Chapter 2: String Figuring Robotic Knitting

> The yarn is neither metaphorical nor literal, but quite simply material, a gathering of threads which twist and turn through the history of computing, technology, the sciences and arts. In and out of the punched holes of automated looms, up and down through the ages of spinning and weaving, back and forth through the fabrication of fabrics, shuttles and looms, cotton and silk, canvas and paper, brushes and pens, typewriters, carriages, telephone wires, synthetic fibers, electrical filaments, silicon strands, fiber-optic cables, pixeled screens, telecom lines, the World Wide Web, the Net, and matrices to come.
> *Sadie Plant, zeros+ones*, 12

Inspired by the twisted materiality of yarn, in this second chapter of the book, I will dis- and re-entangle what I identify as the two strings that are constitutive of my practice of bringing wool to the lab, playing with wool, knitting needles, and the robot arm PANDA, and realising collaborative knitting between humans and PANDA. The first string is formed by the historical entanglements of computational technologies and cultural techniques such as weaving and knitting, and the second string is formed through the collaborative intra-action between entities through the realisation of robotic knitting. Playing with both strings, I aim at allowing new patterns of interference between a cultural technique and cobots to take shape, as well as patterns of collaboration at the human-machine interface. Further, I am especially interested in recuperating historical legacies of such interferences as the basis for stipulating new stories of a technological future with a new generation of automata, working from the junction between handicraft and engineering as one of queer use.

Moreover, carefully assembling two strings, I engage in multiple string figurings of meaning- and matter-making between technologies and persons. In so doing, I not only make tangible existing relations between humans and machine as well as between digital and hand knitting practices, but rather also propel processes of relating differently. Hence, queering the usefulness of the cobot as co-worker, robotic knitting serves me as a tool for exploring the ways in which collaboration between human and machine is a sociocultural, material, embodied, and computational process, based on a host of meaning- and matter-making practices, and also always the result of a collective effort.

2.1 String 1: Knitting and the Digital—Diffracting Dichotomous Relations

The first string is about how the practice of robotic knitting not only centrally challenges common dichotomies between craft and high-tech, as well as virtual and tactile, soft and hard, and also female- and male-coded activities, but moreover challenges the very structure of ordering itself. The point of entry is the relation between knitting as a craft practice on the one hand, and digital practices of computing on the other.

My account of craft practices mainly encompasses spinning, weaving, and knitting. Looking at these practices in their contemporary meaning, they exist in both the private realm of reproduction and the public realm of production. In the first, they display a leisure activity or a hobby that one might have learned at school and pursues mostly at home. At the same time, all three craft practices can also be regarded as engines of industrialisation in the form of the invention of the spinning machine, the industrial weaving loom, and the (large scale) knitting machine. In contrast, the cobot used to be a rather large-scale, stationary technology that has been confined to the sphere of factory halls and by protective cages, while current waves of automation are increasingly pushing the engineering of rather mid-scale, light-weight, and flexible cobots as assistive machines supposedly entering the household (as figured, for instance, in the narrative of "the robots are coming").

As many social scientists have attested, we are living in times in which digital technologies, namely computer soft- and hardware, are ubiquitous as they have permeated every sphere of human everyday lives, constituting the conditions for a digital society (see Lupton 2015; Dourish & Bell 2011). In turn, social relations at work or in the private sphere, as well as forms of political participation, are becoming more and more polarised, either dis- or enabled through the use of digital networked devices. They basically stipulate a translation of analogue into digital data based on the binary coding of 0 and 1 and evolving through operations of formalisation and algorithmisation. In this regard, digital practices are not confined to a specific sphere of human existence, but are rather part of a comprehensive transformation of the sociomaterial grounds of human existence on both the level of cognition and embodiment.

Deborah Lupton's analyses of digital practices through the figures of the *Quantified Self* (2016) and, more generally, *Data Selves* (2019) both make tangible the ways in which people and digital devices are forming embodied "human-data assemblages" (Lupton 2019, 6). The notion of human-data assemblages underlines the ways in which "humans make and enact data" and the ways in which "data make and enact people" (ibid.). This co-creating relation then challenges ideas of the analogue and the digital as two separate spheres, limiting the relation between them to that of a one-way-translation in which everything becomes formalised and digital. Rather, with Lupton, I understand datafication as a much more lively process of entangling human worlds, devices, and spaces, constitutive of human-data assemblages from which (concepts of) bodies and devices with boundaries and agential capacities emerge. Returning to the quote at the beginning of this chapter, my interest in entangled human-data assemblages cannot be cut off from my interest in figuring out the role of the yarn for grappling with emerging, ubiquitous human-robot relations. What can be learned about technological histories, as well as futures by following and playing with yarn—not only in a metaphorical, but in a literal, material sense?

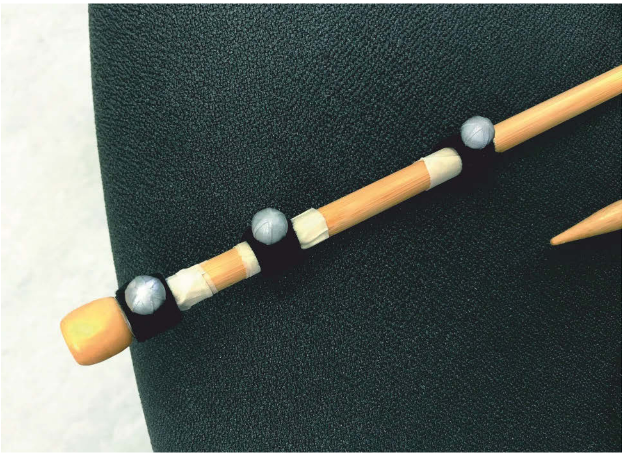
Shortly before the official start of the project *Do Robots Dream of Knitting? (DRDK)*, I already made an appointment with Jan Martin, who was at that time the student assistant at the MTIengAge lab at TU Berlin. Jan is trained in electronic engineering and on that first meeting, we met to wildly associate knitting practices and robotics. This meeting was excellent for doing so, as Jan had not knitted before and I am not an electronic engineer. The yarn then took on the role of mediating between our disciplinarily diverse knowledge worlds, but also moved into the centre of our concerns with assembling ideas on how knitting with a robot could be realised. My very first idea, emerging during this meeting, was what I considered to be a simple transference of movements. It was based on my understanding of what this would imply, namely to conceptualise a sequence of movements which are definable through locations in space. We then just needed a model of the robot in space to which this data in turn could be transferred—at least this was how I imagined what robotic knitting would be about. At the time, I was only slightly familiar with the PANDA robot and motion planning methods. Nevertheless, this pathway of thinking and engaging with the yarn produced surprising knowledge and became one method of challenging taken-for-granted assumptions, including those I was working with.

During that day, I asked Jan to work with me on what I called the *datafication of a 'human knitting practice'*, namely my knitting practice. More precisely, we started with the aim of generating data on knitting movements by recording my practice of the garter stitch through motion capture. The robotic lab was endowed with eight infrared cameras of a motion-capture system. In short, motion capture records the movement of markers (mostly small polystyrene balls covered with a retroreflective material) in a defined space that is recorded from different angles through several calibrated infrared cameras, which together produce a 3D image of the markers moving in space on a screen. In classical human movement analysis, the three markers have to be placed at a selected joint of a human body, representing the x-, y- and z-axes in space. Using a MoCap System body model, these markers then allow one to track the orientation and position of each joint in motion. In the case of knitting, I decided that the goal was not to understand how my arms and hands with fingers are moving—as the robot arm is endowed with a gripper and not with a human-like hand—but rather to track the movement of the knitting needles. If we could locate the exact position and orientation of each needle during the different movements of, for instance, the garter stitch (knit every row), wouldn't it be possible to emulate this behaviour of the needles when the needles are put in the gripper of a robot instead of a human hand? Moreover, my assumption was that the garter stitch, in its repetitive qualities, should produce a pattern of movements in space that are marked by a high degree of uniformity and would therefore be easily reproducible by the precise cobot arms of the newest generation.

Against this backdrop, Jan, Bülent Erik (the head of the technical staff), and I started to think about where the markers should go on the needles. The next step was to figure out how to attach the markers onto the needles. We attached three markers on each needle, representing the needle's location on the x-, y-, and z-axes. We also used the standard method of attaching markers, which is the use of Velcro tape segments to which plastic threads are mounted so that the accompanying markers must only be screwed onto the thread. On this first, more playful occasion, I only brought one pair of needles with me: bamboo knitting needles size 8.

However, the surface of the bamboo needles turned out to be too slick for the underside material of the Velcro tape, so that the tape with the marker could not be placed in a fixed position. Luckily, Bülent came up with the idea to use some crepe tape underneath the Velcro tape to make the needles larger in their diameter and to increase their skin friction. *Figure 1* shows the needles with three markers.

Figure 1: The needle with the markers



After the needles were prepared, I started to knit, while the MoCap System tracked the movements of the needles. The generated data can be displayed in various ways. I was fascinated looking at the numerical version (*Figure 2*), illustrating the exact location of each marker in the coordinate system during each second. My knitting practice never looked like this before.

Without even knowing how to read these numbers properly, their variations nevertheless already challenged my assumption about the uniformity of

Figure 2: Screenshot of MoCap Data

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,,Rotation,Rotation,Rotation,Rotation,Position,Position,Position,Error Per Marker,Rotation,Rotation,Rotation
    ,Rotation,Position,Position,Position,Error Per Marker
Frame,Time (Seconds),X,Y,Z,W,X,Y,Z,,X,Y,Z,W,X,Y,Z,
0,0.000000,,,,,,,,,-0.566814,-0.020205,-0.028210,-0.823115,-0.216869,0.588768,0.382484,0.000408
1,0.008333,,,,,,,,,-0.563579,-0.018922,-0.028494,-0.825354,-0.216837,0.589094,0.382364,0.000408
2,0.016667,,,,,,,,,-0.559275,-0.017465,-0.028715,-0.828301,-0.216825,0.589502,0.382450,0.000408
3,0.025000,,,,,,,,,-0.552099,-0.015599,-0.029729,-0.833103,-0.216866,0.589984,0.382707,0.000408
4,0.033333,,,,,,,,,-0.549878,-0.015222,-0.029117,-0.834598,-0.216890,0.590481,0.383001,0.000408
5,0.041667,,,,,,,,,,,,,,,,
6,0.050000,,,,,,,,,,,,,,,,
7,0.058333,,,,,,,,,-0.548891,-0.016041,-0.025992,-0.835336,-0.216921,0.591922,0.384089,0.000408
8,0.066667,,,,,,,,,-0.543252,-0.014634,-0.026695,-0.839018,-0.216957,0.592327,0.384506,0.000408
9,0.075000,,,,,,,,,-0.542726,-0.014988,-0.026287,-0.839365,-0.216960,0.592640,0.384875,0.000408
10,0.083333,,,,,,,,,-0.543938,-0.015738,-0.025010,-0.838605,-0.216977,0.592900,0.385206,0.000408
11,0.091667,,,,,,,,,-0.543860,-0.016071,-0.024442,-0.838666,-0.216988,0.593093,0.385511,0.000408
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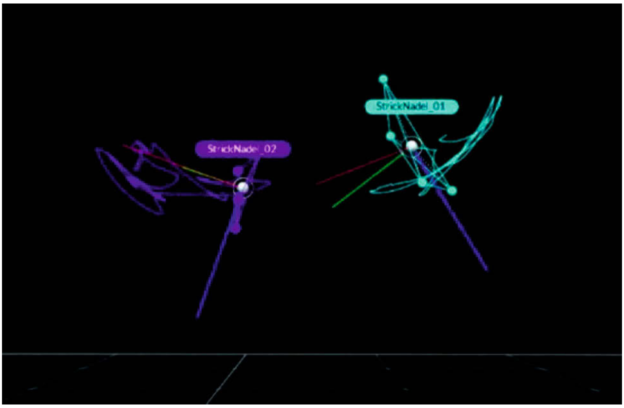
the knitting movement. The rows show similar numbers, but they are never identical—they all vary from each other. If the movement of, for instance, inserting the right needle into a stitch on the left needle in order to open up a new stitch, repeats itself approximately every five seconds, then this movement should have the same numbers in every fifth row. Even more revealing is watching the MoCap animation of this data, as the following screenshot (*Figure 3*) shows:

Figure 3: Screenshot of recorded MoCap tracking



Needle one and needle two (*Stricknadel*) perform movements that do not reveal any kind of obvious rhythm and cannot be identified without an explanation. They show no uniformity at all. At a first glance, the MoCap captured movements that could be loosely associated with hands conducting an orchestra. This visualisation made me pay attention to the myriad of micro-movements that I constantly make in order to control the behaviour of the yarn, the stitches on the left needle, the new stitch on the right needle and the knitted piece. These movements of compensation and correction prevent the individual stitches from slipping from the needles, but also secure an even length of the stitches and therefore uniformity of the knitted piece. Clearly, the practice of knitting with two knitting needles is very different to the automated form of knitting performed by knitting machines.

These initial insights into the nature of 'human knitting' already displayed the different layers of obstacles that we would probably have to encounter in the following course of the project and in its attempt to transfer my knitting movement onto a robot arm. In the case of knitting with two needles, it is essential to note that the behaviour of the yarn turned out to be unpredictable. This, in consequence, also made the behaviour of the yarn and the movements of the needles when hand knitting non-formalisable. In contrast, my vision of automating 'human knitting' relied on producing a data set of replicable movements that in turn can be transferred onto the robot. Nevertheless, I was still—if not even more—intrigued by the idea of having a robot arm knit collaboratively with me.

Motion capturing my knitting practice not only illustrates the unexpected obstacles, but also makes tangible the sociomaterial, embodied circumstances of the digital practice of MoCap. In order to track the knitting needles, we not only had to endow the needles with markers, but I also had to position myself in space in a way that I was visible to every infrared camera and I had to fixate my body in a way so that the needles were performing only the knitting movement. Basically, I was sitting on a chair, bent forward with my arms resting on my upper legs while knitting. This was a very uncomfortable position and definitely not one I would have chosen for knitting if not for the MoCap tracking. I had to practice this form of uncomfortable knitting to prepare myself for the MoCap tracking. Despite my best effort to make 'human hand knitting' datafiable, we did not receive the expected results: A reduction of complexity of the movements through formalisation as a key to motion planning. Rather, this attempt at datafication challenged the very idea of knitting as a repetitive and therefore uniform practice, making tangible the material resistances and stubbornness implicit to forming new stitches.

Moreover, though not producing the expected result, I nevertheless contemplate this first attempt at translating my hand knitting into a plannable motion through MoCap tracking as producing an interference pattern which opened up the possibility to dis- and re-entangle yarn, knitting, and digital practice differently. Further, this result raised questions, such as: How is it possible to mediate between 'human knitting' and the promise of automation carried by the core strength of the latest-generation flexible robot arm? That is, how can we reconcile the robot's absolute and reliable repetition of the same movements with outmost precision if knitting is a practice characterised by non-uniform movements? And, what kinds of human-robot collaboration would emerge from this? Clearly, datafication in this case opened up the need to delve deeper into the qualities of mastering knitting as a technique, as well as the legacies of knitting, challenging my under-complex and very reduced initial image of hand knitting and how it relates or can be related to digital practice.

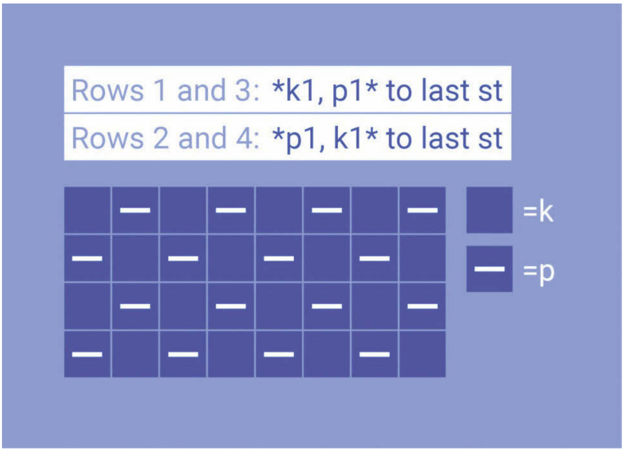
My first encounter with knitting was during my PhD studies. During that time, I would often get frustrated with academic work, the endless hours spent in front of my computer, mostly at home as I did not have a proper office space at my disposal at the time, while feeling at the end of the day that the outcome of the day's work was not really tangible to me. The size of the document files, but also the number of sometimes handwritten notes might have been growing, but I nevertheless rarely felt satisfied with what I had accomplished. In addition, I was also frustrated by the structure of such a day, as I experienced writing my dissertation at home as a process which could take hours of reading, revisiting notes and yet not producing a countable output, namely written pages, while this process could easily stretch into the late evening, transgressing the boundaries of work into my supposed leisure time. Burdened by these circumstances of writing, I started to search for an activity that could balance the writing process and result in a more tangible outcome. By chance, knitting became this activity for me.

At first, I started to learn how to knit socks through a knitting book, but quickly needed to complement the written guide with online video tutorials, as I needed moving 3D explanations of where needles and yarn have to be in order to form new stitches and to understand how I can get them there. Mastering the learning and acquiring the tactile skills needed, the regular evening practice of knitting socks soon meant my involvement in a repetitive, rewarding activity, which accompanied the process of my dissertation writing nicely.

Knitting as a handicraft leisure activity depicts a practice of structuring, involving ordering as well as creativity and meditation. Knitting is the goal-oriented activity and creative practice of producing new stitches and thereby also a knitted artefact, while the repetitive nature of forming new loops requires focus and is at the same time meditative (Wiescholek 2019, 73). It is also a satisfying practice as my experience confirms: The finished socks as the knitted outcome are "a physical manifestation of a knitter's effort, skill, and productive use of time" (Rosner & Ryokai 2008, 2). Thus, knitting as a practice is more than mastering a technique—it also involves the stipulation of different senses, affective states like comfort and satisfaction, and mental activity. The resulting piece will show traces of this embodied, multi-modal, and mental practice. As Daniela Rosner and Kimiko Ryokai (2008, 1) underline further: "A handcrafted artifact can physically embody the skill and time involved in its production. For example, the subtle unevenness of stitches in a hand-knit textile may be an indication of the rhythm and tension of the knitter at that particular point in time those stitches were created." A change of rhythm and tension in knitting socks, for instance, might cause me to produce a pair of socks that differ in width and size, though made with the same number of stitches and rows. Every knitted artefact embodies the history of its production, including the persons involved, the locations of knitting, the skills of the knitter, as well as the varying executions of the planned stitches. The knitted artefact is a manifestation of this story.

Furthermore, an essential part of learning how to knit was learning to differentiate between knitting styles, English and Continental (basically, the yarn is held either in the left or in the right hand), and deciding which one I would like to learn. Next step was to learn not only the movements of my two hands with the two or, when knitting socks, four knitting needles, but also to learn the formal language of knitting patterns. Patterns are written in a code that mainly differentiates between the two stitches knit (k) and purl (p). The basic and important stocking stitch alternates between a knit and a purl row, but as socks are knitted in rows, every round is a knit round. Another very basic pattern which I also learned very early on is the moss stitch, which can be used to add a different texture to the socks, and which requires four alternating rows. The knitting pattern for the moss stitch over 4 rows looks like this:[1]

Figure 4: Knitting language



What immediately stands out is the binary structure of the knitting language. This binary logic is at the core of any kind of (textile) web. Tracing the handling of yarn even further, it is interesting to dwell a bit further on the binary logic of knitting. Hence, in its structuring quality, the binary code of textile is also a pivotal point for a classical, utopian cyberfeminist position. In short, this position emerged at a specific historical junction during the 1990s and "their themes of 'grrrl power' and 'wired worlds'" (Wajcman 2004, 63). It is relevant to situate cyberfeminism within this junction and—in line with Wajcman (ibid.)—as "a new relationship between feminism and technology" that foregrounds empowerment through female agency and subjectivity. For one of the most popular figures of cyberfeminism, Sadie Plant, this new relationship is centrally connected to the binary code in its ambivalent meaning: It represents both the Western patriarchal symbolic order and the potentiality for female empowerment and emancipation.

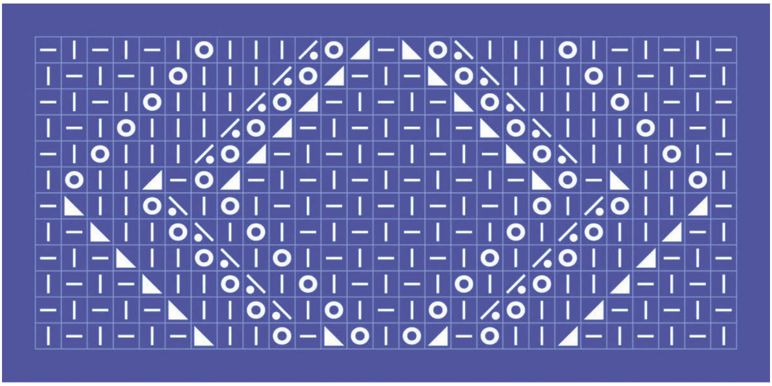
1 *Figure 4* shows the written pattern on the left, and on the right a translation of the pattern code into a chart. The asterisks indicate that the instructions between them have to be repeated—in this case, until the last stitch (last st) of the row.

Plant (1998, 34-35) emphasises that "the zeros and ones of machine code seem to offer themselves as perfect symbols of the orders of Western reality…the difference between…form and matter, mind and body, …inside and out, active and passive, ..yes and no, …male and female." Wajcman (2004, 35) further explains: "It takes two to make a binary, but…1 and 0 make another 1. Male and female add up to man." Haraway's figure of *Universal Man* literally represents this binary logic. However, Plant also differentiates between such a binary logic and the operations enabled by digital technologies, ranging from the (historical) example of punch cards to the modern, networked computer and how women have been and are still involved, as well as the ways in which binary identities become flexible. Thus, she understands these operations primarily as holding the potential to transgress if not subvert a binary logic in its powerful operations of differentiation and classifications. Plant explains this by drawing on technology as the compound of *techne* (art, skill) and *logos*. Further, following Plant (1998, 50), the latter implements the logic of the binary system, differentiating between the one and the other, which is not one (the zero), while the first indicates that technology is "also a matter of the skills, digits, speeds, and rhythms of techno." As she continues: "The techno and the digital are never perceived to run free of the coordinating eyes and hands of logic and its binary codes. But logic is nothing without their virtual plane" (ibid.). After all, the organising unit of the binary digit (bit) is the byte, eight bits. Plant (ibid.) understands this pairing of eight as the basis of digital technologies "full of intensive potential." With this, she re-codes not only the relation between women and technology as inherently intimate, but also between zeros and ones, as "zeros now have a place, and they displace the phallic order of ones" (Wajcman 2004, 64).

Technofeminists, cyberfeminists, and FSTS scholars, more generally, have written extensively on Plant's vision of a feminist cyberculture and cyberfuture, especially her blind spots regarding the exploitive and oppressive dimensions of the cyberverse and her essentialising and determinist tendencies (see Wajcman 2004). However, and as Cornelia Sollfrank (2018, 12), another central technofeminist voice, underlines, such a critique of early cyberfeminisms is in danger of failing to acknowledge the *Wirkmächtigkeit* of the political fantasies evoked by the very notion of cyberfeminism. Thus, reading Plant's take on zeros and ones evokes the possibility to speculate about a transgression of binary logics through a different re-enactment of the ordering structure of the logos in technology. Zero and one then always embody the order (*logos*) and the virtual (*techne*), bringing both into a relation of tension and interference rather than opposition and dichotomy. Plant's work depicts a unique take on yarn as not only metaphorical, but a material component along which the history, present, and future of technological innovation takes shape. Thus, playing with yarn in a robotic lab not only uses the challenge of handling a yarn to disrupt the narrative of "the robots are coming" and generates the possibilities for new stories. Rather, it also moves in such a vein of working through the tension between order and subversion, evoking transgressive potentials, re-joining fields of meaning and of practice, as well as reconnecting histories, presents, and futures. I understand this conjunction of meaning and material in the yarn in terms of the game of string figuring, which diffracts and is performative at the same time: It allows patterns of interference between yarn, knitting (technique), and technology (*techne* and *logos*) to emerge, while iterations of producing structure also always enable new patterns to emerge and to be enacted.

In the case of knitting, the binary basis of the knitting syntax allows complex patterns for various texture effects, such as lace, the intended production of holes. For instance, the diamond knit lace produces holes that form a diamond in the knitted piece. In order to knit such a diamond structure, one has to constantly increase and decrease the number of stitches through the following techniques: knitting or purling two stitches together (k/p2tog = knit/purl 2 together), slipping and stitching over (skp = slip1, knit1, pass slipped stitch over), yarn over (yo), and knitting one or more of these stitches through the back loop (tbl). The diamond lace pattern in a chart looks like this:

Figure 5: The diamond lace chart



This chart helps the knitter to orient themselves in the pattern as it visualises the written code (row 1: ... p1,k1,skp, k1, k1, yo, p, skp, yo,k1, yo, k2tog, ...). It does so by dividing the diamond structure into rows and stitches and allocating the x- and y- axes to them, so the different lace techniques are mapped onto a position on these axes. Moreover, displaying the knitting code in a chart, the chart shows similarities with a punch card. Historically, the punch card originated as a mechanism for improving the work at the weaving loom at the dawn of the 19th century. This weaving mechanism was named after its alleged inventor, Joseph Marie Jacquard.[2] Even though the invention of mechanisms like that of the Jacquard loom were experienced as a threat to the weavers as it "withdrew control of the weaving process from human workers and transferred it to the hardware of the machine," which was further experienced as a process in which "a piece of [the workers'] bodies literally being transferred to the machine" (Plant 1998, 15), this mechanism had a different intent: It was targeted at increasing the artistic quality of weaving. As Birgit Schneider (2007, 295) explains:[3]

> "The punch cards promised the potential to improve the craftsmanship of the silk weavers in order to increase the quality of the fabric, produce more beautiful designs, highly skilled colour nuances and more manifold light effects while simultaneously enormously save on time and in costs."

Thus, what can be noted here is that the modularisation of weaving through the Jacquard mechanism is a very vivid example for a transference of a handicraft practice from human workers to machines. Intriguing to me is that this *automation* was feared to cause humans to not only give up control over their structure-forming and creative craft practice, but to even give up a part of their bodies, while the *mechanism* itself was—when developed—thought of as more as an extension of the weavers' abilities to craft and re-weave.

As Schneider (2007, 294) reminds us, Jacquard's punch card mechanism invented the loom as a "meta-machine" by "dividing the control mechanism from the information." This, moreover, became a point of departure for Charles Babbage and Ada Lovelace to build their model of the *Analytical Engine* in 1838. Celebrated as heralding the modern computer, the Analytical Engine,

2 For a detailed account of the development, implementation and improvement of the Jacquard mechanism, see Birgit Schneider *Textiles Prozessieren* (2007).

3 Selected quotations from Schneider's (2007) book *Textiles Prozessieren*, published in German, have been translated to English by Pat Treusch.

as Lovelace (Lovelace cited in Plant 1998, 18) writes, uses "the introduction of the principle which Jacquard devised for regulating, by means for punched cards, …rendered it possible…to make this engine the executive right-hand of abstract algebra." What intrigues me here is that the Analytical Engine is thought of as becoming a help in algebraic operations, figuring as the *executive right-hand* to 'us' humans. Thus, Lovelace imagined the Analytical Engine to work as a complementing device in analogy to the Jacquard weaving loom. Both mechanisms are based on the punch card as a "storage medium and control module," while the Analytical Engine processes given information by computing an output, the Jacquard loom processes information by realising a "woven image" (Schneider 2007, 298).

Returning to the case of hand knitting, the chart displays information that functions as a helping guide for the knitters' hands. Even though it visualises the different knitting techniques—like p1, k1, skp, k2tog—to navigate through such a complex pattern not only requires to be able to master each technique, to read the code, and to understand the chart of the pattern, but also to attain a sense for the structure of the knitted piece—in this case, the diamond lace (see *Figure* 5). This encompasses developing tactile knowledge of each technique so that the knitter knows how the movement to knit the skp stitch, for instance, feels as well as the structural haptics of the texture produced by this technique in the knitted piece. The visual information on stitches is only one dimension of orienting oneself when knitting such a complex pattern.

The example of the diamond pattern makes tangible the ways in which following such a pattern is—through its repetitiveness and complexity—at the same time a focused and meditative activity of producing a uniform structure with repeating elements in which the unmaking of certain stitches and the making of others provokes the creative moment of the diamond lace materialising. The use of the different stitch techniques is goal-oriented towards producing structure and creating the diamond lace as a set of specific stitch techniques. Sybille Wiescholek (2019, 52) points out that the structure-creating properties of patterns for textiles encompass two dimensions: "The textile creates structure in the human and the textile activity as handicraft is at the same time a mental activity."[4] Here, she brings together the dimension of using a pattern to create a material structure from a thread and the dimension of human patterns of thought and action that reveal themselves in the

4 Selected quotations from Sybille Wiescholek's (2019) book *Textile Bildung im digitalen Zeitalter*, published in German, have been translated to English by Pat Treusch.

textile. Knitting can be understood as both a craft and intellectual activity, while patterns of making and patterns of thinking both are based on their structuring operations. In addition, Lydia Maria Arantes (2017) in her cultural anthropology of knitting as *Verstrickungen* (enmeshment)[5] between *interior spaces*, *women's spaces*, and *economic spaces* (321), develops an account of hand knitting as a technical activity that combines corporal, material, mental and sensual practices (ibid., 86).

Drawing on the complex nature of knitting as a technique, the process of forming a textile structure then can be tweaked through a diffractive lens: The iterative dimension of knitting as well as the way in which norm and subversion interfere through knitting, both depict a way of knowing and enacting structure. These complex and compound meaning- and matter-making dimensions of textile practice also show in the use of string figuring as an everyday analogy for diffraction and my account of knitting in the context of robotics as a practice for challenging existing orderings of human-machine relations to, not least, trace subversive impulses. In short, robotic knitting can be regarded as initiated by a curiosity about the relationship between sociotechnical orderings, regulating how humans and machines can relate, and knitting with a yarn can be seen as an embodied, materially and intellectually structuring, as well as affective practice of ordering and at the same time subverting order. Could a look at the history of knitting reveal its relevance as a cultural technology of structuring? And if so, what can I learn from this about dichotomous relations between craft and digital practice, but also between male and female, and human and machine?

According to Ebba D. Drolshagen's (2017, 25) account[6] of a Western and mostly European cultural history of knitting, there exists no proven knowledge of the beginnings of knitting. The oldest found and dated knitting artefacts, are a pair of "natural white knee highs, stocking stitched and apparently round knitted, with perfect heel, perfect toe, a fit following the calf and a precisely worked, intricate knit-in pattern in indigo blue" (ibid., 28). They are dated back to the 11th to 13th century AD. Due to their delicate makeup, these artefacts clearly do not witness the beginnings of knitting, but rather testify

5 Selected quotations from Lydia Maria Arantes' (2017) book *Verstrickungen* , published in German, have been translated to English by Pat Treusch.

6 Selected quotations from Ebba D. Drolshagen's (2017) book *Zwei rechts, zwei links - Geschichten vom Stricken*, published in German, have been translated to English by Pat Treusch.

that "they are the result of a long learning process" (ibid.). What is known is that, from the 13^{th} century on, the first hand-knitter guilds were founded by professional knitters throughout the area of Europe, while, as Drolshagen (ibid., 33) emphasises, "at least throughout its heyday, …only men were part of the guilds." The boundaries of a proper knitting practice were regulated through its professional organisation in guilds, while the members were almost exclusively male and the practice therefore male-coded.

Jumping to the 19^{th} century, knitting machines became increasingly relevant, while to operate knitting machines advanced into a "purely male profession" and hand knitting as a profession lost its meaning and became "an exclusively female occupation" (ibid.). Tracing such a gendered coding shows how Western symbolic order and cultural technologies are intertwined. As Jack Z. Bratich and Heidi M. Brush (2011, 235) underline, it is the simultaneity of "an economic reorganization of the bodies of male workers" and "the dispersion, deauthorization, and expropriation of women's skills and knowledges along with the destruction of many women's bodies" that is foundational for the interrelated industrialisation of handicraft, the rise of capitalism, and concomitant gender hierarchies. Thus, in what follows, I will present selected historical stations of hand knitting with an emphasis on the structuring nature of knitting, exploring the latter as a momentum of change inherent to the practice of knitting in its quality to reproduce order while carrying the possibility to subvert order.

Though not a proper profession any longer, hand knitting nevertheless is work, especially amongst (sheep) farmers and workers and until the late 20^{th} century, also including every step of yarn fabrication. Here, knitting becomes something to ensure the survival of families. Knitting as existential labour was done mostly by females (women and girls), but also more generally among children as young as three years old. Drolshagen reports that working-class women and women on farms were constantly wearing a small bag with them, even when already working, for instance, as peat cutters, so they could additionally knit throughout the day. She (2017, 71) explains that "a walking knitter…needed 15 kilometres to finish a sock." At the same time, the knitters were dependent on retailers and were mostly exploited. Thus, Drolshagen's (ibid. 77) comparison of hand knitting as labour to *compulsory labour* seems adequate. In German and Austrian regions, compulsory labour was also called *robath, roboth* or *robot* from the Slavic *robota*. In this sense, the women and children had to turn themselves into *knitting robaths* to secure their existence. Hence, the practice of knitting in the reproductive realm at that historical period was far from a pleasant leisure activity.

In addition, in bourgeois circles of the 19th century, knitting became a female virtue. Women were supposed to knit during the day, which should avoid idleness and the danger of falling into sinful behaviour like eating (excessively) or feeling sexual desire (ibid., 107). Knitting served the purpose of disciplining female bodies in line with the gender and class orders and female role patterns of the social elite of that period. Women had to, at the same time, represent the wealth of the family and always be active, but not working (ibid., 109). The constantly knitting, embroidering, or crocheting hands of women and girls can be regarded as emblematic for embodying this ideal. However, and notably, it was also important to not produce anything of use, as Drolshagen (ibid., 110) points out: "Only small, fine, decorative things came into question, which could be held delicately in the hands and did not ruin the femininity of the silhouette."[7] The active hands of the modest females, however, also became a bone of contention for women to start to emancipate from this idealised role. On the one hand, there exists the historical example of the *tricoteuses*, the female knitters with varying class backgrounds, who during the French Revolution knitted in public (mostly during executions) as a mode of female political participation. On the other hand, women also began to revolt against this female role pattern in its condemnation to sit still and knit, crochet, or embroider apparently useless things (ibid., 118-19). In short, the knitting practice is a substantial dimension of the powerful operations of establishing and reproducing normative social orderings and of an emancipation of women of exactly these normative intersectional gendered, classist role patterns.[8]

During both World War I and World War II, knitting became a patriotic act and women and children were called upon to produce woollen socks, hats, and sweaters for the soldiers, turning hand knitting into a "labour of love" and a "service for the fatherland" (ibid., 122). Parallel to this, knitted clothing slowly became fashionable from the 1920s on—from Coco Chanel's famous jersey fashion to hand knitted sweaters (ibid., 148-150). The advancement of

7 As Drolshagen (ibid., 144) also notes: "That [idealised role distribution] was often only a façade." Women also in bourgeois households often had to make extra money with their secretly made handcrafted pieces that therefore necessarily needed to be useful, thus, marketable.

8 For an analysis of historical legacies of global female textile networks as a *catalyst of change*, see for example Sinclair 2015.

knitwear into fashionable clothing, which women could produce for themselves, can be mainly regarded as foundational for the rise of hand knitting as a female-coded hobby throughout the 20th century with its continuation into the 21st century. Clearly, this hobby could turn out very useful during times of financial crisis and also bridge gaps in supply in the 20th century. However, the female hand knitting practice was nevertheless mostly disguised as a hobby, the necessity to knit instead of being able to buy clothes was neglected and knitting became a substantial part of the unpaid and unacknowledged reproduction work provided by women (ibid., 151). At the same time, hand knitting as female-coded practice co-existed as a source of income for women and families from around 1930 until the 1980s in the form of home-based work.

Drolshagen nevertheless underlines the difference between hand knitting as a leisure activity, despite being mostly unpaid labour, and as paid labour, while the latter forced the knitters (women and men) to work efficiently and very precisely. As she (2017, 159) writes: "The fixed gaze towards the market ultimately degraded knitters to breathing hand knitting machines." This description of the working conditions of hand knitters makes tangible the ways in which knitting is an activity that can be automated on a massive scale as it historically has been, but also that there are limits to having machines produce knitwear. In consequence, it seems like hand knitters have had to turn themselves into machine-like producers throughout different historical periods. This process, furthermore, is regarded as reducing hand knitting to the production of knitwear and thus in danger of erasing the creative, but also technically challenging, dimensions. It appears as if the one (machine automation) would have to exclude the other (human creativity) by necessity. Could hand knitting and machine practice be re-joined differently? And if so, through which sociomaterial circumstances and practices?

Nowadays, hand knitting has advanced from a hobby pursued privately at home into a quite fashionable leisure activity, which is widely represented publicly, for instance through knitting circles, craft fairs, and growing numbers of books and magazines, and as organised via the internet. The internet provides a space for connecting with other knitters, sharing knowledge, for instance, on how to knit (which I profited from, too), and potentially for designing and selling knitting patterns, but also handmade knitwear. The most well-known pattern platform is *Ravelry* (www.ravelry.com) and there exists an uncounted amount of knitting and crocheting blogs. One of these bloggers, Stephanie Pearl-McPhee, has coined the term *interknit* as a term that signifies the relevance of "the internet for the global knitting community" (Pearl-

McPhee, cited in Drolshagen 2017, 174). The interknit can be recognised as foundational for different waves of contemporary knitting activism, so called craftism or craftivism—an activism, which is built on craft as a motor for social change.

For the first decade of the 21st century, "an explosion on the popularity of knitting" (Springgay 2010, 111) can be attested. The scenes in which this explosion takes place are multifaceted: Beth Ann Pentney (2008, 1), for instance, locates "an upsurge in Western popular culture," a phenomenon that has been analysed as leading to *celebrity knitting* (Perkins 2004), but is also especially articulated in the form of reclaiming knitting as a feminist, craftist practice in all its paradoxes between empowerment and consumerism (Pentney 2008; see also: Kelly 2013; von Bose 2018). One phenomenon amongst this reclaiming is that of college-educated, white Western women who are quitting their jobs in order to knit or craft and sell their products online. Here, reclaiming knitting seems to be tied to the emergence of a *new domesticity* which is thought of as serving this particular group of women—in line with Käthe von Bose (2018, 198)[9] —to strive for "personal fulfilment through a more natural, more conscious lifestyle with handicraft." Furthermore, von Bose (ibid.) identifies this phenomenon as paradigmatic for the rise of an *aesthetic capitalism* characterised by the neglect of "the complex interconnections and reciprocal conditionalities between creativity and market logic." However, and as von Bose (ibid., 199-200) further underlines, reducing this form of knitting activism to an articulation of aesthetic capitalism fails to take into account "the ambivalent elements of concrete practices of producing DIY clothing…for instance, that traditional handicrafts which are based on haptic, materiality and embodiment, are merging with technologies of digitalisation and virtuality." Decades after the emergence of cyberfeminism, the yarn in its metaphorical and material meaning for the re-formation of social order as well as the shaping of technology seems to regain momentum, leading to a re-joining of handicraft and digital practice in a transgressive manner.

Precisely this relationship between handicraft and digital practice is also at the core of Daniela Rosner and Kimiko Ryokai's (2008) and Rosner's (2018) work on the design study on *Spyn*. Spyn in short, is a digital device designed

9 Selected quotations from Käthe von Bose's (2018) article *‚Mit Liebe handgemacht'. Nachhaltige Do-it-yourself-Mode als körperlich-affektive Geschlechterpraxis,* published in German, have been translated to English by Pat Treusch.

to expand a knitters' possibilities to document and share their knitting practice digitally while using the device to store memories and stories digitally at selected locations in the artefact. Rosner (2018) captures the beginnings of the interknit very vividly when recounting, for instance, her participation in a knitting circle in San Francisco during the time when *Ravelry* went online. The circle was composed like others of "mostly young, white, college-educated women" (ibid., 61) and stands for an essential link between knitting and social media and communication technologies, enabled by the internet, or rather the interknit. Rosner explored the peculiar entanglement of craft and digital practice when creating Spyn, a device that supposedly stipulates the merge of handicraft practice and digital practice even further. Using Spyn, as Rosner (ibid., 63) recounts, knitters produced a "finished artifact [which] worked as a kind of digital container, allowing people to save and retrieve media collected while knitting." This centrally encompassed the "sharing [of] mundane moments" (ibid., 67) and, thus, expand the knitted artefact through the possibility of digitally storing the everyday stories which also contributed to the structure-forming practice of hand knitting. Basically, Spyn worked with an infrared vision recognition to connect media with locations on the knitted artefact. In this regard, Spyn appeared to be an ideal device also for sharing techniques embedded in mundane stories across online communities, such as the emerging knitting circles.

However, even though the device appeared to work just as intended, this is not the end of the Spyn story: Rosner (ibid., 67) continues to explain that as Spyn gained popularity, she was approached by a member of a local knitting guild who asked her "to present the project to her group." In short, becoming a member of this guild herself, Rosner discovers that the knitting practice in this circle is not organised around the interknit, but rather mostly offline and the knowledge, but also techniques, potentially equally embedded in mundane stories, are shared through meetings. In contrast to the young, middle-class, and mostly White knitting circle she had joined before, this group involved "practitioners at the margins—elderly knitters" in different "situations and socioeconomic struggles" (ibid., 77). As a central result, Rosner (ibid.) concludes that knitters are not "a united category of practice." She (ibid., 71) further explains, the guild group differentiated from the interknit circle group as the first was also marked by a "resistance to particular digital tools," for instance, Spyn, despite an initial interest. This, importantly, did not mean that the guild was opposing (digital) technology, but rather that the members of the group had a very different approach to technology than the interknit circles. This could involve, for instance, "using traditional craft skills to transform digital technology" (ibid., 74). Rosner (ibid., 75) further notes: "Computational systems were off-putting when introduced by outsiders as superficial augmentations but also intriguing when incorporated by themselves as enhancements to existing traditions of practice."

What intrigues me the most about Rosner's design storytelling with Spyn is her insight into the simultaneity of dissimilar craft practices across and within different hand knitting circles, while their dissimilarity is interconnected to each group's take on the relation between handicraft and digital practices. Here, the main research interest transforms from how knitting can be aligned with the digital to how to take into account the ways in which needlework is a resource for probing, challenging, and potentially also improving digital practice. Consequentially, this encompasses "formulating engineering *as* craftwork" (ibid., 74; emphasis in original). Working with this inference between knitting and digital practice to emerge and exist is a matter of care, or in Rosner's (2018) words, a matter of *critical fabulation*, while allowing interferences to take shape is an essential part of Rosner's account of critical fabulation as a diffractive design research methodology.

Against the backdrop of my own experience in both knitting and field research in contemporary humanoid robotics, developing a curiosity about the potentials of collaborative knitting between humans and robots that was not random in its choice of research objects, namely the cobot and hand knitting, was pivotal for robotic knitting. Bringing yarn to the robotics lab is more than what appears at first sight as an amusing and playful, but nevertheless interventionist, endeavour. It is also not limited to challenging contemporary automation technologies through the implementation of an unconventional task of HRC. The structure-forming logic of 0 and 1 entails the potential to subvert order and for creative moments of innovating. Hence, knitting practices appear to exceed the idea of a fixed sequence of definable, rather technical movements. Moreover, built on the binary logic of k and p, knitting cannot be thought of as opposed to or prior to digital practice. Equally, they rely on tactile knowledge and the materials' qualities, such as stubbornness.

Resuming here, my engagement with a first attempt of generating data on hand knitting in order to transfer that onto a robot arm lead me to not only revisit, but also to diffract my previously unquestioned assumptions about the relation between the yarn, my hands, the practice of knitting, datafication, the gripper, automation and digital technologies. I did so by engaging in string figuring with a selection of historical as well as contemporary av-

Figure 6: Playing cat's cradle in the lab

enues of challenging dichotomous relations between handicraft and technology, matter and meaning, as well as knitting and digital practice, but also foundational sociocultural ordering operations like that between male and female, and going as far as the relation between structure-forming as producing order and subversion.

Already the very first practice of knitting in the robotic lab propelled me to develop robotic knitting as a technofeminist tool for not only re-crafting collaboration with robot technologies in a hands-on manner, but also for re-crafting contemporary robotic cultures of striving for robots as co-workers. Notably, it was the initial attempt at turning knitting into data as well as the concomitant enactment of this data which lead me to contemplate hand knitting with a cobot through different eyes, making me wonder how robotic knitting is more than a simple transference of movements onto a robot, but rather the beginning of an exploration of practices of knowing and being in the cobotic lab through forming new stitches with yarn.

2.2 String 2: The Knitting Hands and the Knitting Grippers

In what follows, I will reconstruct selected sociomaterial circumstances of realising collaborative knitting in the robotic lab in detail in order to map this realisation along complex negotiations between different activities and actors—processes which sometimes took different routes than expected, but also showed the potential of the yarn as a material device for literally crossing disciplinary boundaries.

Figure 7: From left to right: Anne Jellinghaus, Melanie Irrgang, Philipp Graf, Raphael Deimel, Pat Treusch, PANDA, and Jan Martin

The project *Do Robots Dream of Knitting (DRDK)* brought persons with disciplinarily diverse backgrounds together, involving feminist science and technology studies (FSTS), computer science, robotics, electrical engineering, psychology, and sociology. From the very beginning, the idea was to establish a project practice which is able to overcome disciplinary boundaries—a practice that I understand in terms of situated co-engineering. Key to this was differentiating between the goal of realising a certain robot task in a robust manner and the path of reaching this as an at least equally central goal of the project. This differentiation allowed us to tackle robotic knitting as more than a challenge for which we had to find a solution, but rather as a method of assembling matters of care in envisioning technological futures with cobots. The process of realising knitting with a robot as the re-junction of digital and craft practice, and its myriad mobilisations and intra-actions of things, ac-

Figure 8: From left to right: PANDA, Anne Jellinghaus, and Katrin M. Kämpf

tors, and activities, is as important as the actual act of knitting with the robot itself.

I experienced the constellation at the lab as an extraordinary combination of sociomaterial circumstances, allowing me not only to become a queering witness to contemporary cobotics, but also to become a robotics practitioner, performatively engaging with yarn in this lab as a technofeminist intervention of spinning new threads of human-machine collaboration and imagining cobotic futures. This was made possible due to my access to the robotic lab, the availability of robots, the funding by the Volkswagen Foundation, and the support of the head of the MTIengAge group, Raphael Deimel, and his team—especially Philipp Graf (sociology) and Jan Martin (electrical engineering). Moreover, I was able to hire three additional co-workers who, with their previous training, were ideally placed to help me in bridging the gap between computer science and technofeminism: Melanie Irrgang (computer science), Anne Jellinghaus (psychology & computer science), and Katrin M. Kämpf (FSTS). My team and I became an intrinsic part of the robotic lab—not only through our presence there, but also, and importantly, through weaving our everyday practices of engineering into the fabric of the lab. The lab provided enough space for several persons to work on different projects at the same time. The room is quite large, extending itself over approximately 90 square meters with panorama windows on two sides. The room is divided into two areas. In the larger area, roughly seven to nine computer workplaces are arranged together with four PANDA robot arms, alongside other robotic projects. The space is populated by a varying number of persons, including employees of the MTIengAge group and students working on student projects or working at these computers with robots.

Located on the second floor of a larger university building, the sun would shine through the panorama windows almost year-round. In order to create steady lighting conditions and to keep the room from being heated by the sun, the blinds are almost always closed.

Figure 9: Overview of the main lab space with robots, computer working stations, and team members

The operation of the computers, robots, and other technical equipment all produces waste heat and I experienced the room's temperature as always a couple degrees too warm, almost unbearable during warm summer days. To air out the room became an important practice and condition for being able to work in and around the cobots for a complete workday, and became the point at which we would pause, take a breath, and reflect on our project work from different angles, allowing us to knit further on our two-sided goal.

Moreover, hand knitting is an excellent example for the meaning of observing and experiencing the working hands in order to learn how to knit. In my case, and as I described above, I used online video tutorials in order to learn how to knit, while in the robotic lab, we worked in teams of at least one experienced hand knitter with one beginner, showing how to knit and then giving instructions during first attempts. We restricted ourselves to teaching and learning one stitch, namely the garter stitch: *k1* last st. This might sound easy, but learning to form new stitches as uniformly as possible was quite demanding even when shown through the hands of an experienced knitter and accompanied by explanations. Mostly during our hand knitting sessions, more than two hands were involved in handling the two needles, testing how hands have to move in order to master the needles, while at the same time, the working hands transferred knowledge and became a central factor of grasping the task of knitting.

More generally, the hand is of central meaning for the development of cognitive capacities, which has been a topic of biology, neuroscience, educational science, but also robotics and cultural science. The hands are used to learn how to count and how to read—a process of incorporating (abstract) signs: the numbers and text (see Robben 2012, 24). In line with recent accounts of embodied human-machine interaction (for example: Dourish 2001), the hand can be regarded as key for embodied experience (see Robben 2012), namely that of *grasping*.[10] This figure then propels an intervention into the Cartesian split between body and mind and the dualism between the abstract, cognitive and the concrete, perceptual and sensuous. The following modification of what can be presumably called Descartes' most popular sentence: "I grasp, therefore I am" (Reiche 2001, 3; translation: PT), depicts the inventive potential of this figure. As put by Bernard Robben (2012, 28):[11] "The hand plays a

10 The emerging paradigm of experience design draws on the German term of "begreifen" in order to signify the inseparability of grasping (greifen) and comprehending (begreifen), see: Robben and Schelhowe (2012). The ambiguity of *be-greifen* is similar to the English grasping something in difference to grasping with something.

11 Selected quotations from Robben's (2012) article *Die Bedeutung der Körperlichkeitfür begreifbare Interaktion mit dem Computer*, published in German, have been translated to English by Pat Treusch.

special role in grasping (*be-greifen*); it is at the same time a sensory organ—of grasping with, touching and feeling—[and] an organ of action—of grasping, grabbing and manipulating." The cognitive process of comprehending then is based on the hand as that which mediates and translates between the tactile sense and the sense of sight (ibid., 29).

Insights into the relevancy of the hand for human development of cognitive capacities on both the evolutionary and the individual level also give textile craft a new meaning. As Sybille Wiescholek (2019, 112) underlines, "As a structuring element which is produced by hand and with tools, [the textile] is the epitome of an intelligent use of the hand." Such an intelligent use of the hand is regarded as equal to the ability to speak and thus the former is considered to be beneficial for the development of cognitive capacities in humans to the same extent as the latter. In this regard, craft as an activity of using one's hands in an intelligent manner, made me wonder about the possibilities of inviting the robot to become a collaborative knitter with us in terms of an expansion of the idea of distributed learning—in this case from each other's hands, including PANDA in a co-learning experience of the working, knitting hands and gripper.

Assumingly, the meaning of the hand as an indicator and enabler of cognitive capacities and behaviours appeals to AI research, robotics especially. Marvin Minsky's famous *Minsky Arm* from the late 1960ies is prominently placed in the MIT Robotics Collection exhibition of the *MIT Museum* in Boston.[12] Minsky's arm is special as its task to build with children's blocks was realised on this arm without pre-conceptual foundations. Rather, the arm in operation is regarded as the inspiration for Minsky's influential work on a theory of mind. The arm, thus, "gave rise to Minsky's theory that the mind is composed of a multitude of little processes called 'agents'."[13] In this sense, Minsky worked with the mechanics of an artificial arm to derive a theory of mind. Beyond Minsky's approach, the automation of the arm is a core figure of historical prevalence. This is evidenced in mechanical machines as early as Leonardo da Vinci's first robot with arms from 1478 (Moran 2007, 104) to the famous automata heralding the first Industrial Revolution, like Jacques de Vaucanson's flute player from 1738 (ibid., 105), to the first commercial industrial robotic arm in 1962 by Unimate, which weighed two tons (ibid., 108). In comparison, the robot arm PANDA weighs 25 kilograms. It can be

12 https://mitmuseum.mit.edu/collection/technology
13 http://museum.mit.edu/150/9

argued that the historical and ongoing fascination with the robot arm unites various interests: a curiosity for the interrelation between body and mind, the automation of tasks previously exclusively accomplished by humans, and the possibilities for improved collaboration between humans and robots.

Sub-String 1: Cross-Familiarisation

At the beginning of the project, it was not only persons who had to get to know each other, but we had to get to know our varying expectations and ideas and the centralised objects of the project, including the knitting needles as much as the cobots. We would mostly begin our workday together in the lab with a coffee meeting where we reported to each other, assembled ideas, and made plans for the day. However, these plans could then be torpedoed by the unexpected behaviour of one of our objects when working with them, like the too-slippery metallic knitting needles or a problem with the cobot's software—experienced on a daily basis. What became clear from the very start of the project was that robotic knitting relies on the collaboration between persons and things, involving a regular, work-structuring exchange, mostly in the mornings, during lunch breaks, and an additional coffee break in the afternoons. In general, our take on the interdisciplinary practice of engineering which is at the heart of collaborative knitting, required a lot of communication across disciplinary knowledge in order to avoid perpetuating taken-for-granted approaches and to avoid compartmentalising the realisation of robotic knitting. The latter would encompass dividing tasks along long-standing disciplinary responsibilities, and thereby might reinforce boundaries instead of overcoming them.

During every full workday at the lab, sooner or later, a point was reached where one of us was asking for fresh air in the room—a point at which we would open the windows, possibly use this pause to take a coffee break, and to reconsider the day's accomplishments from all perspectives involved. Thus, from our need for fresh air emerged an impulse to constantly weave a practice of critical engagement into our own practice of realising the interface between human and cobot through knitting. Another fundamental part of such a practice of critical engagement was a discussion of how to define the outline of DRDK as a technofeminist intervention into reductive, solutionist approaches. This, however, was not an easily completed task, but rather a continuous one which had to be tackled through ongoing conversations and negotiating between the different goals of researching the process of realising collaborative knitting and executing collaborative knitting. While communication was of central relevance to this process, equally important was that we were all meeting in the robotic lab, becoming familiar with the knitting needles and the cobot, and how to operate these objects in order to find ways to bring them together. I suggest understanding this process as one of cross-familiarisation that works with and through the knitting needles, the wool, the cobot in its composition of hard- and software, and the persons, as well as the spatio-temporal arrangement of the lab.

As detailed above, I brought my knitting experience with me to the lab, but was fairly new to handling a cobot. PANDA is a light-weight robot, introduced by its producer, the Bavarian company FRANKA EMIKA, as a robot with "soft-robot performance, smart and industry-ready. Enabling automation for anyone, anywhere."[14] When I encountered PANDA for the first time, I noticed that this robot is endowed with seven degrees of freedom or joints, an end manipulator in the form of a 'two-finger' gripper and LEDs at its platform. This robot is delivered almost completely set-up in a huge cardboard box; one only has to mount the gripper head onto the arm and the arm onto a working station in order to start using the robot.

The MTIengAge lab used smaller tables on wheels as workstations, which reminded me of trolley-tables. On the table's lower tray was enough space for the robot's computer and a multiple-socket outlet. Each robot was mounted to the tabletop with four large screws. An emergency stop was attached to every table—in addition to the robot's own emergency button. The PANDA on wheels turned out to be very practical during our work with it, as it ensured its mobility. We could wheel it over to any computer workplace and work with the robot at this spot.

Upon boot-up, the robot calibrates its joints before going into its initial position, while connecting to an external computer. On this computer, we would start the *General User Interface* (GUI), called FRANKA Desk in order to operate PANDA. Watching the robot's joints calibrating for the first time, the joints making a clacking sound, and the arm moving in a very smooth manner, was very impressive. This already gave me an insight into how the robot can behave as a cobot. At the same time, I also realised that I was not able to estimate the full range of motion, yet, nor anticipate its movements. This lack of knowledge made me uncomfortable to a certain degree. The robot's emergency button, which is connected to the robot by a long cable, helped me

14 https://www.franka.de/

Figures 10 & 11: Unboxing & Assembling PANDA

in feeling safe around the robot. One of us always had to solely operate this button to be able to—in case of any doubt—press it and thus avoid possible collision or harm. Nevertheless, it was equally important for me to keep a certain distance to the robot at first.

At the same time, I brought a selection of different needles and wool with me to the lab. As underlined already in the previous chapter, these objects also appeared to be strange and rather improper objects in the context of the robotic lab, causing amusement throughout the duration of DRDK. However, as Melanie herself is quite an ambitious and experienced knitter, and Anne also knew how to knit but needed a refreshment of her knitting practice, we started our project in the robotic lab by hosting several knitting sessions.

Philipp joined us, while it turned out that Raphael also had a robust knowledge of textile techniques, including knitting and crocheting. It became vital to acquire at least a basic understanding of how the needles and yarn have to behave to produce a new stitch, in order to generate ideas and engineer solutions for transferring this movement to our robot arm. At the

Figure 12: Knitting in the robotics' lab

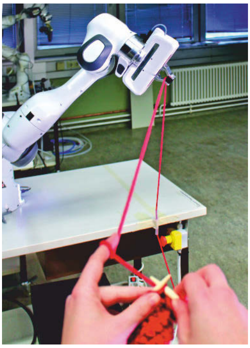
same time, Melanie started the main blog entry series *Knitting for Computer Scientists and Engineers* on our project blog.[15]

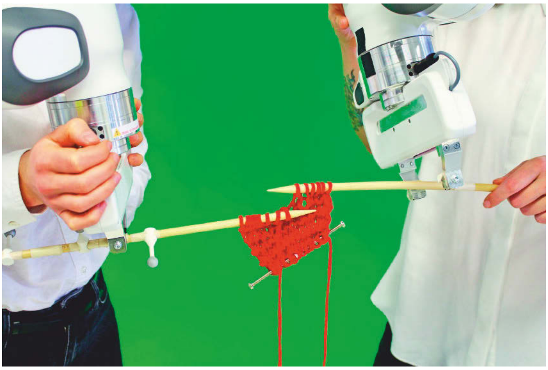
Given this initial situation of a cross-familiarisation between multiple agents, objects, and knowledges, I suggested to work with three different scenarios of collaborative knitting with PANDA, with the plan to realise all of them within the first months of the project to become more familiar with each other and with each object. These realisations should serve as a testbed for evaluating our approach towards collaborative knitting, but also for developing an account of interdisciplinary, situated co-engineering between FSTS and robotics in concept and practice. The three scenarios of collaborative knitting between the robot arm PANDA and 'us humans' were characterised by different degrees of physical distance to the robot arm as well as varying degrees of collaboration as depicted in the following.

In Scenario 1, a knitter is in need of a kind of 'third hand' which is helping in unravelling further the ball of yarn during the knitting of rows. The flow and tension of yarn is a crucial factor in knitting an evenly structured artefact. Without such a 'third hand', one might have to put down both needles in order

15 https://blogs.tu-berlin.de/zifg_stricken-mit-robotern/

Figures 13, 14 & 15: The three scenarios of collaborative knitting





to grasp the ball of yarn and unravel it further. Thus, the cobot's task in this scenario is to unravel the yarn when needed. Clearly, in this first scenario, one of us could knit like they would normally do and remain in a safe distance to the moving PANDA. The degree of collaboration is still quite low. Thus, this appeared to be an ideal initial scenario for getting to know the robot more, watching how it moves through space and becoming gradually more familiar with its capacities as a cobot.

Scenario 2 then was supposed to be based on the initial experience with the cobot from the first scenario. In this scenario, one of us was already knitting with PANDA, handing over the empty right needle to the cobot, while still operating the left needle with the knitted piece and the last knitted row. This clearly requires a fine-grained collaboration between the robot and the human as the robot has to perform the following movements: pierce through a stitch on the left needle, pick up the thread through the stitch (forming a new stitch) and finally let the 'old' stitch slip from the left needle. Informed by my first attempt at a datafication of my own hand knitting, I knew that knitting requires a high degree of orchestrating between the movements of the right and the left needle. So, in this scenario, controlling these two needles is a task which is divided between the person and the robot. The challenge then is not only to realise the 'right behaviour' in the robot arm, but also, and importantly, to coordinate these movements with the movements of the other needle, and to realise this in a collaborative manner.

Scenario 3 is built on the second scenario. After the cobot has been trained to take over the right needle, the next step would be to train a second robot to take over the left needle so that the two robot arms would be knitting together, while the role of the person would be to give and guide the thread. In this sense, the person would have to become the sensory guide to the two robot arms, enabling a form of collaboration in which they become 'the eyes and ears' of the robot—at least to a certain degree. This, I imagined, would display the most advanced form of becoming familiar with each other. The plan was to move along these scenarios, working as a group on realising each scenario and tracing the enmeshment of actors and objects, as well as the emerging negotiations, challenges, and solutions, from the perspective of the queering witness who is herself immersed in these engineering practices.

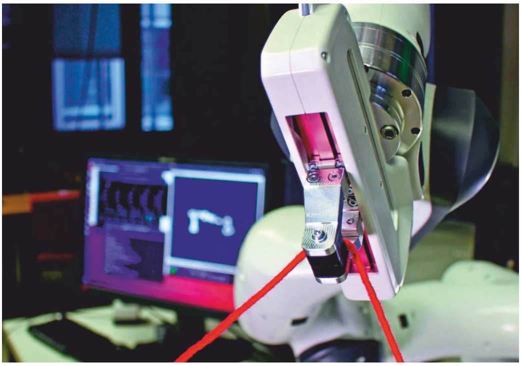
Sub-String 2: *k1* last st—First Collaborative Rows

When starting to work with PANDA, we first realised individual movements as well as shorter sequences of movements on the robot arm, using the GUI FRANKA Desk, and by assembling ideas, materials and practices of realising collaboration. In what follows, I will trace the implementation of the scenarios of collaborative knitting through selected steps of robotic knitting.

In accordance with the paradigm of visual programming, FRANKA Desk has different color-coded buttons. After opening the program FRANKA Desk, the first step is to choose between the Cartesian motion and the joint motion apps. The first enables the execution of a movement based on remembering the position of the end manipulator (the gripper) on the x-, y-, and z-axes at selected points. Working with the second app, the robot arm will remember the constellation of every joint at each point, in addition to remembering the position of the end manipulator. The location of the end-effector on the x-, y-, and z-axes and the concomitant joint configurations are called *states* in robotics and the model of computation behind this account of states is that of a *discrete* or *finite state machine*. In short, states are categorised into either a start state or an input-related state, amounting to a movement trajectory while the state machine regulates the transition between individual states. The main difference between the joint motion and the Cartesian motion apps is the transference from one state to another. To memorise points and the joint configuration is called *forward-kinematics* and, akin to that, *inverse-kinematics* is to memorise the location in space and compute the joint configuration needed to get there (Irrgang 2019). As Irrgang (ibid., 1) explains further in her blog entry on motion planning: "Using a joint motion App, every state's joint configuration is remembered for later playback. Using a Cartesian motion App, only position and orientation in space are remembered, and inverse-kinematics is applied for every state of the movement trajectory." An initial step in realising collaborative knitting was to test the differences in working with a state machine based on either a forward-kinematic model or an inverse-kinematic model. When working with the Cartesian motion app, we would sometimes become very puzzled by the results the inverse-kinematics produced, making it harder for us to grasp the execution of movements, especially given that knitting movements are very small motions. It also happened sometimes that the computed joint configuration would trigger the cobot's collision safety mechanism, provoking a lockdown of the cobot. Thus, we decided to work mainly with the joint motion app, enabling a forward-kinematics model which made the transitions from state to state very tangible to us.

According to our plans, the first scenario we realised was Scenario 1 in which PANDA gives thread while a person knits. The aim of this scenario was for the persons collaborating with PANDA to start working with wool, while remaining at a large enough distance to the arm to not stand in the way of its range of movements. The idea was that the gripper pulls the thread to unravel it from the ball of yarn. However, the first thing we noticed was that the gripper was unable to grip yarn-like things. The yarn would always slip through the closed end effector. The second challenge we encountered was the movement of the ball of yarn which showed an uncontrollable and unpredictable behaviour when being pulled. Together, we came up with a solution for both challenges. We built a guide rail for the yarn so that the position of the thread was allocatable for us, and we could position the gripper in relation to the thread. For this rail, we used a shorter piece of a pneumatic hose, which we mounted onto a smaller piece of wood, which we then attached to PANDA's table. Next, we came up with the idea to not have the gripper properly grip the yarn, but to train a movement in which the arm moves in such a way that the yarn is wrapped around the gripper, and through movement the thread would be unravelled from the ball of yarn.

Figures 16 & 17: Realising Scenario 1



Scenario 1 was a very nice experience of learning how to operate PANDA, that is, learning how to implement a movement and learning how the arm behaves when executing this movement, but was also a nice experience of defining and solving challenges in realising our planned scenarios of collaborative knitting with the robot from an integrative perspective. However, the degree of collaboration between the knitter and PANDA is rather low in this scenario. Hence, we quickly moved on to Scenario 2, in which PANDA is supposed to operate the right needle. We began by asking what this actually implied. As by now everyone was familiar with hand knitting—at least on a basic level—we started by thinking about the whole idea of collaborative knitting in a very hands-on manner.

Usually, when I am knitting, it would not occur to me to hand over the right needle to someone else in order to knit with another person, but if I should, I would probably talk to this person, show them how to hold the needle, and constantly communicate with this person. Ideally, the person who is knitting with me, already has a concept of hand knitting and thus understands not only what the right needle is supposed to do, but also how the two needles will have to interact. However, when aiming to realise this with PANDA, we had to acknowledge that the robot has neither 'eyes' nor 'ears', that is, it lacks the sensors to communicate in a somewhat human-like manner, nor does it know that we are knitting or that there exists a thread that it has to master with a needle in the first place. PANDA will not have a concept of hand knitting. However, at the same time, PANDA belongs to the newest generation of flexible light-weight robot arms, designed to take on new automation challenges, including a host of scenarios in which PANDA becomes a kind of a helping hand to 'us humans'.

I understand the figure of the helping hand as a diffraction pattern emerging from my string figuring with PANDA, wool, knitting needles, technofeminism, and disciplinary boundaries. Already during my doctoral thesis and throughout my postdoctoral work, I noted that robotic hands in their signification of tactile capacities play a major role in imagining, building, and representing robots that are geared at varying forms of so-called 'social interaction' that entail acting with humans in close cooperation. This especially appears to be a foundational aspect in re-locating the formerly industrial high-end functional robot to the realms of the service sector or the household. Clearly, core capacities that are regarded as essential and useful, for instance, in the automobile industry, like the ability to lift heavy things, and therefore to outmatch humans in their physical strength, no longer appear attractive in a setting of human-robot-proximity (see Treusch 2015, 78). Imagine how a person feels when the metal robotic gripper, which appears indestructible and is the epitome of the robot's force, is reaching for the person's hand in a situation like handshaking. Here, the gripper has to be endowed with actuators, as well as sensory and control capacities, which allow it to close itself around a human hand with the right pressure and velocity—not only for a human to not fear the danger that the robot might squash their hand physically, but also to perform the movement of shaking-hands in a manner in which the movement becomes legible as a shake of hands and is therefore socially meaningful. Thus, the robot has to not only be able to grip, but also to grip in the manner of handshaking, which describes a sociomaterial realisation of human-machine relating. Thus, the hand as that which can create, caress, and destroy appears to be of significant symbolic relevance for imagining and realising present and future scenarios of HRI. Robotic knitting not only accommodates this significance of the hand for developing cobotic futures, but also becomes an agent in creating scenarios of how human and robotic hands and grippers can work together. Further, robotic knitting in its technofeminist, interventionist stance aims at tweaking the idea of the capable hands as the embodiment of a friendly encounter by reading it against the grain, or rather, by queering the implied usefulness through a collaborative hand knitting practice. In addition, handling needles and yarn together is a practice which evokes the (historical) junction between computer technologies and textile craft as well as a practice of opening up a field of tension between *techne* and *logos*.

Contemplating about the working hands here further, I become increasingly interested in the nature of hand knitting as a practice. Hand knitting movements are characterised by non-uniformity instead of uniformity. The MoCap picture illustrating this (see *Figure* 3) attests to the complexity of hand knitting as a technique which requires training and experience—even on the level of the most basic stitch, the garter stitch—in order to become able to continuously form new stitches and produce a knitted piece with stitches as even as possible. The latter involves the ability to constantly adapt to the material obstinacy of the yarn. To become proficient in hand knitting is achieved by embodied learning in which hand and mind are working together in using the needles to realise a textile structure. Moreover, what I want to emphasise here is the collaboration between hands, needles, yarn, and concepts as foundational for the creation of textile structures. Thus, hand knitting can be regarded as provoking a junction between the working hands and gripper, which opens up possibilities for re-designing human-machine-relations along knitting practices of collaboration.

Tim Ingold helps me in understanding hand knitting as a process of creation which speaks well to the technofeminist, performative and diffractive outline of this project. Part of Ingold's (2009, 92) rich oeuvre is to overcome a "hylomorphic model of creation" in favour of what could be called a process-ontological model. This model "assigns primacy to the process of formation as against their final products, and to the flows and transformations of materials as against states of matters" (ibid.). Drawing on Ingold's notion of creation, it is exactly the myriad unfoldings and becomings of a form which build the core of practices of making; to adhere to and engage in these forces and flows then are key dimensions in learning a *skill* like knitting. Ingold (ibid., emphasis in original) further suggests calling this "the *textility* of making" or the textility model in contrast to the hylomorphic model. Knitting encompasses to follow the lead of the yarn, how it behaves, but also the lighting conditions and colour of the yarn, its material qualities, like how firm individual threads are spun, the slipperiness of a needle (for instance that of a bamboo needle compared to that of an aluminium needle), and the emerging stitches of a row. Foregrounding material agency over the control of matter through the activity of human hands here, I draw further on Ingold's work on textility to conceive of hand knitting in his words. Making a stitch in line with Ingold (ibid., 94) "is not so much imposing form on matter as bringing together diverse materials and combining or redirecting their flow in the anticipation of what might emerge." The working hands of knitting are but one factor in this process of anticipation and combination, equally "*possessed by the action*" (ibid; 95, emphasis in original) as are the wool, the needles, and the technique (the garter stitch). This account of hand kitting tweaks the meaning of the working hands and gripper across the assembled fields of knowledge and practice in this project, making them a matter not only of embodied inter-as intra-action, but also of a re-valuing of forming over forms, materials over things, in human-machine interaction, and opening up the possibility to re-craft collaboration across the different agents, materials, and flows engaged in the task of hand knitting collaboratively. Describing the working hands in our hand knitting sessions reveals how this is already the case in human-human practices of teaching each other how to knit, which I experienced as very tangible and graspable processes of transferring skills of combining and following the materials of hand knitting in order to be able to create an artefact. In addition, learning how to operate PANDA can also be captured as a sensuous, embodied process. At stake is an exploration of the textility of knitting as a skill, in relation to human-machine collaboration through knitting.

When starting to realise Scenario 2, we decided to work mostly as a team of three (Melanie, Anne and me) when realising a task with the robot: One of us sitting at the computer, the other standing next to the robot, and the third person holding the emergency button (see *Figure* 18).

Right at the beginning when we started to knit, one foundational question emerged through our haptic engagement with the selection of needles and wool which I initially brought with me: What material qualities must the yarn and needle have to enable human-robot collaboration through knitting? Clearly, we had to investigate the question of knitting materials further.

We quickly found out that each of us might answer this question differently when it comes to our personal experiences and preferences. Depending on how tightly or how loosely one knits, the gauge, firmness, and the twisting of the yarn matter a lot in the forming of new stitches. In addition, the

Figure 18: Working on Scenario 2

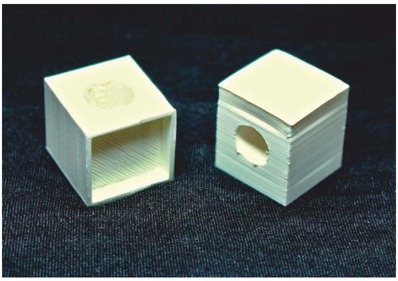
Figures 19 & 20: Needles and yarn

materials of the needles shape the behaviour of each yarn differently. Our experience was that bamboo needles show the right kind of slippery qualities between too slippery and too dull for learning to knit and for teaching both other persons and PANDA to knit. Our next insight then was that the needles should not be too small and the gauge of the yarn not too big. Such a combination of rather big needles and a not too thick yarn produces larger stitches and makes it easier to pierce through the stitch on the left needle with the right needle to then pull the yarn through the old stitch and form a new one. The yarn which became our preferred one is a quite soft quality yarn which is not twisted in a classical manner, but woven. This microstructure made it at the same time flexible and firm enough so that, for instance, it does not dissolve into individual threads when the yarn is moved around a lot during the knitting—a behaviour that other classically twisted yarns have shown.

While finding the right needles and yarn for us, we also discovered that the robot's gripper is not only not made for gripping yarn, but is also not made for gripping needles. Rather, the core grasping target for the gripper seems to be box-shaped things. The inside of the two gripper 'fingers' is endowed with plastic grooves. These are clearly meant to enhance the gripper's ability to grip. However, in the case of working with knitting needles, the needles could not be gripped properly due to the grooves, so the idea behind their design turns out useless for our desired application of the gripper.

This mismatch between gripper and needles needed to be fixed. We started to tinker with different materials and practices. First, we used crepe tape to increase the gauge of the needles. This already worked pretty well towards fixing the mismatch between needles and grippers. However, the relation between needles and grippers was still far from ideal. There was also a 3D printer in the lab and one morning when I entered the lab, Anne and Jan surprised me with a small 3D-printed box with a hole in it, through which the needle could pass. Thus, with the help of the box, we turned the round needle into a box-shaped object for PANDA to grip. This turned out to be the ideal solution for enabling the gripper to grasp the knitting needle.

Figure 21: The 3D-printed box; Figure 22: The box with the needle in the gripper's grasp



Notably, assembling the materials needed to realise Scenario 2 was not a linear process as it might appear when recounting this here. Rather, we would spend a large amount of time tinkering and testing in a rather playful manner of engaging with materials. This would include everything that was already part of the lab (like the pneumatic cable we used in Scenario 1 or the 3D printer), materials we newly introduced to the lab (like the wool and knitting needles), as well as constant conversations across disciplinary boundaries, which made the whole process a team effort that unfolded through iterative circles of engaging with materials, defining challenges, discussing new approaches, testing ideas, and finding workable solutions. However, we also worked with a provisional account of solutions that was open to revisions and changes. This openness proved central to establishing a practice of following the flows and probing combinations of materials. Furthermore, my account of realising Scenario 2, namely to give the right needle to PANDA, makes tangible the ways in which this is not one discrete task, but rather is composed of several sub-tasks involving various steps that we had to work through in order to accomplish the task. Describing our sub-tasks, and the ideas and practices involved in detail here, I want to make tangible the ways in which robotic knitting displays what Ingold calls the textility model of creation, making it necessary to follow the flow and composition of materials and practices.

Another integral part of realising Scenario 2 was to understand the operations of the right needle. Forming a new stitch without the involvement of visual or tactile sensors as we, the humans in this project, were endowed with, is obviously a different task. Thus, we decided to work with the differentiation of basically three individual movements of the right needle as they are explained to persons who are starting to knit. These movements are: (1) stitch through, (2) wait and pull yarn through old stitch, (3) wait and let old stitch slip from left needle. We could then define each movement as a set of points in space located through the end-effector in combination with a specific configuration of joints and called this task *knit the right needle* (krn). At first sight, to transfer knitting onto the robot arm by defining sub-sets of points in space might appear like robotic knitting is an easily accomplishable task. However, what complicates this is the collaborative dimension of robotic knitting, namely the left needle in the hands of a person meant to be knitting together with the right needle held in the gripper of the cobot. Thus, we not only had to make these three movements transferable, but also had to have the robot execute these movements in a way that they made sense in the overall setting of knitting collaboratively.

Prerequisite for starting to implement krn was to already have knitted a couple of rows, before handing over the right needle. The first few rows of a new knit artefact turned out to be too delicate and fragile to combine with the effort of handing over a needle to the robot. Thus, we would first knit a few rows before handing over the right needle. Working with a knitted piece on the left needle, and now perfectly prepared to hand over the right needle, the first steps with the cobot were easy, encompassing releasing the brakes, enabling the teaching mode, and using the gripper app to tell the end-effector to close around the needle with the white cube. In the next steps, joint motion apps had to be combined with pause apps in order to assemble the order krn. Each joint motion app had to be filled with information. Working at the computer, this combination of apps was just a mouse click on differently color-coded buttons. Melanie who was operating the robot arm in the so-called teaching mode, then had to start with defining points in space while moving the arm to these points. This involved pressing the guiding button above the gripper, which enabled her to move the arm. Notably, the guiding button has to be pressed in the right manner: If pressed too soft, the arm wouldn't move and if pressed too hard, this would cause an emergency stop and the arm again wouldn't move. So, becoming able to guide the robot arm is to learn how to press the guiding button. This can only be learned through a trial and error approach. Then, pressing and holding the guiding button in the right manner, one can guide the robot arm to move in a specific direction. Importantly, the movements we wanted to implement on the robot had to be always perceived of as well as performed in relation to the left needle. In the scenario described here, this meant transferring Melanie's movements of the right needle onto the robot arm, which is far more than 'just' the three basic movements of the garter stitch as identified above. Rather, it also encompassed not only the individual hand knitting style, but more generally, the ways in which the needles have to be orchestrated in order to form new stitches.

Stitches, yarn, and the knitted piece are constantly moving when knitting, and it seems impossible to predict how they will move. Splitting the activity to knit between a person and PANDA not only emphasises how complex knitting is, including the many different smaller movements which are natural to an experienced knitter, but also emphasises the complexity of realising this mode of collaboration between humans and a cobot. Thus, hand knitting is a movement which can be formalised and automated, as the example of the industrialisation of knitting illustrates nicely, and at the same time hand knitting also always exceeds the reduction of this practice of forming new stitches into a set of formalisable movements. It seems like at the core of hand knitting remains a textility of creation which defines this practice as the engagement with flows and combination of materials that cannot be controlled by hands, but rather instructs a process of being possessed by actions in the forming of new stitches. A core challenge was to do justice to this quality of the practice of hand knitting—to make it our matter of care—and thus to transfer not only a set of sub-movements, but rather a *skill* onto the robot—of course within the limits of the technological constraints of the cobot, while acknowledging that the hands and gripper needed to be possessed by action as integral to knit collaboratively.

Against this background, zooming further in onto the practice of transferring knitting movements to the robot, the challenge of transferring more than a movement becomes tangible on many occasions. As I will continue to argue, it is precisely the quality of knitting in its not only structure-forming (order and subversion) quality, but also the working together of the hands and gripper as well as the flow of materials, which also make tangible the many different forms of collaboration that are prerequisite for realising the task of knitting collaboratively. A very vivid example is the practice of guiding, as the core element of PANDA's teaching mode. After learning how to press the guiding button as explained above, the person who is guiding PANDA also had to then not only press the button throughout the entire movement that the robot should be trained, but also first execute the movement and while doing so, second, press the enter button at the robot's pilot in order for it to memorise points on the x-, y- and z-axes. Again, this might appear to be a rather easily accomplishable task, nevertheless, it demands that the person guiding PANDA does different things at the same time, like emulating a desired movement through moving the robot, deciding points in space that the robot should memorise in order to be able to execute this movement afterwards, and pressing two buttons.

Thus, Melanie had to first study herself practicing hand knitting, especially how her right hand with the needle moves, to then become able to abstract individual movements and translate them into several stations of her right needle that can be thought of as points in space—always in relation to her left hand with needle. Hence, we discovered that the practice of guiding PANDA is itself something that we had to practice intensively. Notably, this turned out to be an embodied process, demanding an interplay between materials and agents, but also involving different senses. In line with Ingold, I

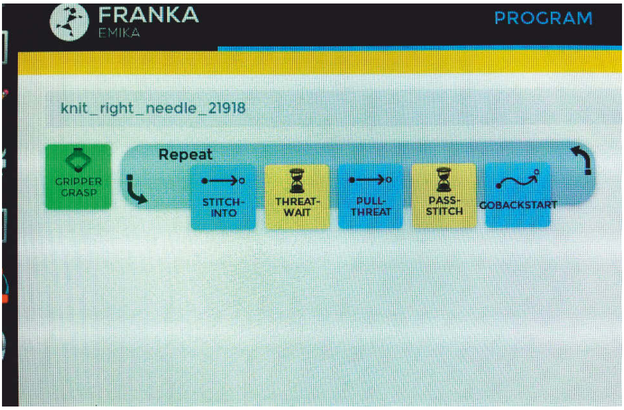
Figures 23 & 24: Melanie guiding PANDA

describe this process as stipulating a practice of becoming possessed by actions. Precisely at this point in which guiding PANDA unfolds as a *skill* on its own, the intra-active nature of collaboration between humans and cobots crystalises. When guiding PANDA, bodies intra-act, deployed by what Morana Alač (2009, 496) calls practices of "'getting into' the body of the machine." Getting into the body indicates a set of practices of attaining a multi-modal and embodied sense for the robot. This account of interaction challenges the idea of the individual body and of agency as a property of the individual and thus tweaks interaction towards intra-action: The knitting movements of the right needle of my hand-knitting practice become the guiding of PANDA (conditioned by touching, moving, engaging, experiencing, material flows, but also obstinacies and many other sociomaterial factors) and the subsequent movements of the robot arm, which again become the movements of the right needle of my hand knitting practice. Guiding then is a lot about finding a shared rhythm of moving together. Highlighting the dynamics of bodies in intra-action, I suggest an account of collaboration at the human-cobot interface that takes into account these dynamics as its matters of care.

Moreover, when working in the constellation as shown above (*Figure* 18), we would use the possibility to hit the enter button on the screen instead of on the pilot, so that Melanie did not have to press the enter button any longer, but could transfer that to my fingers on the computer mouse. We agreed that she had to signal me with the word "now" when I had to click on the set a point button on the computer screen. This division supported Melanie in the highly pre-requisite guiding. In addition, my role cannot be reduced to clicking the mouse as neither can Anne's role to identifying a potentially dangerous scene and pressing the emergency stop button. Rather, the three of us were constantly collaborating, Melanie explaining her movements with the robot arm, drawing Anne and me into her practice of getting into the body, making decisions on how to move and where to set a point, possibly erasing a point. Thus, PANDA, Melanie, Anne, and I were acting in concert. Anne and I would eventually sit and stand at our positions while observing Melanie and at the same time, also getting into her/the robot's arm with our own right arms in order to guide with her. We literally and figuratively became co-guiders.

In the next step, we could start testing the actual execution of collaborative hand knitting. The spatial arrangement and composition of persons, computers, and the robot would remain the same for this. My role now was to pull up the order krn, to release the robot's brakes, and to then wait for a sign from Melanie that she is ready before clicking on the play button. At the same time, Melanie would check if PANDA was in the correct start position, and if not, guide it there, then put the right needle in PANDA's gripper, hold the left needle as well as the yarn with her left hand and position herself in a way that made it possible to start knitting now.

Figure 25: krn on FRANKA Desk



As Anne was continuously watching over this scenario, after the first couple of executions of krn, she figured out that we always needed "five warm-up stitches," before the actual knitting started to be performed more smoothly. This established itself as a rule which all of us were able to confirm through our experiences. Further, I regard the phenomenon of the five warm up stitches as displaying how not only guiding, but also the execution of a movement with the cobot illustrates the intra-active nature of knitting collaboratively, that is, entangling oneself in the assemblage and flows of materials of forming new stitches together with the cobot as a practice that challenges precision and accuracy. Carrying out krn then is not simply the execution of a movement, but rather the experience of this movement through the robot arm, based on the constant orchestration of hands, grippers, needles, buttons that is enabled through practices of getting into the body, the embodied and multimodal process of attaining a sense for the robot—a process which is—equally to guiding—a lot about finding a shared rhythm of moving together.

After successfully implementing collaborative knitting, we also invited others from the MTIengage group to test the realisation of Scenario 2. On one of these occasions, Philipp took over the left needle, who at that time still was not very secure in practicing hand knitting and had not been a knitter before the project. In this composition of persons realising krn, the robot's ability to perform the krn movement with a quite high precision and in endless repetitions worked nicely towards teaching Philipp how to knit. Now, Melanie and I would look both Philipp and PANDA over the shoulder, guiding Philipp in how to get 'into' the arm of the robot with the right needle as his right arm as the robot arm. We, the three observers, in turn, nevertheless had to attain a sense for the robot's arm as Philipps arm, and how we could support the learning process. This was an embodied and situated experience of developing and sharing skills across entities. Thus, the example of learning to knit with PANDA makes tangible the ways in which not only attaining a sense for the robot, the yarn, the needles, and the collaborative knitting are enmeshed practices of relating, but also the concomitant process of assembling matters of care as well as how different agents engage collectively in krn.

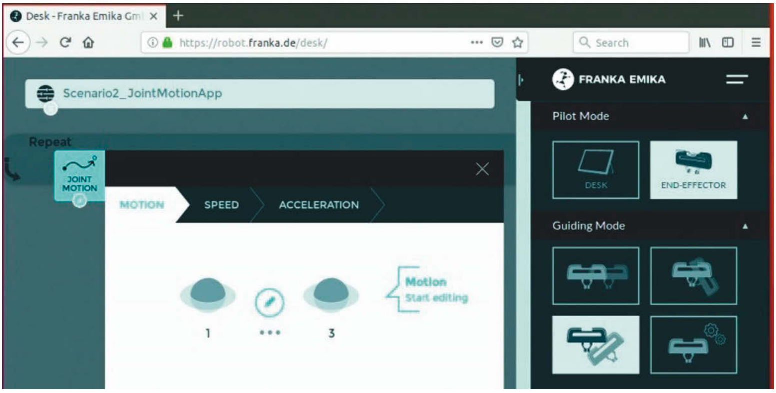
Finally, after working on and experiencing Scenario 2 for a while, we decided to move on to Scenario 3, even though, built on our experience, we already assumed before testing Scenario 3 that Scenario 2 might be the most exciting of the three scenarios with regard to probing collaboration between humans and cobots. What appeared very obvious to us was to base this new implementation on what we had learned from the previous implementation of krn. Thus, we decided to combine krn on one PANDA with *knit the left needle* (kln) on a second PANDA. Moreover, I believed that characteristics of the robot arm, like the ability to execute always the same defined movements iteratively in a very precise manner, would be helpful in having two arms working together, while a human then could take over the part of orchestrating the flow of materials in forming new stitches. We worked in a team of more than three persons in order to realise this scenario and quickly found out that the guiding of the right arm and left arm could not be separated, but needed to be reciprocally related: One of us was guiding the left needle and the other the right needle, attempting to train each robot arm the pre-defined movements while also knitting with each other. This turned out to be highly challenging for everyone involved.

In addition, and especially compared to Scenario 2, the collaborative aspects in Scenario 3 appeared to be limited to either human-human or cobot-cobot collaboration, neither of which were my main interest. However, we continued with our attempt, driven by a curiosity about how our efforts will turn out. The same conditions and circumstances applied to the execution of krn in combination with kln as to the execution of krn: The persons at the computer each had to press the play button with a mouse click. What we noticed immediately was the importance of timing in this. Both play buttons on each computer had to be hit at absolutely the same time in order for the two arms to move in synchronicity. We first started to try to count and hit play, but this did not work so well, so Melanie proposed to use the rhythm of a song we all knew and define a point in the song at which we would press the button. This worked much better in reaching the desired synchronicity. However, despite the identical settings on each robot arm and reaching the synchronicity in pressing the play button, the execution of movement of each cobot turned out very asynchronous, so that one needle would operate approximately 10-15 centimetres above the other needle. This happened every time we repeated the execution of kln in combination with krn. As a result, and, at the end of the day, mainly my frustration with Scenario 3 on the level of human-cobot collaboration as well as its execution, led to the decision to not further pursue this idea.

Sub-String 3: Improving Collaboration: From Precision to Increasing Flexibility

When implementing krn, we could adjust the execution of movements by changing the settings, mainly by changing the velocity of it. In the following screenshot (*Figure* 26), each sphere represents a state.

Figure 26: Adjusting settings in the joint motion app



Despite this possibility of adjusting the execution of states, when Melanie trained the krn and I took over from here in the execution of collaborative knitting with the cobot, I would experience different challenges. One challenge was that the way PANDA was moving the right needle represented Melanie's hand knitting practice, which differs from mine. This, again, underlines the ways in which hand knitting does not only consist of a set of sub-movements which are apparently the same for every hand-knitter, but that hand knitting is a skill. Another challenge was the velocity of the execution of movements by the cobot. I preferred a faster execution, for instance, compared to Melanie and Anne. Thus, in our experience, the possibility to change the basic settings of krn was very helpful in adjusting the collaboration between PANDA and different persons through knitting.

Besides these and other rather easily accomplishable technological improvements of collaborative knitting, we also experienced a certain boredom with krn after a while. First, of course, we were all excited and fascinated by our success in implementing this movement onto PANDA in a quite robust manner which allowed each of us to engage in knitting with the cobot, from the re-engineering of the knitting needle by making it a box-shaped object to adjusting the velocity to individual preferences. However, the execution of krn also encompassed certain qualities that we could not change, like the very basic principle of executing a movement along points on the x-, y-, and z-axes on the one hand, and on the other that the cobot arm is rigid during this execution. The way PANDA would execute krn is that the end effector would go to every memorised point, constantly switching between acceleration and stopping, and thus kind of moving in what could be framed as classical robotic movements, characterised by fragmentation in the flow of movements. We were affected by the disruptive quality of both behaviours that cause fragmentation, namely jerkiness and pausing, and while we experienced them as helpful in the beginning of the project, we now started to regard them as limiting our experience of collaborative knitting. Melanie, who knitted the most with PANDA, described it as painful and fatiguing not only to wait for a transfer to be completed, but also to have to work in states, and therefore in fragmented movements, when executing krn. Such a movement from state to state is implemented by the preferred motion planning app, joint motion, and results from the forward-kinematics on which this app is based. What we experienced in an early stage of the project as a benefit of this model, the comprehensibility of states, thus, was also the source for our frustration with the execution of movements at a later stage of the project.

Luckily for us, throughout the duration of the project DRDK, the head of the MTI-engAge lab, Raphael, was also working on his behaviour control program, called *PhaStaProMP* (Deimel 2019a; 2019b) and invited us to try to implement krn not only using FRANKA Desk, but also PhaStaProMP. The major differences between the visual programming of the GUI and the behaviour control program developed by Deimel with regard to our project are first, how one trains a movement and second how the robot then performs the trained movement. In what follows, I will briefly describe the technological differences, then give details on how we approached working with PhaStaProMP in order to make tangible the ways in which the latter was able to improve our practice of collaborative knitting.

The basic idea behind PhaStaProMP is to enable "reactive interaction" (Deimel 2019a, 1) between a robot and a human. Notably, this encompasses reworking the model of the discrete state machine towards a "phase-state machine" (ibid.), which "can implement regular state machine semantics, but it additionally has the built-in capability to provide and adjust phases and blend consecutive movement primitives for smooth operation" (Deimel 2019b, 1). In short, working with the blending of states, Deimel's phase-state machine model PhaStaProMP would ideally erase the fragmentation of movements as it works with "dwelling in *states*" (ibid., emphasis in original) in contrast to the "*state transitions* (guarded jumps)" (ibid., emphasis in original) of the discrete state machine based app we had been working with so far.

Such a dwelling in states is realised through different mathematical methods of implementing transitions between states, including, for instance, working with a differential quotient to establish a pulse for the process of cycling through states, as well as probabilistic decision-making. In short, the outline of the PhaStaProMP state machine is to combine the definition of a state with different circumstances of its execution as well as the synthetisation of that state in order to generate a continuous movement. What intrigued me as a technofeminist scholar, neither trained in robotics nor mathematics, was what I understand as the idea to realise an approach to robotic movements which operates with the basic concept of a state and at the same time challenges the very notion of a state by re-working the relation between states and transgressing the notion of proper boundaries between motions. In my view, this approach to robotic movements can be read as reverberating with the idea of the hand knitting practice in terms of being possessed by action—so, the question at hand now is: How did PhaStaProMP change our krn practice?

Training PANDA to perform a movement with PhaStaProMP is radically different from working with FRANKA Desk, even though we would still be working as a team distributed at the PANDA, emergency button, and computer screen stations. The interface was no longer a GUI but a *Python* command prompt window. Thankfully, Deimel wrote a step-by-step how-to manual of commands and settings for working with PhaStaProMP which was also intelligible across disciplinary diverse backgrounds. Working with PhaStaProMP, the first step was to activate the phase state machine, then to train states through demonstration.[16] The latter is comparable to the guiding process, but not the same. As soon as the guiding button is pressed, the motion will be recorded, including the configurations and velocity and the recording stops when the guiding button is released. The recording of movements produces training data with which it becomes possible to generate a trajectory of defined states. We only needed three iterations to work with an additional number of synthesised movements that were generated based on our iterations. Each demonstration should be as similar as possible, preferably producing variabilities only within a certain degree and therefore

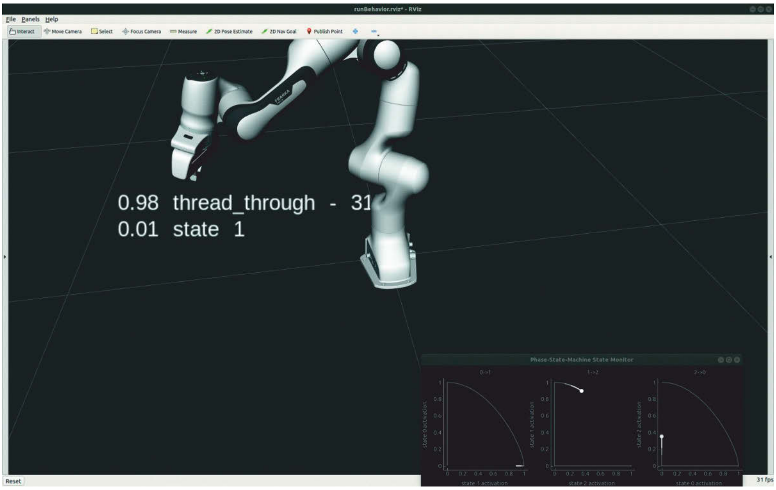
16 For a detailed description of this process, including video footage, see Melanie Irrgang's blog entry (2019) on *Time for Action – Scenario 2*, https://blogs.tu-berlin.de/zifg_stricken-mit-robotern/2019/05/03/8-knitting-for-computer-scientists-and-engineers-scenario-2/

deliver the data needed to first simulate and second learn a movement from demonstration. The demonstrated movements have to reveal the range of the ideal movement, also allowing to define that which limits this range, namely the discardable. To produce such data requires a form of what could be called disciplining of one's own body, a process that in our case was stipulated by our already (toward the end of the project) rich experience in implementing krn with FRANKA Desk. When Melanie demonstrated krn, she had to first get into the cobot now operated through a phase-state machine and train herself to move not only in the right manner, but also to control her arm in a way that she was able to replicate this movement with high precision for three iterations. Thus, attaining a sense for krn now became a process of experiencing the simultaneity of attaining a sense for PANDA and PhaStaProMP as well as disciplining her embodied movements. I suggest thinking of this process in terms of becoming a human-data-assemblage which enabled us to generate the data for transferring a continuous movement onto the cobot.

After the recording and synthetisation of all krn movements, the next step was to use the PhaStaProMP label app and define states. We worked with the three states (1) in, (2) out, and (3) wait. Here, labelling means to categorise movements along these three labels. When labelling, the trained movements are displayed on a virtual model of PANDA, which gave us the opportunity to discard movements which deviated too much from what it should look like. Next, we would run the labelled and therefore trained behaviour on the virtual model. As PhaStaProMP was still in the process of being developed, early in the DRDK project, the movements were too small for the phase state machine to recognise them as movements, resulting from the relation between the friction force necessary to move the cobot's joints, the force needed to actuate the phase state machine, and the force required to demonstrate our knitting movement. Deimel constantly presented us an improved and adjusted version of PhaStaProMP, enabling us to make knitting collaboratively also a test case for his phase-state machine. In turn, we made knitting part of the development of PhaStaProMP, a phase-state machine fitted to the obstacles of realising hand knitting movements on a robot.

After the simulation of the movements, we had to adjust the settings of the execution of krn, like the velocity, but also, and importantly, the controller gains of PANDA regulating the stiffness and softness of each joint in executing the movement. This became central for improving our practice of krn and thus for knitting collaboratively with PANDA. Finally, typing "run on real robot" into the command prompt window, PANDA would start executing the trained

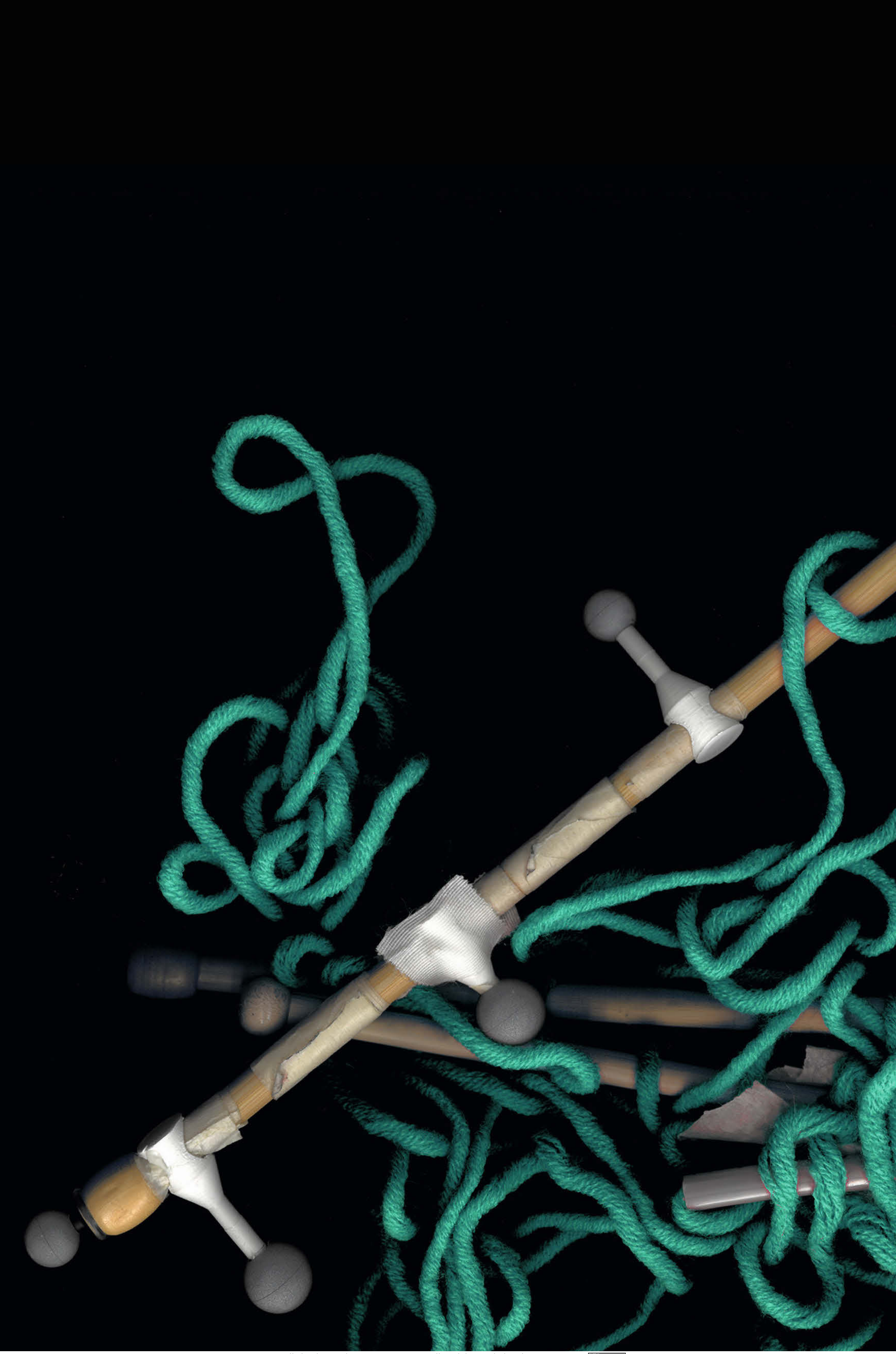
Figure 27: Running the trained behaviour on the virtual robot with blending of phases



movement. The two most important improvements were: first, that the states would be executed in a blended fashion without fragmentations, and second, that we could adjust the stiffness of the individual joints. After a few tests, we figured out that krn worked best if the fixed end with which the robot was mounted to the table was stiff and the part of the end-effector with which we interacted was adaptable and flexible.

The confinement of the one part to stiffness while liberating another part from stiffness meant to reduce precision and increase adaptability and flexibility. Both the continuous transition of states as well as the differentiated controller gains generated a new quality of collaboration. Knitting with PANDA through PhaStaProMP, Melanie described her experience as less exhausting and more in synchrony with her movements. In contrast, when implemented through the joint motion app, we often encountered the problem that the human knitting with PANDA was either moving too fast or too slow. PhaStaProMP allowed us to develop a common pace, especially based on the difference between iterations (noise programmed by Deimel) and the option to correct the cobot's movement because of the flexible joints. For instance, when PANDA and I knitted collaboratively and lost the yarn in the process of forming a new stitch, I would push the cobot arm slightly to the right in order to adjust to the flow of materials in forming a new stitch, while the cobot would find its way back to its trajectory of krn, operating in a very fluid behaviour. In addition, the continuous instead of fragmented movements also increased this impression. As a result, everyone in the team who knitted with PANDA experienced the circumstances and practice of krn realised with PhaStaProMP as a more authentic form of collaboration than with the joint motion app, potentially moving in the direction of realising hand knitting as a skill together, rather than just executing a purified set of motions. Tentatively arguing, I suggest tweaking the interconnection between an increase of our digital practice and the increase of collaborative capacities, resulting in the improvement of performing collaborative hand knitting as an embodied skill, adhering to the flow of materials. What appears to become tangible here is that the increase of our digital practice in the form of implementing krn through PhaStaProMP not only depicts an embodied skill itself, characterised by the intra-active and rhythmic relating between bodies, data, movements, and materials, but also might open up new avenues for forms of human-cobot co-creation, that is, practicing co-textility.

In this chapter, I did not approach dichotomous relations as given, fixed, and non-disputable common-sense knowledge, but rather as, first, permanently performatively enacted and, second, as itself generative in meaning- and matter-making. Thus, my account of challenging the nature and the power of such dichotomies follows a diffractive methodology, which engages playfully with objects, allowing different aspects to move from the foreground to the background, and vice versa, in order to enable new patterns of relation to emerge. Thus, the three sub-strings are written in such a style of moving aspects of the relation between hand knitting, automation, and digital practice to the fore- and background. From time to time, I as the writer, also felt moved by the strings of knowledge and experience that I am bringing together here—rather than feeling in control and as the only agential entity engaged in this writing. These strings emerged as unasked-for patterns of relating between storylines, forming into string figurings of human-robot entanglements of collaboration through hand knitting.



CHAPTER 3
KNITTING TOGETHER: COLLABORATION AS CAREFUL COBOTING