What the Sensor Knows: More-Than-Human Knowledge Co-Production in Wood Carving

Charlotte Nordmoen
c.nordmoen@qmul.ac.uk
Queen Mary University of London
London, United Kingdom

Andrew P. McPherson
andrew.mcpherson@imperial.ac.uk
Dyson School of Design Engineering,
Imperial College London
London, United Kingdom

ABSTRACT

From an engineering perspective, sensors provide measurements of phenomena in the world. Sensor data might be noisy, biased or otherwise subject to error, and these labels presuppose the existence of an objective ground truth the sensor is intended to approximate. This paper explores an alternative look at sensor signals as situated observations entangled with the systems they seek to measure, where meaning can be carried in qualitative particulars rather than quantitative and statistical analyses. Karen Barad's 'agential realism' [3] and Graham Harman's 'tool-being' [29] inform our approach to understanding *together with* the sensors, which become co-investigators and co-creators of the subsequent knowledge. We illustrate our collaborative effort with the sensor through a case study where we examine sensor signals from a device designed to query the experience of woodcarving by making the experience unfamiliar. We seek a qualitative approach to knowledge (co-)creation with sensor data from a more-than-human perspective.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

intra-action, qualitative analysis, signals, meaning-making, more-than-human

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1 INTRODUCTION

This paper is an experiment in meaning-making with more-than-human configurations. We are particularly interested in exploring how we as researchers co-produce knowledge with sensors, rather than the more classical approaches of understanding how sensors co-produce meaning for users of an interactive system or how these users experience and make sense of their interaction with the system.

Traditionally, sensor equipment has been seen as a way to access an idealised underlying 'truth' about the object or phenomenon in question, provided the appropriate sensors have been used and that noise and bias have been accounted for. This sense-making process often involves some form of numerical or statistical analysis and, more recently, some form of machine learning. We aim to explore a complementary, qualitative approach to understanding sensors and their signals. We make use of Karen Barad's 'agential realism' [3] and Graham Harmann's writing on 'tool-being' [29], examining sensors as co-investigators and co-creators of the consequent knowledge.

To unpack these ideas, we examine sensor signals from a device designed to query the experience of wood carving by making the experience unfamiliar. The first author has made a device that digitally alters the experience of carving wood by hand as part of a larger research project into understanding how the material influences woodcarving practice. A study of four woodcarvers using the device yielded physical artefacts, interviews about the carving experience, and signals recorded by sensors in the device that relate to the carver's interaction. Within a more-than-human framing, the woodcarvers are not at the centre of our focus, and their experience is presented as more peripheral in this paper. Our motivation for directing our attention to the sensors is to explore alternative ways of working with sensors and data as qualitative and through bodily meaning-making processes. We address the navigation of the interpretation process of sensors as co-producers of knowledge. We do not intend to speak on behalf of the sensors but rather illuminate our entangled effort at making sense of signals as a collaborative effort with the sensors.

The purpose of this paper is twofold: first, we wish to define a space where the sensor can become a collaborator in the meaning-making process; second, we examine our own role as researchers in this process. We ask ourselves: *What knowledge can sensors bring as concrete, situated observers of the study with the woodcarvers? How can we (the researchers) access that knowledge? What does it mean for our practice as HCI researchers to collaborate with and interpret sensors?* We start by presenting the theoretical framing that allows us to recast the sensor as a collaborator rather than an inert scientific instrument. Then we explore our role as researchers and how we might interpret the data with and through our bodies. To understand our interpretive relationship with the sensor, we turn to scholarship around meaning-making through the body [35, 40, 50].

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2 THEORIES TO THINK WITH

HCI is a multidisciplinary field drawing both on the positivist practices of science and engineering and on social science's constructivist approach to reality. These two approaches are ontologically incompatible and, as a result, tricky to consolidate [21]. We will not spend too much time and detail on the different sides of the argument but will briefly outline the challenges with each perspective. From a positivist perspective, a sensor is a tool for observing the world; it is ideally a more-or-less invisible window for viewing an external 'truth'. Within the positivist perspective in HCI, the sensor often only becomes visible if and when it fails to do the task it was designed to do, what Heidegger referred to as 'present-at-hand' [29]. In contrast, through the lens of social science, the sensor is seen as embedded and situated within a research culture [27, 38, 48]. The sensor is to some extent socially constructed [9, 54] and cannot escape that culture [28]. In other words, there is an implicit human-centred hierarchy that renders nonhumans, including sensors, only accessible as part of (human) culture.

We need theories that see the sensor to some extent as separate from culture, of having a 'being' of its own, rather than remaining a tool inscribed by humans with meaning [2] and politics designed by humans [58], or remaining an invisible measuring tool. Philosopher Graham Harman proposes to extend Heidegger's *Dasein*-being to include not just humans but everything [29]. In other words, tools have an effect on reality independent of being used by humans or not. Harman writes [29, p.19]: *'inanimate objects are not just manipulable clods of matter, not philosophical dead weight best left to "positive science." Instead, they are more like undiscovered planets, stony or gaseous worlds which ontology is now obliged to colonize with a full array of probes and seismic instruments-most of them not yet invented.'* Although Harman's object-oriented ontology (OOO) gives the objects a being, it is often criticised for losing sight of social, historical, relational and political effects [6, 22]. OOO cuts everything into separate pieces and it can be hard to find the connections again, the force of things when situated within histories and culture.

Agential realism sidesteps this issue. Instead of focusing on the separateness of everything, STS scholar Karen Barad takes the 'entanglement' of everything with everything else as a starting point [3]. They argue that *"animate and (so-called) inanimate creatures do not merely embody mathematical theories; they do mathematics. But life, whether organic or inorganic, animate or inanimate, is not an unfolding algorithm."* [4, p. 207]. We take two important points from this. First, algorithms might be used to describe observations but they are not 'there' to be uncovered with the right sets of tools and clever scientists. Secondly, reality is performative and everchanging rather than something stable and fixed. These perspectives are gaining interest in HCI, particularly through what has been called the 'fourth wave' of HCI or 'entanglement HCI' [22].

3 RELATED WORK

Urgent and complex social and environmental issues have led to an increased interest in a more-than-human research agenda within HCI [13, 14, 56]. There is no longer a single user or user group, rather complex networks of stakeholders, both human and nonhuman [18, 20], and our lives are increasingly entangled with and shaped by the technology we live with [22, 34]. What follows is a series of current methods and approaches that relate to sensor and data work from a more-than-human perspective.

3.1 Collaborations with sensors

There are already some examples in the HCI literature where it could be argued that the researchers are collaborating with sensors. In particular, sensors can provide insights into user behaviours that would otherwise be difficult to surface in conventional qualitative research methods (such as an interview). Hutchinson et al. describe how their technology probes collected data on usage that provided additional information to that which was discussed in interviews [37]. 'Thing Ethnography' [25] shifts the research space further to the more-than-human by letting a kettle collect data about how people use it. The kettle is better placed to understand how people interact and use it than the human researcher — or the human user, for that matter.

However, this concept of the data knowing more about us than we do is fraught. The ideology of technology as something all-knowing and objective, the modern-day equivalent of the 'modest witness' [28], is questionable. 'The modest witness' is a phrase originally used by STS and feminist scholar Donna Haraway to describe the approach of the experimental researchers of the 17th century, modest men belonging to a 'culture of no culture'.

This is not the stance and belief of Giacardi et al. [25] nor Hutchinson et al. [37]. Their approach is closer to ethnographic research with sensor technology [42]. In Nafus's ethnographic work, the sensor signals are approached as situated and especially meaningful to the person who generated the data. By presenting an incomplete picture of data, they are able to draw rich observations and discussions with their participants [42]. In other words, the sensor becomes, to some extent, a collaborator in gathering insights. The data collected contributes to specific, situated narratives rather than a generalisable whole.

3.2 Attending to data through lived experience

Another approach is to look at current methodologies within HCI scholarship that question and rewrite relationships with data, examining how data is interacted with and made sense of with and through lived experience [33, 52]. Intimate and personal relationships with data are explored through touch [17] and listening [36] with the intention of questioning and disturbing current ways of relating to data as a quantified representation of experience. These thoughtful approaches to resisting a capitalist agenda resonate with us and guide our approach to data analysis. In our work, we are not seeking to understand the signals of the hand carvers to improve their performance, nor is our goal to digitalise or automate their labour. Rather, we hope our research will give further insight into the way the material influences their practice.

Data can be seen as performative through interaction rather than a representation of some aspect of reality. Resisting the traditional understanding of data as representation, Lucian Leahu proposes a performative interpretation of data [39]. Here, users encounter their data as externalised and anthropomorphised through an object they need to care for and soothe. As a result, users make sense of (i.e. analyse) their data through their own individual lived experience, rather than experiencing the data as a reflection of their reality or 'objective' truth.

3.3 From reading to listening to signals

Social scientist Helmreich takes the Calvino short story "Reading a wave" as a starting point for 'reading' a wavefinder buoy. Through his various readings, he demonstrates how each reading illuminates particular aspects of the buoy's semiotic, material, political, presence and effect while hiding others [31]. However, it is commonly accepted that any perspective gives priority to certain ways of understanding and interpreting at the cost of others [30]. What is interesting here is the presentation of multiple readings in the same paper; together, these readings create a richer understanding of the buoy than any one perspective would by itself. In his conclusion, he speculates as to whether the bouy itself can become a *"human-nonhuman sensory delegate [...] generating new species of hybrid writing, operational impressions, and sensory practice."* However, using terms like 'reading' and 'writing' implies human activities. Language is symbolic interpretation, not experience itself; there is a separation between an experience and the words used to describe that experience [41].

What would change if we moved from 'reading' to 'listening'? The composer Pauline Oliveros sees listening as a whole-body experience not limited to the ears [45]. She has invented a method of attending to sound called "deep listening" where she opens up to sound. Sonifying signals is a strategy used in several design contexts to give immaterial signals a tangible 'handle' [1, 44], but it is not the only way to make sense of data through non-linguistic-terms. Somaesthetics takes a body-centric approach to designing with and for the body [35].

Embodied skills are often seen as either pre-reflective [49] or part of conceptual and cognitive reflective practices [53]. Dancer and researcher Buttingsrud evidences a "state of embodied reflection" [12] through interviews with skilled professional dancers. She argues that dance offers "a way of thinking (bodily) without thinking (conceptually)" [12], though this embodied reflection is not limited to dance, Anthropologist Marchand proposes an embodied, lived way of mathematising, drawing on his fieldwork with artists and artisans. While he is not trying to recreate the body-mind dichotomy in mathematics, he believes conceptual thinking to be inseparable from embodied forms of cognition in creative activities [40].

4 CASE STUDY

The signals were collected as part of a larger study to understand how the material influences woodcarving practice and how people pay attention to it as they work. For this paper, we will focus on what the sensor signals can tell us about material relationships and 'intra-action' during the carving tasks of the study. *Intra-action* relates to Barads's concept that agency is a process (performed), rather than a pre-existing attribute of an individual person or object [3]. This section provides the context and grounding for the section that follows and the discussion.

4.1 Research device

The device we used is made of plywood, a Bela embedded computer, four load cells (strain gauges), a piezo disk contact microphone, and a custom carving tool fitted with two Lofelt haptic actuators. The load cells were supplied with an analog-to-digital converter (HX711) with a slow sampling rate and high resolution, which is suited for taking static measures of pressure (e.g. weight on a scale). We were interested in capturing the interaction over time, rather than capturing a specific moment with high precision. As this was not possible using the provided converter, we built our own amplifiers using an amplifier chip designed for general instrumentation (INA125). See Figure 1 for a diagram of the system and Figure 2 for a picture.

The device produces haptic, audio and visual feedback to the professional hand carver participants as a means of querying their experience through defamiliarisation [7]. This feedback is provided in real-time, based on the carvers' interaction with the system (sensors). Specifically, this happens through a visual projection on the material, a haptic actuator in the tool and auditory feedback through noise-cancelling headphones. The result is a digitally augmented carving experience. In addition to generating feedback for the carving experience, the device also records the signals from the carving session as a multichannel audio file.

When the woodcarvers press their tools into the limewood fastened on the top of the platform, the load cells record the changes in pressure. As the carvers cut through the wood, the piezo captures the sounds created by cutting through the structure of the wood. Sensor signals are read as high-resolution analog inputs through the Bela computing platform.

4.1.1 Audio and Haptic. The feedback is generated through a *Pure Data* patch designed by Giacomo Lepri. The load cell signals and piezo are treated as audio signals and processed through low- and high-pass filters to remove noise. The sound design is based on Andy Farnell's jet-engine sound design [19]. Sandwiched tightly between the wood and the carving platform, the piezo captures high frequencies from the friction between the tool and wood. This forms the foundation of the haptic and the auditory feedback. The load cells modulate the sound model and piezo signals, creating an engine-like sound. This sound was chosen specifically to be incongruous and non-musical. The device is not meant to be a musical instrument, so the audio feedback had to be designed with a focus on noise-like qualities rather than timbre and harmonics. We used the built-in pitch shifter from Pure Data to move the feedback for the haptic actuators to a lower frequency range more suitable for the actuators.

4.1.2 Visual. Elements were designed in openFrameworks (OF) and based on a shader example in Patricio Gonzalez Vivo and Jen Lowe's 'Book of Shaders' [55]. Before passing the signals over to OF, two biquad low-frequency filters have been applied for noise reduction, which creates a smoother and more stable experience for the carvers. Figure 3 shows the resting projection when no pressure has been applied. The tessellated lines subtly move and distort as the woodcarver puts pressure on their tool to carve on the device. We designed the projection to be predictable to some extent — when pressure is put on the platform the visuals will distort, while remaining ambiguous in how exactly the system works.

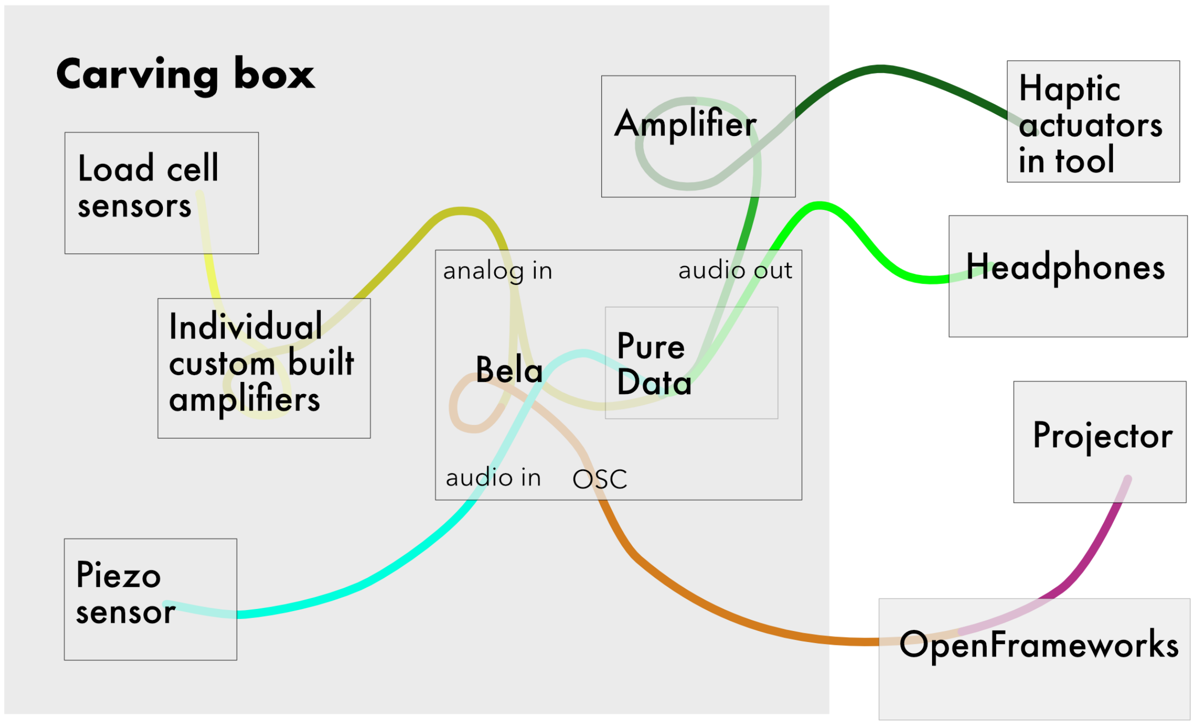

Figure 1: Diagram of how the signals move through the carving device. Processing of the signals is illustrated through colour changes

4.2 Study design

The aim of the larger research project is to understand how the material influences woodcarving practice and how the carvers pay attention to the material as they work. For this paper, we will focus on the role of the sensors and what the signals bring to understanding material influence in woodcarving practice. Woodcarvers with at least one year's experience were invited to participate. Four participants of varying experience have taken part.

The device was set up in a workshop at Queen Mary University of London. Each participant was given information about the purpose of the study and signed a consent form before taking part. They were introduced to the device and given 10 minutes to familiarise themselves with it. Then a brief interview about their experience and an opportunity for them to ask any questions about the device and study. Finally, they were given a 15 min task of carving a leaf using the device. The participants were given an example design for guidance and inspiration. The study concluded with an in-depth interview.

Participants came back for a second session after a week or longer to give time for noticing particular aspects of their practice and reflecting on the study and how it relates to their daily work.

All interviews are inspired by the Micro-Phenomenology interview method [47]. This method is of growing interest in the HCI community for resurfacing implicit and pre-reflective aspects of experience [32, 50, 51]. Given that much of woodcarving practice relies on implicit and pre-reflective knowledge, Micro-Phenomenology is well suited to bring these aspects to the fore.

4.3 The carver's experience of the study session

As the aim of the case study in this paper is slightly different from the overarching study goal, we will focus on a particular encounter with the sensor device. After reviewing all the carving sessions, we chose to examine the two sessions with the most experienced carver.

The carver started both carving sessions by sketching out a leaf design on the carving block. He then made a series of stab cuts with the back of the chisel's cutting edge against his drawn line; moving from tip to stem of the design. On the following pass, he makes a series of shallower cuts towards the design, 'meeting' his previous

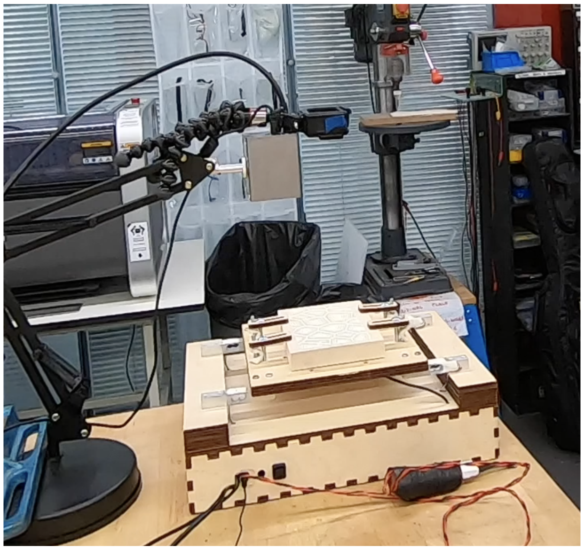

Figure 2: The carving device, located in a fabrication workshop where the study with carvers took place

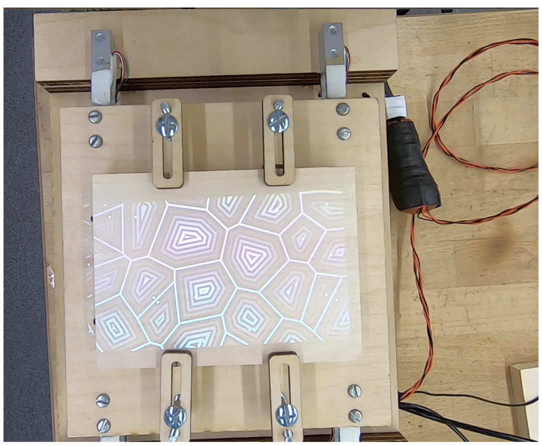

Figure 3: The visual feedback at the start of the carving session. The patterns change slightly as the carver presses their tool down on the carving platform

cuts. By removing material in this way, he created a depression around the leaf design, making it stand out from the background of the carving block. This procedure was repeated over again on both sides of the leaf in both sessions.

Carving on with the device was challenging, as the light from the projector made the work look flat. One of the first things the carver asked for as he started to carve was a lamp to light the work from a certain angle. *"You want the pieces to come together cleanly and again that's difficult to judge because the light is so flat [...] there's no shadow to read the depth of the of the cut and how they're coming together"*

The outcome from the second session was more refined than the first. In the interview, he said he was doing what he calls 'cheating' by holding his hand in front of the projector, making it easier to see what he was doing. He added that he never did this on purpose, just that the angle of his hand sometimes happened to shade the work in this way, and when it did he enjoyed the experience and perhaps worked in this way longer than he would have otherwise.

4.3.1 Focus and Presence. During the interview after the first session, the carver explained that his thinking is focused on *"what's happening at the cutting edge of the chisel and whether that's approaching the grain from the right angle, creating the right shape, the right sort of and form"*. Yet locating a singular moment such as a singular cut within the experience is difficult. He explains, *"carving is attrition, so that singular moment I mean it's occurring all the time, but I suppose what I'm trying to give you is the climax which is the most exciting bit"*. ... *"so if we're going back to that singularity of you know the incremental step towards that final achievement then that's happening as well but I suppose it's just it's so constantly present that it doesn't seem remarkable enough to really talk about that this is [...] the drudgery of every day"* The carver's comments also suggest a form of presence towards the future — 'the climax' when the final form is released from the carving block.

4.3.2 Carving mindset. In the interview, he tells me how he noticed in the time between our sessions that he approaches his work in two mindsets. One is more 'technical', where the goal is to achieve a good finish, but it's not very creative. He gives the example of a pot lid he was mending for a neighbour. *"That was a purely technical process, and all I wanted to do was make the lid fit."* He wanted the result to be good, for the lid to fit well and look nice. In contrast, he tells me of the project he is currently working on — a piece of carving with lots of natural elements. *"Whereas if I'm doing if I was carving a leaf or a face or something then the considerations are different I want it to have a sense of presence in a different way."* This metaphysical presence is hard to express in words but could perhaps be described as a form of liveliness that goes beyond realism or likeness to the original form (e.g. design).

5 HOW TO LISTEN TO SENSORS

We follow Braun and Clarke's viewpoint that analysis is not objective [11] but is constructed by the researcher. Meaning does not objectively bubble up to the surface like a spring of water or lay on the forest floor ready for collection with the right tools. Researchers actively engage in a meaning-making process through their analysis. We understand this activity to include not just qualitative data analysis but also quantitative approaches [26].

We analysed the signals as audio recordings by reproducing the audio feedback the woodcarvers heard when they carved as waveforms in the Reaper digital audio workstation (DAW). Reaper allowed us to align and synchronise all the sensor recordings, the reproduced feedback and a video track, and present them as single channels. Both video recordings were combined into a single frame (see Figure 4) to let us see both perspectives at once. The top-view footage was rotated to match the position of the woodcarver in the side-view footage.

At the beginning of the analysis process, we were attentive to the sensors themselves, their quirks and particularities, and their

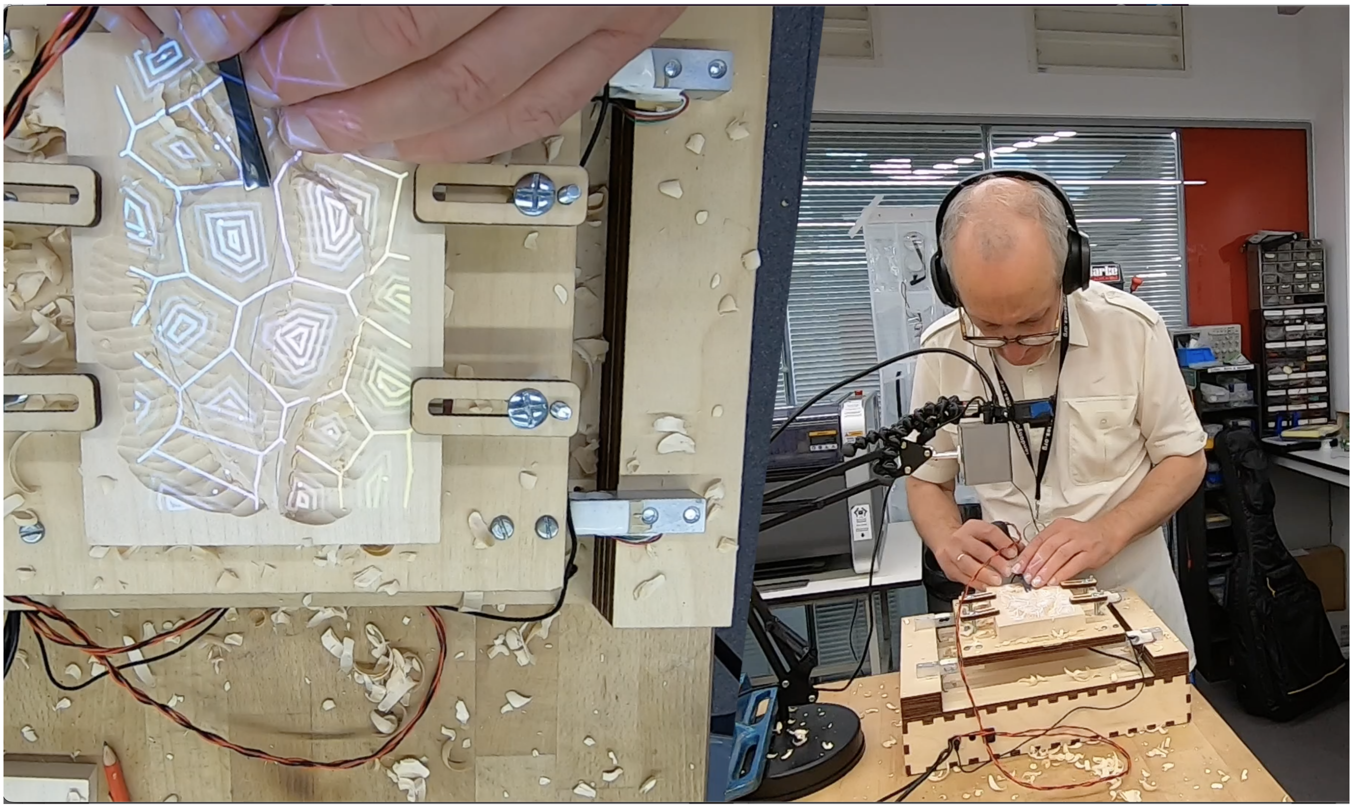

Figure 4: Still from analysis video. Top view of what the carver is seeing and a side view of the whole setup

unique presentation. We took note of how the signals vary between the four load cell sensors.

We approached the data from an embodied perspective, meaning we were interested in not just making a cognitive analysis of the data but also gaining an understanding with and through our bodies [35]. Practically, this meant that we watched and listened to the data with an open presence [45], rather than actively looking for patterns and moments of interest [16]. We let the data 'wash' over us and listened over and over again to particular moments. We then analysed the signals using a qualitative analysis software (atlas.ti). After watching the videos a few times we started to categorise the cuts based on what the carver was doing. The cuts were classified depending on their depth, length and direction, relative to the grain of the wood. Cuts that are shallow are usually longer whereas stab cuts, going straight down are shorter — they travel a shorter distance across the grain. We saw patterns and correlations between what the carver was doing in the video and what we heard or saw of the signals at that moment. We discovered a rhythm to the cuts when we listened to the audio feedback. This initial attempt at categorisation was used as a tool to pay close attention to what was happening, rather than for the sake of creating categorical descriptions of the data.

We then moved on to examine single cuts, asking ourselves: what do they mean? What can the sonification tell us about the cut or what is happening at that moment? Our assumption is that the intra-action we were looking for is very fine-grained and likely to be present within every single cut, within each encounter.

Most of the listening was done by author 1 on headphones in their office while watching the video. They listened to the quality of the sound: its shape, its pitch, the rhythm it produced over time. Some listening was done together by both authors from a laptop while examining the waveforms in Reaper.

The process of developing meaning and patterns is tacit/felt. It's something careful and sudden [46], rather than a linear process of understanding. Insights were developed in conversations and through discussions.

6 WHAT DOES THE SENSOR SAY?

Now that we have identified how we listened to the sensors, what story did the sensors tell? This section presents an analysis of the combination of the signals recreated as *auditory* feedback heard by the carver and the visual representation of the load cells as waveforms seen together with the video recordings.

The story the sensor tells is one where the material and tool are in focus – the contact point, the cutting edge of the chisel slicing through the soft summer wood and the denser grain of the winter growth. These irregularities give the otherwise smooth peaks of the load cells' signal's waveform texture. The woodcarver withdraws from the story told by the sensor. His presence can be seen through the peaks of the waveforms: the force he uses behind his cuts. However, his intentions and the purpose behind the cuts

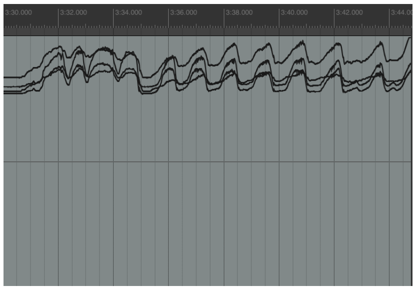

Figure 5: Load cell signals represented as waveforms from the second carving session

are absent in the sensor's story. Originally a main character when we encountered him at the beginning of the analysis process, he is no longer the focus of the story of the sensor. Similarly, the sensor reveals nothing about the growing conditions of the tree, or the process of going from a living organism to a 'carving blank' mounted to the device.

The sensor, on the other hand, is concerned with texture and pressure: the texture of the wood as it is cut and the force used on the material. This is evident in how the cuts going across the grain have a lot of sounds while cuts going along the grain have little or no sound, only a little 'ping' as the tool cuts away out of the wood.

6.1 Variation and nuance

The first thing we notice when we listen back to the signals and examined the waveforms is that each encounter between the wood and chisel is richly nuanced and distinguishable from the other (see Figure 6). These variations are also present in the waveforms of the load cells, though more subtle. Looking at the waveforms of the recorded signal, we identify patterns that correspond with the actions of the carver. While there are similarities across similar types of cuts, there is also a lot of variation (see Figure 5). The peaks and envelopes are most clearly defined in the signals recorded from the sensor the carver is working closest to, and slowly shrink as the carving moves further away from that particular sensor. Most peaks are irregular with bumps when examined in detail. These irregularities might tell us something about the grain of the wood. They suggest micro changes in pressure that are not deliberately done by the woodcarver but rather the result of particularities of the material - the harder growth of the winter wood and the sudden or rapid change to the soft summer wood. Some bumps tell stories about the moment when the chisel breaks out through the wood – the extra force needed to cut out combined with the particulars of the wood at the place of the cut.

Listening to the signals as the feedback heard by the woodworkers, we first identify a link between the shapes of sounds we hear from the sensors and the types of cuts the woodworker is performing. Long shallow cuts across the grain have the longest and most complex sounds. Short and deep cuts across the grain have some complexity but are compressed over a short period. Cuts that go with or against the grain create very little or no sound at all apart from a little tapping noise the moment the chisel exits the wood. Listening more closely, we discover the variety within every single cut.

In Video Figure 1 [1] which was taken during the second carving session with the woodcarver, he made a series of long shallow cuts going across the grain, and the signal's pitch became higher and higher as he cut. Examining the visual representation of the audio feedback during the annotation phase of the analysis process illustrates the variety of the signals. Figure 6 shows the audio waveform of this movement of carving as represented in our qualitative analysation software. There are few common elements between the different 'shapes' of sound. In other words, to make a generalisation about what we see here is hard.

At one point in the analysis process we identify our language and annotation has been predominantly focused on the actions of the woodworker, while our argument is to listen to the sensor: what does it say and know? The woodworker is part of the story of the sensor signals; without them, there would be no signals. However, we noticed how staying close to the signals, and by extension the wood allowed us to see the chisel before the woodworker.

6.2 Cutting apart

When listening to the sensor, each encounter between the chisel and wood becomes unique and separate. By recording the signals as audio, the encounters are bound together through temporality. They become, in Bowker's words, *'thin slivers of reality'* [10] as all other relationships are lost. The signals are forever in the present, with each cut existing independently of the other. Time binds them, as opposed to there being a relationship between what happened before and what might happen next.

By contrast, we could examine the wood cuttings on the floor. At first glance, these two data points have in common the record of individual encounters but as we examine the wood cuttings we notice traces of previous cuts on the top. Here the temporal aspect has been lost; what remains is part of a historical and spatial relationship of the encounter that came before in that precise location. Additionally, the chip holds predictions about the future; if the wood chip comes out frayed the woodworker is likely to go back over the cut again.

6.3 Relationality

The sensor signals affect the intra-action. Unlike the 'modest-witness' [28] these signals are actively entangled in the phenomena they are observing through the feedback they provide. The woodcarver had noted in his interview how he enjoyed the auditory feedback to the extent that he considered making the auditory experience his main focus. Nonetheless, he went back to focus on form-giving with his tool – we speculate as to what extent the sonic qualities shaped the execution of his design. Cuts going across the grain provide a richer sound experience than cuts going with the grain. The carver placed the design of the leaf in such a way that produce mainly carving cuts going across the grain.

In this sense, the sensor can offer a counterpoint to a human-centred worldview. Through the sensor, we notice the encounter of matter before framing it in the context of the woodcarver's actions. Matter in this sense includes the material world; nonhuman, human

[1] video included in companion material

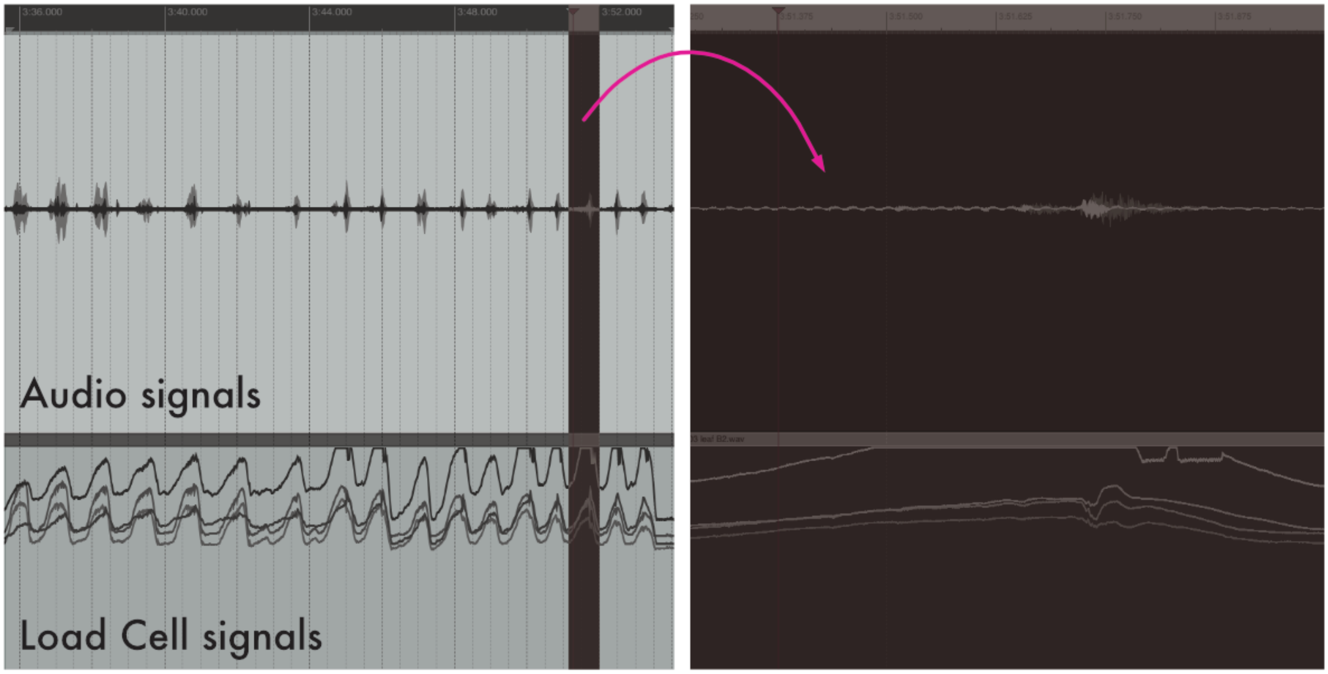

Figure 6: Audio and load cell waveforms from second carving session

digitally augmented or not. These particular sensors have an effect on the work that is produced with the carving device. They are actively engaged in the phenomena they are observing.

7 DISCUSSION

Throughout our discussion, we will stay with the sensors to understand their role in how knowledge is co-produced. We start by examining how we encounter the sensor data and how we come to understand the data. We then move on to explore what the sensor might be. Finally, we speculate what the sensors do and how that affects our understanding of the data they produce.

7.1 Encountering sensor data

In this paper, we have chosen to focus on the sensors and the knowledge they bring to us (the researchers) as we seek to understand how materials influence carving practice. An alternative approach could have been to understand the behaviour of the carver. We could have done this with the help of the sensors. In order to quantify the behaviour of the carver we would need more information. We would assume that there is a ground truth out there that can be known and discretised. We could start by looking for a correlation between what is happening in the signal and how that corresponds with the behaviour of the woodworker. This might involve making a judgement on the quality of the cut the woodworker is making, but what quality is that? How do we know that the judgement we make is appropriate? Does even the woodworker themself know? Is there an *optimal* pressure? These insights gained through machine learning (statistics) could then be used to optimise the craft, to train novices or perhaps even robots.

However, starting with the behaviour of the carver presuppose that the carver has agency - that carving is a 'behaviour' to be studied rather than a phenomenon that emerges through intra-action. We are interested in how the sensor can destabilise the human-centred tendencies in our research culture to account for a more-than-human understanding of carving practice.

The signals are by no means neutral or innocent. Questions along the line of: 'what will you use the data for?' were repeated by all participants. This implies a concern that the data could be distilled and used to train a machine to do the hand carvers' work. Our data has a political edge even without our explicit intention.

Resisting technosoloutionism and optimisation for the sake of it, we want to dwell on the materials — the sensors. We want to understand through and with the sensors what we can't understand by asking the carvers. This fine-grain detail of their practice of attending to the material in the search for the form. The 'lived' situated 'experience' of the sensors is not something that a human can necessarily make sense of. In the sensor's own terms, however, something surely can come from collaboration. We propose meeting the sensors halfway [3] through our lived experience. By engaging with the signals through our lived experience we draw on embodied ways of thinking and reflecting [12, 35, 40]. *"All life forms (including inanimate forms of liveliness) do theory. The idea is to do collaborative research, to be in touch, in ways that enable response-ability."* [4, p. 208].

7.2 Where are the boundaries of the sensor?

In other words, what is the sensor? It might be helpful to pause for a moment to think about what we refer to when we talk about 'sensors' so we can better understand what kind of knowledge the sensor brings. Let us start with the basic and obvious. The research device uses one piezo disc and four strain gauge sensors mounted to aluminium rods, commonly referred to as load cells. This sensor consists of a physical material that changes resistance based on material deformations of the machined aluminium piece the conductive material is attached to. This is what is typically referred to as the sensor. The signal these load cells provide is so minuscule that some form of amplification is needed to make use of the signals. However, these sensors can not sense anything by themselves; they need to be part of an electric circuit to translate changes in resistance to a voltage that an analog-to-digital converter can measure. Electricity alone is not enough to make use of these sensors; we need some device that receives, parses and records the signals produced by the deformation of the materials in some form or another. In the carving device, this system is a Bela embedded computer. During the study, a laptop powered the Bela, and the laptop (MacBook Pro) was plugged into the mains. We see a mesh beginning to emerge enveloping the sensor: it is no longer set apart, separate from everything else.

Latour's actor-network theory is trying to get at this enmeshment by drawing connections between discrete 'actors' in a 'network' [38]. Barad's idea of entanglement and intra-action makes room for less predetermined interpretations. The actors emerge through intra-action and the 'apparatus' used for the interpretation of the phenomena [3].

Where does the sensor then end? Does it end with the plug at the mains? We could follow the power to its source — a wind farm or power station via the grid. Or we could chase the design and production of the various elements that went into the production of our specific sensor entanglement. The material production of everything that constitutes the sensor also has a social, human side with effects and implications beyond the materials themselves. Where do the metals come from? Who made all the parts? Humans and nonhumans are entangled throughout the process. Geological histories of soil and dinosaurs, of technological development and scientific knowledge, oppression and exploitation are woven together in this mesh. Additionally, there are the signals produced by the sensor — what is commonly referred to as 'raw data' [26].

To not get lost in the vast mesh of the sensor, I will re-draw the boundaries of the sensor with the aid of Graham Harman [29]. Object Oriented Ontology cuts the physical presence of the sensor apart from the 'baggage' of history and relations. Using Harman's 'tool-being' as an apparatus, we transform our sensors into *sensor objects*, concrete entities situated in a specific time and space instead of abstract and general *sensors*.

7.3 What does the sensor object do?

Now we have a clear idea of what the sensor is. What does the sensor object do? The typical answer would be to say that it senses. Gabrys proposes the term 'sensing practices' [23] as a way to recognise more-than-human ways of sensing.

The *sensor object* introduces another set of entanglements with humans and nonhumans. To unpack this, we need to ask ourselves what is the purpose of the 'sensing practice' done by the sensor. Who or what is being sensed and why? In an HCI context, sensors are often used to understand human behaviour [5, 8] Although Giacardi et al.'s approach are different in its thing-focus [25], their aim remains the same as more traditional HCI: of understanding the human (or at least the human in relation to the thing/object). By contrast, our sensors were not used to understand carving practice (e.g. the carver) as such. Other sensors and interfaces would likely be more appropriate as our system is deliberately distorting the carving practice. Instead, we used the sensors as observers of an encounter between the woodworker, tool and material that is challenging to understand from a human perspective alone.

This leads us to ask: do all sensors measure? Are there other modes of sensing that are not measurements? Measurement implies metrics, units of measure, an object or phenomenon to be measured; these form a methodology or even ideology of measurement that is commonly found in science and engineering. We propose *observation* as a contrast to measurement. An observation presupposes there is something to observe, but it does not come with a clear stance or assumption of how the observation should be done or what it might reveal. Our particular sensors further trouble a classical understanding of observations by actively participating in the phenomena they observe. Although our sensors are explicitly entangled, the physics community has long recognised the effect observations have on the observed [3].

Designing a sensor for observation becomes then a different process than designing for measurement. We propose that to design for observation is to work with a sensor as a co-investigator rather than a transparent lens or subservient tool. Similarly, the data analysis process is different in the two different scenarios. In practice, this means that designing apparatuses for observations prioritises values typically found in design research [15]. It's an open-ended approach with an emphasis on knowledge creation through the process as much as in the end result. We see parallels with Wakkary and colleagues' 'Morse Things' [57], Gaver et al.'s cultural probes [24] and an interest in the particular rather than the general. However, where they were interested in understanding how human lives and stories are entangled with technology, we see our approach as suited for a more-than-human agenda that gives nonhumans an equal footing to humans. This kind of work requires the researcher to attend to the sensors differently throughout the process, starting with seeing the sensors as materially concrete and situated [43] throughout the process.

8 CONCLUSION

The wood carvers have difficulty accounting for the singular cuts, and — unlike handwriting, for example — there is no record to look back at and evaluate. Only the final cut remains; all previous attempts have been chipped away. The sensors, on the other hand, exist in the present — they record changes independently of past experiences and future goals. They provide a different perspective on the same event. Some might call it an objective view. Their numerical nature makes it tempting to categorise, model and make predictions of the experience-behaviour-phenomena. We recognise that the woodcarver's side of the story has become peripheral in this paper and wish to examine further the dialogue between the woodcarver and our apparatus in the future.

In this paper, we have prioritised the sensors' role in our research study. By foregrounding the sensors as material objects, we explored an alternative interpretation of the sensor data, where the sensors become co-producers of the knowledge. Through this process, we notice how staying close to the sensors subtly decenter our research practice to include nonhuman collaborators. We propose this approach as an extension of existing methods, particularly emphasising a more-than-human agenda. We do not propose a step-by-step method for attending to sensors as co-producers of knowledge; instead, we wish to open up the possibility of other configurations with sensors and sensor data, hoping to strengthen more-than-human approaches for a more livable future.

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