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ABSTRACT

Up until now, Human-Robot Interaction (HRI) has been largely defined by the influences both humans and robots exert on each other across various interaction modes. Robots follow human purpose and serve goals determined by humans with various degrees of agency. Humans act, respond, and adapt to robot behaviors while simultaneously advancing technology to increase robot's affordances. Abstracted by this dyad, HRI has left out the material background making this exchange possible: Nature. The current planetary crisis forces us to reconsider the importance of contextualizing HRI within a larger picture, and invites us to ask ourselves how this relationship can be better served by considering Nature as the driving agent in this binary relationship. In response to this reflection, we present a first attempt of a speculative paradigm in HRI: Nature-Robot Interaction. We discuss ethical and design underpinnings of this approach to HRI, introduce initial guiding principles, as well as examples of potential affordances, embodiments and interactions. While we begin in the realm of the speculative and recognize the infancy of our proposal, we invite the HRI community to it as a serious design principle moving forward.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**; **Contextual design**.

KEYWORDS

Human-Robot Interaction; Nature; speculative design, interaction paradigms, Nature-Robot Interaction

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1 INTRODUCTION

The environmental crisis surrounding the use of computing devices and electronics, under which robots are a clear category, appears as spinning out of control. According to the United Nations Institute for Training and Research, in 2019 alone, 53.6 Mt (Megatonnes) of e-waste was generated globally: the rough equivalent in weight of 18 million adult elephants. A figure that is projected to increase to 74.6 Mt by 2030 against a sobering 17.4 percent recycling rate as reported in 2019. This astonishing amount of material is the result of a 2.5 million Mt increase in Electrical and Electronic Equipment (EEE) every year [32]. On the producing end, the manufacturing of this category of products is increasingly requiring the use of precious metals and other raw materials, which are beginning to become scarce. Communication devices and embedded computers, common in robotic applications, concentrate high levels of base metals such as copper, platinum or gold. A figure calculated at 14 Mt of virgin material [32]. On the disposing end, recycling rates are not keeping up with the demands imposed by production, creating large transnational flows of e-waste material. The direction of this flow is usually directed to the Global South or to nations where the policy and infrastructure for e-waste management are limited or non-existent. As a result, hazardous materials contaminate all components of natural environments across these geographies, place e-waste workers at enormous health and safety risks [7, 119], and incite social unrest in nations far removed from the places where these technologies are used [73, 91]. Lastly, as HRI moves towards autonomous interactions between humans and robots, the computing necessary for this level of robot agency to take place makes energy an important consideration. Some of the Neural Architecture Search (NAS) Natural Language Processing (NLP) models, for example, require an estimated 1515.43 Watts of energy, the equivalent of 274,120 hours of energy provision, roughly 626,155 pounds of CO_2 [102]. And although some of this energy comes from renewable sources, these are not environmentally neutral [37]. Not to mention the material footprint of an increasing data computing infrastructure around the globe. HCI researchers have described the intertwining of several of these dynamics as "wicked cycles"[23].

These factors will inevitably intersect with the steadily increasing market for commercial and industrial robots. Their manufacturing, deployment and recall will represent a burden the planet can not withstand [105]. Despite several calls to consider the negative planetary and societal impact of robotics manufacturing [11, 40, 108], there is an astonishing lack of data reporting its material contribution to the global issue of e-waste, for example, with virtually no available data.

If we go outside our global boundaries, the story is not different. We are increasingly littering our orbital commons with defunct satellites and debris, without any perspective for improvement in the future [33]. Finally, beyond earth, the current anthropocentric "space colonization" is yet another example of a utilitarian and Nature-adverse approach: we are exploring space with robots that will become, eventually, outer space trash, with disregard for their impact on the extraterrestrial environment.

As we echo this call for reflection within HRI, and as engineers, designers and roboticists, we are attuned to the complexities of crafting, passing and enforcing national and international laws that

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can help ameliorate the challenges of e-waste, mining and energy infrastructure and consumption. However, when contextualizing our role, specifically within the HRI community, we see great potential in intervening upon the imaginaries surrounding robots at design point, instead of at *wicked cycles* point.

In this paper, we argue that one of the most important reasons why the environmental reverberations of robotics, specifically within the HRI community, have stayed out of the limelight has to do with a historical dominance of human notions as the driver of the human-robot relationship. This emphasis has generated an incomplete picture of the "human" in the "human-robot" dyad. A picture that removed the human from the background that makes the human-robot interaction and life itself possible: Nature. We contribute an attempt to break this human ruling in HRI by imagining a new paradigm. We call this speculative direction: Nature-Robot Interaction (NRI). This paradigm aims to blur anthropomorphism in HRI design and present roboticists and other technology designers with a new creative space by drawing attention to the possibilities of centering in Nature. Moreover, NRI seeks to foster a conversation around the need to factor in known material limits when thinking about the future of robotics.

1.1 Social and environmental challenges ahead for HRI

The robotics sector overall is on the rise. By 2014, sales of domestic robots to individual costumers alone recorded at 3.35 million units. Forecasts put that number at 5.3 million for the next decade [44], and the market appears to be following this predicted behavior. This figure does not include the considerable market penetration of industrial robots in the past decade [103].

The environmental footprint of these market and consumer shifts raises deep concerns. Approximately 83 percent of the end-of-cycle material produced by these manufacturing flows creeps through an obscured network of regional and international trading or non-compliant, environmentally harming recycling practices, all of which release large amounts of toxic materials [89]. These hazardous components contaminate water sources [67, 116], negatively shift the quality of air [43, 63], and of soil and terrestrial environments [61, 68], required for the wellbeing of all living species, including humans [123]. A recent report on the health of Artisanal and Small-Scale Mining (ASM) workers showed that 144 out of 176 health studies reported at least one instance of *"(i) prevalence or incidence of diseases and other adverse health conditions [...](ii) signs and symptoms related to chemical exposures [...]; and (iii) musculoskeletal disorders, injuries, and fatalities [...]"* [21]. Ironically, research has found that e-waste handling causes some of the very health impacts that HRI has tried to solve through decades of research.

Exposure to toxins during the unregulated recycling of e-waste can lead to changes in neurodevelopment [64, 66] and overall growth [121], hearing loss [117], and disadvantages in learning outcomes [97], among others. All conditions occur to the most vulnerable, pregnant women, aging populations and children.

Wildlife can also be affected by this phenomenon. Illegal and uncontrolled mining practices creates a situation where miners are forced to transform key global ecosystems in order to both mine and survive in the process. In his book *Coltan Boom, Gorilla Bust: The Impact of Coltan Mining on Gorillas and Other Wildlife in Eastern DR Congo*, biologist and conservationist Ian Redmond estimated that the footprint of coltan miners in the Bukavu region could have eradicated the 3,700 elephant population and most of the 8,000 gorillas until then protected by the National Park system. This burden is then passed to smaller species such as chimp, buffalo, antelope, tortoises, birds and other small animals, irreversibly changing the natural landscape [87].

The complex nature of many robot hardware systems, particularly robots using screens and sensor arrays to interface with humans, makes it so that they require a large quantity of different materials. So much so that at end-cycle, a consumer robot is likely to fall under five of the six UNU-KEYS benchmarking macro-categories of e-waste developed by the United Nations University [111]. This increasing demand, shared with other popular EEE products, creates considerable demand over raw materials, eventually leading to scarcity, as it was the case with silicon during the COVID-19 pandemic [51]. A towering amount of common raw materials such as iron, aluminium, and copper. are needed for robot production. The broad EEE category of products which includes robots, recorded by 2019 an approximate 39 Mt of material at the production line statistic [32]. This goes along with all the plastics required in robotic hardware, all the way from casings to cable insulation. The majority of these production practices are far from being circular, as the recycling statistics show [32]. Even in an ideal scenario in which all the iron, copper and aluminium resulting from e-waste (25 Mt) is recycled, the world would still require approximately 14 Mt of iron, aluminum and copper from primary resources to manufacture new electronics (11.6 Mt, 1.4 Mt, and 0.8 Mt, respectively) [32]. This indicates that the gap between the secondary iron, aluminum and copper found in e-waste and their demand for the production of new EEE is quite large: a consequence of the continuous, unchecked growth of sales of EEE.

Alongside more common raw materials, precious metals make this picture more complicated. The race for rare minerals has deepened the aforementioned environmental challenges while fueling internal and international conflict among nations involved in illegal mining of these materials. The global demand for gold and coltan, for example, widely used for the production of capacitors, semi-conductors and other internal parts, have sprung regions in Sierra Leone, the Democratic Republic of Congo and Colombia just to mention a few, into spiraling violence, more often than not connected to international human rights violations [2, 47, 74]. These geopolitics of sourcing and disposing of materials are creating social and environmental disarray and placing the burden at the end of this material cycle in nations across the Global South, many of them seen as "low-rights environments" [28]. These countries usually lack the appropriate management infrastructure and systems to handle these waste streams, setting the stage for vulnerable working, health and environmental conditions [7, 30, 119].

1.2 The human within Human-Robot Interaction

Our proposition is that the most prominent reasons for the future (and present) negative ecological impact of HRI have to do with (1) the centering of the human in this relation, and (2) the abstraction of the human from the natural world. When seen from a historical lens, a significant portion of the work within HRI has focused on how to harmonize interactions between humans and robots, particularly with the objective of enriching or optimizing the human experience. Making robots easy to talk to [54, 80], visually and interactively more compelling [15, 39, 60, 115], comforting within situations that challenge us [53, 88, 99]; robots that can help us learn better [76], improve our emotional well-being [19], our health [20] support disabilities [107], make aging meaningful [57, 79], and even help us find solace in our intimacy [52].

Once deployed, either through human in/out of the loop models, these robots usually perform constrained tasks, allowing humans to maintain control over the interaction, assess it and iterate over it. This workflow requires several considerations, including safety, animacy, dependability, and intelligence, among others, all defined by humans, which in turn builds an implicit, sometimes defined hierarchy between humans and robots. This *anthropo-centrality* extends to the majority of the interaction metaphors in HRI in the form of anthropomorphism [17, 29, 94], particularly within social robotics [31]. The pinnacle of this anthropocentric approach takes place when robots have to navigate, actuate, and interact from within the human body, either for diagnostic [18, 20, 72] or enhancing purposes [122]. In this scenario, the environment is the human body itself, and it is mandatory to preserve the welfare of the human host.

This sustained focus on the human has left us with a wealth of technologies, methodologies and insights, a product of decades of careful study across different domains. As a result, it has reinforced the synthetic, artificial separation of humans and Nature in HRI. We argue that this separation is a mirroring of a larger western position that creates a binary out of Nature and culture where in reality, both of them are intertwined and interpreted across different cultures: *nature-cultures* [59, p.30]. It is this very binary that makes it possible for robot designers to move ahead with business as usual, regardless of the overall negative output on Nature as a result of our practice.

Another consequence of this anthropocentric approach to HRI can also be seen in the perpetuation of bias underlying some of its systems; human flaws reflected upon technological artifacts. Instances of this phenomenon are offered by the current track record and perception of facial recognition technology [13, 35] and voice recognition [58, 104]. More importantly, prioritizing the human in the design and development of robots and their interactions perpetuates a narrow and myopic vision of their universal role beyond human lives.

This emphasis on the human as the center of gravitation for robot behavior and purpose leaves plenty of room for divergent paradigms. Although some exceptions to this paradigm are beginning to appear, for example, by inverting the direction of the interaction hierarchy in HRI to Robot-Human Interaction [98], or investigating shifts in agency directly from the robot and not the human. We build on these kinds of provocation, aiming to move our imagination towards a more radical shift.

1.3 A shift within the practice and paradigms of design

Along with the positive advances in technology for the manufacturing, disposal and energy consumption of robots, we propose that a shift in the way robots are imagined within HRI can be as, if not more, impactful moving forward. In this section, we provide some ideas inspired by recent conversations and debates from within the field of design. In his 1973 book *Tools for Conviviality*, Ivan Illich argued that the demands of the industrial age had made it so that the tools we built within this era push us further into an environmental brink. To counteract this, he calls for designers to imagine technological possibilities, tools and systems that benefit both humans and Nature, in contrast to *"the conditioned response of persons to the demands made upon them by others, and by a man-made environment"* [50, p.24]. There is another equally powerful insight into Illich's conceptualization of a *convivial* tool: the capacity of a user to understand the technical underpinnings of a tool. Although some of the systems underlying the functioning of a robot can fall outside this category (e.g. the inner workings between inputs and outputs within deep neural networks), any robot designer should have a clear understanding of the environmental and social tensions created by the required energy [9, 102], water [77, 96] or land terraforming [82] for renewable energy, behind the computing power required to operate a cloud-based robot for example. Understanding the natural background that serves us when designing robots, as well as considering the implications of our designs upon that background, will better prepare us to design *convivial robots*.

As the materiality of computing and manufacturing becomes more visible, friction between different relations to the land that makes possible its necessary resources will come into view. The water protection movement led by Standing Rock Sioux tribal members across the Missouri and Cannon Ball Rivers to stop the building of the Dakota Access Pipeline [113], and the Kanaka Maoli resistance to the building of the 30-meter telescope in Mauna Kea [70] serve as examples of how land relationality manifests in the context of technology. These examples serve as a reminder that human relationships with the natural world are not universal. In other words, different human groups experience and act upon the world differently. As a result, what constitutes mere material extraction for some (e.g. mining), means the harming of one's most sacred thing (e.g. Nature) for others. The Māori notion of Kaitiakitanga, or the idea that humans belong and are meant to guard Nature instead of dominating it [56], or the Place-Thought framework stemming from Haudenosaunee and Anishnaabe cosmologies, underlying the risks of assigning agency to the human over Nature, or the holistic vision of integration of humans and the natural environment proposed by the Buen Vivir (Good Living) Andean philosophy [1, p194], are only some examples of this worldviews difference. Recent debates in design theory have foregrounded the notion of *ontological design*, or the observation that as we design in a world, that world designs us back [114]. This profound insight serves as an invitation to seriously engage and encounter other worlds, meaning other webs of relationships between living beings (including humans) within the natural world, and is of great inspiration to the notion of Nature-Robot Interaction. It also serves as a reminder that failing to attend to these differences, can lead robots to turn from a technology for the future to a *defuturing* technology [34, p10]. This plural vision of the world is already finding its way into related fields such as sustainable computing [25], artificial intelligence [62, 71] and Human-Computer Interaction (HCI) [3] just to mention a few. In this paper, we argue that a shift towards different ontological positionings when designing robots can have a profound positive social and environmental impact moving forward.

From a design practice perspective, several efforts are currently ongoing, particularly coming from the field of soft robotics [46], and what has been called *ecobots* [108], looking at new fabrication materials [118], new bio-inspired actuators [16, 75, 81, 112], new generations of green electronics [12], and different arrays of energy sourcing to allow robots to be less environmentally burdensome. A recent special issue of the Biological Cybernetics on "Animal-robot interaction and biohybrid organisms" is setting the stage for the type of shift we suggest with the Nature-Robot Interaction paradigm [90]. Although we recognize these advances represent significant improvements, and would like to stress they are crucial for moving the field in a different direction, we contend they are not enough; we are in need of going beyond [40]. We argue that the most significant change for the field might come from a radical shift in frame; from a renewed imaginary that privileges Nature over humans.

In what follows, we engage this imaginary and envision how this new mindset could take place. We set the stage for the need of an NRI lens, and present a possible set of laws guiding its practice, along with underpinnings and considerations both positive and negative. While acknowledging the early stages of our proposal, we present possibilities and scenarios where NRI can unfold. We map out NRI in relationship to other Nature-friendly moves in robotics and close with some of the limitations of our exercise.

2 NATURE-ROBOT INTERACTION

We start this section addressing an important conceptual clarification: what is taken as Nature in NRI. In developing his theory of "The Parliament of Things", Bruno Latour argues that the divisions such as nature-culture, subject-object, as modes of classification in the "modern world", are merely synthetic. He points out that phenomena such as the production of computer chips and the making of the ozone layer blur these lines encompassing culturally-dependent natural and human factors [59]. Therefore, if we embrace the notion that non-human agents are worthy of agency on the basis of their acting in the world (e.g. natural ecosystems, human tools), we accept the possibility that Nature can be culturally constructed. This larger conversation is known in the field of anthropology as the "ontological turn" [84], a view on how the world is constructed that dates the rise of the field of anthropology as pointed out by critical Indigenous thinkers [106]. In our speculative take on what form the NRI can take, we subscribe to this view of Nature(s).

The outlook of Nature-Robot Interaction brings into view a new breed of robots: brought forth by Nature's raw materials, powered and animated by Nature's diverse and sustainable energetic forms, directed to feedback to Nature following the end of its life cycle. From a form perspective, this paradigm calls for robots that are designed to be both efficiently materialized and ingested by Nature's ecosystems. From an interaction point of view, while still offering the possibility to focus on the human-robot dyad, NRI requires each interaction to be constructed as actively mediated by Nature, never outside of that frame. This is a path for designers to be forever tethered to the material implications of the robots they create. Moves towards this outlook, this type of *'retributive technology design'*, are already taking place: the use of water-based composites in tandem with robotic fabrication. Chemically tuned decay [27, 65]. A form of material cycling and ecology long practices by various cultures around the world.

Nature drives both human and robot decision-making. At the human level, this already happens, particularly in rural areas worldwide where culture and Nature are harmonically entangled. The global practice of agroecology and Indigenous farming are living examples of it [14, 38]. Robots will align with this behavior through continuous environmental sensing and behavioral reinforcement from humans, living creatures and other robots. This acting of humans over robots on behalf of Nature, supports the programming of robots for NRI purposes until robots can directly program themselves to serve as Nature's proxies.

This design paradigm travels all the way from the choice of materials and processes of manufacturing to the goals a robot is built to achieve and the data that feeds its decision-making systems. This is a way in which Nature *acts* and takes priority within the human-robot dyad. This acting can be more than passive, it means that robot designs will default to overriding protocols for the purpose of protecting Nature (e.g. disobeying human instructions in exchange of securing the welfare of natural ecosystems). Nature systematically plays an active role.

These robots move seamlessly across ecosystems, much like information through Nature's rhizome [8, p.126]. They mimic Nature, some of them are Nature [10]. Even if distributed, these robotic machines can assemble to recreate Nature's conditions when Nature is incapable of doing so (e.g. imitating micro-climates that allow bees to move in space when natural weather conditions do not allow for it). They continuously survey the health of living organisms with which they interact (including humans), and make meaningful suggestions for how to improve wellbeing all across. When it comes to the health of Nature's core functioning, they proactively act in its protection. This can include, but is not limited to robots having the capability to remove pollutants from air, water and soils, sequestering carbon and greenhouse gases, and promoting adequate conditions for pollination when appropriate. This acting in guardianship of Nature is to take place even if at the expense of human goals or action (e.g. impeding mining where ecosystems are being stretched outside their limits).

In line with the position in Nature we take at the beginning of this section, NRI imagines a world where robots respond to particular cultural positioning. As the Haudenosaunee follow an ethics of balancing all life and sees humans as "responsible for taking actions that positively affect seven generations hence", for example, we imagine robots that operationalize this directive through programmatic routines that follow a Haudenosaunee worldview of balance [109, p.41]. This decentralization of robots negates the possibility of universalizing needs, avoiding the domestication of Nature and subsequent acceleration of the human transformation of earth's raw materials into 'standing-reserves' [48]. The place-based ethical positioning of NRI, allows for robots and its designers to escape the narrowing set of origin stories behind technology.

In summary, this fictional picture of what NRI can offer us, is characterized by the aforementioned principles:

- Robots are animated by Nature. Powered by it, directed by it and consumed by Nature at the end of their material life cycle.
- Nature as a driver of human and robot decision-making both as setting the priorities of robot designs, and by way of requiring a concerted action on behalf of Nature's welfare
- Humans serve as Nature's proxies when programming robots for NRI until robots can directly program themselves to serve as Nature's proxies.
- Robots as place-based ethical artifacts, dependent of culturally-rooted understandings of Nature(s).

A complete understanding of this paradigm shift requires us to delve deeper into the philosophical underpinnings that favor a Nature-centric approach, how it weaves into the constructs of culture and community, and what its possible benefits and drawbacks can be. Nature-Robot Interaction exists as a conceptualization to aspire to. We recognize our current technology is not yet at a level that allows for a complete NRI vision to be achieved, yet our state-of-the-art is developed enough to invite roboticists to begin moving the needle toward this direction. In continuing to envision a future where Nature-Robot Interaction design takes places, we return to the realm of the speculative to imagine a set of laws governing the existence of robots built under this paradigm.

2.1 The laws of Nature-Robot Interaction

The first of the famous laws of robotics proposed by Isaac Asimov centers on humans with no regard for the natural world. Even with its refined version in the Foundation and Earth, the law centers humanity, still signaling humans as the most important species, and Nature at their service [6].

We take inspiration from Asimov's laws of robotics to provide guidelines for how NRI could take place. Notably, these laws are entirely based on imagining the outcomes of interactions between humans and robots [5]. Any other version of laws of robotics, to our knowledge, has not centered Nature or consider it as a prominent actor. We suggest the following four laws:

(1) **First law:** a robot's existence and interactions with and within the world must not harm Nature, including all its life forms, either by action or inaction.
(2) **Second law:** a robot must follow the provided protocols by its programmer, Nature, human or robot, except where such orders would conflict with the First Law.
(3) **Third law:** a robot's programming must take into account the cultural norms defining a harmonic relationship between intelligent forms and Nature as long as such norms do not conflict with the First or Second Law.
(4) **Fourth law:** a robot must protect its own existence as long as such protection does not conflict with the First, Second, or Third Law.

Our first law seeks Nature's welfare above all. Nature was here before humans (and will be after), as humans were before robots. One cannot conceive the existence of humans or robots, and life in general, without Nature's thriving.

The second law considers robot's agency and highlights the possibility of Nature to act as an agent driving robots', or for robots to drive their own behavior. It foregrounds the possibility of multiple agents acting upon robots along with the potential conflict inherent to this mode of interaction. It is worth noting that in recent times, tensions or conflict between humans and the natural world (e.g. human-wildlife conflict), assume agency and even legal representation over non-humans. In the same way that rivers in Colombia, Ecuador and New Zealand have rights, agency and legal standing, future conflicts over multi-agency over robots, can draw inspiration from these experiences [55, 78]. In the context of HRI, it also means that robots might not require human intervention to interact with Nature.

Our third law acknowledges how different communities see the harmony between their societies and Nature. It emphasizes the possibility of different ways to thrive without negatively affecting Nature. In the same way evolution has found different solutions to a similar natural problem, different cultures can set different directives to accomplish Nature's welfare. We leave an open question for how robots programmed by different cultures will interact amongst themselves and outside their "local" ecological/cultural boundaries, though we suggest that the notion of "partial connections" can provide a way to understand the unfolding relationships of two entities that are related to each other by way of containing one another, yet not possibly reduced one to the other [24, 101, p.52,p.32].

The fourth law, in the face of the possibility of self-aware and conscious robots, presents the duality between self-preservation and Nature's welfare. We highlight the importance of recognizing agency for all living forms, hence our Nature-centric approach, to avoid past mistakes made by human societies when subjugating other life forms.

Same as Asimov's, our proposed laws of NRI are susceptible of multiple ethical dilemmas and conundrums. In an effort to explore some of these, we continue with an exploration of a small set of potential benefits and drawbacks of this fictional paradigm.

2.2 Benefits of NRI

Given Nature's omnipresence as the backbone supporting all human and robot activities, NRI presents multiple potential socioeconomic, cultural and environmental benefits.

Socioeconomic: A Nature-centric lens will lead to changes in socio-economic policies, both local and global, prioritizing the environment and communities' welfare above that of personal and private interests. With a shift from consumer-focused economies to Nature's welfare-oriented markets, human comfort, and personal and private interests, will not be at the center of the equation anymore. This new approach to the forces of the market will promote changes in economic behaviors and incentives, overriding geopolitical interests. In consequence, we expect an increase in benefiting actions towards solving the global environmental challenges, including better allocation of natural resources.

Culture and Community: Local communities and cultural practices will gain traction and recognition in the socioeconomic and political space. Given their deeply rooted relationship with the environment, they are better suited for a Nature-centric lifestyle. As robots' follow a place-based orientation, the variety of possible designs is naturally increased, instead of concentrated under a dominant design paradigm. This variety can also promote collaboration between communities, particularly as Nature's welfare cannot be achieved if tackled by atomized and isolated working islands.

Environmental: In focusing on Nature's welfare, NRI promotes sustainable practices by having agents directly responding to human and non-human needs. In this context, an increase in data collection and sharing by robots will mean better models about the world and the possibility of developing better tools to prevent, or respond to, natural disasters. A focus on Nature's welfare could also lead to higher investment into technologies, including robots, aiming at solving pressing global challenges. Robots will act in service of improved agriculture, energy harvesting, recycling and trash management, pollutants removal, human research, animal and plant studies, especially as these agents will adapt to respond to these activities' environmental variables. Finally, in the context of enterprises intrinsically creating negative environmental consequences on Nature (e.g. logging, mining, and resource extraction), a Nature-centric approach will allow robots to find optimal scenarios to maximize extracted resources while considering Nature's welfare, while alternative approaches are discovered and put in place.

2.3 The dark side of NRI

As the focus on human agency is displaced, unforeseen potential harms, drawbacks, and ethical challenges come into view. Steering away from a human-centered focus reveals novel and creative ways to approach compelling questions within HRI, while potentially benefiting Nature. Regardless of this positive framing, several scenarios require an open debate, especially in light of cultural dependencies guiding NRI. Ethical concerns such as privacy and data handling, and the effect robots have on Nature are already being discussed [41], along with potential uses (positive and negative, foreseeable and unforeseeable) of all the data collected when robots interact with Nature [93]. This also encompasses discussions on the ecological impact of deploying robots into the wild, in particular the effect of robots in untouched environments and in the species it interacts with [26]. Building on these, we highlight some of the limitations and concerns to be considered. We present different scenarios, not to propose solutions, but rather to bring these aspects into consideration.

- *When Nature and humanity are on opposite sides of the scale, how will robots take action?* Consider resource extraction or agro-industrial farming necessary to sustain human needs: a Nature-centric lens requires either a substitution or complete freeze of any of these activities regardless of its impact on human welfare. Would a robot measure the loss of human life and weigh it against the environment and other lifeforms? What could such a metric be, and what characteristics are important when assessing the value of human life versus Nature's welfare?
- Using the same example, it is now robots the ones in need. *When Nature and robots are on opposite sides of the scale, how will robots take action?* If a robot needs to draw materials from Nature to stay operational, what would the value comparison be between Nature's possible extracted materials and the robot's existence?
- *Nature's welfare hierarchies.* With a myriad of actors taking steps on behalf of Nature, and with Nature largely defined through cultural notions, how will Nature find balance across this difference? *When humanity and robots' existence depend upon Nature's possibilities, how will humans and robots act in the face of planetary crisis?*

All these scenarios require us to take into account the *rights* of Nature. Over the last decade, Indigenous and grassroots communities have led efforts to operationalize them into practice. Examples include the inclusion of Nature's rights in Ecuador's Constitution [4], the declaration of the Atrato River in Colombia as a subject of rights [36], and the establishment of the Te Urewera forest and Whanganui River in New Zealand [42, 49], all rivers in Bangladesh [95], and the Mar menor lagoon in Spain [100] as legal entities.

2.4 Efforts towards a Nature-friendly HRI

In considering an alternative to current HRI design patterns, we consider some of the alternatives already out there, in an effort to map out how NRI might fit within this picture. Most efforts in robotics, and technological advancement in general, are currently focused on sustainability and technological efficiency. Different variations of how technology is developed and deployed in a Nature-friendly HRI include:

Ecological design - ecodesign: In line with sustainability trends promoted by environmentalists, ecological design was adopted by the design community in the 1990's [69], and has inspired robot researchers and innovators alike. Ecodesign is a model calling for an *"ecological informed enlightenment"* where Nature is not "...something to be overcome and subordinated...", but one that harmonizes "...the human enterprise with how the world works as a physical system and how it ought to work as a moral system" [110]. This approach places a strong component in how culture creates, shapes and evolves the relationship of communities with their environment, their concepts of value, and how technology is created and implemented [110].

End-use innovation: An approach to dealing with tensions between human and Nature-centered goals, focused on the search for more innovation and technological investment, i.e. end-use innovation. It imagines how several of the negative effects of a human-centric life are diminished through the increasing of technical efficiency (productivity), reducing the need for Nature's resources (energy, raw material, physical space) [22].

Biodegradable robots: Focusing on innovations from material science, chemistry and biology, biodegradable materials are allowing the development of electronics and robots that can fully return to Nature after accomplishing its tasks [120].

Green robotics: This is a current approach that focuses on sustainable robotic design and how to enforce circular material cycles following the operational life of robots. It covers structural and manufacturing materials, electronics and actuators, all the way to a robot's energy consumption, integration into ecosystems, intended purpose, and its impact on Nature [45, 83].

Although these steps towards a more Nature-friendly HRI are commendable and necessary, HRI's centering on humans as the driving force, leaves too many open questions when it comes to considering the impact of its practice in Nature, as explained in the first half of this work. To counter this, NRI offers a perspective that we argue better aligns with both human and Nature's needs; a perspective we recognize comes with caveats and uncertainty.

3 IMAGINED INTERVENTIONS OF ROBOTS IN NATURE'S REGULAR COURSE

Lastly, we present some scenarios where robots' actions and non-actions follow Nature-centric and/or anthropocentric approach. For NRI-compliant robots, most cases reveal that Nature's welfare can be seen immediately as human's welfare (e.g. natural disaster assisting robots) while in others, they look the opposite in the short term (e.g. forest conservation).

(1) **Farming:** *HRI:* In the anthropocentric paradigm, automation of mechanized agriculture has promised to bring high productivity and lower costs to farmers around the world. But automated agriculture is expensive [124] and only available to a few (mainly big land owners); it favors monocultures (leading to erosion and subsequently soil desertification [92], and promotes waste by using technologies that mainly harvest standardized produce (usually leaving behind odd produce in the plants). Beyond technical drawbacks, *"there are legal, ethical and social concerns associated with autonomous agriculture"* [92, p.306]. *NRI:* a Nature-centric vision of automated agriculture treats the food availability problem through a different lens. It aims to optimize the soil's biomass to support crops and animal species in the long term. It aligns with sustainable agriculture and promotes biodiverse farming while replacing the use of fertilizers and pesticides with sustainable practices, which have been employed for millennia by Indigenous collectives.

(2) **Animal research:** *HRI:* robot agents supporting animal research are focused on the improvement of animal interventions (e.g. high-precision surgeries and molecules delivery) [86], not so much on creating conditions to exclude animals from current research models, in spite of the challenges animal models present for translational medicine [85]. *NRI:* under this perspective, a drastic reduction in the use of animals in any research activities is favored in exchange for putting NRI-compliant robots at service of the development of micro and nanobots. These could improve the development and implementation of tissue, organ and systems of organs platforms where physiology, pharmacology and other studies can be carried away. Such platforms might help ameliorate issues regarding the species difference problems introduced by animal models.

(3) **Space exploration:** *HRI:* current space programs have placed its efforts on the mission objectives and the system's fail-safes. They have given almost no attention to the impact space waste will have on the environment. This is critical as more robots, with limited life spans, support space missions. Examples of such approaches are the expendable launch vehicles (rockets), and robots currently circulating across the solar system. *NRI:* infrastructure development in the context of space programs will include as default the reuse of space parts, and the return of robots to Nature. In recent years reusable space launch vehicles have proven to be successful, less expensive, and highly reliable. Moreover, once their life cycle has ended, future robots exploring space could complete their last mission goal: return to Nature.

(4) **Forest conservation:** *HRI:* current robot agents function as proxies for human interests and needs. In this context, they act as sensing units tracking the state and conditions of the forest to support socioeconomic, environmental and political goals (e.g. informing logging industries, calibrating carbon credits based on carbon absorption), with such data rarely openly available to the public.
NRI: future models of robot agents centered on Nature's welfare will not only sense and distribute such data but will be designed and deployed to accomplish specific Nature-centric missions, to intervene and promote the forest's conservation, and hence all the biodiversity they contain. Robots could track and treat disease damaging fungus colonies in the forest, or assess and restore the chemical unbalance in the soil. Robots are to be present in Nature to support it, not to primarily respond to human needs.

(5) **Solar flare protection:** in this scenario, both HRI and NRI approaches deem the same outcome though the means to achieve the goal might differ. Under *HRI*, any space mission prioritizes the anthropocentric goal of survival as the driver, regardless of the impact any robot action or inaction could have on other living beings or Nature itself. *NRI* would require a careful assessment of the impact the mission could have on Nature as a whole, in spite of the benefits of protecting human-made hardware and avoiding the disruption of human activities.

Beyond these prototypical scenarios, NRI could allow the development and deployment of new robots to satisfy Nature-welfare needs and the decommission of robots created and deployed to accomplish anthropocentric goals.

4 LIMITATIONS AND FUTURE WORK

Our initial proposal for a Nature-Robot Interaction paradigm focuses on a specific set of challenges faced by Nature and brought upon the current state of affairs in robotics. This analysis is not comprehensive as it leaves out important considerations regarding the use of energy in robotics and the current state of robot manufacturing at scale. Future work could focus on these and other additional considerations, with the goal of providing a more holistic image.

Although we proposed a set of guidelines to drive the practice and notions behind NRI, taking inspiration from science fiction, further work is required in considering a broader set of scenarios. This analysis could include current debates in robo-ethics and ethics in Artificial Intelligence, which have provided key advancements for dealing with unforeseen outcomes of practice within these fields.

As roboticists and designers who participate in environmental activism, particularly at the intersection with technology development, we recognize our bias towards the imperative protection of

Nature, particularly in light of the current state of Nature's ecosystems. Regardless, we recognize the importance of nuance and participation of other points of view. Future work should counterbalance the *radical* proposals offered by our work.

Finally, we recognize that as academics and practitioners with the privilege of formal training, we enact a particular position within a matter that concerns unprivileged groups. Our hope is that, as this conversation grows and expands, underprivileged groups will be brought into the conversation. Similarly, a more meaningful engagement with knowledges outside of the scientific frame is required. We have made an effort to foreground some of the important contributions these knowledge systems can offer to HRI, but recognize there is much more ground to be covered.

5 CONCLUSION

In this paper, we proposed a new robot interaction paradigm that places Nature at its epicenter: Nature-Robot Interaction (NRI). This approach seeks to blur anthropomorphism in HRI design by suggesting alternatives to how humans and robots relate to Nature and the environment. We propose a set of laws and principles that we hope will spark a dialogue in the HRI community and help guide the design and deployment of new generations of robots driven by Nature's welfare. Although our speculative exercise falls short in considering what is a multi-dimensional, complex problem, we recognize the importance of adding to this conversation. Therefore, our paper is an explicit call to imagine robots that do not use Nature as their material source, but rather as a source of inspiration.

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