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MAIN PAPER

The fabrication of humanoid robots: methods, media and artefacts

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Abstract

In recent years, social and cultural science research has examined both the human–robot relationship and the social discourses that accompany the development of humanoid robots. Research has focussed less intensively on the development of this type of robot. This is where the article comes in: it provides empirical insight into the research practice of symbolic robotics, its procedures and media. It observes and analyses roboticists as they sketch robotic movement in space by hand, develop mathematical formulas and transfer them to the digital script of programming. The paper understands these developmental steps as iterative-recursive phases of an experimental setting of robotics laboratories and analyses the relationship between physical and digital artefacts, epistemic objects and media of thought, representation and communication, as well as the practice of roboticists. With their designing and testing, correcting and recalculating, which the essay understands as a continuous confrontation with their designs and programming, the artefacts and materials, roboticists shift the boundary between their (non-) knowledge and what is still unknown.

Keywords Sociology of robotics · Engineering sciences · Laboratories of robotics · Technical knowledge · Material infrastructure

1 Introduction

With the advent of the digital computer, the idea of the retraceability of humanly understood properties in and through machines became a recurring theme. By formalising and mechanising human knowledge, it became possible to embed computational processes within electronic components, aiming to create forms of knowledge that rival human cognition. With the development of artificial intelligence and robotics in particular, the question of the relationship between humans and machines has shifted once again. In robotics, human-likeness is not only achieved through increased computational capabilities—what might be referred to as the machine's "cognition"—but also through the refinement of physical markers that mimic human features. Even minimal technical simulations of eyes, mouths, ears, and limbs are often sufficient to attribute human-like qualities to robots. These material symbolic allusions shift attention away from the machine's technical composition and towards how it is interacted with. The design of humanoid robots, with their goal of appearing human-like, not only creates complex illusions but also plays a critical role in ensuring the social acceptance of these machines. Research indicates that the balance between perceived similarity and dissimilarity is crucial: to maintain the artefact's authenticity, its machine-like characteristics must be preserved within its human-like form, highlighting the distinction between human and machine (Suchman 2006).

The practices of symbolic robotics are based on the longstanding idea that the world has a symbolic correlate in the human mind. They assume a direct correlation between the physical world and its symbolic representation. Accordingly, the central task of roboticists is to discover features of the real world, analyse them mathematically, reconstruct them symbolically, and to enable the robot's software to compute relations and send control information to the corresponding body parts, e.g. to move a hand. Symbolic robotics aims to technically and symbolically implement all possible states of the environment and the robot before the robot operates in its environment. The goal is for the robot to eventually navigate a symbolic internal map that mirrors its real environment.

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Furthermore, symbolic AI conceives robots as symbol-processing systems whose (re-)actions are data- and computing-intensive and whose capabilities remain within the scope of the programming (Boden 2004). This technical architecture is guided by a notion of intelligence, which is based on a central symbol-processing unit. Working on this unit by means of programming is thus at the centre of roboticists work and—related to this—mapping and representing the environment in which the robot is to move (Dreyfus/Dreyfus 1988). Overall, symbolic robotics has a deductive character: "intelligence" is assumed to arise primarily through software calculations and not through physical interaction with the world.

Other lines of development—the so-called sub-symbolic or connectionist robotics (e.g. Miikkulainen 1993)—are based on inductive operations of artificial neural networks, which refer to neuroscientific models of the human brain and thus to the interaction between semi-autonomous software systems, and on the concept of learning. It is assumed that humanoid robots can only 'learn' if the robot body also relates to the environment to which it is supposed to react (Breazeal 2002).[1] These newer developments, which are based on natural evolution and development, rely on emergence rather than pre-programming (Pickering 2002). Their aim is to technically equip socio-humanoid robots to select and categorise data according to binary distinctions (e.g. true/false, human/non-human, importance/unimportance), and perform subsequent actions. In this repeated calculation of data, the artificial neural network operates in a repetitive process of abstraction, accumulation and feedback such as the backpropagation algorithm (Rumelhart 1997). Metaphorically speaking, these computers 'learn' that means that they can generalise what they have cumulatively stored and calculated using statistical methods. Arising errors are registered by the system as a difference between the output and target variables and used by the artificial neural network to adapt the operations. This also means that errors are initiated by the already defined result value, which in turn is part of the mathematical design of the neural network.

Various developers (e.g. Breazeal 2009) assume that socio-humanoid robots can only interact adequately if they are technically set up for 'learning'. Learning is conceptualised as analogous to processes in caregiver–child contexts, in which reactions of the caregiver are utilised as learning input for the robot (Keller 2007). Therefore, interactivity is connected to technical developments. Japanese researchers, for instance, have developed an architecture which allows the robot to perform a cultural practice of dancing by imitation; through this connection to quotidian life, an attempt was made to achieve cultural acceptance (Šabanović 2014).

Beyond the distinction between symbolic and sub-symbolic research, robotics is seen as a graphically formal craft, where symbolic representation through written media plays a central role (Suchman and Trigg 1993). It is also viewed as a cybernetic project aimed at transcending species differences (Haraway 1985), a benchmark against which human theories are tested (Keller 2007), and a challenge to replicating human sociality (Castañeda & Suchman 2014). Empirically observed testings included the recognition behaviour of robots (Muhle 2019) and the role of the human body in programming machine movements (Alač 2009). Other studies are dedicated to situations of practical interactivity with machine beings. These studies examine the spatial organisation and coordination of human–robot interaction (Alač et al. 2011), compare the use of emotional robots in elderly care and therapy in three European countries (Klein et al. 2013), use the example of therapy for autistic children to ask about the translation work between the human and the technical (Dautenhahn 2007), and explore their function in intimate relationships (Levy 2007) and in the military (Lin et al. 2017). What these studies have in common is that they assume that it is social interaction that shapes these technical objects in iterative steps and, furthermore, that they point to the limits of an implemented AI that cannot 'learn'.[2]

Although these studies and approaches differ significantly, they share a common focus on the nature of the relationship between humans and 'intelligent' machines, and on how these entities (should) interact. With a few exceptions (e.g. Treusch 2015; Lipp 2023), they also share the fact that their inquiries begin after the production of socio-humanoid robots, assuming their fabrication without examining it in detail. In contrast to these studies, our contribution analyses the work on the fabrication of socio-humanoid robots before they leave the laboratory and, thus, the forms of knowledge that comprise their work.[3] There is a rich tradition of empirical and theoretical engagement with laboratory practices in the sociologies of science (Social Studies of Science; Science and Technology Studies, etc.) (for example, Latour 1999; Knorr Cetina 1999; Rheinberger 1997). However,

[1] Since the early twentieth century, ideas about the human brain have been the subject of intense and controversial debate in neurophysiology. For the history of this scientific debate, see, e.g. Giessmann 2024.

[2] We do not address the question of technical innovation but see Schulz-Schaeffer et al. (2024).

[3] The adjective 'humanoid' qualifies an object (here a machine) if it corresponds to the appearance and qualities of a human being (Cambridge Dictionary). Human-likeness is not an inherent property of an artefact, but a socially ascribed category. Nor does it simply exist but it is the result of robotic laboratory practice. Categorization as 'human-like' (i.e. humanoid) primarily includes shape, movement and the ability to interact and thus visual, audible and haptic aspects (Zitzewitz et al. 2013).

the ways in which roboticists construct their knowledge of humans, particularly through the navigation between human and non-human agency, has been largely overlooked. The production of robots reveals that social and cultural studies know little about how ideas about humans or the human are inscribed in these technical artefacts. In line with Lucy Suchman (2006), we argue that robotics and AI projects contain cultural notions of humans that make machines appear as somewhat autonomous.

The production of human-likeness is not a self-evident effect of robotics and not a given characteristic of its constructed machines, but the result of a practice and an effort to achieve movements can be recognised as human-like by potential users. This dimension also refers to a broader context of this research, i.e. the envisaged marketability of these machines in the very future. In some laboratories, they are being designed to be able to take over household-like activities, i.e. to populate the world of private households. Functionality and human-likeness are a prerequisite for their acceptance. The aim of the paper is twofold: first, we explicate socio-material practices that give rise to interactive, human-like artefacts; we analyse how humanoid robots are enabled to perform human-like movements, i.e. how everyday movements are inscribed in them that can appear as human-like. Second, we analyse the use of media and technical instruments and the role they play in the aforementioned manufacturing process. This is to highlight the challenges faced by roboticists as well as the fact that humanoid robots are not (yet) the perfect assistants they are often represented as. In this sense, the paper contributes to a demystification of humanoid robots as autonomous beings—an image which mobilises the naturalisation of culturally specific ideas of human beings.

According to the Cambridge Dictionary, being autonomous means being "independent and having the power to make your own decisions." In this sense, an autonomous machine would be a machine which is "able to operate without being controlled directly by humans". Thus, a humanoid robot can act independently of humans once it has been set up (e.g. performing a movement). It has a framed and time-limited autonomy, but is not sovereign, as it is designed and set up by its inventors or users. In other words, they are materially present in the machine with their assumptions. Furthermore, a machine must not only be put into operation, but, also maintained and serviced. Human-like robots, even though they might give the impression of being self-evolving or sovereign, and thus almost natural beings, are dependent on continuous human involvement. This applies both to the practice in the robotic laboratory and to the natural environments (e.g. retirement homes, Schulz-Schaeffer et al. 2023) into which humanoid robots are introduced.

To explain the process of development and manufacturing empirically, we observe the experimental arrangements with which roboticists work on their artefacts. In other words, we study practices of roboticists as much as the material reality of robots and the instruments they utilise to perform an activity (such as an arm movement) that is supposed to be similar to human movements. Robotics research attempts to understand and technically realise how people do or implement everyday things. In doing so, they follow both scientific and, above all, common-sense knowledge about human beings while also adopting a de-differentiating position; they attribute no relevance to socio-cultural affiliations (origin, gender, religion, ethnicity, etc.) and thus generalise human beings.[4] In the context of laboratory practice, humans, their bodies, their actions, their thinking, etc. comprise a heuristic utilised without the intention of completely imitating the human being. That is to say that roboticists have an idea or concept of human beings that they refer to. In this way, laboratory practice is orientated towards humans, their ability to think and react, but it is oriented towards humans in order to create something distinct or new that differs from them. It is a robotic otherness, i.e. a technically realisable robotic mimesis. The contours of this otherness are currently still blurred and are only beginning to emerge through further research. At the same time, it can also be observed how the reference to humans in laboratory practice competes with technical-material forms of knowledge, how these references oscillate in their significance and are thus de-thematised and rendered irrelevant.

We conducted 13 interviews with roboticists and performed 12 weeks of ethnographic fieldwork in three German robotics laboratories. Besides conducting ethnographic interviews (Spradley 1979), we observed the professional practices and infrastructural features of the laboratories, took video and photographic excerpts, and collected documents (Emerson et al. 1995). The data corpus consisting of interviews, ethnographic protocols, documents, and visual material was analysed using grounded theory (e.g. Strauss/Corbin 1990) and document analysis (e.g. Prior 2004). The laboratories we observed fabricating robot bodies (or body parts) as well as conducting behavioural experiments and demonstrations were by no means uniform but differed in terms of internationality and size. The first laboratory was remarkably large, both in terms of staff and physical space. The department occupies an entire building on campus, and adjacent to this office complex is a vast hangar that functions as a major laboratory space. Here, robots are tested, assembled, and fine-tuned, and various instruments as well as older robots are stored. The team is notably diverse, with English being the primary language. Researchers and students

[4] There are links here to "I-methodology ", which is used to capture the cultural bias of programmers (Oudshoorn 2004); in the case of robotics, it is a question of de-differentiation.

from across the globe come here to work and study. In contrast, the second laboratory we visited presents a different approach, both in terms of its organisation and internationality. It is much smaller with a more intimate atmosphere, consisting of one professor, two staff members, and, at the time, two student fellows from the US. While there is some level of international presence, it is far less pronounced than in the first lab, and the primary language spoken here is typically German. The third laboratory, also internationally oriented, consists of three researchers, including the professor as the lab-manager. It is a particularly new laboratory still in the making but with a remarkable political and financial support. In addition to observing experiments and the gradual completion of the space, this laboratory provided insight into planning for both fundraising and public outreach.

In this paper, we analyse symbolic robotics and its practice of constructing human-like robots. The empirical data documented in this paper focuses on two experiments conducted by a group of roboticists from the same laboratory with the experiments focusing on different ways to conduct arm movements. The first experiment specialised on modelling the object (a cabinet door) to be manipulated; the second experiment concentrated on so-called 'behavioural cloning,' which here implies imitating human arm trajectories while opening a door in a wall. At first glance, robotics laboratories are not organised very systematically but create an atmosphere of creativity and bricolage through their consistently heterogeneous object landscapes. They are hybrid spaces in which one or more robots are connected to a series of computers and everyday objects coexist with crucial technical infrastructure. This type of robotics laboratory does not isolate areas from one another but is trans-epistemically orientated towards vital workflows: towards practical knowledge needs in a seemingly chaotic technical and objectual infrastructure of the laboratory. This creates informational laboratory areas which are demarcated by a series of (discarded) objects. When roboticists leave the laboratory, the developed experimental arrangements, such as research landscapes, usually remain in place and form a familiar image over time, supplemented or replaced by other objects. These laboratories are characterised by the fluid transition from scientific experimental setup, workshops, offices, and storerooms. Servers and other critical technical equipment are surrounded by parked bicycles, broken robot parts, and empty boxes, as well as expensive computers, fragile sensors, 3D printers, many metres of cable, and the latest platforms.

Conceptually, we represent a sociology of (scientific) knowledge that ties in with practice-theoretical considerations embedding actions and knowledge of the actors in situated practical execution (e.g. Knorr Cetina 1999, Latour 1999) while maintaining a special appreciation for materiality and media theory (Gillespie et al. 2014). We are interested in the situated actions of roboticists, in their knowledge and their practical approach, as well as in the media and artefacts involved and their effect on and autonomy in the production process. The focus here is on knowledge practices that are documented in the (everyday) practices and activities of the actors, whether in the form of applied scientific knowledge, as individual capacity for knowledge, and as skills and knowledge materialised in the artefacts. We are thus concerned with a sociality and practice with things that also includes the formatting of practice through its materialities and procedures.

The following sections are oriented towards the development phases of laboratory practice and thus towards the social use of media of visualisation, formalisation and calculation. From the perspective of the sociology of knowledge, the paper shows how handwritten sketches are used as cognitive instruments to develop and record initial ideas (3). Following the logic of computers, the formalisation of the initial considerations in and through mathematics is a necessary second step. The section shows which methods are used by the roboticists to model the movements of the robot body in space (4). The penultimate section explains and analyses the practice of programming, its pitfalls, and corrections (5). The paper concludes with a summary and outlook (6). Before this, however, we address the question of how the work steps and development phases are to be understood, how they are linked to each other and how they refer to each other (2).

2 Recursive development cycles

In addition to computers, the roboticists we observed mostly work with pre-made robot platforms equipped with basic software architectures. In our observations, these platforms included a PR2 and KUKA robots. The PR2 features somewhat human-like traits, such as two arms, a torso, and a small 'head' with two cameras, though it lacks facial expressions or skin-coloured body parts (whatever that may look like). It is a bulky 226 kg grey machine that moves slowly. In contrast, the KUKA robot, with its massive single arm and protruding joints, bears little resemblance to human proportions. It would seem odd to draw similarities to humans, who can only be imagined as holistic entities rather than isolated components; at the same time, the KUKA's design loosely mirrors the structure of a human arm. Adding to that, the tasks both platforms are supposed to perform are oriented towards basic human practices, which are a) opening a cabinet door and b) opening a door in a wall.

Working with platforms is generally oriented towards software-related issues rather than crafting the robot body, i.e. controlling and monitoring movements of the humanoid robot. Questions of appearance (shape, facial expression, etc.) recede into the background for symbolic robotics, while technical capabilities such as navigation and object manipulation are focussed on. In this research approach, human-likeness is realised through movements that can be attributed to human dimensions. However, in everyday laboratory work, 'human dimensions' can refer to more than just bodies, cognition, or sociality; they also encompass cultural objects, spaces, and practices that are relevant to human action. These elements are integrated into development in two ways: first, they are used as locations and scenarios to demonstrate their applicability, but at the same time also pose (solvable) technical problems. For instance, the kitchen and the activity of setting or clearing the table are popular scenarios for testing domestic assistance capabilities and technically realising complex action sequences. This means that contexts of human practices are assumed and used as more or less systematised test environments. Second, symbolic approaches to robotics in particular model the understanding of world relations as if there were a correct representation of the world outside the cognitive system. The work of symbolic robotics therefore consists of discovering these independent features, analysing them mathematically, and reconstructing them symbolically. Within this semiotic system, the robot's AI system can calculate correlations and send control information to the corresponding parts of the body (e.g. a movement of the hand).

In contrast to linguistics and translation studies, which use the concept of translation to address the transformation of languages, language boundaries and language belonging (e.g. Derrida 1977; Dizdar 2009), we use the concept of translation to describe the socio-material processes by which material objects are transformed into drawings (graphic objects), drawings into formulas (operative writing) and formulas into a programming language (digital writing). Each step in this transformation process confronts the roboticists with the question of how they bring the object into a different material or semiotic form and considers how these changes impact its representation and perception. The object's existence in the programming language differs significantly from its physical form (Latour 1999: 24 pp.).

The programming process consists of several steps or stages. it begins with the modelling of world contexts, usually on the basis of an analogue object (1), moves on to the handwritten sketch with plan figure, dimensions, angles, etc. (2), then to the operative writing and thus to the elaboration of an adequate mathematical formula (3) and ends with its conversion into the digital writing of programming (4). On the one hand, we are talking about procedural steps that are organised linearly, i.e. that follow one another and cannot switch their position in this chain at will, as they refer to one another and presuppose the previous step. On the other hand, it is a recursive process in which each step or phase refers to the previous or subsequent step, goes back in the chain, is reversible, makes corrections, re-designs or re-examinations in order to then resume the only temporarily interrupted action step. This means that at every point in this chain there is the possibility of having recourse to an earlier phase by reinterpreting it and integrating it into the current context in a different form. In this way, initial drafts are shifted, and the previous results are re-evaluated and adapted. This means that the end product—e.g. the movement of a robot—is not simply produced but is manufactured in the laboratories in a constant back and forth between the analogue object and the requirements of digital writing (programming), between developers and users, which in our case coincide in the robotics engineers. Finally, each step itself is also organised into a series of productions, potentially complex acquisitions,[5] interruptions, training to compensate for not knowing, work on designs, and feedback—practices that also follow for a cyclical-iterative logic. For example, interruptions are caused by international conferences, which are essential for roboticists due to their thematic focus. They design experimental robotic setups and submit them as presentation proposals. In summary, this means that the transition from an analogue object to its digital representation with the outlined adaptations, heterogeneous materials, negotiations, etc. defies a simple linear conception. The different phases observed do not represent separate temporal organisations. Related ideas about the linear genesis of technology have been criticised and rejected many times in the past (Godin 2006). In their place, more open design-scientific models emerge, to which developers orientate themselves with their respective professional traditions and styles.[6] As we will show, this translation process is not self-evident for the roboticists but poses challenges that sometimes reveal the limits of their knowledge. This means that even if we assume this translation or transformation chain, we are not assuming a linear process, but one that is messy and contains various ad hoc attempts and assumptions about solutions.

3 The handwritten sketch

Research in the sociology and history of science (see only Latour 1999; Knorr Cetina 1999; Rheinberger 1997) as well as studies in cultural theory (e.g. Krämer 2015) have

[5] The manufacture of a robot requires the purchase of components, which involves a considerable amount of administration. This can lead to everyday disruptions that require mundane management expertise: Orders and deliveries are unclear, as are inventories and delivery blocks.

[6] On the relevance of visions of use for the development of software, see Lente (2000); on the repercussions of robot-supported visions of the future on the current perception of human capabilities, see Hayles (2005).

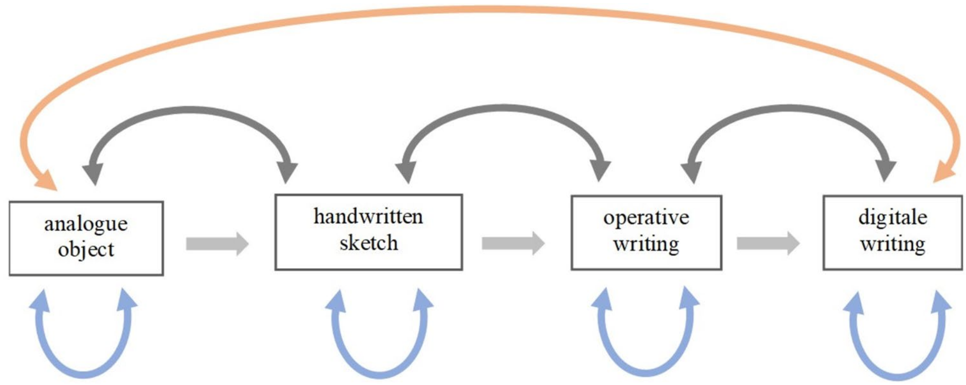

Fig. 1 Translation from objects to writing

emphasised the relevance of both the written word and writing for scientific practice. Accordingly, writing, recording, and drawing are epistemic practices integrated into the processes and procedures of the laboratory. The establishment of a scientific object, however, is not merely tied to its written elaboration and development but only acquires its specific form in the written act: as "knowledge in draft" (Hoffmann 2013). Writing opens up a creative space of possibilities in which the imagined, or the given can be (re)organised, placed in relation to one another or even changed (cf. Fergusson 1994; Henderson 1999). At first glance, writing, scribbling, and drawing can be done at will; at second glance, these activities are framed by the (imagined) objects to which they refer, as well as by the mastery of the cultural technique of writing, the practised handling of the materiality of the writing utensil, and eye-hand coordination. Our analysis does not focus on the gestures of writing but on what is put on paper - the durability of the signs, their practical use, their design, and their experimental character.

Before even the first tentative sketches can be made, a large number of other activities have already taken place. Not unlike other disciplines, roboticists receive, and process published papers, because although technical innovation can also be seen in finished prototypes, it can primarily be recognised by way of publications from the relevant sub-field of the discipline. This transfer of knowledge is organised collectively—in social form—and may also be initiated by (international) guest lectures, which in turn launch ideas, considerations or even solutions. With regard to the very first sketches on paper, it can be said that they represent rough outlines of the robot components. These paper sketches are cognitive supports or the cognitive medium in which to record and simultaneously stimulate and further develop. This is followed by considerations focusing on questions of feasibility: What platforms are required; what is available in the laboratory; what needs to be purchased; are available robots suitable or does the intended experiment jeopardise their stability or functionality? For example, training a robot to perform a certain arm movement may require multiple processes, which in turn wear out the robot material (such as metal, silicone and plastic). Sometimes laboratories also decide to carry out experiments that require long practice runs in the form of digital simulations. If work on the software is to begin, roboticists concentrate on whether the robot will be able to solve the task for which it is intended or whether changes will be necessary. Fig. 1.

Once this preliminary work is done and questions have been clarified, the work—in a narrower sense—on programming the robot movement begins. From an ethnographic protocol:

> Today, Max wants to model the cupboard that the robot will later open. When I ask him how to do it, Max replies that you basically have to know all its mechanisms. "That's the problem with modelling. Ideally, I would have built the thing myself," he sighs. With these words, he stands up, grabs the folding rule and goes to the cupboard next to the robot. He crouches down a little and places the folding rule on the right outer edge of the cupboard, then on the inner edge, then on the cupboard door: inner edge and outer edge. In between, he goes back to the desk next to the robot. Here, on the corner of the desk, he has stored his sheet of paper and pencil. He pulls the sheet towards him with one hand and draws a line while standing. He quickly takes a big step and turns back to the cupboard. And so, it goes on: Max measures with his folding rule, then comes back and draws another line that connects to the other, drawing angles and transitions, labelling one with alpha, then the next with beta. He looks concentrated: quietly, with a furrowed brow and narrowed eyes, he measures and draws, measures and draws, until he sits down at my desk again. Next to his drawing, he jots down equations. Every now and then he goes back from the equation to his drawing with his pencil, erases parts and adds new ones. After a while, he explains that it is very important not to make any measurement errors.

The scene documented in the extract shows how a roboticist, equipped with a measuring instrument (folding rule) and documentation media (pen, piece of paper), switches back and forth between the material object and the sketch. The object of the sketch is a cabinet with a horizontally folded door whose front parts are the same size and whose movement—opening or closing—is supported and made possible by a hydraulic mechanism. This cabinet is an object produced for the laboratory and its experiments, which provides a framework for its modelling through its materiality (same size of the front parts). At the same time, the experiment is based on an everyday object (in this case kitchen equipment) and thus makes the general background of the experiment recognisable, i.e. the usability of its results for robotic assistance systems (see Fig. 2).

From the perspective of a sociological document analysis, two dimensions are of interest here, namely the content (what does the sketch show?) and the form of mediation (how does the sketch show what it shows?). In part I, the open lower front with its points (S, P, Q) and side lengths (38, 27, 16) is sketched with loose strokes; the angles (α; β) indicate the rotation. Part II notes the lengths of the sides and assigns unknowns to the side lengths (x, y, z). In part III, the roboticist sketches simple circular movements of the three sides, which are opposite to each other. With the line drawing (part IV), the roboticist looks from the side at the imaginary opening movement and at the position of the cabinet frame and both front sides. When the lower front side is rotated upwards, the angle (α) increases and the angle (β) decreases. At the same time, the upper front side only opens when the lower front side has already been moved. These sketches make it clear what kind of practical problem the roboticist has to deal with: modelling the force required for the rotation and modelling the speed and length with which this rotation is to be carried out.

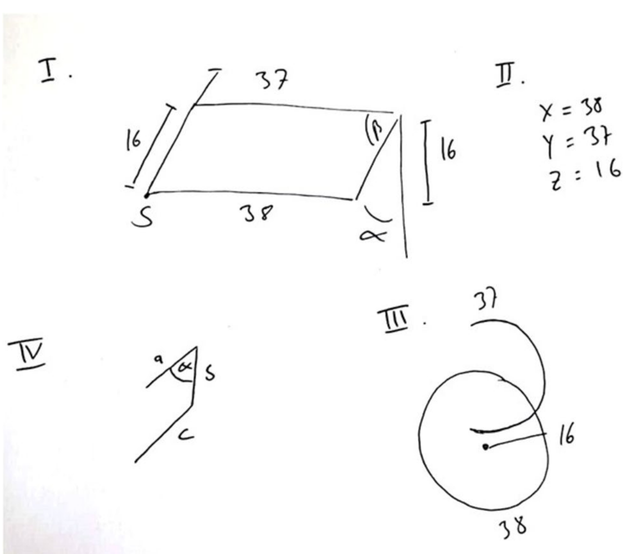

Fig. 2 Handwritten sketch: lines and signs

With regard to the form of mediation, it should be noted that the two-dimensional sketch functions as a particular space whose geometric flatness is intended to visualise the rotation yet to be realised and thus document a possible technical future. The cabinet itself is not drawn, but rather, the three-dimensional movement of a surface is brought into a two-dimensional form (point i), and the position of a movement is recorded in its two-dimensionality (point iii). The sketch is also characterised by its draft character, which is recognisable by its imprecision (alternation of upper and lower case letters) and incompleteness (e.g. lack of units of measurement)—as it seems to make sense to the draughtsman for pragmatic reasons. In addition, the order of the sketch—the elements are next to and below each other—follows a right-left and top–bottom scheme and, with this division, the European culture of writing. It is now the lines and dots that circumscribe surfaces or simulate movements, while the alphabetical and mathematical symbols ("S", "16") identify these dots and mark lines—and thus make them nameable. Something that is not visible in this way is sketched as a draft (e.g. rotation, angle), and is made available as a representation. These inscriptions on paper are no longer just simple lines or dots but features of an object (corners, extensions, etc.) to which they refer. The assumption, however, is that with the diagrammatics of the sketch—directionality, flatness, alignment, etc. (Stapleton et al. 2008)—a generalisable geometric form is possible and given. Furthermore, from the point of view of the roboticist , the sketch stands for a movement of the robot arm that is external to the sketch. On the other hand, it also stands for itself and is the starting point for revisions and further modelling with the help of mathematical symbols. The sketches thus tend to visualise the cognitive steps, bodily skills and reasoning of roboticists, which are later concealed or black-boxed by a seemingly autonomous operating robot.

In the case of another laboratory that follows the subsymbolic approach, roboticists sketch a three-dimensional space in which the movement of a robot hand is cognitively anticipated. This small example should highlight that while sketching may be used extensively in symbolic robotics, it is also a fundamental tool for other approaches. The idea visualised in writing is that mathematical formulas (i.e. quadratic equations from the field of quadrics) are used to control the joints of the robot (such as the 'elbow' and the 'shoulder') and the virtual actuation space.

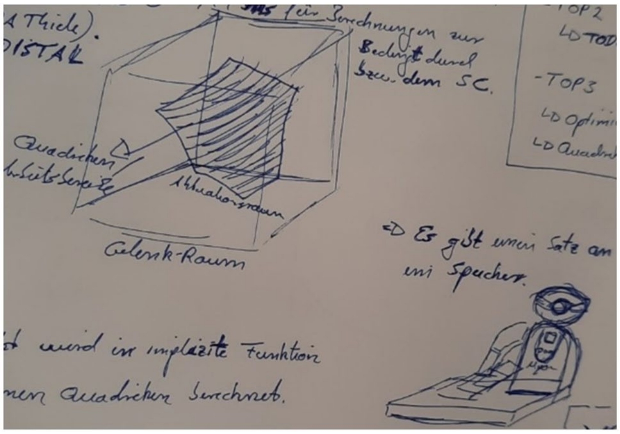

Fig. 3 Actuation space

$$\mathbf{p} = \begin{bmatrix} \cos\left(\alpha - \frac{\Pi}{4}\right) \\ \sin\left(\alpha - \frac{\Pi}{4}\right) \end{bmatrix} \bullet \mathbf{y} \quad \mathbf{q} = \mathbf{p} + \begin{bmatrix} \cos(\beta) \\ \sin(\beta) \end{bmatrix} \bullet \mathbf{Z}$$

Fig. 4 Draft formula

Actuators are responsible for the movement of the robot ‘arm’ in space, which converts electrical signals based on the mathematical formula into a movement of the ‘joints’.[7] This space also consists of a large number of points with which the control by the actuators can be determined with pinpoint accuracy in order to know where the joints are when the robot moves (see Fig. 3).

In this case, too, the power of handwriting lies in the fact that initial ideas are sketched out, first thoughts on an algorithm are written down, and object recognition is hatched by humanoid robots. All these handwritten notes, drawings, and scribbles record what could otherwise be lost, but without recording everything else. In addition to their pragmatic documentary function (see above), they open up a space for ideas and concepts that can be connected to and worked on, adopted, and forgotten. However, these material things—pen and paper—are not only to be understood as a “semiotic technology” (Barany/MacKenzie 2014) in the hands of the roboticists but also as their cognitive tool, which, through its relative slowness and provisionality, sets thought processes in motion, keeps them going, and supports them. In this sense, robotics laboratories are, too, a scriptorium for designing, correcting, and reflecting with a pen in hand.

4 Formalisation with operative writing

In mathematical research, proof functions as means and object of communication and understanding (Heintz 2003). While mathematics centres on proof and the question of whether the possibility of proof itself can be proven, in symbolic robotics laboratories, the focus shifts to modelling movements (e.g., rotational motion) or artificial neural networks. To this end, roboticists work with mathematical or typographical signs, among other things, to create a formula that makes sense from their point of view. These formulas are therefore the result of a process of translating empirical facts into signs that can be used for further operations.

This practice of calculation continues in the next step with the use of pen and paper. In this second step of symbolic robotics, the aim is to transform the (geometric) sketches into discrete mathematical (numerical) signs, which we refer to as operative writing.[8] This means that writing is (initially) done on paper, but in the medium of operative writing. The conversion is accompanied by a formalisation, which in turn is a prerequisite for programming and thus for digital writing. Two aspects come together in the first handwritten formulae: from a technical point of view, the problem is to convert force into rotation and to develop or apply an adequate formula for this. From a social point of view, the problem is that roboticists do not always have the mathematical knowledge necessary for this mathematisation. They compensate for this knowledge gap—“I’m not a mathematician” (participant)—by exchanging ideas with other roboticists or engineers, for example, via messenger services or exchange platforms. They usually communicate their technical problems, receive tips on possible errors, discuss other approaches to solutions, etc. Sometimes they take part in crash courses (“bootcamp”, participants) in maths to find and apply solutions for their approach. The centre around which these social activities are arranged is the search for and discovery of a (seemingly) adequate solution, whereby the knowledge can circulate between the actors, but the actors themselves are tied to the laboratory. The handwritten notes represent an initial formalisation of the task of modelling movement (rotation) and force. Algorithms or equations are written down by hand as non-linear illustrations (see Fig. 4).

In this non-linear mapping, the roboticist notes points in space (P, Q) and the rotation matrix of the vectors, each with

[7] This process is familiar from the field of smart homes, for example. There, actuators mechanically implement a digital signal (“raise shutters”)—sent from a smartphone from Paris to Berlin, for example.

[8] Operative writings “do not emerge from the written form of spoken language, but are graphic systems *sui generis*, which can then at best be verbalised. The special feature of this writing is that it does not refer to speech sounds, but to cognitive objects” (Krämer 1997: 115, our translation); they are also a medium for the representation of objects and a tool for symbolic operations with these objects.

two dimensions. An attempt is therefore made and tested here to model a rotation of the unit vector by the angle alpha or beta, which is reduced by an eighth rotation. The second vector is also a unit vector and describes the rotation of this unit vector by the angle beta. With the use of a mathematical tool (the Jacobi Matrix), the roboticist derives values for the movement/rotation and thus for the force required for forward movement in a three-dimensional space. Point by point, the position and movement of the joint angles are calculated. This movement is intended to bring the gripper into a certain position as the last link of a kinematic movement. In other words, the roboticist models the movement and speed of joints with each joint containing a derivation to the next joint. The roboticist implements this step by step, with ongoing corrections and new trials.

An ethnographic protocol states:

> Max has solved the problem we observed a few days ago, namely that the robot yields to the resistance of the door - i.e., its wrist bends. He has adjusted the direction of the calculation. Namely: if a certain resistance becomes apparent, a formula calculates how the remaining joints from the elbow to the shoulder must be positioned. “It’s a very simple formula,” says the robotics expert with fascination.

The adaptation of the direction of movement through a modified calculation takes place by working on the aforementioned matrix. If, for example, the robot hand (the gripper) needs to be in a certain position to open a cabinet and not bend, then the position(s) and movement(s) that the joints successively assume are differentiated by new values.[9] The use of the Jacobian matrix is also associated with a change of medium - from handwritten notes to working on the computer.

To summarise: While the handwritten sketch still allows for transitions, connections and overlaps, the formulas, despite their trial stage, stand for a strict sequencing of self-contained units. They are either arranged one behind the other or on top of each other, and have dispensed with any connections and transitions. Moreover, the sequence of these works is reversible which means in case of doubt, that the geometric drawings are corrected if they do not seem to fit with the mathematical formulation. In this way, the roboticist constantly switches back and forth between the formula and his/her previous drawing; one could also say that the drawing informs the transcription of the other mathematical signs. In this process, references can change from the cabinet to the drawing, from the drawing to the formula and from the formula to the digital model. One roboticist describes this change as follows: “The worst case is when you realise that what you have done physically does not work in the modulation”. It is not the artificial model that has to fulfil the requirements of the physical world, but the other way round: the latest, purified version of the representation forms the reference point for programming efforts. This means that human contexts of action are then only regarded as a perceptible starting point, but no longer as a target variable. They are broken down into a series of tasks to be processed technically.

5 Digital writing and the bodies of roboticists

The third step is based on the preliminary work outlined here: programming the formula(s) in programming software. First, however, the developed formula will have to be transferred into a programme:

> The roboticist solves and visualises the equation using different software. Frome time to time, he looks at his handwritten calculations and drawings; he shakes his head and explains that he is trying to use *Wolfram Alpha* to solve his handwritten equation. But what it spits out as a solution is far too complicated. He tries another program, he announces, leaning forward and starts typing. After a few minutes, he sighs again. “Okay, so it can’t cope with multiple designations. It calculates AB as A times B”. The programme, he explains, then suggests several interpretations of the function. He moves his finger across the screen and points to individual lines and translates for me: “Here it says: If y=0, then the solution looks like this “and moves his finger along the characters. “But Y is 37! (...) That means he has too little information,” he explains. “What’s more, the proposed solutions are far too complicated. (…) You see, with Python, it starts over here and goes up to” - he scrolls -” up to here! It’s just messy and complicated”. He continues typing, now in latex, waits briefly, looks at the screen and leans back again, looks at his formula on the paper, sighs: “Okay, now I have to fumble out b everywhere.” The problem now has to be redefined, he explains, with vectors so that the programme understands it.

Three things are identifiable from this excerpt. First, switching between programmes, with the expectation of achieving fewer complicated solutions; second, checking the typewritten output against the handwritten preliminary work. The validity of the software’s ability to produce correct and unambiguous results is tested based on the preliminary work. It becomes clear that software programmes do

[9] Inversion is also possible: The position of an object that is to be manipulated is then entered in order to derive how the joint angles must be positioned.

not read discrete mathematical units uniformly and therefore create room for interpretation, which can also lead to unexpected results. The work of the roboticists then consists of clarifying the ambiguity of the mathematical symbols that make up the formula in such a way that they can be processed correctly by the programme. Third, the transfer from handwriting to computer writing using specialised software appears to be surprisingly complicated. In contrast to the ideal of linear mathematical practice, mathematical equations appear to be “messy” and ambiguous.[10]

Once this mathematical simulation of the cabinet has been completed, the next step is to programme the robot to manipulate the object—opening the cabinet. To do this, the robot not only needs the cabinet simulation, but also a model for motion planning and information about the motion sequence—the participants refer to this as the “motion trajectory”—of the opening cabinet door. For the latter, Max uses so-called markers: these are large QR codes that provide information about the position and rotational movement of the door and are stuck to the edges of the cabinet door. The robot can then read and calculate the QR codes as soon as the camera on the robot’s head is pointed at the cabinet. The roboticist has also created a navigation function that regulates how the robot arm moves. This function consists of reaching a surface point of the cabinet and furthermore of moving the robot arm. For this purpose, a target which the robot should reach with the programmed forward movement of its arm is mathematically formulated, whereby the closed door is defined as the initial state of the cabinet as follows: q^0.

Time and again roboticists sit—sometimes for hours—in front of their two or three screens, which show, for example, various programmes or what the robot ‘sees’ and are immersed in the programming activity.

> The roboticist is typing on the computer, we are silent. After a while, he exhales audibly, I look up and meet his gaze. He continues: “It’s always stupid to debug other people’s code - and to use other people’s code in general, at least if it’s not good”. “When are they not good?” I ask back. He laughs: “Well, when I don’t like it - just when they’re not uniformly named or have lots of side effects and aren’t properly formatted”. (...) Now he is completely turned towards the screen, physically almost immobilised, so that only his hands, move and his comments relate to what is visible on the screen. He continues to stiffen up, typing, mumbling now and again (“frame seven”) and typing and typing. (...) A little later, he sits bolt upright in his chair; his fingers fly over the laptop keyboard. Apart from his fingers, his body does not move; only occasionally do his lips silently form a few words. Hardly anything happens outside the clocked finger movements. His gaze wanders from the keyboard of his laptop to the right-hand screen, lines jump up, and the roboticist writes on them as if he were replying to them. Although it is very hot in the hall, he shows no signs of discomfort, no sweating. (...) He has been working like this for an hour. He doesn’t talk. and apart from his fingers, only the characters on the screens move. He has positioned his hands so that they don’t have to move while he is typing: While his index, middle and ring fingers alternate between hitting individual keys, his thumbs remain motionless in the air - as if they were stiff foreign bodies that have nothing to do with the rest of his hand. Much less often than the other fingers, they move down to the space bar. He can easily reach any key with his fingers without having to adjust his posture or hand position. He remains motionless in his position while his fingers do their work. His gaze is strictly focussed on one screen or the other. He doesn’t even look down at his fingers, which strike the keys in a well-rehearsed rhythm.

The programming establishes a connection between human cognition, human preparatory work, and machine signals that are prescribed by the programming. The programming roboticist remains in a very concentrated pose in front of his three screens for an extended period of time (approx. 1.5 h). He is not ‘Lost in Translation’ but has temporarily become one with his activity: no despairing or doubting over unsuccessful or inaccurate preparatory work, no rejoicing over successful steps or working formulas, no wandering eyes over the landscape of the laboratory, no explanations and no chatting with the ethnographer, who follows the action from close up. Nothing comes to the visible physical surface that the body might still feel: too concentrated, too focussed The roboticist experiences a flow of programming, only the fingers move in the same position and in the same rhythm over the keyboard—and produce a digital document that seems to be coherent and meaningful to the roboticist. In this close human–machine coupling, other aspects are irrelevant; keeping the flow going is all that counts.

The detailed definition of the rotation properties of the cabinet doors (or other objects) and the relationships between the state of the cabinet and the arm movement of the robot (e.g. if 0 then backwards movement, if 1 then forwards movement) do not necessarily result in a functioning object manipulation. It is repeatedly checked whether what was previously defined and written down actually works on the physical robot platform. This is recorded in an ethnographic protocol:

[10] We will not go into the fact that roboticists appear to suffer physically (‘sighs’).

> "The problem now is that it's beating up the cupboard, but at least we now know that it has enough power," laughs the roboticist, "it's beating up the cupboard?" - and grinning, he turns to his laptop, presses the start button and points at the robot. The robot arm moves forwards towards the cupboard, faltering violently and starting up again and again. At the same time, its circular movements take place mainly in the air and hardly seem to be synchronised with the position of the cabinet. When the gripper touches the cabinet, it does so only peripherally at the edge of the handle, where it then slips off and bangs loudly against the cabinet surface. "Shh, shh, shh" says the roboticist, as if trying to calm the robot down like a small child. The robot obviously has a problem with its navigation function: "It has problems with narrow objects. The gripper is supposed to move away from the edges. But if the object is narrow and the movement is too sweeping, then the robot arm is right at the next edge." So, the robot gets stuck in a path movement loop.

It becomes apparent here that the deductive operationalism of symbolic robotics also draws on inductive approaches This is a tentative experimental practice that sometimes refers to knowledge gaps but tends to irritate ideas of a linear approach. In this context, one can also recall the experience of programmers who "simply (cannot) know what a certain sequence of characters does as long as the code is not executed" (Labatut 2023: 233; own translation).

Formalising an arm movement in an algorithm is a practice, having it successfully executed by the robot is not always an expectable result. First, in the instruction of the programme code—move away from the edges—specific properties of the object, such as having only a narrow grip, are not yet sufficiently taken into account. It seems that the dimensions of the movement or the physical objects that become relevant in the actual application cannot be fully anticipated in the planning and modelling of the arm movement. Second, formal descriptions of the movement of physical objects on the one hand and the forms of interaction between robot and object on the other hand convey a space of indeterminacy in the medium of mathematical symbols. Dimensions that are coherent with calculation paths and logics can (also) unfold a certain absurdity in their application on the robot platform: a robot "bashes" a kitchen cupboard. The absurdity of the situation is emphasised by the participants through playful anthropomorphisation.[11] These almost affectionate commentaries accentuate less the failure of programming efforts, the failure of an experiment and an intended publication, but rather they create time. For in these moments, the roboticist's paralinguistic utterance formats ("pscht, pscht, pscht") calmly take account of the fact that software and hardware, body and algorithm cannot be translated into each other without difficulty. The serenity demonstrated here transposes the erroneousness and normality of everyday life in the laboratory. The pressure of time and publication, career worries and frustration over failed experiments seem strangely absent here. Obviously, the error-proneness of the experimental setup is something that is expected. But less relaxed situations can also be observed:

> Two roboticists are working on the robot. Omar is holding a remote control with a large red emergency button on it, which can be used to stop any of the robot's operations. While one roboticist sits at the PC in front of the robot, the other, who is standing next to the robot, sticks markers on the robot's gripper. "Careful!" one roboticist shouts loudly and energetically to the other, "I'm going to move the robot a little bit". The other nods and takes a step back. Although the gripper arm only twitches briefly and only moves downwards by about 2 mm, this loud warning is obviously not disproportionate for the second roboticist—no smile, no flippant remark. But I have to smile—in view of the big warning and very small movement.

Two roboticists work on the robot arm in a focused manner, sharing the workload. While one is working directly on the robot, the other is working on the programme code and trying to control the arm. This reveals a pronounced scepticism as to whether the instructions formulated with the algorithm will actually be implemented by the physical platform. This is made clear both by the permanent presence of the emergency button and by exclamations ("Careful!"). Whereas before, expected misbehaviour was dealt with calmly, here it is much more a potential crisis and danger situation that is triggered by the lack of knowledge about how the robot will behave. Roboticists do not control these platforms; rather, they are artefacts to be tamed, and their control is a practice that must be performed again and again. At the same time, a discrepancy is revealed between the ethnographer's expectation and the robot's arm movement. For roboticists (in contrast to laypeople), it is an everyday task to harmonise software and hardware and not (yet) know how the robot will react at all. This risk of not knowing relates to whether what has been programmed or written will unfold on the physical robot platform as intended and imagined. However, the roboticists also saw this discrepancy, to which they reacted with humour, as a sign of the danger posed by the robot.

[11] For an analysis of the concept of human-likeness and the imaginations, it triggers, see Rhee (2018).

6 Summary and outlook

This paper has provided empirical insights into the experimental settings of symbolic robotics laboratories, tracing the intricate scientific practices involved in creating seemingly autonomous robots. Our analysis sought to analyse the fabrication of humanoid robots by revealing the extensive human labour behind their development. This makes it necessary to shift the current discourse from the question of whether and how humanoid robots will replace humans to the efforts and constellations in the laboratories. The assumption that these robots are autonomous machines should be replaced by an analysis of the processes by which they are created.

The article has empirically explicated and analysed technoscientific practices. Three aspects characterise these practices: first, the intensive work on the software moves the robot with its body to the periphery of the scientific interest. This peripheralisation results in the robot itself being only partially accessible to the roboticists, as it reveals its full functionality only when software and hardware are coupled. Second, when roboticists transfer an algorithm to the physical platform, they must align software and hardware, i.e. write programme codes into the platform in the way the robot is supposed to execute them, whereby the robot specifies how it can read which code. Thus, it is not primarily the programme code that determines how the robot moves. Rather, the robot's affordances pose challenges to the roboticists; in executing experiments, the robot platform reveals itself. Third, our contribution emphasised the role of (hand)written and visual media in the context of symbolic robotics. From the perspective of this paper, it would be short-sighted to differentiate them pragmatically as mere recording media and not also take into account the cognitive dimension of reflection, modelling and imagining that is expressed in these practices of sketching, noting and formalising. Our analysis underscores the complex, recursive connection between these media and their social use by roboticists, rather than suggesting a linear transmission of engineering knowledge onto paper.

We have analysed the documents referenced in this article in terms of their internal relationship and in relation to the question of which version of reality is created by this constellation. As shown, these documents collectively create their version of reality by instructing roboticists who create or handle them to develop and apply rules (algorithms) and programme codes. At the same time, this practice also points beyond these documents and media to the robot platform with its specific codes. It is this constellation of the material infrastructure of the laboratory, robot platforms and (hand) written and electronic media, etc., in which the research and its (routine) practices unfold. It is not a question of only needing to apply technical knowledge. Rather, the roboticists we observed are systematically and constantly confronted with the precarious outcome of their research. For them, it is a question of considering how the carefully constructed components will function once they have been assembled or of "a feeling" (Keller 1984) for an artefact whose internal structure is and remains more or less unknown. In order to balance out this uncertainty and stabilise their knowledge, they repeatedly test and try out what they have developed, partly to get a sense of the robots' workings. It can therefore be said that the research practice of roboticists oscillates between three states, namely between approaching the machine, feeling the machine, and understanding what might be going on in the machine. It is evident that the analytical gaze is abandoned to a certain extent to close epistemic gaps.

The practices of representing serve to bring the reality in which the robot body ought to move into a two-dimensional form. As illustrated, the object to be manipulated (a cabinet) and the planned robot movement (opening the cabinet) underwent a multiple translation process. Thus, the epistemic object of the roboticists—the opening of a cupboard door by a robot body—is represented in the form of a hand-drawn sketch using various written media, calculated using conventional mathematical formulas and integrated into the robots' computers as a digital drawing object, i.e. programmed. This means that the media and methods used not only represent the movement of the robot and make it calculable but also produce it.

Regarding the discussion of the human-likeness of humanoid robots, the article has traced the work, complexity, and pitfalls of robotic practice in detail. The production of human-likeness goes through these phases of iterative work on formulas, translations and materials. The astonishment about the somewhat fetishised humanoid appearance of these robot types is countered by an empirical insight into these practices and strategies of technical humanization. Finally, this article raises the question about the societal relevance of humanoid robots, and thus about the future society with a technically designed intelligence, the full development of which is not yet foreseeable. That is to say that engineers design possible future interactions with human-like machines, which in turn are semantically described and promoted as assistants but can also potentially replace humans. This case opens up the powerful effects robotics may develop: the influence of engineering science on the (technical) design of human sociality when their product has left the laboratories. Not only is a technical artefact being developed, but human sociality is being designed. Yet, it is an empirically and theoretically open question how roboticists do not just use media of representation and calculation as tools but make those media subjects of their research.

The article has demonstrated that the realisation of ideas about humans or the human is closely linked to the different representational media that roboticists make use of. A major challenge for any (ethnographic) research on robotics is to capture the often invisible and silent labour of programming as a sensual immersion of the roboticists in the software they develop. The corporality of this practice eludes direct observation and verbal articulation. Furthermore, our study captures only a small section of the broader field of robotics, which encompasses multiple developmental paths and specialisations. We propose two strategies for future research: first, further ethnographic studies are essential to expand the social and cultural understanding of this field. Second, to our knowledge, there is no constellation analysis of the field of robotics that relates the various research approaches and material resources, the orientation to the (potential) market or to basic research, the more national or more international orientation, etc. (see Bourdieu 1987). Such an analysis would be able to explain, among other things, how institutional affiliations help shape the production of knowledge and technology in robotics.

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