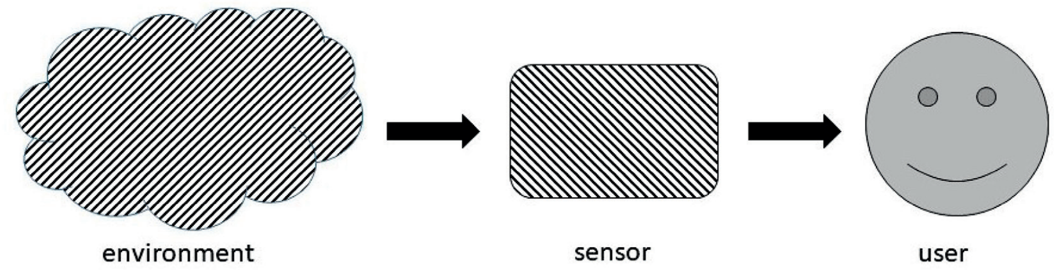

Fig. 1. The traditional sensing setup. The flow of information is linear.

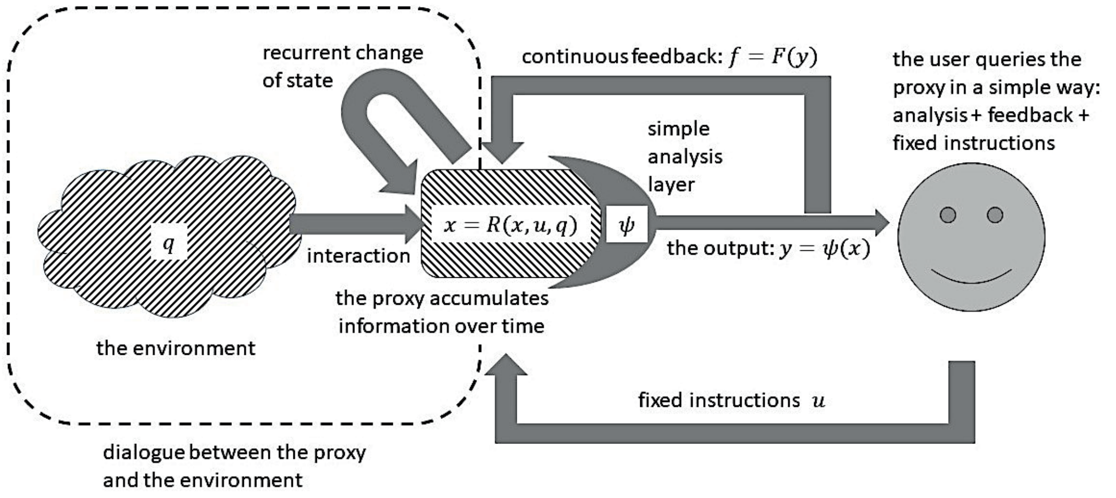

Fig. 2. The SWEET sensing setup. Dialogue 1: There is an ongoing dialogue between the environment and the proxy. During this dialogue the proxy accumulates the information about the environment. Dialogue 2: The user interacts with the proxy in a simple way to infer what the environment looks like.

has the tendency to make the system "sharper" or simply more "intelligent," especially if it is provided with a delay in time. This improvement is a well-known fact,[6] and is nothing specificity to the SWEET setup. The delay can be explicitly engineered, but it can be also an intrinsic part of a dynamical system since such systems clearly exhibit some sort of "memory behaviour". The state of a dynamical system depends on everything that the system experienced in the past. Furthermore, dynamical systems might have the ability to "propagate" behaviour through the system to different locations, which could bounce around, causing a natural delay. All very exciting possibilities. Perhaps the simplest way of explaining the SWEET sensing concept is through the following thought experiment (*cf.* fig. 3):

- *The sensing problem (the environment):* Imagine that we are sitting in a room without windows and that we are interested in the weather outside. Thus the object of our interest is the weather. However, we are not allowed to open the window and peek out to see what the weather is like. Likewise, we are not allowed to use the phone or any other means of communication with the external world.

- *The proxy:* A person comes into the room and we are allowed to interact with the person to figure out what the weather is like. This is our only chance to infer about the weather.

- *The interaction with the proxy:* By assumptions, we are not allowed to ask direct questions like "What is the weather like outside?" This constraint is very common in practical applications that are close to engineering. We cannot interact with the proxy in any way we please. There are likely going to be constraints imposed on how we can interact with any system. For example, we cannot easily measure the positions of all atoms in a gas. We could try to measure their average velocity, which gives us an idea about the temperature of the gas. Thus to illustrate that aspect of the problem, in our thought experiment we are restricting the way we can interact with our human proxy. Naturally, the more direct questions one can ask the better. However, the main idea is to "interview" the person about the weather. Ask small questions and try to assess what they imply. Here the emphasis is on the full set of answers we are getting, not on a particular answer to a specific question. The way we can interact with the proxy is critical. For example, if we can assume that we can observe the person, we could try to see if the person carries a wet umbrella. A wet umbrella would imply that very likely there is a rain outside. But one cannot be sure. It could have rained few hours earlier but we cannot be certain. Even a dry umbrella might imply a bad weather. For example, it could be that it is cloudy outside. Clearly, if we are not allowed to ask a direct question, the dialogue is the best option. Through a dialogue we can acquire information. For example, we can ask the person how she/he feels like. If the person appears grumpy, then it might have to do with the bad weather, but there could be other reasons. For example the person might have lost a shoe, and that could be inferred from follow up questions. If the person appears happy, very likely the weather is nice. But, again, we cannot be sure. The person could have won the lottery, and more follow up questions would be needed to determine this.

- *The feedback mechanism:* In this particular instance a useful feedback mechanism would be to ask some provocative questions. For example, if the person is happy, we might try to provoke the person into angry response and from that judge the original "degree of happiness" that the person had before he/she entered the room. Likewise, if the person appears calm, we could ask provocative questions to see if there is some discontent lurking behind the surface. All this would indicate that we are likely dealing with the case of the bad weather.

In fact, the sensing solutions we envision resemble a thought experiment discussed above. The SWEET setup mimics the way of how humans communicate experiences and process exchanged information, rather than how a machine would perform similar tasks. This article explores the ways of realizing the human

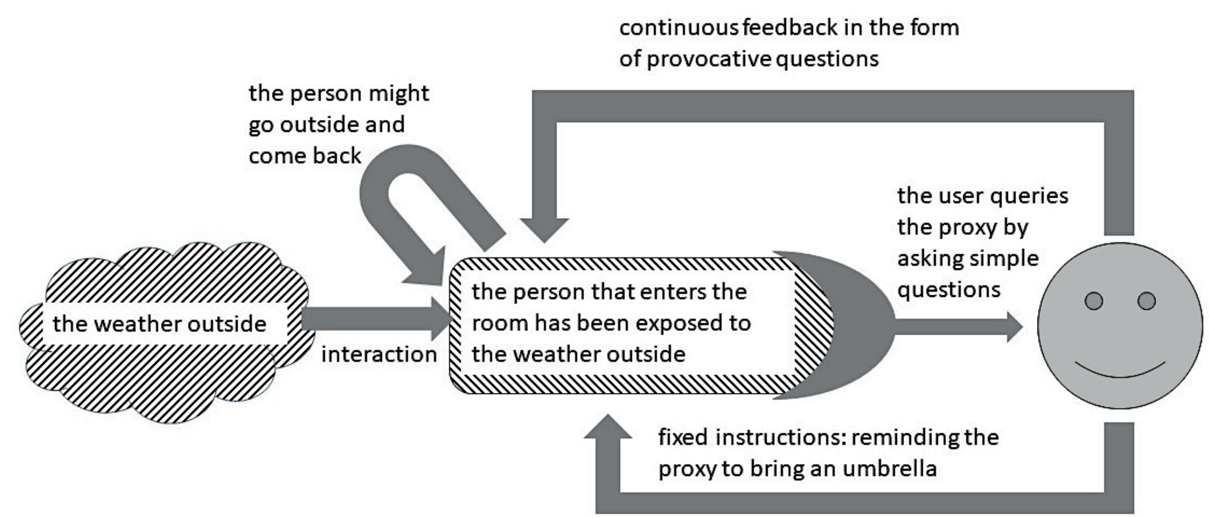

Fig. 3. An example of implementing the SWEET sensing setup.

way of understanding and analysing environment in the engineering context. This is the main point behind the SWEET sensing setup. Instead of a human one uses a generic dynamical system as a proxy. In pretty much the same way as the mental state of mind of a human is influenced by weather, so is the state of the dynamical system influenced by the environment. The existence of this interaction is the minimal requirement for the SWEET setup to work. However, the trademark of our sensing setup is that it is extremely flexible.

Why should one bother with such unconventional sensing setups? There are several reasons, ranging from pure engineering/practical towards more profound:

To begin with, there are many instances in the information processing engineering where the goal is to collect and analyze information *in situ*. For example, in the traditional setup, remote sensors might collect information and channel it to a huge data center where this information is *stored* and *processed*. However, the disadvantage with such a setup is that one might need to both store large amounts of data, and most importantly, perhaps, arrive at simple conclusions, after all the fuss. It is much better to make such conclusions locally, and simply send the results of the analysis. For example, a bridge operator only needs to know one bit of information, whether the bridge is stable or about to collapse or in somewhat simplified language "everything under control" versus "trouble." It is much simpler to send this information instead of constantly streaming sensor data from dozens of sensors.

The more subtle reason is as follows. The whole SWEET setup is powered by a very simple idea discussed above, and because of that it is extremely flexible. Since SWEET is a template, an engineer only needs to implement its key mathematical abstractions (essentially the various forms of the dialogues introduced earlier). Of course, this is a bit of oversimplification (if it were that easy), but in the nutshell this is what needs to happen. Regardless of the practical difficulties the implementation strategy is very clear. One can think of the SWEET setup as a very generic user manual, where the user can exercise a great deal of flexibility in implementing. One might think of it as a "religious text" in which the principles are given but the followers are supposed to interpret it and apply it in everyday life. Because of that, our sensing ideas could be of relevance for other areas of human endeavour, including humanistic sciences.

Naturally, one might even have to modify the setup depending on the problem but the core idea of a two-fold dialogue will likely survive if the setup is applied in other areas:

> We have investigated numerous options ourselves. All the sensing problems we have investigated hatched from vastly different application contexts: monitoring ionic solution for rare ions that are hard to detect, monitoring ECG (electrocardiogram) signals using simple hardware, predicting chance for the occurrence of sepsis for intensive care patients. These might be considered as standard engineering problems, very typical for natural sciences.
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> We gave a serious thought of applying the SWEET sensing setup to tackle a range of completely unrelated problems to the ones we published on. We have thought about other much more "crazy" ideas such as helping spine-cord injuries to heal, we have explored some innovative information processing options in the IoT (Internet of Things) context related to creating a gigantic intelligent sensing substrate to realize distributed sensing, and believe it or not envisioned the setup to enhance human learning, and finally tried to think about ways of enhancing the outcome of a psychotherapy session.

These rather bold aspirations listed above ought to justify the title.

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[6] L. Appeltant *et al.*, "Information processing using a single dynamical node as complex system," *Nature Communications 2*, 2011, 468/1-6. See Vasseleu's poignant discussion of "fantasies of disembodied mastery" in C. Vasseleu, "Virtual Bodies/Virtual Worlds," *Australian Feminist Studies 19*, 1994, 155-169. For a critical discussion of "contemporary technoscientific corporealizations of the 'almost human,'" see C. Castaneda, L. Suchman, "Robot visions," *Social Studies of Science 44(3)*, 2014, 315-341.