ANIMAL ROBOTS

The beehive of the future is a robot socially interacting with honeybees

Donato Romano[1,2]*

A robotic beehive may unveil insights into honeybee collective behavior and sustain the colony in harsh weather.

Positioned at the interface between robotics and behavioral ecology, the field of animal-robot interaction is generating a wave of scientific and technological advancements with potential influence on human society and the environment (*1*–*3*). These biohybrid systems emerge from the deep integration of technological artifacts (such as robots) into animal populations and communities. Artificial agents and animals interact and share their abilities collectively in an organism-robot augmented system. Just like in cyborgs, in animal-robot mixed societies, the technological component (in this case an artificial agent) can monitor, control, restore, or enhance functionality of the biological system (such as an animal colony) in which it is integrated. Conversely, animal intelligence can inform technological systems, enhancing their performance in real-world challenging scenarios. The applications are many, ranging from fundamental biological investigation to bioinspired engineering design. One aim of animal-robot interaction is biodiversity preservation and improvement of environmental sustainability. The indiscriminate use and improper management of natural resources for economic growth have led to an unprecedented decay of both terrestrial and aquatic ecosystems, requiring urgent attention to dampen the effects of human activities on the environment (*4*). Animal-robot interaction can play a key role in mitigating anthropogenic negative effects on ecosystems. Writing in *Science Robotics*, Barmak *et al.* (*5*) aimed at supporting honeybee colonies to survive extreme winter temperatures by developing a robotic beehive capable of monitoring and interacting with honeybees, which are of great ecological importance.

Honeybees (*Apis mellifera* L.), along with wild bee species, are considered to be the most important pollinators, playing a central role in the production of crops and the maintenance of biodiversity (*6*). However, the spread of diseases and parasites, monocultures, climatic changes, industrialization, and agrochemical abuse have played a major role in the severe decline of the populations of both domestic honeybees and wild bees. In addition, it has been reported that there is increased mortality in honeybee colonies during the winter season in non-tropic regions (*7*), the causes of which are still poorly understood. Honeybees survive the winter as a colony, unlike wasps and bumblebees, but being ectotherms, they adopt collective behavioral strategies to reach and maintain a temperature threshold allowing them to be active and remain viable. The key strategy to allow this is the "winter cluster" (*8*), consisting of a dense aggregation of bees that can move within the nest to find nutrients and thermally optimal locations. In the core region of the cluster, temperatures are much warmer than in the periphery, creating an optimal microclimate for honeybees within.

Barmak and colleagues took advantage of the bees' sensitivity to temperature to develop robotic hive combs that are capable of thermically interacting with overwintering colonies of the honeybee subspecies *Apis mellifera carnica* Pollmann. This robotic system was used to observe the colony by constantly collecting spatiotemporal thermal profiles of the winter cluster over a long-term experiment. The robotic combs, containing a data processing and control unit, silicon-based temperature sensors, and thermal actuators, were embedded in the honeycombs, enabling biohybrid interaction with the honeybees while having a minimally invasive influence on the architecture and structure of the nest. Barmak and colleagues successfully established a biohybrid society where the robotic system used its sensors to perceive different states of the insect colony and produced responses in a closed-loop interaction (Fig. 1). The robot was capable of activating and deactivating thermal actuators to investigate the effects of temperature change on the collective behavior of the bees, such as their temporal position within the hive, in response to specific temperature inputs from the robot. Furthermore, the robotic system could also be used to balance the temperatures on the basis of the heat produced by the honeybees. The robotic system proposed by the researchers was also shown to be critical in providing a potential life support tool for honeybee colonies most vulnerable to winter collapse. During winter when the temperatures drop drastically within the hive, weakened bees can fall into a state of chill-coma, often leading to their deaths. The robotic hive was able, through the activation of its thermal actuators, to restore motility and normal behavior in previously comatose bees, thus preventing the immediate decline of the colony.

In the context of both research and domestic beekeeping, there is growing interest in the development of multiparametric smart sensor–based hives for monitoring bees to identify possible causes of their decline and ultimately to inform approaches for alleviating these threats (*9*). Moreover, robotic agents have already been used to interact with one or a few groups of honeybees (*10*). In the study by Barmak and colleagues, their robotic system could monitor and interact with the entire honeybee colony made up of thousands of individuals, which is crucial in investigating self-regulation

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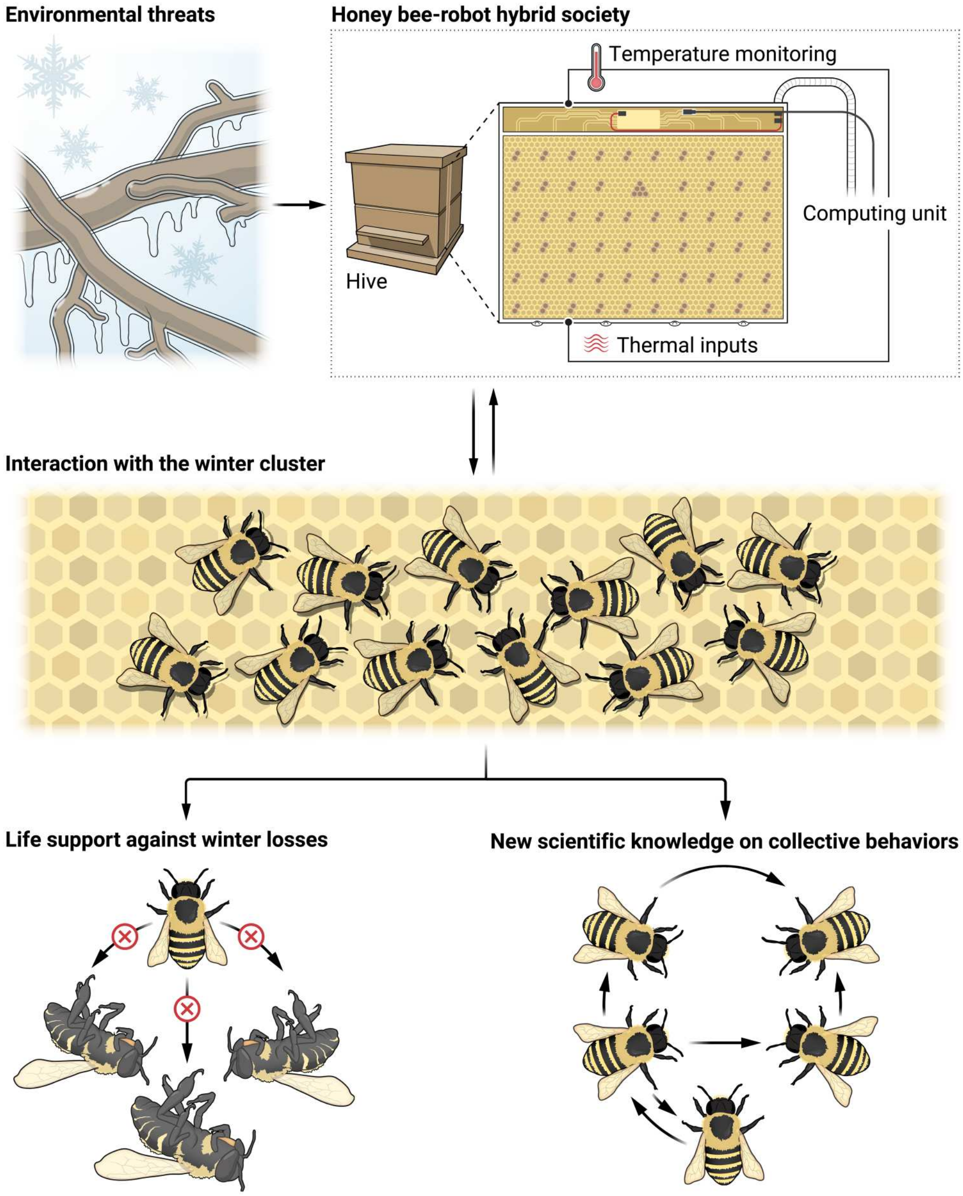

Fig. 1. Schematic of the honeybee-robot hybrid system and its possible scientific and environmental uses. Closed-loop interaction between the honeybees and the robotic system enables modulation of collective behavior to study social thermoregulatory processes and support the life of the colony during adverse climatic conditions.

processes and other collective dynamics in responses to thermal stimuli. This robotic system could be instrumental in further elucidating emergent collective thermoregulatory behaviors in overwintering honeybees. Moreover, the compatibility of the robotic system with box hives and the minimal disturbance imposed on the insects make it suitable for traditional hives used in apiculture. This offers a unique advantage that could be fundamental in investigating the causes underlying the current collapse of honeybee colonies worldwide. In addition, the possibility of intervening in temperature-related detriments affecting the bees' health makes this robotic system potentially capable of protecting and resuscitating the colony, augmenting the bees' ability to overcome the increasingly challenging temperature extremes as a result of climate change.

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