IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 17, 2022, accepted May 2, 2022, date of publication May 5, 2022, date of current version May 12, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3172980

Cyborg Insects: Bug or a Feature?

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ABSTRACT Cyborg insects are a major part of the vision of future interactions of the living world and technology, including but not limited to the Internet of Living Things (IoLT). They are crawling or flying insects with additional electronic circuitry allowing remote control of their movement and collection of sensory data. In this critical review, we survey the historical development of cyborg insects engineering, from the first backpacks on insects used for communication and sensing, to different methods of control and actuation of insects' locomotion. We review the suggested applications of cyborg insects ranging from military use to agriculture, pointing out the problematic connotations of swarms and cyborgs in these contexts. We address the applications and the narratives around engineered insects from the perspective of philosophy, economy, law, and politics. We add perspectives on emancipatory potential of cyborg technology and where the future of it could lie.

INDEX TERMS Cyborg insects, Internet of Living Things, Internet of Things.

I. INTRODUCTION

"Your scientists were so preoccupied with whether or not they could, they didn't stop to think if they should." The oft-quoted line from the fictional complexity and chaos theorist Ian Malcolm in the film Jurassic Park [1] is widely used in academic papers on ethics of research. Engineering the nature, then leaving it to itself to evolve and mutate, while having a clear-cut business plan to exploit it–it is unsurprising that the film resonated with the audiences worldwide since its premiere in 1993.

It was in the same year that the first flying insect backpack was reported: a locust was equipped with a sensor monitoring muscle activity and transmitting it wirelessly [2]. The science of cyborg insects has come a long way since then, moving from mere sensing to various methods of actuation and developing new use cases for cyborg insects [3], insects whose sensing or actuation have been interfaced by technology. In this review, we report on these developments through multiple lenses, both in terms of social sciences, and natural sciences, engineering, and technology.

The necessity of such a review in an engineering venue can be inferred from Fig. 1 where we have used Connected Papers (http://connectedpapers.com/) to identify related work to a critical essay on cyborg insects [4] published in the journal *Society & Animals*. While the paper links together societal, ethical, and philosophical implications of cyborg insects with the engineering developments, the graph of connected papers creates the illusion that the only related work in the field is that from engineering–which regularly omits critical considerations [4]. This is the space we wish to fill with our review, and collect materials for a multifaceted view on cyborg insects.

In particular, we present here the historical development of cyborg insects engineering, its relationship with robotics, communications, and sensing. We also provide a perspective on the applications of the technology, reflecting on both the applications and the engineering aspects. We also reflect about the topic inspired by philosophy and established narratives around cyborgs, insects, and cyborg insects. The parallel with other related fields are present.

With that in mind, our paper is structured as follows.

- Section II discusses the history of the insect cyborgs, including the first implementations, challenges in the development, and how communications and energy supply are deployed.
- Section III presents the main use cases for insect cyborgs, namely military, agriculture and search and rescue.

The associate editor coordinating the review of this manuscript and approving it for publication was Cong Pu.

- Section IV provides a philosophical reflection and how cyborgs have appeared in fiction, which (more or less) shapes the design of this technology.
- Section V introduces two different related research fields that are important to understand and design cyborg insects, namely cyber-physical systems, human-machines interfaces and the Internet of Living Things.
- Section VI concludes this paper, indicating our proposed future developments in this domain.

II. THE HISTORY OF CYBORG INSECT ENGINEERING

Information as a scientific concept is used across different fields, many times with different roles in the theory [5]. Biological information usually refers to different (and complex) biochemical and/or electrical signaling that enables, for instance, reproduction of life and physiological processes [6]. One of the fathers of modern control theory, Norbert Wiener, has already indicated the similarity and potential convergence of biological information and communications engineering in a then new field called cybernetics [7], first published in 1948. The combination of technical tools and living beings organically combined have been also part of the philosophical thinking of Georges Canguilhem around the same time [8], in a lecture presented in 1947. This indicates the early stages of the research and development of cyborgs, as well as a deep philosophical implications of it.

Very frequently, cyborgs are associated with human-machine interfaces. Less investigated, but equally interesting, are the developments of cyborg insects; this field seems to have a lower ethical threshold in what can be done. This section covers relevant technical progress focusing on the history of the cyborg insect engineering following [9] and [10], indicating some ethical issues that will be discussed later on.

A. THE FIRST BACKPACKS

As any cybernetic system, cyborgs need sensors and actuators to exist as such. The first steps towards an insect cyborg is the development of (wireless) sensor nodes that can be attached in insects to take relevant measurements for researchers in biology. This line of research has been boosted by the research linking neural dynamics to naturalistic behaviour [11]–[13]. For instance, an interesting experiment was conducted to study the effects of different weight loads in their flying patterns [14]. Although this is far from a cyborg insect, this approach indicated the feasibility of having a patch to be attached in insects, which opened up new possibilities with the development of microelectronics. Few years later, a specialized wireless sensor was proposed and tested to measure physiological characteristics of locust flying [2]. What is interesting in this case is the actual development of what we call today ''wearables'' for insects, which in that time (early 90's) was very challenging because of the hardware limitations (size and battery of data acquisition devices).

To produce insect cyborgs, it is still necessary to move from these first stages towards actuators and then biobots.

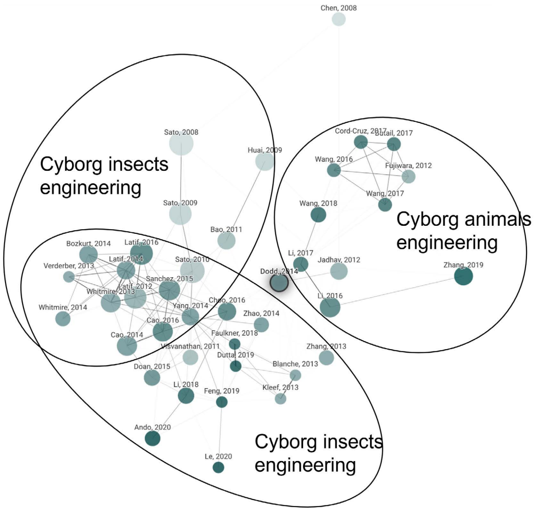

FIGURE 1. Connected Papers graph for A. Dodd, The Trouble with Insect Cyborgs [4]. Each node is an academic paper related to the origin paper, papers are arranged according to their similarity, node size and colour correspond to the number of citations and the publishing year, respectively.

In this context is it worth mentioning the contributions of Alper Bozkurt. He and his research group have been reporting several implementations of insect cyborgs (e.g., [15]–[20]), including actuation to wirelessly control the flight of insects. The proposed development started by building an insect–machine interface [15] designed to control thoracic flight muscles of a specific insect species, namely *Manduca sexta*. From this, many other papers followed to report the domestication of locomotion, as to be presented next. Other research lines considered the development of ''senses'' like hearing [21] and vision [22].

Fig. 2 illustrates the concept of an insect cyborg. It uses a *backpack* that contains just sensing capabilities, sensor and actuators with a non-invasive system. It is also possible to implement them in an invasive way through a surgical intervention, and even add during the metamorphosis phase of some insects [23]. The most usual approach to control the movements of insects is electrical stimulation in the muscles of the insects to control flying patterns or legs for jumping, depending in the species considered (refer to [9, Sec. 3.1.1]). However, other less direct approaches have been developed, namely sensory stimulation that leads to the desired control outcome. For example, the commercially available *RoboRoach* (https://backyardbrains.com/products/roboroach) works wirelessly through microstimulus in the antenna nerves of cockraches, ''signaling'' to the insect to move to one side or to another [24, Fig. 5]. However, if more sophisticated control is desired to perform specific tasks, a domestication of the movements of the insects is required [25].

B. DOMESTICATION OF MOVEMENTS

Ando and Kanzaki [26] describes well the challenges of a closed-loop control of cyborg insects, including a human operator in the loop, while providing a good overview of

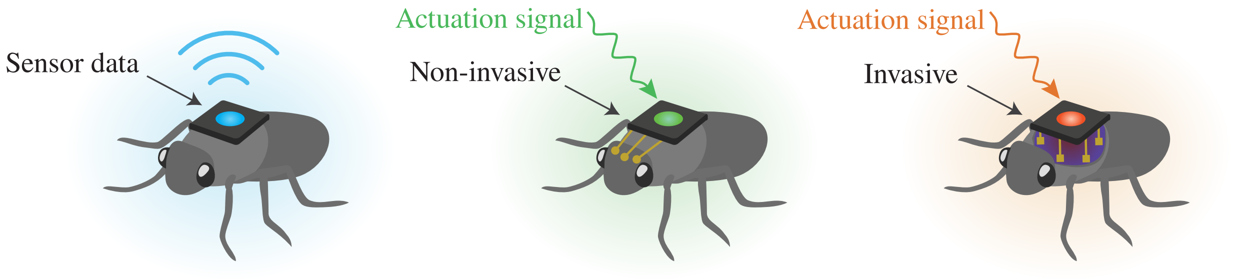

FIGURE 2. Sensing and actuation principles.

the current technologies available mainly focused on flying insects. An experiment of control the walking path of a beetle was reported in [27], indicating the location, levels and frequency of electrical stimulus to guide/stimulate the insect to move forward or sideways. Reference [28] provides a detailed characterization of the biomechanics of leg movements of insects in order to produce robot insects and, more importantly for our study, the mechanical and neurological details of climbing movements of cockroach.

In more concrete terms, Li *et al.* [29] showed issues in the stimulation of beetle related to an adaptation of the stimulus signal, which motivates them to propose a new protocol that provides a more effective control. A more systematic overview of the insect cyborgs developed by Li and Sato is presented in [30]. An extension of that work was presented focusing on the altitude control for flying insects using traditional tools of control theory, namely proportional-derivative control but integrated to environmental processing of altitude (see Fig. 3) [31]. Bozkurt and his team have been developed a similar approach but considering their specific method described in [15] and [20] where the implants are inserted during the metamorphosis phase of the insect development. It was reported a method to guide the movement in a curved line by tracking the path of a roach equipped with the "backpack" that is coupled with a controller that sent electrical stimuli based on the biophysical reactions of the insect; the experimental setup includes wireless connectivity [32]. Using a disaster scenario as motivation, it was pointed out the main challenges in the development of a cyber-physical infrastructure that could support a swarm of biobots, with a focus on the reliability of control architectures [25]. A more practical deployment is presented for a search and rescue mission, including a specific method for localization and communication ad hoc infrastructure to control a swarm of cyborgs and a purely robotic drone as a mission leader [18].

Other research groups have also developed different neuro-machine interfaces. Tsang *et al.* proposed in [33] a method based on nanotubes to fabricate flexible neuroprosthetic probes (FNP) to remotely control flights of insect cyborgs, where the stimulus is related to electrochemical processes in the neural cord. A new cyborg concept for beetles was proposed that combines the backpack stimulation with an artificial leg spines that are used to control forward and backward movements by (electrical) muscle stimulation [34]. A detailed—and relatively simple—architecture was proposed in [35] by Feng *et al.* considering a friendly user interface in computer to control the movement of beetles using electrical stimulation in the longitudinal muscles. A flexible interface without the need of complex controllers based in antenna stimulation of the insects is developed and shown to be a viable alternative to search and rescue missions [36]. Other similar solutions are reported in [37] and [38].

Those solutions were mainly based on direct or indirect electrical stimuli. Other different types of actuators have been proposed based on: (i) thermal stimulus considering different species of beetles [39], (ii) optrodes to control the flight of dragonfly based on flexible waveguide arrays [40], (iii) biochemical molecules for muscle relaxation by a specific type of liposome [41] , (iv) plasmonic nanotattoos [42], (v) artificial claw open–close cycle mechanism [43], and (vi) explosive chemical vapors [44]..

Actuation in cyborg insects poses ethical questions that have been systematically indicating in [45]. Different domains are identified and the effects of the media coverage is mapped, trying to indicate different types of application with their moral judgment. The (questionable) view taken by that paper refers to a tradeoff between utility and potential pain that insects may suffer during the actuating for controlling purposes. More on ethical issues will be discussed later on.

One of the central ethical questions underlying cyborg insects is whether insects experience pain in a similar way that other animals do. Animal pain is still a topic of debate [46], mostly because pain is a subjective experience that can hardly be assessed by objective physiological measurements. All lifeforms, from bacteria to mammals, evolved the ability to avoid dangerous sensory stimuli (nociception), which we as humans commonly refer to as painful stimuli. However, it is argued that the behavioural ability of sensing and avoiding a damaging stimulus does not grant one the capacity to experience pain [47]. For instance, Adamo [48] reinforces that pain results from the integration of sensory signals, memory, emotion and other higher-order cognitive processes in the central nervous system, thus the lack of such intricate network in insects points at a low likelihood of pain experience in these organisms. Despite a significant literature on pain in a variety of animal models [49], it was only recently that

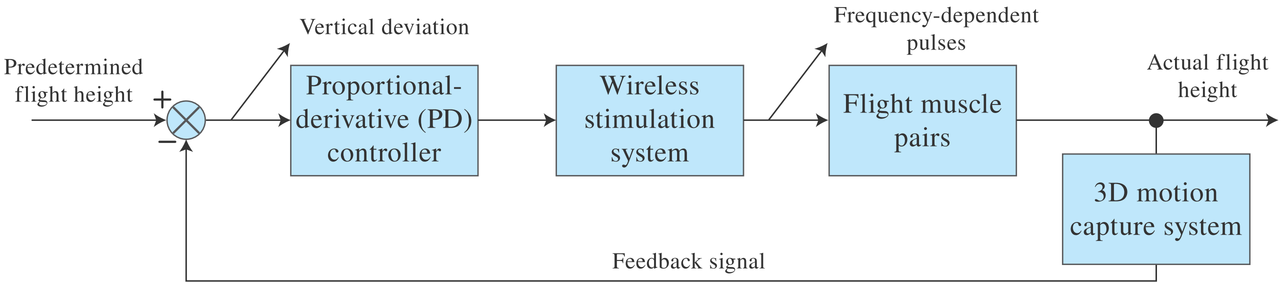

FIGURE 3. Example of the feedback control loop used in cyborg insects. Adapted from [31].

Khuong *et al.* [50] provided the first molecular evidence of chronic pain in insects, that is, a long lasting sensitivity to stimuli. Overall, whether insects experience pain remains unclear.

C. COMMUNICATION AND POWER

As briefly discussed before, communication is necessary to enable the feedback control loop in the cyborg insect. Wireless connectivity has clear advantage: it allows for the mobility required for the insect movement [10]. In this paper, the authors compare the different specifications of the wireless solution used in terms of transmission range and RF channels used. They included the early developments for telemetry and the most recent deployments of cyborgs. In 2010, three different implementations were reported [10]:

- Sato *et al.* [51]: 8-channel system with the Texas Instruments CC2431 microcontroller with transceiver;
- Bozkurt *et al.* [52]: 2-channel AM receiver with pulse-position modulation using a PIC12F615 microcontroller;
- Daly *et al.* [53]: system-on-chip receiver operating at 3–5 GHz on the 802.15.4a wireless standard with Texas Instruments MP430 microcontroller.

In any case, what is important to remark is that the particular selection of the wireless system to be deployed depends on the tradeoffs involved in the experiment including the specific insect to be used that defines, e.g., the size and carrying capacity, the task to be accomplished and the availability of energy.

This last aspect, related to the availability of power to run the ‘‘backpack’’ (transmitter, controller, actuators and sensors), is also important to construct insect cyborgs. Different solutions are reported from simple [51] to solar-powered batteries [18], [54] and biofuel cells [55]. As for the communications, the most suitable solution for powering the cyborg depends on the specifics of the case to be experimented.

III. USE CASES FOR CYBORG INSECTS

Here we present three major use cases of cyborg insects that have been proposed so far. Use cases like these, set in an early stage of a technological concept, sell it to the investors and the public: those listed below reinforce the existing socioeconomic models and fit right in ‘‘selling smartness’’ (as Sadowski and Bendor [56] describe the imaginary of smart city and large corporations driving it) as the Internet of Living Things looks for its place in the Internet of Things. Figure 4 represents three families of use cases of interest to us: military, agricultural, and search and rescue applications.

A. MILITARY APPLICATIONS

The major push for the proper cyborg insect development (i.e. actuation) came with Defense Advanced Research Projects Agency (DARPA) starting its HI-MEMS Hybrid Insect Micro-ElectroMechanical Systems (HI-MEMS) programme in 2006 (https://web.archive.org/web/20071008203450/http://www.darpa.gov/mto/programs/himems/index.html). To quote the official project website, ‘‘The HI-MEMS program is aimed to develop technology that provides more control over insect locomotion, just as saddles and horseshoes are needed for horse locomotion control.’’

Weaponisation of insects is by no means novel: from deploying bees in the ancient times to dropping crop-eating insects during the Cold War, insects have been a part of the military arsenal [57], [58]. Before gaining control over the movement of the insects, their sensing capabilities have been put to use for landmine detection [59] which has the potential to tie in with the tracking backpacks [60]. The modern uncrewed aerial vehicle (UAV) warfare has been much influenced by the insects as well (as the term *drone* already suggests).

B. AGRICULTURE

Robotic pollination is hard for regular flying robots, even if they are insect-inspired, and it was suggested that the cyborg insects were to bridge the gap [61], with existing capabilities for monitoring of pollination levels via backpack sensing [62]. The DragonFlEye project [40], [63] took pollination as one of the use cases for its cyborg dragonflies, opening the discourse on cyborg insects and the economy of plants. Interestingly, DragonFlEye cyborgs are called *hybrid drones*, which does remind us of hybrid seeds in agriculture and the economy thereof [64], [65]: no reproduction is possible, making the farmer dependant on the seeds/drones manufacturer. Furthermore, electronics and wireless communications allow building a business model around a killswitch technology

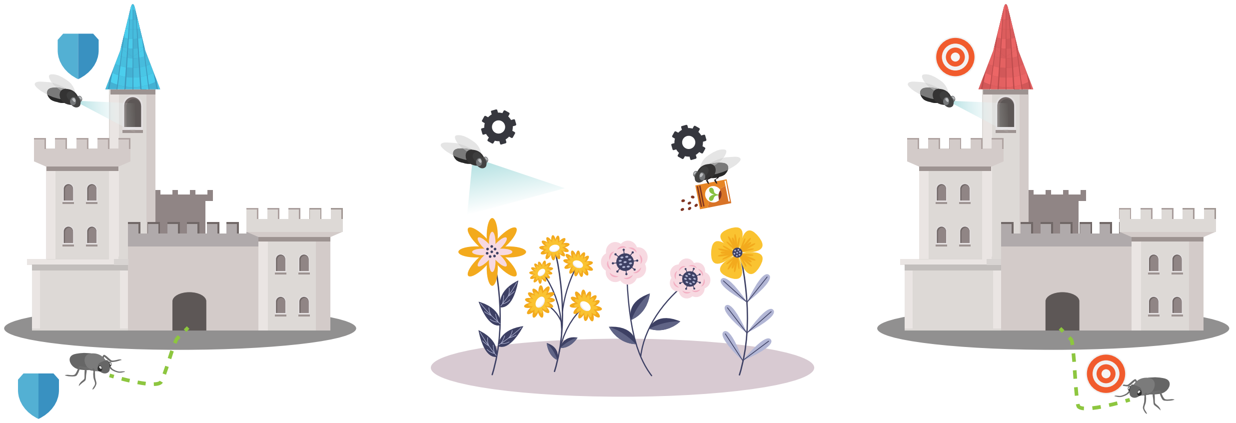

FIGURE 4. Use cases of cyborg insects: (a) military applications, (b) agricultural applications, (c) search and rescue. Benefiting from and contributing to these practical use cases, cyborg insects are also a relevant platform for testing biological hypotheses.

which would allow the vendor to provide drones as a service, rather than giving ownership over them to the farmer.

Furthermore, the pollination use case is a textbook example of an ecosystem into which these cyborg species would be introduced. Cyborged ecosystems have been researched for some time [66]: it is not necessary for a living member of the ecosystem to be technologically manipulated to produce a cyborged ecosystem, mere technological intervention is enough. With the invasion of cyborged species, the complexity (already present in ecosystems [67]) rises even more, and it is hard to predict the evolution and adaptation of the eco-system around it, giving rise to unintended consequences and system-wide changes. This is represented by the nested loops in Fig.5. While this figure uses the example of pollination, other use cases can be linked to its inherent complexity as well.

C. SEARCH AND RESCUE

Both animal-inspired robots and cyborg insects often put forward search and rescue as a relevant use case [68]: be it in large outdoor spaces where a lost, and potentially injured person is waiting for help (e.g. mountains) or in a collapsed building where the corridors are unapproachable because of the debris [69]. However, it rarely goes unnoticed that search and rescue has dual use counterparts, where the first part may still be search, but the latter can range from surveillance and policing to neutralisation of military targets. For example, in [70] (a reference aptly titled ''Domesticating the Drone''), demilitarisation of drones is extensively studied–recognising search and rescue as a straightforward repurposing of existing military technology. Another article with an interesting title, ''Cyborg Insects Could Someday Save Your Life'' [69], puts together the national security and search and rescue as means of saving lives. The author also recognises that for both applications, the current level of development with 50% success rate is not sufficient and requires substantial improvement.

The advantage of cyborg insects over robots (e.g. robot insects) in such an application comes from the nature of their locomotion [71]. For the robots, significant portion of the power budget provided by the on-board battery goes into the effort of walking/flying, while in the case of the insect, the energy for this comes from the insect's metabolism, and the battery power can then be used mainly for sending control signals, which are several orders of magnitude lower in power than the walking/flying itself, well under a milliwatt [72]. When compared to the tens or hundreds of milliwatts required for locomotion of robot insects [73], it is not surprising that the robot insects would deplete their battery in just a few minutes, while cyborg insects could have a much longer mission time without recharging. Furthermore, the insects have a natural predisposition for efficient movement and obstacle avoidance, therefore simplifying the hardware and software control [71].

D. BIOLOGICAL HYPOTHESES TESTING

Given the ability to record relevant biological variables and precisely stimulate circuits, fully awaken cyborg insects may constitute a relevant framework for testing biological hypothesis. For instance, while several insects (such as flies and honeybees) rely on vision for flight control, in beetles it seems that vision is superseded by other modalities [78], but it has remained unclear why during flight beetles stretch out their forelegs, which increases air resistance, in contrast to other insects. The hypothesis that beetles' legs have a different role in flight control has been tested in a series of studies [79]–[81], including tethered experiments, with and without electrical stimulation, and free-flight studies. The authors found that beetles' legs are fundamental in flight directional steering and in controlling wingbeat during landing, which can have profound implications both in further understanding motor control but also in designing novel miniature flying robots.

In another example, Ejaz *et al.* [82] and Huang *et al.* [83] used a cyborg fly to investigate the role of the H1-cell, a central component of the neural circuit underlying optomotor reflexes, in closed sensorimotor loop scenarios. They found that, for this particular cell and task, open- and closed-loop cell responses are similar, contrary to what would

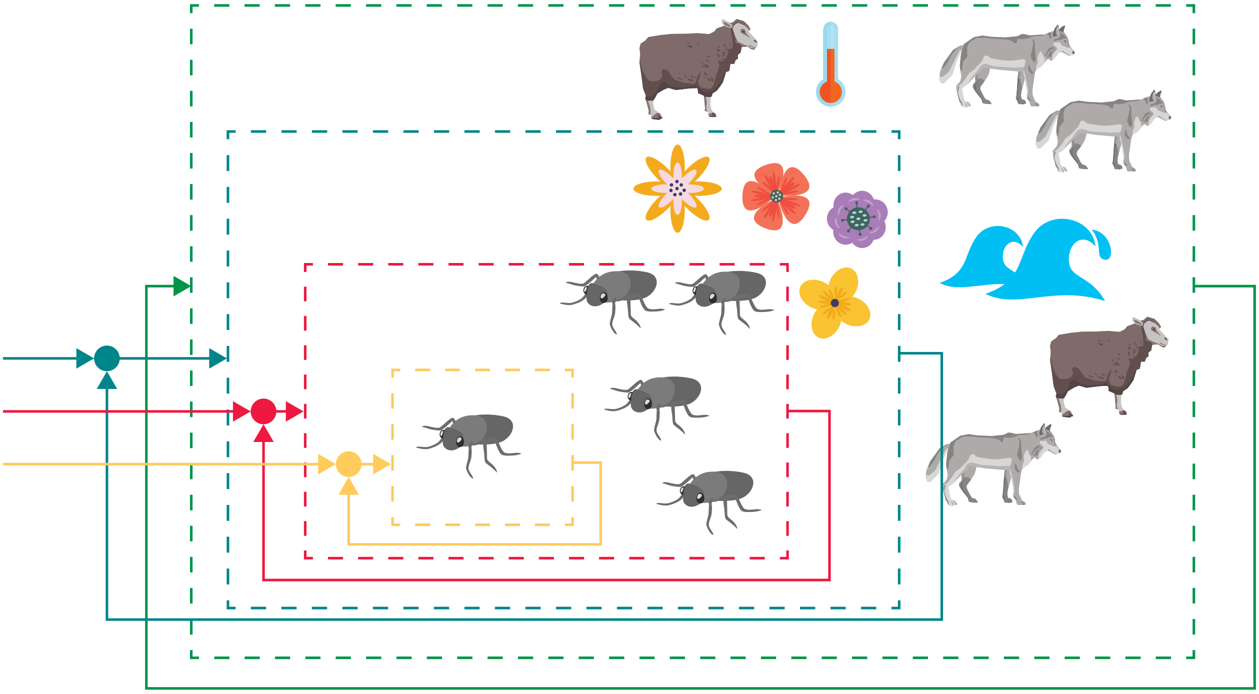

FIGURE 5. Nested loops and hierarchical control in a cyborg insect application. The motion of a single cyborg insect is controlled in a loop which is subordinate to the loop guiding the swarm. The loop guiding the swarm is itself subordinate to the task. All these are closed feedback loops that are at least to some extent controllable. The loop that encompasses them all, the eco-system, is autonomous and may have unintended consequences.

TABLE 1. Summary of use cases for cyborg insects.

Use case	Insect	Control strategy	Implant site	Reference
Flight control	moth[1]	Radio controlled neuromuscular electrical probes	antennal lobe; neck muscle	[74]
	beetle[2]	Radio controlled neuromuscular electrical probes	optic lobes, brain, posterior pronotum, basalar flight muscles	[51]
	moth[1]	Immature stage implanted microfluidics	dorsal/ventral thorax; head; abdomen	[75]
	dragonfly[3]	Optogenetics	target-selective descending neurons	[63]
Land locomotion control	cockroach[4]	Radio controlled electrical probes	antenna; prothoracic ganglia	[32], [37], [76], [77]
	beetle[5]	Radio controlled electrical probes	leg muscles; pronotum; elytra	[27], [34]

[1] *Maduca sexta*; [2] *Mecynorhina polyphemus or Mecynorhina torquata*; [3] *Anisoptera*
[4] *Periplaneta Americana, Gromphadorhina Portentosa, Blaberus discoidalis*; [5] *Zophobas morio, Mecynorhina torquata*

be expected, and further characterised the electrical dynamics of H1-cells with respect to optical flow. Thus, their work may support the development of novel bioinspired vision sensors and motor control algorithms.

Finally, cyborg insects can also be a valuable platform in studying social behaviour, evolution, and interactions in mixed animal societies [9], [26], [84].

IV. THE PHILOSOPHY, THE NARRATIVES, AND THE IMAGINARIES OF CYBORG INSECTS

While famously no technology is neutral, cyborgs as a form of an invasive technological intervention into a living body have straightforward philosophical and ethical connotations. Furthermore, such interventions into the fabric of life have been in the focus of human imagination before technology that would allow them even became possible, and these narratives and imaginaries tie in with some of the basic ideas and beliefs of human societies. Finally, humans have been fascinated by insects since the dawn of time: their power in swarm, their pervasiveness, and their apparent otherness. We write about the relationship of the human societies, cyborgs and insects in this section.

A. PHILOSOPHICAL PERSPECTIVES ON CYBORGS, INSECTS, AND CYBORG INSECTS

"Like any important technology, a cyborg is simultaneously a myth and a tool, a representation and an instrument, a frozen moment and a motor of social and imaginative reality. A cyborg exists when two kinds of boundaries are simultaneously problematic: 1) that between animals (or other organisms) and humans, and 2) that between self-controlled, self-governing machines (automatons) and organisms, especially humans (models of autonomy).'' This quote from Donna Haraway's Primate visions [85], well-correlated with Haraway's landmark Cyborg Manifesto [86] gives us a visual representation of the cybernetic system of systems we are observing here. Haraway proceeds by calling the cyborg a ''figure born of the interface of automaton and autonomy.'' We will keep returning to this link of autonomy and automat(i)on in the remainder of this article.

One philosophical framework that is a necessary component of a cyborg discussion is that of Deleuze and Guattari [87]. Deleuze and Guattari have, like many before, discussed the concepts of machines and organisms and their points of separation [88]. Hard points of separation are tricky in this context–as Haraway writes in the Manifesto, ''late twentieth century machines have made thoroughly ambiguous the difference between natural and artificial, mind and body, self-developing and externally designed, and many other distrinctions that used to apply to organisms and machines.''

The two terms from the Deleuzian perspective we bring here are becoming and body without organs. Becoming, in Deleuzian context is ''a rhizome, not a classificatory or genealogical tree. Becoming is certainly not imitating or identifying with something; neither is it regressing-progressing; neither is it corresponding, establishing corresponding relations; neither is it producing, producing a filiation, or producing through filiation. Becoming is a verb with a consistency all its own; it does not reduce to, or lead back to, 'appearing', 'being', 'equalling', or 'producing'.'' [87] Relevant to this discussion is Smith's interpretation of Deleuze: ''The body without organs is the full set of capacities or potentialities of a body prior to its being given the structure of an organism, which only limits and constrains what it can do: it is ''what remains when you take everything away.'''' [88].

We see that in both becoming and the concept of body without organs, there is the removal of hierarchy and fitness, letting the change happen in a networked, complex way freed from control. Become-cyborg [89] in that context is about freeing the actions and posibilities from the feedback loop of the organism, allowing new ways of acting. In that sense, let us have a look at the cyborg insect research: in one example, researchers have discovered that the application of their control mechanisms for locomotion could make an insect go backwards–ability not possible in nature for the non-cyborged insect [34]. While it is hijacking the control loop from the organism, it is a part of a bigger control loop of the future application of this insect cyborg: going against becoming-cyborg.

While on the topic of becoming, what about becoming-insect? The insects have been observed as creatures of alien nature; the metamorphic sequence of their literal becoming from an egg to a mature insect has been a fascinating topic for humans; these two observations led to becoming-insect and becoming-woman (reproductive role, change of body, birth, difference from men) being connected in the Western eye [90], [91]. We will return to feminist and queer visions of insects in the following section as well.

Finally, when we speak of Deleuze and Guattari's separation of organism and the machine, it is worth mentioning the analogous effort from Canguilhem [8], [92] before Deleuze's time, and that of Lewontin and Levins [93] after. Both approaches observe the Cartesian idea of the organism being a mechanism, commonly cited as organism being like a clock. Descartes put it as a metaphor, but since then, according to Lewontin, ''in the minds of natural scientists and a large fraction of social scientists as well, the world has ceased to be like a machine, but instead is seen as if it were a machine. Cartesian reductionism, which regards the entire world of things as, in fact, a very complicated electro-mechanical device, is not simply the dominant mode of thought in natural science, but the only mode to enter the consciousness of the vast majority of modern scientists.'' [94]. In the context of cyborg insects, it is straightforward to see the pitfall of the machinistic view of the world or an organism. Reductionist view on the role of the insect (e.g. as a pollinator) in a mechanical interpretation of the wider eco-system, or the view of a leg muscle as a motor that can be replaced or bypassed by the novel electro-mechanical control loop. Returning to Canguilhem, he ''takes all tools and machines to be extensions of the body, and part of life itself (which does not make machines any more good or bad than every living organism is good or bad)'' (interpreting [8] in [92]). Compare this view of machines as extensions of the boy and the Deleuzian one interpreted by Samuel Butler in The book of the Machines where he suggests humans are part of the reproductive system of the machines, like pollinators [95]. They both create an interface between the two, one that is not simple to engineer, but one that welcomes cyborgs.

B. CYBORGS, INSECTS, AND CYBORG INSECTS IN FICTION

When referring to the 19th century entomology observing insect societies as complex and almost technological [91], Franciska Cettl writes ''It could be argued that Shelley anticipated this coming discourse by positioning the electrically animated creature-as-insect as not quite fully organic but negotiating the unstable boundary with the machinic and technological.'' [96]. Cettl speaks of Mary Shelley's reference to insects in Frankenstein [97], a reference where other critics have recognised the treatment of the insect as radically other [98]. Cettl's interpretation is tuning right into the idea of cyborg insects: they are viewed as something of a machine even before any intervention. This is repeatedly stated in robotics, from early days to the modern era, for example in [99] we find ''Insects can seem more machine-like than many other living creatures. They can appear to go about their tasks as if they were programmed to do so, with little variation. Many of their behaviours seem to occur as fixed reactions to environmental stimuli. (…) As such, insects can seem robot-like, and this, together with the apparent greater simplicity of insects can make the goal of using robots to artificially replicate them appear to be more achievable than that of creating an artificial human being or mammal.''

From there onwards, across two centuries of science fiction, Cettl follows representation of insects, insect-like aliens, and robotic insects. With the robotic insects, examples like the glass bees from Ernst Jünger's eponymous novel [100] where artificial insects outcompete the natural ones and lead to their extinction is interesting for us, as it reflects the intuitive recognition of complexity of ecosystems and the ripples engineering of ecosystems makes. And then, Cettl brings up the recent example of robotic killer bee swarms linked in with social networks in the TV show Black Mirror, which ''as they 'pass between hives, they switch from one jurisdiction to another, like a phone between cell masts', as we find out in the episode ('Hated in the Nation' 2016). However, this folding of the agency of the organic swarm into the agency of the digital network raises the key biopolitical question—of who can possibly control these uncannimedia and for what purposes exactly—which is already anticipated in Jünger's novel.'' [96], [101].

Here, switching between jurisdictions just like switching between wireless networks is an interesting line of thought for cyborg insects in our review: the control networks and the communication networks are large, distributed, highly interacting. Who can possibly control the swarm is another major question–as the swarm embeds into a digital network. We return to that in the following section.

Lauren Wilcox reflects on what insects represent in fiction: ''In the genre of science fiction, insects, swarms and hives represent a continual source of terror, whether against female sexuality and reproduction or Communist hordes threatening individualism (Jackson and Nexon, 2003). Wars are frequently fought against insect-like interstellar aliens (...) The alien-mother of Ridley Scott's Alien is insect-like. Woman as becoming-insect is a fearful spectre in many works of science fiction; it is often portrayed negatively as a warning against tampering with uncontrollable forces of nature and represented by the threat of reproduction uncontrolled by masculine sovereign power. Kurt Neumann's 1958 cult classic, The Fly (1958), and Star Trek's 'Borg' are two examples of insect life linked with the threat of 'becoming-woman' that also exemplify the way in which 'insects signal a high degree of imbrication of the organic with the technological' (Braidotti, 2002, p. 152). As Braidotti (ibid., p. 277) notes, 'insects are only the most evident metaphorical process conflating a number of irreconcilable terms such as life/nonlife, biology/technology, human/machine'.'' ([102] referencing [103], [104]). The insect is also a disease-carrier in dominant narratives, the hidden infiltrator, the parasite. It is worthy to note, however, that in the cyborg insect vision of exploitation introduced by DARPA, it is the human who is the parasite on the natural body, as Zerner [105] puts it: ''In this vision, the microelectronic mechanical component becomes the parasite ''harvesting'' or, more darkly, ''scavenging'' energy from living organisms. A distinct version of the alien-invasion narrative is sketched: Nature is drained of its lifegiving energy by mechanisms.''

These fictional narratives affect the imaginaries in technology. Shoshana Magnet explains how insects, swarms, and robotic insects are overly militarised (in the spirit of war machine to which we are arriving in the next section), but also offers an optimistic future prospect, recognising the power of metaphors and imaginaries: ''How might we wake up these metaphors involving robot-insects? Insects, their bodies and their relationships remain complex. They are not easily reducible to robotic machines –and using machines to describe them and swarm behavior invokes white supremacist tropes that have very troubling implications. We need to think about how to wake up to these sleeping metaphors so that we might think about collective ends for our communities, ones that are not obsessed with imperial forms of racist containment, but ones that look in substantive ways to the relationships we have with the natural world, including swarms, to think about how to work together, how to organize collectively, and how to move not as independent units with opposing interests, but instead to swarm as one.'' [106].

C. SWARM OF INSECTS AS A WAR MACHINE

When autonomous robots entered the war theatre, the concern in the general community, as well as the professional community of the international humanitarian law, was the one of removal of the human from the loop, as the robotic weapon does everything autonomously, including the choice of the target. One straightforward reaction was the call to keep the human in the loop [107], for example. However, these discussions, as Matilda Arvidsson recognises [108], do not distinguish between swarms and singular (often antropomorphic-masculine) visions of killer robots.

Arvidsson follows the argument on the swarm being a war machine in the sense of Deleuze and Guattari [87]. The war machine is nomadic, rhyzomatic, opposed to the phylum and structures of the state, emergent and transformative. Now, ''[c]odification strives to territorialize and order war and the war machine'' [108] and we observe just how codification of swarms works. While Arvidsson examines robotic drones, i.e. robot insects, there is an even greater complexity in cyborg insects.

In [109] a list of very practical issues of codification and governance of the cyborg insects: which state agency in the US should do which part, from airflight to biological modification, safety and security. The swarm as war machine links well to the interpretation of war machine in Mbembe's Necropolitics. [110]. When Mbembe speaks of war machine's capacity for metamorphosis, very insect-like in linguistic sense already, there is also ''borrowing from regular armies while incorporating new elements well adapted to the principle of segmentation and deterritorialisation.'' It is a swarm, free in space, and joining the eco-systems it flies through, extracting resource from them and not recognising those state constructs that are irrelevant to it.

D. CYBORGS AS AN ACT OF COLONISATION

The language around cyborg insect research is telling: from the "domestication of locomotion" to "saddles and horseshoes", it is the language of taming, submission, conquest and control. On the opposite end, another article on ethics of technological development that starts with the same quote as ours is titled *Taming Technology*. [111]. This power struggle shapes the discourse.

Swarms and insects have been an orientalist trope in the west as well. Edward Said cites an 11th century European account of the Eastern armies as having "all the appearance of a swarm of bees, but with a heavy hand" [112], and Fanon writes that "Hostile nature, obstinate and fundamentally rebellious, is in fact represented in the colonies by the bush, by mosquitos, natives, and fever, and colonization is a success when all this indocile nature has finally been tamed" [113]. It is not misplaced to compare this view to that of the war machine vs state in Deleuze and Guattari and once again see the swarm as war machine.

It is by no means a coincidence that the Blue Mountain Declaration from 1995 states that "[i]ndigenous peoples, their knowledge and resources are the primary target for the commodification of genetic resources. We call upon all individuals and organisations to recognise these peoples' sovereign rights to self-determination and territorial rights, and to support their efforts to protect themselves, their lands and genetic resources from commodification and manipulation."

Renisa Mawani's discussion of bee swarms in the context of landmine detection is relevant here [114]. Mawani speaks of "the feral quality of bees, their unpredictability and ungovernability" that "have rendered them potential rather than actual forces in war. The honeybee may be "a zoosensor of the future" but for now, it remains an architect, not only of her own cells but also in the planning and production of military knowledges and tactics" (the last part of Mawani's quote is a reference to both [59] and [115]). The swarm is an ungovernable (by Western standards and hierarchies, ranks and structures) force to be reckoned with, and the cyborg insect gives a chance to maintain the swarmlike behaviour while having some control over its direction and application. This gives a new life to insect mercenaries [116] concept, while still maintaining the alien nature of swarm, and removed responsibility from the operator.

V. CYBORG INSECTS AND RELATED FIELDS

This section provides a complement to the review carried out so far by drawing parallels between two other broader related research fields, namely cyber-physical systems and human-machine interfaces.

A. CYBER-PHYSICAL SYSTEMS

In *Cyber-Physical Systems: Theory, Methodology and Applications* [117], the concept of cyber-physical system (CPS) is defined by three layers: physical, data and decision. Generalizing the idea of cybernetics, CPS involves the self-development of systems constituted by physical and logical relations that determine how decisions about potential actions are taken. In this way, the CPS is theoretically characterized by a structure of awareness from logical relations and structure of action where agents or actuators intervene in the physical system (modifying its physical relations); note that in the general case, CPSs are multi-agent systems. This approach has the advantage of splitting the physical and cyber domains, allowing for their relatively autonomous dynamics, while articulating their close relation; by doing so, the dynamics of the CPS can be understood not only at different layers but also at different scales from global to local.

This characterization may also be employed for cyborg insects, either working individually or in swarms. In concrete terms, the technical description presented in Section II can be seen as the stages of constituting the data acquisition to map physical processes to the cyber domain where quantifiable attributes are used to monitor the physical process and act according to a predefined plan; this is illustrated in Figs. 2 and 3 as usual feedback control loop where the insect is part of it. However, this could be further developed in cases of swarms (i.e., multi-agent system) where different cyborg insects would be logically related in the virtual domain to jointly perform collaboratively joint tasks, leading to a dynamical, self-developing, system where *the whole is more than the sum of its parts*. In other words, individual control of actions following a feedback control is not enough to control the swarm, which in turn requires coordination through logical (not physical) links and fused data for proper decisions. Such direct brain–to–brain links have been shown to facilitate cooperative problem-solving tasks in rats and monkeys [118], [119], resembling an organic computer, thus swarms of cyborg insects may lead to novel, complex intelligent systems.

B. HUMAN-MACHINE INTERFACES

Human-machine interfaces (HMI) are rapidly becoming a major topic of research. The great progress in neural recording technology [120] allied to novel immersive virtual reality over wireless networks protocols [121] provide a suitable framework for interfacing humans with machines. HMI have applications in basic neuroscience research, health, entertainment industry, among several other fields.

Importantly, a new era of HMI based on brain-type communications [122] is set to benefit the development of cyborg insects, considering the research effort towards wireless neural recording and stimulation technology. One of the most significant features of HMI is the simultaneous access to neuronal signals (both recording and stimulation) and human (animal) behaviour. Motor and cognitive processes, including those affected by neural disorders, are better understood if brain–body–environment interactions are taken into account [123]. Thus, in addition to animal experiments, robots have been used to shed light into different aspects of neural correlates of behaviour [124], [125]. In this

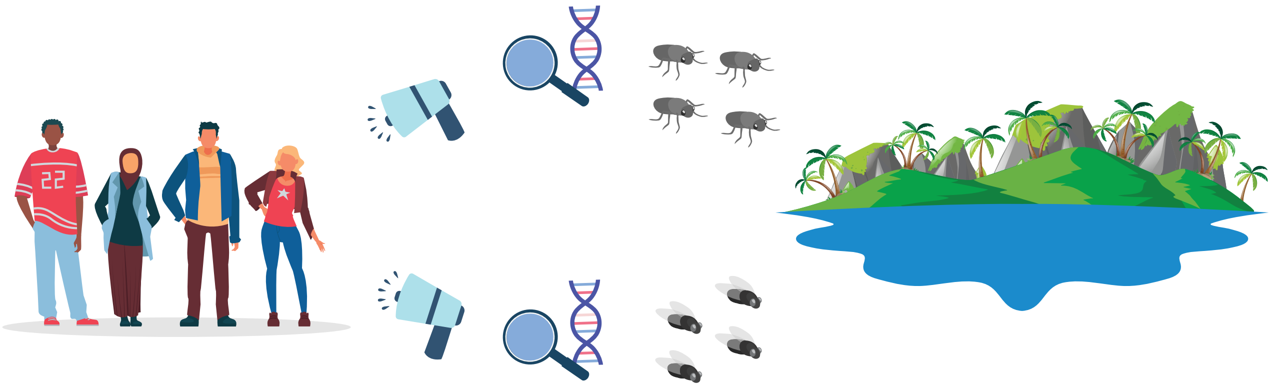

FIGURE 6. Genomic sequencing in cyborg insects as a tool for amplifying the alarm raised by these "canaries in coal mine" as the deterioration of living conditions in eco-systems affects their genome and well-being. It would serve as a component of the natural-social hybrid entity in decision-making.

way, brain-based human control of cyborg insects [126] can become another relevant field of research.

Finally, there are recent results showing that neuromuscular electrical stimulation, similar to that used extensively in cyborg insects, may restore sensory-motor functions in chronic stroke survivors [127]. In this way, cyborg insects may reveal themselves as a significant research platform due to technical, ethical, and economical advantages when compared to vertebrates and robots.

C. INSECTS AND CYBORGS IN THE INTERNET OF LIVING THINGS

The formulaic term "Internet of X-Things" has been used more and more ever since Internet of Things has been introduced [128]: internet of underwater things, internet of space things, etc. It is not surprising to see that Internet of Living Things means different things to different research groups in this point in time. Some use it to denote networks of miniaturised genomic sequencers and computational resources needed to interpret the collected genomic sequences [129]; some use it as a term for wireless sensors attached to humans, usually in healthcare context [130]; finally, some use it for sensor networks in macroscopic biological context interacting with technology, e.g. smart IoT-enabled agriculture [131].

Where do insects and cyborgs come into play for authors who use the term Internet of Living Things for these different concepts?

In [132], Internet of Living Things has plants and farm animals as things, and insects are only mentioned when explaining what a *plantoid* is to a plant (what an android is to a human). Plants require insects for reproduction, plantoids do not–turns out that plantoids need humans (cf. our earlier reference to Butler [95]).

The vision of "[a] global network of stations provisioned with sequencers, computational hardware and autonomous samplers [which] could track the shifting spectra of species in space and time, an Internet of living things, a world in which organisms act as transducers of biosphere change" [133] places insects, alongside other living species, in a role of sensors that are capable of tracking change that could not be sensed by e.g. measurement of physical parameters, counting, behaviour observation, etc. Here, insects can have a special place for their pervasiveness.

In [134] Andrea M. Matwyshyn observes the legal aspects of the Internet of Bodies, which builds upon human cyborgs. Matwyshyn references the genomic Internet of Living Things there, and goes further–with a companion essay titled *The Internet of Latour's Things*. Internet of Bodies is not only about humans and their cyborg variants; it is rather about *everything*, given the nature of Latour's Parliament of Things, where everything, i.e. different nature-society hybrids, have a voice.

Inspired by these visions of the Internet of Living Things and the implicit hint of insect's place in them, here we offer a vision of a different cyborg insect imaginary, represented in Fig. 6. In the climate emergency we are experiencing, and the demise of biodiversity, a metaphorical voice of insects could be amplified through cyborg technology. It is far from being a solution, but it is a component in empowering the eco-systems in the Latour-like parliament of things.

VI. AFTERTHOUGHTS AND CONCLUSION

There is an emancipatory potential in cyborgs, or rather in becoming-cyborgs. However, emancipatory potential of a technology (e.g. often praised decentralisation with distributed ledger technology) is rarely tapped into, as the use cases get co-opted into the current systems, therefore denying the becoming. Similarly, with the cyborg insects–if they are co-opted in the feedback loops big and small that perpetuate the imaginary of exploitation. In positive terms, different technological artifacts and methods are ambivalent as argued by the philosopher of technology Andrew Feenberg [135]. This means that, despite the fact that most widespread technologies are (explicitly or not) designed for domination and control, they are also open for unexpected interventions and uses that might become emancipatory. Emancipation here refers to increasing the space of action of humans living in society without exploitation. In other words, insect cyborgs may be designed and employed for extending the abilities of humans. For example, search and rescue activities after hurricanes or floods where the cyborgs can be employed extending our senses, or it may also be used to develop the scientific knowledge of neurosciences, supporting medical interventions.

In this sense, we foresee the following challenges to further develop insect cyborgs in an emancipatory way considering what has been already developed and the ambivalence of the current technology:

- Introduce limitations in the commercialization of systems that can be used in large scale operations, keeping them available for specific operations like search and rescue.
- Define strong regulations to military applications of insect cyborgs.
- Support further studies of hybrid ecosystems and living beings.

Ethics concerns underlie all of aforementioned challenges. Some insects, like cockroaches or flies, are perceived by the society as pest, thus being expendable, while other species, such as bees, gather far more sympathy for their clear value to humans. In any case, research that relies on any animal species, regardless of their utility value, are subject to the constraints established by the relevant ethics committees, including the minimisation of suffering, respect, and sensitive assessment of benefits gained from the approach (in line with the reduce, replace, and refine guideline). Therefore, care must be taken on developing cyborg-insects.

ACKNOWLEDGMENT

The authors would like to thank Arthur Sousa de Sena for producing the graphics used in this article.

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