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What is robotics made of? The interdisciplinary politics of robotics research

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Under framings of grand challenges, robotics has been proposed as a solution to a wide range of societal issues such as road safety, ageing society, economic productivity and climate change. However, what exactly is robotics research? From its inception, robotics has been an inherently interdisciplinary field, bringing together diverse domains such as engineering, cognitive science, computer science and, more recently, knowledge from social sciences and humanities. Previous research on interdisciplinarity shows that this mode of knowledge production is often driven by societal concerns and political choices. The politics of who gets to make these choices and on what terms is the focus of empirical research in this paper. Using a novel mixed-method approach combining bibliometrics, desk-based analysis and fieldwork, this article builds a narrative of interdisciplinarity at the UK's largest public robotics lab, the Bristol Robotics Laboratory. This paper argues for the recognition of the plural ways of knowing interdisciplinarity. From citation analysis, through tracing of the emerging fields and disciplines, to, finally, the investigation of researchers' experiences; each method contributes a distinct and complementary outlook on "what robotics is made of". While bibliometrics allows visualising prominent disciplines and keywords, document analysis reveals influential and missing stakeholders. Meanwhile, fieldwork explores the logics underpinning robotics and identifies the capabilities necessary to perform the research. In doing so, the paper synthesises plural ways of locating politics in interdisciplinary research and provides recommendations for enabling "structural preparedness for interdisciplinarity".

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> "The primary mission of Bristol Robotics Lab (BRL) is to understand the science, engineering and social role of robotics and embedded intelligence. In particular, the key challenges surrounding adaptive robotics, namely: dealing with people and their unpredictability, unstructured and uncertain environments, and equipping robots for flexible roles."
>
> Mission statement of the Bristol Robotics Laboratory (BRL, 2020).

Introduction

We encounter robots with increasing regularity in everyday life. Emerging from secluded military settings and heavy industry, and now characterised as self-driving vehicles, assistive living technologies and home cleaning, robots are designed to work both *in* and *for* society. Grand challenges and industrial strategies frame and fund such technologies, often justifying them in terms of their contribution to addressing societal problems such as road safety, an ageing European society, economic productivity and even climate change (Ridley et al., 2014; Waldrop 2016; Chance et al., 2017). Notably, robotics—the design and application of robots—is often presumed in policy to be something that happens after politics; technology as a palliative for economic and societal ills.

For example, innovation in self-driving vehicles is today's quintessential case of robots entering society. Here, as with other forms of innovation, technology development is itself a site of political contestation (Winner, 1997; Noble, 1984; Feenberg, 2002). Moreover, at these sites lie a host of political questions and choices. In the case of self-driving vehicles questions are so often framed narrowly around road safety. However, if the transformation of our public and private transport systems are to be as radical as proponents make out, other questions arise. Who will benefit from these transformations and how will those benefits be distributed? Will inequalities in society worsen? What environmental or economic harms might be created through the manufacture and use of such technologies? How will self-driving vehicles re-shape personal responsibility on roads and in public spaces, and with what consequences for litigation, education and regulation?

The political challenge of research in self-driving vehicles and robotics more broadly is not to scale up technology with utmost haste. Rather, it is to ensure the most appropriate possibilities for society, the economy and the environment come to fruition (Sparrow and Howard, 2017). More consequentially for this paper, redirecting technological change in ways that are more beneficial to society requires political action that extends into the procedures and practices of research (Stilgoe, 2020; Lo Piano, 2020)—taking the form sometimes of policy, but often of mundane everyday choices made by researchers.

Interdisciplinary robotics is twice implicated in these politics and choices. First, in how interdisciplinary modes are so often championed in addressing grand challenges (Hrynaszkiewicz and Acuto, 2015). As robots, autonomous systems and underlying infrastructures are integrated into the fabric of social worlds, they require a wider range of actors to engage with them (Goulden et al., 2017). In particular, the expansion from military and industrial development to domestic and non-industrial applications (e.g., cars, carers, cleaners) has led to the interdisciplinary inclusion of social sciences, humanities, arts, end-users and policymakers (Goulden et al., 2017; Patel et al., 2019). By funding interdisciplinary projects, typically industry-academia collaborations, governments hope to bring science and technology closer to the citizens, hastening public acceptance and adoption.

Second, robots are both material *and* social—robots shape society as much as people shape robots (Šabanović, 2010). Politics in technology development comes about then because the emergence of science and technology is co-produced with social orders rather than a product of them (Jasanoff, 2004). And so, in this paper we aim to understand how robotics is co-produced both within research institutions and with wider society.

Our research questions are: what are the politics of interdisciplinary robotics research? What can this tell us about what robotics is made of? Finally, how could research projects be structurally prepared for interdisciplinarity, so that they're aligned with the public interest?

In answering these questions, we understand politics in three complementary ways. A first kind assesses, cartographically, how interdisciplinary robotics is. What are the kinds and number of disciplines involved, the modes and tools of integration (Siedlok and Hibbert, 2014), and the knowledge communities that emerge from these relations? A second kind is discursive and institutional; it highlights the multiple and contested interpretations over the potentials and performance of robotics research. Moreover particularly, how these interpretations are used as logics that legitimise, shape and steer the development of technologies and the co-production of social orders (Barry et al., 2008). A third kind is based on the capabilities that underpin the doing of interdisciplinary work, and making the everyday research choices we mention above (O'Donovan et al., 2020). These capabilities typically include technical and disciplinary skills, but also collective powers to convene, to work collaboratively and to negotiate alternative visions for robotics futures (ibid.).

Rather than focussing on a narrow application domain, say self-driving vehicle technologies, we locate our enquiry at the Bristol Robotics Laboratory (BRL) as a whole, together with its' researchers and partners. The paper proceeds by investigating the cartographic, discursive and institutional features of interdisciplinarity and its politics at BRL along with the capabilities that underpin interdisciplinary practices.

In the next section, we expand a co-productionist account of the politics of technology to help us understand how science and society are mutually implicated in robotics. We then propose an evaluation of the politics of interdisciplinarity as a form of cartographic-discursive capability assessment. In section "Methods", we operationalise these ideas using a novel mixed-methods framework integrating cartographic scientometric analysis with discursive document analysis.

Results are further discussed in section "Results", where we introduce three case studies, each used to identify capabilities valued in three interdisciplinary research areas at BRL. Through the cases we assess, respectively, an ongoing portfolio of self-driving vehicle research projects; bioenergy research; and research on assisted living robotics.

In section "Discussion", we discuss the implications of these politics for how researchers at BRL might better structure projects and align them with societal needs. In other words, we provide recommendations enabling "structural preparedness for interdisciplinarity" (Engwall, 2018). In particular, we argue that cultivating interdisciplinary capabilities at every research stage is the key aspect of acknowledging and addressing the politics of robotics.

Locating politics in interdisciplinary robotics research

Coproducing robotics, coproducing robots. The emergence of modern robotics can be traced back to World War II when Soviet and Nazi armies launched remotely operated mines and tanks (Murphy, 2019). In 1962, Unimate, the first industrial robot, began working on a General Motors assembly line in Ewing

Township, New Jersey (Diodato et al., 2004). Since then, the main logic of robotics has been replacing “dull, dirty and dangerous” jobs (Takayama et al., 2008). Meanwhile, universities have embraced this opportunity and established several research centres and industry collaborations. Since the early 1960s, artificial intelligence laboratories at Massachusetts Institute of Technology, Stanford, and The University of Edinburgh have worked on the design, development and conceptualisation of robotics (Diodato et al., 2004).

These labs, and others, have included scholars from a wider diversity of disciplines. As Birk (2011) argues, robotics is interdisciplinary, applied and collaborative by nature as it “combines electrical and mechanical body with computer brains” (p. 94). Furthermore, the emergence of new applications (e.g., transport or healthcare) enabled the opening up of the field towards new disciplines like biosciences, cognitive sciences and psychology (ibid.). The disciplinary distribution of publications in robotics between 1989 and 2009 (Fig. 1 adapted from Birk, 2011) shows the rise of bio- and cognitive sciences. How has the interdisciplinary landscape of robotics changed since then? Moreover, what are the dominating logics of robotics research and innovation?

Currently, the public funding landscape for robotics research is characterised by “grand challenges” or “mission-oriented” interdisciplinary funds, the ongoing work towards ethical standards and AI Ethics governance frameworks (DBEIS, 2019). Under this paradigm, robots and robotics are “co-produced”; they co-evolve with the people, processes and policies (Jasanoff, 2004). Jasanoff (ibid.) challenges linear modes of innovation, which emphasises science push or demand pull. Instead, innovation is susceptible to political influences, which can be traced in everyday practices and policies (ibid.). Co-production arises through interactions and collaboration; this includes interdisciplinary mode of research. It can be found in the milieu of institutions, imaginaries and infrastructures in and around robotics labs. Therefore, focusing on the work inside robotics labs provides a viewpoint on the “making of” technologies, science, standards, controversies and problems (Stephens and Lewis, 2017).

Steering robots for the society. From the IEEE ethical product standards (Winfield, 2019; O’Donovan, 2019), through robotics legislation (Palmerini et al., 2016), to AI ethics frameworks (Floridi, 2018), numerous initiatives are working towards enabling collaborative, reflexive, responsible and ethical research on robotics. While they are designed to align the direction of innovation with the contemporary social challenges, standards and high-level frameworks do not always reflect research activities on the ground. Concerns about robots in society, voiced through social movement organisations, collective action, media commentary and academic research suggest that the existing governance of robotics and autonomous systems technologies is insufficient (Torresen 2018; Winfield et al., 2019; Johnson and Verdicchio, 2017; Döring and Poeschl, 2019). In particular, Johnson and Verdicchio (2017) argue that the fears about AI and robotics governance focus too much on software capabilities. Instead, the missing object of governance is humans who make decisions about designing embedding robots and AI in society.

Whether ethical frameworks are possible to enact through research activities depends on people’s capabilities to perform socially beneficial interdisciplinary research. Drawing from O’Donovan et al. (2020), we understand capabilities as opportunities to conduct interdisciplinary work valued by researchers themselves. Foregrounding capabilities is a critical feature of our approach. It shifts the analytical focus to the cultivation of means rather than solely measuring outputs or achievements. As such, we ought to acknowledge that capability building starts well before the research activities commence. Embedding non-academic partners in the research setting, building user testing infrastructure and living labs, and establishing professional networks are all common tools for enhancing collaborations in the UK research settings (Carnabuci and Bruggeman, 2009; O’Donovan et al., 2020).

For that reason, we regard mapping interdisciplinarity as a form of capability assessment, and further, capability building. Taking stock of interdisciplinary activities means funders and policymakers know what is going on inside research labs, what their strengths and gaps are. We argue that a systematic analysis of multiple ways interdisciplinarity is organised will enable us to think better about research evaluation and enhance traditional research quality metrics with considerations of responsibility, ethics and power.

Defining, describing and measuring interdisciplinarity. Disciplines come to life through establishing common concerns, sets

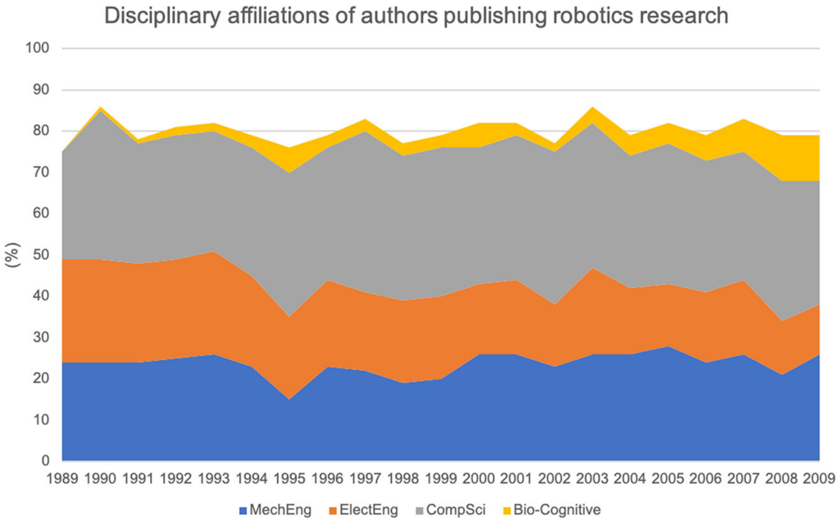

Fig. 1 The distributions of disciplines in academic publications of the top ten robotics journals indexed in Web of Science between 1989 and 2009. The figure shows a rise of biological and cognitive sciences in addition to engineering and computer science disciplines underpinning robotics (adapted from Birk, 2011). This figure is not covered by the Creative Commons Attribution 4.0 International License. Reproduced with permission of Brik, copyright © Birk, all rights reserved.

of methods, and vocabulary. They are then reified through disciplinary journals and academic departments (Strathern, 2004; Barry et al., 2008). However, as Huutoniemi et al., (2010) noticed, "disciplines aren't watertight boundaries". This is particularly true of the emerging, evolving or challenge-oriented fields, which have more flexibility to incorporate the contributions from other disciplines (Abbot, 2001).

But *inter*disciplinarity is a slippery concept, escaping rigid definitions, typologies and measurements (Klein, 1996). It is not always clear, for example, when and how the integration of disciplines happens. Huutoniemi's et al. (2010) review of 20 typologies of interdisciplinary research concluded that we can analyse interdisciplinarity according to the following foci of interest: 1. Which disciplines are integrated? 2. How is it done in practice? 3. Why does interdisciplinarity take place?

Kelly's (1996) conceptualisation of "wide" and "narrow" interdisciplinarity addresses the first question. "Narrow" collaborations are carried out within the framework of an epistemologically and methodologically homogeneous field; while "wide" interdisciplinarity originates from conceptually diverse areas. Consider Shen's et al. (2019) analysis of interdisciplinarity in robotics surgery. One way to conceptualise it is labelling it as "narrow" interdisciplinarity, as disciplines involved (surgery, engineering; radiology, nuclear medicine, medical imaging; and neurosciences) typically share a positivist epistemological position, and often, an overarching scientific method (Kelly, 1996). While analysing the breadth of interdisciplinary integration is the first step to understanding robotics, lab ethnography studies show that we ought to pay attention to work practices behind the labels of disciplines. As Knorr Cetina (1999) shows, there is no such thing as a single "scientific method" as each lab can be distinguished by their particular "epistemic culture"—a set of practices used to advance knowledge in particular fields, colloquially known as "tricks of the trade". For example, robotics' epistemic culture can be characterised by conventions in publishing that aren't present in, for example, neuroscience. While robotics encourages publication of prototypes and patents, in neuroscience, it is commonplace to see publications focusing on theory development (Fitzgerald et al., 2014; Callard et al., 2015). Therefore, we ought to investigate both conceptual relationships between fields and practices hindering or enabling interdisciplinary collaborations. Such integrated accounts have a solid empirical grounding and contribute to a deeper understanding of political processes underpinning interdisciplinary research.

Previous research on interdisciplinarity shows that this mode of knowledge production is often driven by societal concerns and political choices. The politics of who gets to make these choices and on what terms can be revealed through the analysis of research practices. Indeed, this follows a rich tradition of lab studies within the field of science and technology studies (STS) (Sormani, 2016; Latour and Woolgar, 2013; Stephens and Lewis, 2017; Collins, 1985; Knorr Cetina, 1999). Past STS accounts of interdisciplinary collaborations called for an analytical shift from measuring disciplines alone to investigating lived experiences and practices (O'Donovan et al., 2020; Holmes et al., 2018). In particular, O'Donovan et al. (2020), highlighted that capabilities to perform inter- and transdisciplinary research go beyond cognitive abilities to synthesise theories, methods and concepts across faculties. They called for effective steering towards societal challenges and opportunities for researchers to build networks. Indeed, paying attention to actors involved in collaborations and their roles allows building a comprehensive case of interdisciplinarity at research institutions (Holmes et al., 2018).

Finally, interdisciplinarity is analysed through the lens of its guiding logics and motivations. Barry, Born and Weszkalnys (2008) specify accountability, innovation and ontological change as key drivers for interdisciplinarity. The political backdrop of this shift towards interdisciplinarity is, as Nowotny (2003) describes, a rise in accountability culture and a growing interest in justifying research applications for commercial or industrial settings. However, while innovation and accountability seem to be the most frequently used justifications, interdisciplinarity cannot be reduced to them. For Barry et al. (2008) the key rationale of interdisciplinarity is ontological change—reframing technical objects as both material and social constructs.

No single method would suffice to analyse, measure and evaluate interdisciplinarity (McLeish and Strang, 2016; Balsiger, 2004; Huutoniemi et al., 2010). This is partially due to the multiplicity of its logics and practices, which precisely make interdisciplinarity impossible to essentialise. This paper, therefore, follows calls for mixed-method approaches (Huutoniemi et al., 2010), as it incorporates qualitative (document analysis, workshops, interviews) and quantitative (bibliometrics) methods. Building on an approach from O'Donovan et al. (2020), we argue that mixed-method account of interdisciplinary capabilities will shine a light on how robots and robotics knowledge are coproduced in research labs.

Methods

To answer the research questions, we use a set of complementary quantitative and qualitative methods to build an in-depth case study on interdisciplinary research conducted at a single site, the Bristol Robotics Laboratory (Flyvbjerg, 2012; Eisenhardt, 1989). To visualise interdisciplinarity at an institutional scale, we conducted a bibliometric analysis of peer-reviewed publications coauthored by BRL researchers between 2004 and 2020. We augmented this knowledge with information about how collaboration and disciplinary integration happens at the project level. This was achieved through content analysis of publicly available documents on 63 recent BRL projects. Finally, a set of three embedded case studies of research areas within BRL were constructed from observational and desk-based research. These methods were designed to draw out researchers' experiences of interdisciplinary research practices and the related research capabilities they valued.

Case study description. Bristol Robotics Laboratory is one of the major academic centres of public robotics research in the UK. Founded in 2004 as a multi-research group lab, it hosts over 300 researchers and industry practitioners (BRL, 2020). The laboratory is a collaboration between two local universities: The University of the West of England (UWE) and the University of Bristol. The site also provides professional services priming local and national innovation and entrepreneurial activity, such as Knowledge Transfer Partnerships, internships and start-up incubators. Finally, BRL's reach extends beyond the robotics industry as the lab frequency partners with UWE's Science Communication Unit to run programmes of public engagement activities.

The lab, according to its website, is organised in 16 groups addressing contemporary robot capabilities and applications (Table 1). While this structure indicates how the lab presents itself to the general public, funders and potential collaborations, it is less indicative of how BRL constitutes its day-to-day practices. For that, we undertook our empirical research (Figs. 2 and 3).

Bibliometrics: peer-reviewed publications 2004–2020. We analysed peer-reviewed publications in pursuit of indicators that account for how research is performed at BRL. A corpus for analysis was compiled using publications retrieved from Scopus

(644 publications) and Web of Science (WoS; 485 publications) as these databases yielded the most comprehensive datasets in the field (Carley et al., 2017). We searched for variants of "Bristol Robotics Laboratory" in the "affiliation" field. Our search returned results for the entire period BRL has been in operation (2004–2020). The corpus includes peer-reviewed articles, as well as conference proceedings—the most frequently used output formats for dissemination in robotics.

Interdisciplinary collaborations were visualised using VOS-viewer software based on how each article was categorised under the respective schemes used by Scopus and WoS (Leydesdorff and Rafols, 2011). WoS, for example, decomposes its entire collection into 255 categories, what we call *WoS categories*, each of which can be considered a field of science (Carley et al., 2017). In graphs created using WoS data, each node represents a *WoS category* while connections between nodes indicate interdisciplinary collaborations. Furthermore, clusters of cognate disciplines based on citation flows in the overall WoS corpus are represented by nodes sharing the same colour (Shen et al., 2019). For this paper, we followed Carley et al. (2017) clustering of WoS categories: (1) biology and medicine, (2) psychology and social sciences, (3) chemistry and physics, (4) ecology and environmental science and technology, (5) engineering and mathematics. We complement the visualisation of *WoS categories* with keyword analysis. For this purpose, we use Scopus corpus showing the co-occurrence of the most prominent keywords associated with BRL publications and relationships between them, based on publications' citations (van Eck and Waltman, 2013).

As Martínez-Gómez (2015, p. 209) noted, the popularity of bibliometrics as a tool in science studies can be explained as it "provides a certain sense of objectivity for descriptive purposes". Bibliometric analysis is time-specific and accounts for the tangible outputs of research projects. However, while the method provides a useful overview of interdisciplinarity at BRL, as with any method, resultant knowledge is partial in several regards. First, the analysis was bound to the papers co-authored by BRL affiliates, excluding potential BRL-related outputs written only by partners from other institutions. It, therefore, means that the analysis can provide insights on interdisciplinarity at the publication level, rather than at a project level. Second, due to the academic nature of the Scopus and WoS databases, the analysis excluded output types such as policy reports, public engagement or patents. Finally, the long timescales of peer-review and databases indexing lag of up to a year in some disciplines affected the completeness of the dataset for 2020. These limitations are mitigated through careful triangulation with qualitative data discussed below.

Table 1 Research groups and centres at the BRL.

Research groups and centres at the BRL
Aerial robots
Assistive robotics
Bioenergy and self sustainable systems
Biomimetic and neuro-robotics
Connected autonomous vehicles
Embodied cognition for human-robot interactions (Fig. 2)
Medical robotics
Robots for hazardous environments
Robot ethics
Robot vision
Safe human-robot interaction
Smart automation
Soft robotics
Swarm robotics
Tactile robotics (Fig. 3)
Verification and validation for safety in robots

Content analysis: research documentation, 2015–2020. To find out about how interdisciplinarity is enacted beyond the peer-reviewed publications, we analysed publicly available documents on 63 recent projects at BRL using content analysis (Mayring, 2008). The qualitative review allowed to see how interdisciplinarity is conceptualised through project proposals (grant announcements at "Grants of the Web"; EPSRC, 2019) team building (staff profiles at university websites, partnerships with non-academic organisations) and results' dissemination (news releases and project reports). Owing to the limited availability of information on the earliest projects, we focused our review on the projects active in the past 5 years (2015–2020). This resulted in a comprehensive review of 63 projects (including the publicly available information on Ph.D projects and Knowledge Transfer Partnerships). In some cases, we supplemented the review of the secondary materials with email information requests to lab research theme leaders, so they could ensure the validity of the answers. Out of 16 email requests sent to lab leaders, we received 4 responses.

We analysed the project data combining the following techniques: (1) charting collaborations between disciplines, as well as practitioners to analyse who is and who is not involved in coproducing robotics at BRL; (2) content analysis of how researchers themselves conceptualise interdisciplinarity in reports,

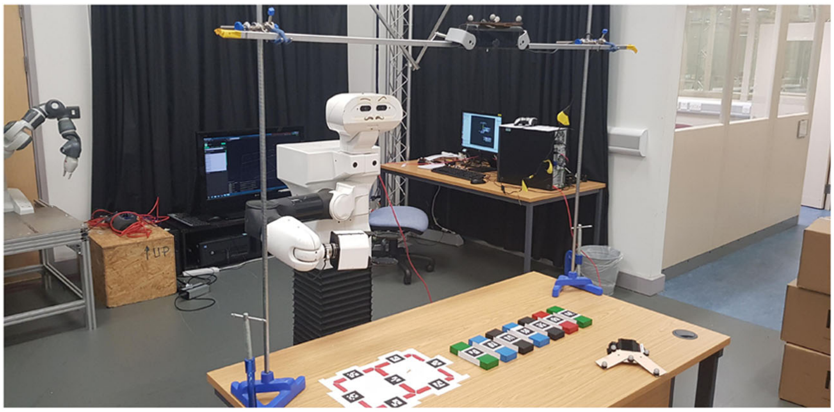

Fig. 2 An experimental setup for investigating human and robot cognitive behaviour in human-robot collaboration. Participants and robot use the blocks to create alphanumeric characters on a seven-segment using coloured blocks. (Credit: Mehdi Sobhani).

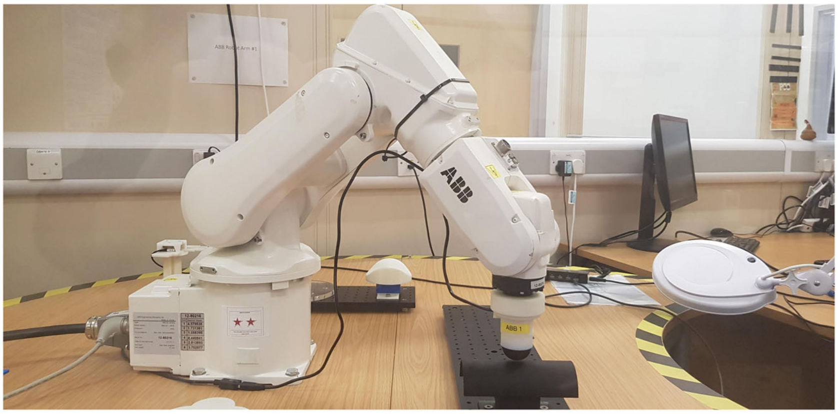

Fig. 3 A robot arm equipped with a TacTip sensor. TacTip (black semi-sphere) is developed to create a sense of touch for the robots so when the robot touches a surface of an object it can detect patterns and shapes based on deformation of the TacTip sensor. (Credit: Mehdi Sobhani).

Table 2 The analytical framework for content analysis.

Analytical techniques	Concepts
(1) Charting collaborations	Collaborations with non-academic stakeholders Collaborations with other universities
(2) Charting interdisciplinarity	Wide, medium, narrow interdisciplinarity Research framed as responding to the societal challenges Research framed as responding to the industry needs Research framed as predominantly theoretical

proposals and staff websites. Table 2 summarises concepts guiding our analytical framework.

Assessing the research situation through interviews, observation and workshops. A series of grounded qualitative data generating tasks were carried out between November 2018 and March 2020 as part of a wider project investigating innovation practices and policies in robotics and informed by principles of situational analysis (Clarke, 2007) and discourse analysis (Keller, 2012). The analytic goal in the analysis was to specify which entities—of varying scale and composition—make a difference to the situation at BRL. Moreover in turn, to assess how the situation influences, shapes and co-produces action, both strategic and routine. Specifically, we were interested in the conditions that make interdisciplinary practices acceptable at any given time.

Research tasks included fact-finding visits to BRL for tours of the main facility, as well as off-site research and development infrastructure. Semi-structured interviews were then conducted with 13 staff from BRL and research partner organisations. All interviews were transcribed and coded with the help of QDA software, as were documents and images.

BRL researchers were also included in research tasks at the European Robotics Forum in 2019 and 2020—one of the European robotics community's major annual networking and dissemination events. At the 2020 forum, one of this paper's co-authors organised three practice and policy workshops, which included current and former BRL staff. We performed a conceptually informed coding of materials (Corbin and Strauss, 2008) and created analytical maps that progressed from charting the interdisciplinary field and identifying gaps in the materials, to the relations in the field and their meaning. Data collection and analysis thus mutually reinforced each other. These data and analysis are presented in the form of three embedded narrative case studies in section "Embedded case study narratives: interdisciplinary research projects at BRL".

Reflective note. For the purpose of this manuscript, we formed an interdisciplinary team and took an interest in our own research practices. The first and the second author are social scientists, external to BRL, while the third author is a roboticist based at BRL. With all of us being early career researchers, we are usually positioned in the middle of research activities, yet far away from the discussions (and decisions) on funding, strategic directions or hiring processes. This allowed us to gain a critical distance, as we were liberated from the pressure to "sugar coat" our analysis. Yet, we believe we were able to draw a fair and constructive critique of the lab—we acknowledged successes and recommended practical opportunities for the expansion of interdisciplinary capabilities.

Results

Diversity of disciplines and topics. A research profile of BRL is constructed using bibliometric data and illustrated in Figs. 4 and 5. This highlights disciplines and topics represented in the lab's research, their relative frequency, and proximity to other fields. According to the WoS database, the ten most frequently occurring disciplines (ranked by their relative sizes) are: robotics, computer science, automation control systems, biomedical engineering, instrumentation, material science, multidisciplinary sciences, applied physics, optics, pharmacology.

Furthermore, Fig. 4 groups five coloured interdisciplinary clusters based on the number of citations between WoS categories. Here, we overlay the BRL publications data on top of the default VOSviewer base map (Carley et al., 2017). To reflect how WoS categories apply to BRL, we name them as follows: machine software (purple), machine hardware (blue), environment (yellow), medicine (green), human factors and society (red). Notably, disciplines in a red cluster (social sciences and human factors) are overall further apart from their counterparts. They are also much less prominent in the BRL portfolio in terms of peer-reviewed outputs.

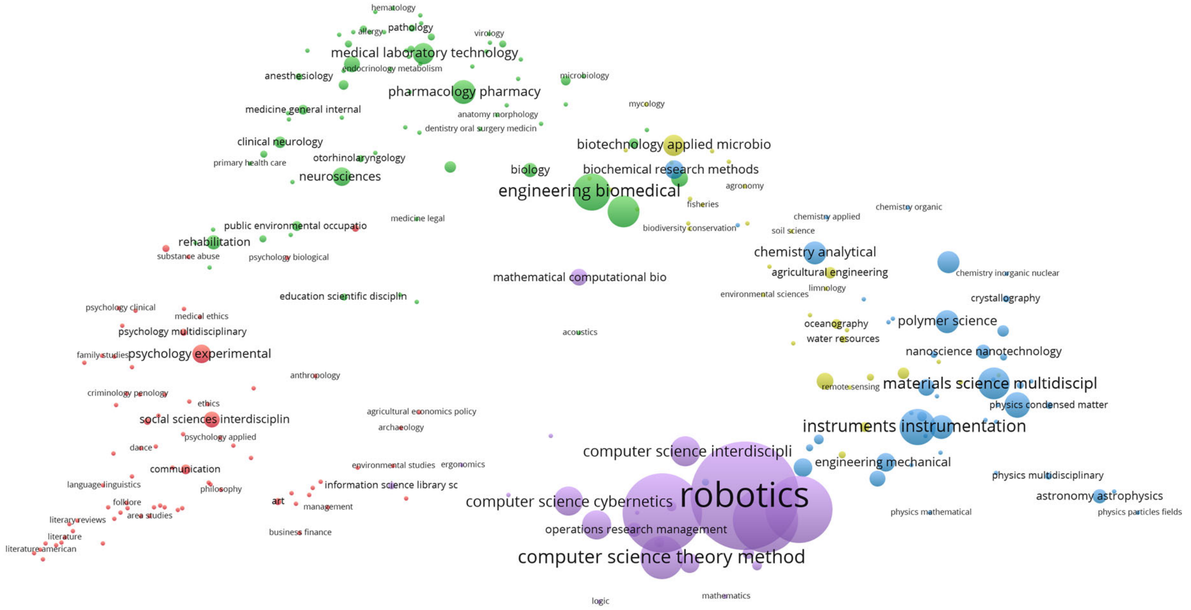

Fig. 4 Bibliometric research profile of BRL using a science overlay map technique (Carley et al., 2017) illustrating key disciplines represented in BRL publications indexed in Web of Science. The overlay map illustrates the following "disciplinary" clusters: machine software (purple), machine hardware (blue), environment (yellow), medicine (green), human factors and society (red) (based on 485 publications; 2004–2020).

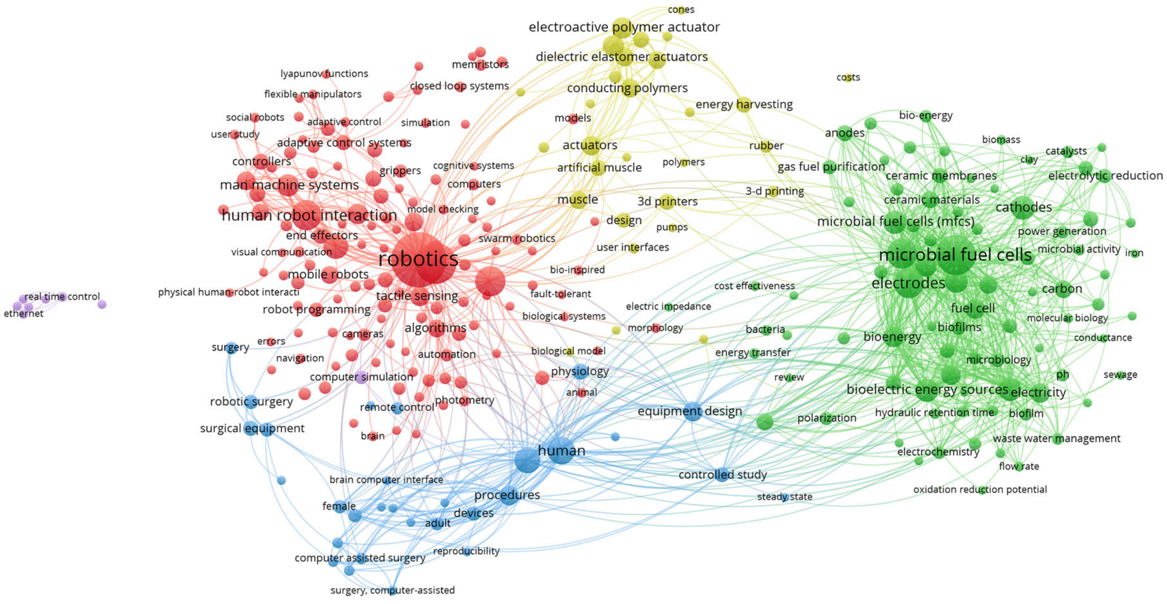

Fig. 5 Bibliometric research profile illustrating the most prominent keywords found in BRL publications indexed in Scopus (644 publications; 2004–2020). Nodes represent 1000 tops author keywords with co-occurrence ≥2; keywords were found in individual articles and the size of the node indicates relative prominence of the keywords in the corpus. Links represent co-occurrence relations between keywords in individual publications.

Although BRL researchers might not publish in social science and humanities venues, they do have a lot to say about "humans", based on Fig. 5 visualisation of top keywords. Indeed, Fig. 5 draws our attention to certain usages of the term "human": (1) to denote emerging fields like "human-robot interaction" (Winkle et al., 2018; Sobhani et al., 2015); (2) to describe people as subjects of experiments, i.e., references such as "controlled study", "adult", "reproducibility" (3) to exemplify beneficiaries of robotic inventions, e.g., recipients of robotic surgeries (Tzemanaki et al., 2014). However, judging from the poorer representation of social sciences and humanities journals in Fig. 4, "humans" are yet to feature in BRL as contributors to the political debates.

Taken together, Figs. 4 and 5 indicate a number of prominent research themes in the lab. For example, there is a large green cluster around "microbial fuel cells" (e.g., Ieropoulos, Greenman and Melhuish, 2008) in Fig. 5 and a similar interdisciplinary cluster in the top right corner of Fig. 4 (the convergence of biochemistry, biotechnology and applied microbiology). Similarly, the yellow "electroactive polymer actuators" cluster in Fig. 5 (e.g., Chorley et al., 2009) is commonly referred to as "robotic muscles" and used by medical roboticists (green "medicine" cluster in Fig. 4). In other words, Figs. 4 and 5 illustrate success stories from the perspective of the lab, where a measure of success are peer-reviewed publications and citations.

Next, we complemented bibliometrics with content analysis of recent projects. An inductive discipline categorisation of 63 recent projects at BRL revealed that computer science is the most common discipline present in 37 projects. This is followed by mechanical engineering (18 occurrences), robotics (17) psychology (13), electronics engineering (12), design (9) and medicine (9) (Table 3). The importance of psychology and design ought to be noted here. Furthermore, content analysis of the recent BRL projects shows how inherently interdisciplinary certain fields of robotics are. Integrating citation flows in Figs. 4 and 5 with content analysis, we found several fields that would be difficult to place into a single discipline such as: design, synthetic biology and bioinformatics. We characterise them as the emerging interdisciplinary areas where BRL researchers are actively influencing the direction of the field.

Following Kelly (1996), we conceptualised "wide interdisciplinarity" as BRL projects involving social sciences, humanities or arts. "Medium interdisciplinarity" included diverse positivist disciplines (i.e., "human factors" disciplines like cognitive sciences, behavioural sciences and psychology) and "narrow disciplinarily" was limited only to "traditional" robotics fields (i.e., engineering, computer science; see Birk, 2011). Tables 3 and 4 summarise the results of content analysis while Appendix 1 details line-by-line analysis of each project.

Further analysis of project documents reveals numerous idiosyncrasies about the ways interdisciplinarity is mobilised. We found eight cases of research projects solely justified through framings of industry need, for example, a machine vision project on characterising window cracks in automotive vehicles or a project on underfloor insulation (Appendix 1). However, not all projects were explicitly applied, whether to the societal or industry challenges. We identified 25 projects that were predominantly framed as "theoretical", most commonly in swarm robotics and bioenergy centres. These labs were also found to push disciplinary boundaries and work with emerging fields, such as synthetic biology or bioinformatics.

Still, the framing of "societal challenges" was the most frequently occurring one, with 40 projects charted in this category. In the case of "societal challenges" research, the knowledge base is often drawn from non-academic partners. For example, a project on self-driving vehicles drew legal and ethics expertise from a law firm and an insurance firm; a project on the future of care robots derived gerontology expertise from a care home. It is not uncommon for research projects to be framed as simultaneously responding to societal and industry challenges; we found this characteristic across 13 projects. For example, a project on applying drones to volcanic observatories, arctic research stations and bridge measurements also aims to "accelerate the commercial exploitation of unmanned air systems"; (CASCADE, 2020). Similarly, these challenge-oriented projects made the biggest claims about what we call "wide" interdisciplinarity, i.e., integration across technical disciplines, life sciences and social sciences.

Table 3 Disciplines present across the recent 63 BRL projects.

Discipline	Occurrences
Aerospace engineering	4
Agronomics	4
Animal behaviour	1
Animal welfare	1
Anthropology	1
Architecture	3
Arts	1
Behavioural ecology	1
Bioinformatics	1
Biology	7
Biomechanics	1
Business	1
Chemistry	5
Civil engineering	3
Cognitive science	6
Communication studies	2
Computer science	37
Control engineering	4
Critical management	1
Design	9
Economics	2
Education	2
Electronics engineering	12
Engineering maths	5
Environmental science	2
Ergonomics	1
Ethics	7
Evolutionary ecology	1
Innovation studies	1
International development	1
Law	2
Materials engineering	6
Mechanical engineering	18
Media studies	1
Medical engineering	8
Medical humanities	1
Medicine	9
Movement ecology	2
Neuroscience	5
Occupational therapy	1
Physics	2
Physiotherapy	3
Policy studies	3
Psychology	13
Rehabilitation science	1
Robotics	17
Social psychology	1
Social science	2
Social work	1
STS	1
Synthetic biology	5
Systems engineering	3
Transport studies	4
Zoology	2

The majority of the large consortium projects were funded by the European Commission or EPSRC, however, a few initiatives were industry-led R&D collaborations funded by Innovate UK or commercial firms. In terms of industry stakeholders, agronomics, automotive, defence and tech companies were the most prominent. In contrast, arts and voluntary sector organisations were the least common. These observations encourage reflections on the power relations present in the academic-industry collaborations and ethical concerns arising

Table 4 Summarised content analysis of the recent 63 projects at BRL; analysis of collaborations, framings and interdisciplinarity (IDR).

Analysis	Projects framed as "responding to the industry needs"	Projects framed as "responding to the societal challenges"	Involves non-academic collaborators	Classified as Narrow IDR	Classified as Medium IDR	Classified as Wide IDR	Research framed as theoretical	Involves other universities
No. of projects	22	39	32	11	28	24	25	33

For a full dataset, see Appendix 1.

from the positionality of funders and stakeholders. Ultimately, they point at the need to understand what logics and narratives are present when performing research across explicitly interdisciplinary fields of robotics like "human factors", "ethics" or "design".

Using this research profile as an entry point, we examine in closer detail three cases of how interdisciplinary research has been done at BRL, revealing logics and capabilities underpinning a set of research projects.

Embedded case study narratives: interdisciplinary research projects at BRL

Aligning capabilities with funders' requirements at Bristol Bioenergy Centre. SlugBot was "the world's first artificial predator", according to Time Magazine, (2001) "one of the world's best inventions of 2001" and an early exemplar of interdisciplinary robotics at the lab that went on to become BRL. It worked by "hunting and catching slugs, and fermenting the corpses to produce the biogas, which is its sole source of energy" (Kelly et al., 2000; Kelly and Melhuish, 2001, p.470). The goal was to build an agricultural robot that was both computationally and energetically autonomous. This could be achieved only through an interdisciplinary approach that brought together diverse knowledge areas: visual identification and obstacle detection, gripper and robot control engineering, GPS, mobile robotics, ecology and, finally, biogas and fuel cell sciences.

SlugBot is notable for two ways in which it contributed to a nascent interdisciplinary culture at BRL. First, for its foundational position in BRL's cluster of bioenergy expertise (the large green cluster around "microbial fuel cells" in Fig. 5). Using Microbial Fuel Cell technology developed in SlugBot, researchers later developed an influential series of robotics innovations, which were the building blocks of the Bristol Bioenergy Centre (e.g., Eco-bots or Urine-tricity bot; Ieropoulos et al., 2010; Davies and Ieropoulos, 2019).

Second, the project was an exemplar of opportunistic, adaptable funding capabilities cultivated at BRL. The project was initially funded through a single seed-corn grant from the EPSRC. Further and more substantial funds were later secured from national funding agencies in the UK and the Bill and Melinda Gates Foundation (Ieropoulos et al., 2013). In particular, the Gates Foundation funded research on "pee-powered toilets" aimed to tackle the issues of personal safety and access to electricity in the poorest regions of the Global South. Over the last few years, Ieropoulos' team have further developed and trialled urine-powered lights, which have been fitted inside toilets in Uganda and Kenya (Robial, 2020).

This is typical in that early funding successes coupled with industry recognition allowed BRL researchers to cultivate and maintain capabilities at the intersection of knowledge domains, in this case, bioenergy and robotics. Yet research funding is not neutral—funders influence not only who and what gets funded, but how interdisciplinary knowledge production is shaped along the way. One senior roboticist told us:

> "The EPSRC and the [European] Commission tend to slice the domain differently. So EPSRC slices it by discipline… Whereas the European Commission is intrinsically cross-disciplinary. It doesn't slice by discipline; it slices by problem domain."

The point here is that the European model favours the type of applied interdisciplinary research BRL was coming to specialise in—developing deep interdisciplinary capabilities in application domains such as bioenergy. Our interviewee continued:

> "So [in the UK] people who were making cars might be doing some robotics or doing research into making cars might be doing some robotics. People who were doing underwater things might be doing some robot, robotics, you know, underwater surveying. People who were doing space engineering might think, oh, we need a bit of robotics. But the funding streams were all focused on the application domains and then each one of them might have a bit of robotics in it."

As a result, robotics capabilities were diffused across industrial sectors and academic disciplines. Moreover so, developing an interdisciplinary research culture was core to BRL's unique proposition as a multi-research centre robotics lab. In words of one of our interviewees: "the core question we were asking ourselves [was] 'how should we even try to do robotics, regardless of what the application is?'"

This is an important question because, according to the same interviewee, certain kinds of research are possible only if robotics is central to a project's aim. BRL responded to this funding regime by developing interdisciplinary capabilities in fundraising and network building with European collaborators that would keep European Commission money coming in.

> "So if the problem domain, it, it chooses to focus on a search and rescue…Then it doesn't care, you know, it, it doesn't determine, it doesn't prescribe that that has to be solved by mechanical engineers or mathematicians or… Essentially all EU projects, and, and I think this is one of the great joys and strengths of EU projects, is that they're a mixture of disciplines.

And so, part of the BRL growth story has been the ability of researchers to marry not only the funds, but the interdisciplinary cultures of the *funders* in building capabilities in house. And to align their capabilities with the needs of funders. Yet funding is by no means deterministic. Cultures of interdisciplinary research at BRL are plural and shaped by other exogenous and endogenous factors as the following cases illustrate.

Driving autonomous vehicle research at BRL. "Fully self-driving cars on the UK roads by 2021"—that was the plan announced in the UK government's 2017 Industrial Strategy (HM Government, 2017). A bold ambition given the driverless technology innovation is led by a small number of powerful firms such as Google, Uber and Tesla, with traditional manufacturing giants following behind (Borrás and Edler, 2020). Public research is not in the driving seat. Nevertheless, the UK government has been seeking to develop capabilities in the testing and trialling of driverless technologies committing £250 m to this aim since 2015, via the Centre for Connected and Autonomous Vehicles (CCAV, 2020) and its portfolio of projects. CCAV promises "highly automated solutions", "real-world benefits", and a model of interdisciplinary innovation in which projects are typically mainly funded by the government with significant industry contributions.

BRL has participated in six CCAV-funded projects; Robopilot, Venturer, Capri, Flourish, MultiCAV, Connected Autonomous Vehicles (CAV)-Forth (Appendix 2). This work intersects with and builds on several of BRL's stated research themes including Assisted Living, Safe Human-Robot Interaction, Swarm Robotics and Verification and Validation for Safety.

A logic of testing underpins interdisciplinary research present in CCAV. Driverless technologies require a large amount of cyber-physical infrastructure in their testing and ultimately in their deployment. And so, rather than develop driverless vehicles from the ground up, BRL researchers are applying their capabilities specifically in testing environments. These social and technical infrastructures are mobilised in procedures to test issues such as technical competence, safety and public acceptability (e.g., Flourish project).

In recent years, engineers and robotics researchers have increasingly transgressed the lab's boundaries to conduct experiments and trials closer to the public, in living labs, test-beds and on public roads (Engels et al., 2019; Marres, 2020; Paddeu et al., 2020). However, the infrastructures, procedures and capabilities of testing don't merely produce test-results. Testing is generative in itself; expert-led testing deliberately introduces something new into society (Marres and Stark, 2020; Marres, 2020). The explicit goal of CCAV's test-beds, after all, is not so much to gatekeep driverless technologies, as to get them onto Britain's roads as quickly as possible. The stakes here are high because once self-driving technologies are widely diffused within our transport systems, "we are relatively powerless in our attempts to individually opt out of something to which we are all collectively locked-in" (Stilgoe, 2020; p. 16)

All this means that the procedures of testing being established by BRL researchers, as well as the end results of this testing are deeply implicated in how technologies and society progress. Researchers, unbeknownst to them or not, have assumed the role in what is an emerging regime of experimental governance of driverless technologies. Broader societal concerns of accountability (Strathern, 2004), responsibility (Bryson et al., 2017) and democracy (Laurent, 2011) are brought to the fore.

Capabilities that might test these broader concerns are often unacknowledged in official documentation such as bid documents and projects or siloed in narrowly defined low-resource work packages. Yet concerns about these issues are evident in post hoc reflections on BRL projects (Parkhurst and Lyons, 2018), who critically reviewed the narratives of inevitability and the vested interests of actors influencing CAVs. They proposed that the research on CAVs should acknowledge deep uncertainties and be explicit about assumptions made about technologies adoption. However, it is unclear if these valued capabilities are available to researchers.

This matters because of a second observed interdisciplinary logic, that of market creation and market growth. This logic is evident in how certain kinds of social orders are produced through testing. Project documentation includes aims of addressing "blockers and drivers to the wide-scale adoption of CAV capability" (Venturer, 2020) bringing "autonomous racing technology to the light commercial vehicle market and demonstrate SAE[1] level 4 autonomy" (Robopilot project; quote from UKRI, 2020). The emphasis here is on bringing together a network of actors and research to drive the take-up of "publicly acceptable" driverless technologies.

Under this logic, it is the market that will be both the arbitrator and the arena of arbitration for the issues of accountability, responsibility and democracy that are central to governance. Involvement by a wider set of actors, be the researchers, end-users or others, is foreclosed without debate. As a result, through their role as experts in testing, BRL researchers have developed capabilities to accelerate or decelerate. We find less evidence for capabilities that would allow them to steer innovation. Nevertheless, we anticipate that with the explicit foregrounding of the themes like "ethical black boxes" and "responsibility" in the recent projects on driverless vehicles (i.e., Robo-TIPS and Driverless Futures?[2]; see Appendix 1 and Sitlgoe, 2020) BRL will be better situated to align robotics with the societal challenges.

Assistive living robotics. Even before Covid-19, a logic of crisis was driving research in adult social care (O'Donovan, 2020). Ageing populations, insufficient finance in health and social care budgets and shortage of care workers are all rationales for innovating urgently in this domain (Prescott and Caleb-Solly, 2017). Assistive Living Robotics (ALR) is one set of responses to these challenges. From a research funder's perspective (ibid.), ALR can be understood as a knowledge production phenomenon of crisis response in which interdisciplinary logics of innovation are mobilised in pursuit of societal challenges (Strathern, 2004). Motivated by this rhetoric, robotics in health and social care has been identified as a target area for development by several funding bodies including the EPSRC Healthcare Technologies Grand Challenge and the Long-Term Care Revolution initiative from Innovate UK (EPSRC, 2019; Marshall-Cyrus, 2016).

In particular, BRL has built research capabilities in the area of *independent living*. Here, interdisciplinary robotics technologies are used in support of maintaining an independent and healthy homelife. For example, robots like CHIRON are made of interchangeable material components connected to a user's room. CHIRON can help people with a range of domestic and self-care tasks such as fetching, moving and lifting day-to-day objects in the home (see Appendix 2). The explicit goal of ALR technologies in these situations is to provide the support that could help avert an early move into institutionalised care, and, so goes the rhetoric, contribute to economic efficiencies and individual end-user wellbeing.

Advances in the mechanisms of behaviour modification, human robotics interfaces, participative design methodologies, surveillance technologies and machine learning techniques offer an opportunity to both health and social care practitioners, and prospective end-users for change in the provision of care services (Spanakis et al., 2016).

An effective strategy to introduce robotics into social care sectors requires that roboticists partner with actors in those sectors (Prescott and Caleb-Solley, 2017); people in need of care, their formal and informal carers, healthcare and service providers, clinicians and third sector organisations. Practically, this means designing and testing robots that will be acceptable and even enjoyable to use and ensuring that the technology meets ethical and cultural requirements. In determining and addressing these requirements, the research progresses not only through technological advances, but through innovations in methods, notably interdisciplinary approaches in Human-Robot Interaction such as participative design (e.g., Winkle et al., 2020), and the cultivation of relevant capabilities that underpin them (Table 5).

An important component of ALR research at BRL is testing infrastructure. The most prominent example of this is the Anchor Robotics Personalised Assisted Living Studio, a replica test-bed apartment centrally located within BRL's main building. The living lab is a critical resource in facilitating research methodologies for doing innovation together with the end-users. It facilitates interdisciplinary methods that aim to understand people's context of use, social situation, and issues of acceptability. Moreover, the living lab is a built and existing asset, deployed in response to funding calls that seek to frame, mobilise and address socio-economic challenges. As such, the living lab demonstrates historic research success, as well as future potential.

Living labs and test beds are, however, an approximation of reality that necessarily rely on a range of assumptions about social use contexts, regulatory and market conditions, and cultural acceptability. These assumptions, and the choices underpinning them, create challenges for "scaling up" from such test sites to wider society or transferring the user experiences to other contexts (Engels et al., 2019). For BRL's ALR researchers three challenges are notable. Socio-economic challenges such as social isolation, ill health and poverty mean people who most need assistance are the least likely to gain access to the living lab. Challenges relating to the complexity of care makes it difficult for assistive technology to stay useful over time, as people's needs change (Buhalis and Darcy, 2010). There is also an issue of taking this technology out of the lab and making it operational in the real-world (Spanakis et al., 2016).

These are challenges that cannot be met through the provision of more testing infrastructure. Instead, researchers are addressing them by up-scaling researcher-practitioner networks for interdisciplinary research and broadening out their analytic focus on the service user. One outcome of such partnership was a Ph.D research project, which conducted a series of field experiments with social robots placed in retirement villages (see Socrates project, Appendix 1; van Maris et al., 2020). In such settings, researchers see success as reliant on "building strong connections with local health and social care providers and older adult organisations"[3].

In recognising a plurality of social and technical complexities, ALR researchers de-centre material robotics technologies in a shift to building relational aspects of interdisciplinary knowledge production, and human-centred methodologies. What is interesting here is the choices taken by researchers in addressing given crisis framings. In establishing a network of partners from wider society, researchers are blending a logic of innovation, with logics of accountability (Barry et al., 2008). Better robotics solutions here, according to the robotics researchers, are those mediated and co-created with a wider range of end-users and societal actors. This is in stark contrast to historic and contemporary anxieties of automation—which fear how technology might close-down personal and collective freedoms (Bassett and Roberts, 2019)—and demonstrates how interdisciplinary capabilities might support a plurality of possible robotics futures.

Discussion

Politics of interdisciplinary research. In this paper, we set to investigate what at first seems to be a simple question: *what is robotics made of*? We have shown that even within a single robotics lab, BRL, there is no single way of performing interdisciplinarity. We argue that highlighting the plurality of interdisciplinary activities helps to improve the understanding of robotics labs. In avoiding a one-fits-all blueprint for public robotics, we demonstrate how different actors: funders, scientists, industry partners and end-users both gain and lack capabilities to steer the direction of research and research policy.

Through a mixed-method approach, our research revealed a range of conceptual, relational and material characteristics of Bristol Robotics Lab: prominent disciplines and keywords, funding strategies, leading researchers, relationships with non-academic collaborators and testing infrastructures. In terms of the breadth and depth of interdisciplinarity at BRL, we found that the majority of recent research projects crossed multiple disciplines. As many as 28 (out of 63) projects were classified as "medium interdisciplinarity" and 24 projects were charted as "wide interdisciplinarity". Most importantly, 40 projects were framed explicitly as "responding to societal challenges". Researching robotics beyond the narrow questions of hardware and software translates to the academic impact, where biology and medicine-inspired innovations like microbial fuel cells (aka. Urine-powered

Table 5 Summary of interdisciplinary research politics across three research areas.

	Bioenergy centre	Driverless vehicles	Assisted living robotics
Societal challenge	Renewable energy Provision of sanitation infrastructure in the Global South	Mobility for the future Road safety	Maintaining care for the elderly Current and future labour shortages
Scope of interdisciplinary research	Initially medium (biology and engineering), leading to wide (international development, creation of a spin-off company)	Wide (engineering, computer science, psychology, transport studies) However: End-users are often subjects of research rather than its co-creators Social science expertise often located in law or insurance firms	Wide (human-robot interactions, psychology, medical engineering, physiotherapy), Civil society organisations and regional care providers involved; Users may sometimes ask research questions
Logics of interdisciplinary research	Experimentation Tackling poverty	Testing innovation Market growth	Innovation as crisis response; Market creation; Accountability
Capabilities noted	Capabilities to align the needs of funders with the lab's own narratives Capabilities to evolve and adapt robotics to emerging societal challenges	Capabilities to build a diverse network of regional stakeholders Capabilities to accelerate innovation Capabilities to steer innovation (absent) Capabilities to explore uncertainties and assumptions (valued, but not always realised)	Capabilities to include the end-users in knowledge production; Capabilities to maintain infrastructures Capabilities to build a diverse network of regional stakeholders

toilet lights) and electroactive polymer actuators (aka. Robot muscles) have become flagship technologies at the lab.

Yet, researchers and funders ought to be careful about how they mobilise expertise on social issues, especially in the growing robotics-related fields like ethics or law. As the analysis of CCAV projects has shown, it's common for robotics projects to be comprised of large multi-stakeholder consortia of universities and commercial enterprises, with end-users having limited capacity to co-create the research agenda. Although our analysis of CCAV projects shows "wide" interdisciplinarity in terms of diversity of knowledge areas and stakeholders, capabilities to steer the research framing were kept firmly in hands of the automotive industry. On the other hand, ALR projects included the end-users at multiple stage in their design, through the development of participative methods and infrastructures. This contrast presents an opportunity for future inclusion of the end-users and critical social sciences. What our research shows is that with ample government financial support for robotics, there is a diversity of possibilities for distributing, rather than concentrating, research resources and power. Moreover, the political decisions that guide distribution of resources and research can take place at multiple levels. Indeed, some roboticists at BRL have built methods that at least in part facilitate a diversity of approaches to epistemic power and the politics of decision making in research.

Mapping how researchers and funders contribute to research at BRL provides further evidence on actors present and missing from "the making of" robotics. As such, while organisations from automotive industry, agri-tech, health & social care, and defence industry were frequent collaborators, voluntary and community sector organisations were rarely included in the projects. This, once again, does raise a question about the representation of end-users' interests. "Humans" might be at the centre of the BRL's agenda (as Fig. 5 shows), but these "humans" are often rid of their complexities, relationships or socio-economic contingencies. Like the mythical "average man" in design and medicine, humans in robotics often exist outside of the society (Perez, 2019). Meanwhile, we argue that humans are inherently relational and political—the research on robotics in the society should reflect that. There is a risk that if end-users' role will be limited to appraising usability and public acceptance, some more critical questions about justice, data rights, labour or sustainability will not be raised.

Structural preparedeness for interdisciplinarity. If societal challenges are to be addressed systemically, they ought to meaningfully involve societal partners and critical social sciences. We call for careful assembling of interdisciplinary work. While large interdisciplinary consortia may involve a diverse range of stakeholders, they do not necessarily disrupt the power dynamics of knowledge creation by design. This could be achieved by precise steering of research, which invites different voices and opens up research spaces to those usually excluded from them. In doing so, researchers and funders should pay attention to the power arrangements situated within such collaborations: who sets the agenda? Who defines the key terms? Who can afford to critique? We offer some practical steps how to act on these questions in Box 1.

Although knowing disciplinary representation is informative for mapping the scope of BRL's cognitive efforts, we have shown how interdisciplinarity can be understood as more than simply the synthesis of two or more disciplines. In practice, the performance and rationales of interdisciplinary work here are revealing. As are the infrastructures (i.e., test beds, living labs) that are being built. We showed several rationales that motivate the work of roboticists.

- Bioenergy centre: experimentation, tackling poverty
- Assistive living robotics: accountability, innovation, market creation, dealing with crisis;
- Connected autonomous vehicles: testing innovation, market growth.

These logics and infrastructures are important as they demonstrate how BRL engages with the "real-world needs" such as government agenda, funders' criteria, collaborators' expectations. Ultimately, the logics of interdisciplinarity shape the nature of funding (i.e., the EU, UKRI, commercial), as well as the disciplines involved. Often the "choice" of research motivations is mediated by the funding criteria. In other words, BRL's interdisciplinary activities shapeshift to fit perceptions of the world, which are co-constructed and negotiated between the researchers and funders (Weingart, 2000).

Finally, we investigated capabilities developed to mobilise interdisciplinary collaborations and enable "*structural preparedness for interdisciplinarity*" (Engwall, 2018). We have shown that BRL has developed capabilities to: (a) align the needs of funders with the lab's own narratives; (b) build a diverse network of regional stakeholders. However, we found ambivalent capabilities to steer innovation and challenge assumptions underlying key narratives around technological progress. In case of projects with a significant influence of industrial partners, we found that BRL researchers could accelerate or decelerate innovation, rather than open it up to critical questions. We recommend that BRL researchers and funders stay reflective of the power relations present in the academic-industry collaborations and ethical concerns arising from the positionality of project stakeholders (Box 1).

Conclusions

In this article, we sought to understand how interdisciplinary research at BRL is positioned to address grand challenges. While the researchers used a number of strategic motivations to gain funding and build collaborations, they also demonstrated a willingness to engage with interdisciplinary robotics at the ontological level. In its early days, roboticists were asking themselves: "how should we even try to do robotics, regardless of the application?". And so, through iterations of experiments and

Box 1. | Recommendations for BRL

1. Reflect on your research proposals: who sets the agenda? Who doesn't?
   Who can critique? Who cannot? In particular, put effort into *steering innovation*: open it up to political and ethical questions.
2. Assemble interdisciplinary teams with care, so that new actors and disciplines are able to disrupt, or at least question, the existing power arrangements.
3. Support and cultivate initiatives aiming to connect BRL with the community sector and charities.
4. Consider the implications of your research environment: how are participants affected by being placed in a lab, a test-bed, or a public road?
5. Embed these practices in every aspect of your research culture: from building partnerships, bidding, setting research questions, conducting empirical research, dissemination to, finally, research evaluation.

prototypes, we can see emerging innovation practices that are often co-creating robots, making choices together and doing politics with a wider range of societal actors

Our paper presents a practical intervention into the politics of interdisciplinarity at BRL. Based on the rich and diverse empirical data, we highlighted the current capabilities and recommended further opportunities to create better robots. After all, robotics research reflects the values and possibilities of society itself. Importantly, how that society is represented, is not given, but a result of funders', researchers', practitioners' and (to a lesser degree) end-users' *political choices and contingencies*. In opening some trajectories of the future, while closing the others, these choices and contingencies are what robotics is made of.

Data availability

Where appropriate, data generated or analysed during this study are publicly available via appendices as well as data repository: http://researchdata.uwe.ac.uk/579/

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Notes

1 SAE International, (previously known as the Society of Automotive Engineers) is a U.S.-based, organisation developing standards and convening engineering professionals across various industries.

2 These projects are funded by the UK Research Councils, rather than the Government's CCAV initiative.

3 As quoted from a presentation to the European Robotics Forum, Malaga, Spain, March 2020.

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Author contributions

OM: design and analysis of data (bibliometrics, content analysis), manuscript drafting (introduction, literature review, methods, results, conclusions), manuscript revising, final approval. COD: design and analysis of quantitative data (bibliometrics), manuscript drafting (methods) manuscript revising, final approval. MS: design and analysis of qualitative data (interviews), manuscript drafting (results), manuscript revising, final approval.

Competing interests

The authors declare no competing interests.

Additional information

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