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Methodological Challenges of the Use of Robots in Ethological Research

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Abstract – Artificial models have been used as interactive partners for decades to study the social behavior of animals. Recent technological developments have opened up novel possibilities by allowing researchers to use remote controlled and autonomous objects in these studies, and Animal-Robot Interaction has become an emerging field of behavior science. However, there are theoretical, methodological and practical issues in ethological research using robotic agents. Here we aimed to provide an overview on robots by classifying them along different aspects to facilitate future research, and to present some novel approaches that could be considered as a guide for researchers who are new to the fields of animal-robot interactions (ARI) and human-robot interactions (HRI). The present review may facilitate future collaboration between biologists/psychologists, robot developers, engineers and programmers that further contributes to the development of novel research methods and procedures.

Keywords – Animal-robot interaction, Ethorobotics, Methodology, Social robotics, Human-robot interaction, Animat

The application of robots in ethological research can bring forth new perspectives by studying social behavior and the underlying mental abilities using highly repeatable, reproducible, and controlled methods, including the creation of artificial social partners. One of the main advantages of using robots to investigate social behavior derives from the ability to separate the embodiment and behavior experimentally, and it also enables researchers to study the importance of different features of the embodiment and elements of behavior, independently from each other (for reviews see Frohnwieser, Murray, Pike, & Wilkinson, 2016; Krause, Winfield, & Deneubourg, 2011).

Using animal models to study social behavior is not a new invention. (Here we use the term *model* to refer to an object or machine that resembles an animal in some aspects of its embodiment or behavior.) In the early years of ethology, dummies and decoys were used to study social behavior of different species (e.g., territorial behavior in three-spined stickleback (*Gasterosteus aculeatus*), e.g., Łąck, 1943; Tinbergen, 1948, 1954). These models were used to systematically vary the stimuli that, among other findings, led to the discovery of sign-stimuli that elicit specific movement patterns (modal action pattern).

With the advancement of technology, researchers and engineers are now able to create robots with capabilities extending far beyond the previously used models. These robots have to perform complex behaviors that require elaborate locomotion patterns or moving in groups (Butail, Polverino, Phamduy, Del Sette, & Porfiri, 2014; Rubenstein, Cornejo, & Nagpal, 2014; Sahin, 2005), simultaneously moving multiple actuators (e.g., AIBO: Kubinyi et al., 2004; MogiRobi: Lakatos et al., 2014), producing vocalizations or signals in other modalities (Halloy et al., 2007; Partan, Larco, & Owens, 2009), or even showing human-like facial gestures and reacting to emotional expressions when interacting with humans (Kismet: Breazeal, 2003; Kaspar: Kose-Bagci, Ferrari, Dautenhahn, Syrdal, & Nehaniv, 2009).

There is no generally accepted terminology for such robotic agents. In some papers on animal-robot interaction they are referred to as ethnodroids (Wiles et al., 2016), but this term is too anthropomorphic, while another frequently used term, animat, refers not only to robots but also to computer simulated virtual agents (see the *International Conference on Simulation of Adaptive Behavior*). In human-robot interactions, robots are named variously as humanoids (Tahir, Rasheed, Dauwels, & Dauwels, 2014), androids, or geminoids (Becker-Asano & Ishiguro, 2011; Oh et al., 2006) depending on their perceived similarity to humans. Considering the long utilization of the term *animat*, we suggest that it should be used in general by researchers to refer to these agents.

At present, the use of robots has diverse aims in behavior research. Some are constructed for studying human or nonhuman (animal) social behavior experimentally, other robots are built explicitly for applied utilizations, such as social companions (Robinson, MacDonald, Kerse, & Broadbent, 2013) or as assistance for humans (Fischinger et al., 2016), which are capable of adequate interactions in social contexts (see social robots, Fong, Nourbakhsh, & Dautenhahn, 2003). Presently however, there are theoretical, methodological and practical issues with using robots in ethological research. The aim of our article is twofold. (1) We provide an overview on robots to facilitate future research, and a short guide for those who are planning to do research involving robots. (2) We also aim to introduce novel aspects that should be considered in animal-robot and human-robot interaction research (ARI and HRI, respectively), that may also facilitate future collaboration between different research areas. We consider this review as a brief guide that gives a perspective not just for biologists, but for robot developers, engineers and programmers too, while highlighting the benefits of using ethological methods, which are less known in HRI. Throughout the paper we also refer to humans when discussing topics relevant mainly for ARI; however, considering that HRI has become an independent area we also deal with this field separately.

Robot Design and Use

Many robot designs lack any (or major) theoretical underpinnings. Investigators constructing a robot that is planned to interact with rats or pigeons may develop robots that ‘look like’ a rat or a pigeon, but what does this really mean in terms of ‘similarity’? What do we, and what do other species consider to be “similar”? What counts as more “similar” to a cockroach, for example: a cockroach-looking or a cockroach-smelling robot? Visual similarity from the experimenter’s perspective may not ensure in any way that the animal recognizes the animat as a potential social partner (conspecific) (see also Frohnwieser, Pike, Murray, & Wilkinson, 2018). Thus, when planning an experiment, we should consider what type of “similarity” do we need, or whether we need any (see below in detail).

Ethorobotics (de Margerie, Lumineau, Houdelier, & Yris, 2011; Miklósi & Gácsi, 2012; Miklósi, Korondi, Matellán, & Gácsi, 2017; Partan et al., 2009; Porfiri, 2018) is an emerging interdisciplinary approach that offers to combine ethological and technological knowledge in order to design socially compatible animats. Its aim is to use these animats to investigate behavioral and cognitive skills of animals by facilitating collection of a larger amount, more precise, and more objective data. It regards ‘similarity’ as an experimental question, leaving behind naïve and trivial ideas of similarity, e.g., when agents that resemble dogs (*Canis familiaris*) only with regard to visual features are regarded as dogs (Kubinyi et al., 2004). Such questions have long traditions in ethology. Researchers using different artificial models (see above) aimed to find out those features (physical/morphological and behavioral) that characterize members of a specific species (*c.f.* studies on 'species' recognition, Mendelson & Shaw, 2012, also see Frohnwieser et al., 2018).

Designing animats for behavioral research is difficult, as researchers and engineers have many preconceptions originating from subjectivity, neglecting ethological knowledge, and lack of such knowledge. For example, when planning a communicative interaction between an animal and an animat, researchers tend to rely on signals and cues that they consider as important. However, for other species, other features may be more crucial, and they can be able to process different sensory stimuli as well, which researchers perhaps do not think of (see also Frohnwieser, Willmott, Murray, Pike, & Wilkinson, 2016). There are also differences in the processing of similar types of sensory stimuli, either regarding the varying degrees of how much different species rely on these senses (e.g., hearing or producing sounds at frequencies that are beyond our sensory abilities), or the differences between the signals that the sensors can detect (e.g., use of color patterns detected only by UV vision; Cuthill, et al., 2000). We also have to be aware of disturbing features of the robot. For example, many robots use ultrasound sensors for navigation, which can be heard by many animal species, or they can display unintentional cues.

Humans rely mostly on visual stimuli; therefore, we tend to emphasize the importance of these features over others when designing robots. However, a good example is the study by Halloy et al. (2007) who used odor coating on the robots to be accepted by cockroaches (*Periplaneta americana*). These factors are important to consider not only from the viewpoint of the physical features of the animat and the behavior it displays (whether the individual accepts it as a social partner and is able to recognize its behavior), but also for autonomous robots, as they need adequate sensors to recognize the signals/cues emitted by the individual. For example, when interacting with a dog, the robot should be able to detect differences even in similar types of vocalizations emitted in different contexts (e.g., growling in playful situation, when guarding food or when threatened by a stranger; Faragó, Pongrácz, Range, Virányi, & Miklósi, 2010).

To overcome the above issues, it is important to consider several features of the robot in advance. We use an ethological perspective to introduce three aspects that we consider to be important in the design of interactive robotic partners: (1) embodiment, (2) autonomy, and (3) behavioral skills.

Embodiment

For practical purposes, the term embodiment is used here for all non-behavioral features of the robot. It seems that, depending on the specific research question, and also on the limits of robot design, animats (1) can be perfect matches (copies) of the studied species regarding some specific aspects (e.g., Partan et al., 2009; Patricelli, Coleman, & Borgia, 2006; geminoids, in case of humans: Ishiguro, 2007); (2) can mimic only specific features of the studied species (feature-mimicking), including sign stimuli (e.g., two eyes) (e.g., Halloy et al., 2007; May et al., 2006); or (3) they can look completely different from the species under investigation (e.g., Abdai, Gergely, Petró, Topál, & Miklósi, 2015; Gergely, Petró, Topál, & Miklósi, 2013). See Figure 1 for examples. Not only are visual cues important, but for example, the similarity (presence or absence) of smell or body temperature (e.g., Halloy et al., 2007; Michelsen, Andersen, Storm, Kirchner, & Lindauer, 1992) are important as well. Importantly, the embodiment has to be determined by the specific research question in mind. Due to this, it would be impossible to provide a general description of the relation between the studied topic and the embodiment to be used. For example, in case of investigating how different coloration of male birds influences the mate choice of females, we would suggest to use a robot with an embodiment that is a perfect match to the studied species (and manipulating only the male-specific coloration). However, we can also investigate the effect of male behavior during courtship on its own, in which case feature-mimicking may be enough (and advantageous). In the following, we provide examples by referring to existing research to give some ideas.

If one aims to study natural interactions such as species recognition, territorial behavior, mate choice, nursing behavior, cooperation under natural or semi-natural conditions, then resemblance of the animat can be crucial (but see above). For example, Patricelli et al. (2006) deployed a robot that looked like a female satin bowerbird (*Ptilonorhynchus violaceus*) to study how male bowerbirds change their courtship displays in response to the females' behavior. They found that if the robot was startled, males reduced the intensity of courtship display compared to the control treatments in which the robotic females were not startled (this change in behavior increases successful courtship).

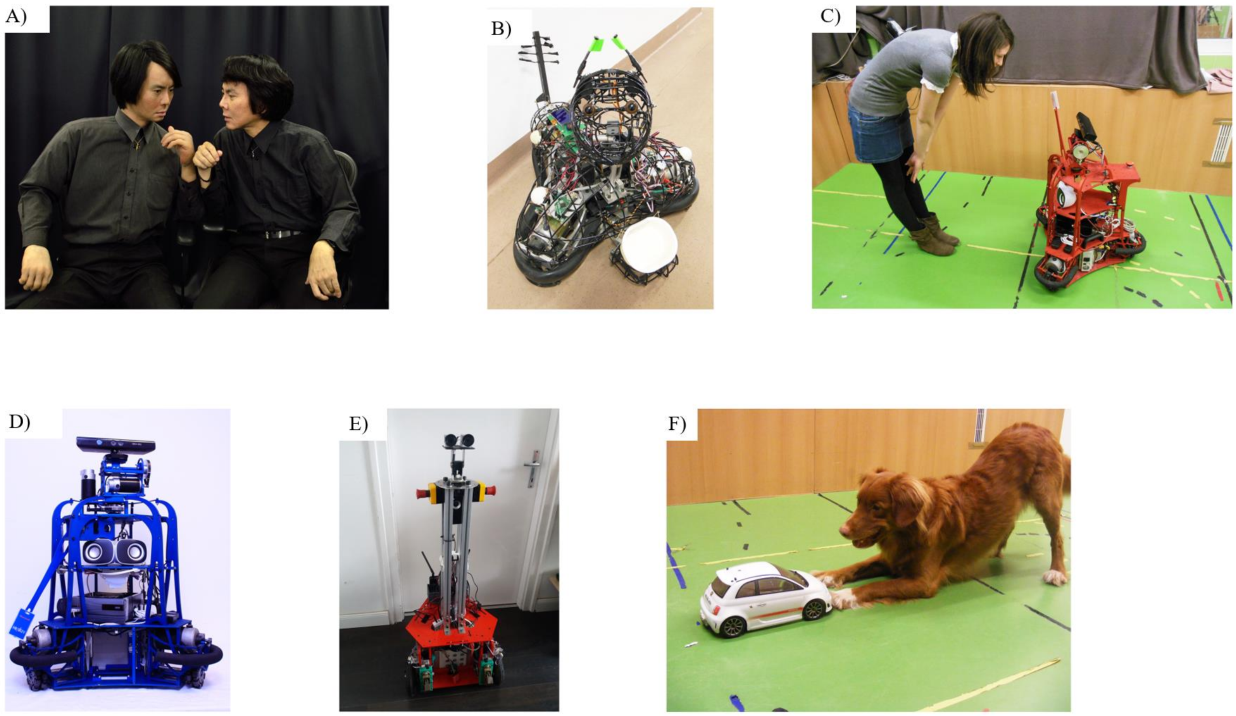

Figure 1. Examples of the similarity of physical features between robots and the studied species. **A**) the robot (on the left) is a perfect match to the studied species (Geminoid™ HI-2 has been developed by Hiroshi Ishiguro Laboratories, ATR); **B**) the robot mimics only specific features of the studied species (MogiRobi (*Mogi caniformis*): Lakatos et al., 2014); **C-F)** the robot is completely different from the studied species (**C**: *Ethonis vulgaris rubrum* (Tajti, Szayer, Kovács, & Korondi, 2014); **D**: *Ethonis vulgaris caeruleus;* **E**: *Ethonis longicollis*; **F**: UMO (Abdai et al., 2015)).

On the other hand, in some cases, feature-mimicking may be enough to establish an interaction between the animat and the animal individuals. The iRAT (Wiles, Heath, Ball, Quinn, & Chiba, 2012), the PoulBot (Gribovskiy, Halloy, Deneubourg, Bleuler, & Mondada, 2010) and the robotic cockroach (Halloy et al., 2007) had the same size as an adult rat (*Rattus norvegicus*), chicken (*Gallus gallus domesticus*) or cockroaches (respectively), but, even for an untrained human eye, they looked rather different from the conspecific animal partner. In these cases, the rather limited resemblance was partly due to constraints of the technology, and investigators aimed to balance this by adding smells in the case of the iRAT (Quinn et al., 2018) and the robotic cockroach in order to increase the chance of interaction.

In specific cases, not only can the similarity in embodiment be negligible, but the research can even aim at investigating the importance of behavioral cues alone. In a series of studies conducted with dogs, researchers used a robot that did not resemble any animal species (Figure 1F) (e.g., Gergely et al., 2013; 2015; Gergely, Compton, Newberry, & Miklósi, 2016). Utilization of this type of embodiment was intentional because it allowed researchers to investigate whether dogs engage in social interaction with a novel partner (unidentified moving object, UMO) in the absence of any bodily cues, solely relying on behavioral cues (see also below). The acronym, *UMO*, has been used to describe robots, which could be any type of robot that is unfamiliar to subjects (both from the viewpoints of previous experiences and embodiment), and can show different behaviors (from simple locomotion to complex social behavior) depending on the research question.

In HRI there has always been a trend to strive for building the most human like robots, but along the road to achieve this objective, researchers had to face theoretical, experimental and technical challenges (see also below). Here we constrain the discussion to so-called social robots that are capable of functionally meaningful social interactions with humans (Fong et al., 2003; Miklósi & Gácsi, 2012). At the theoretical level, the hypothesis of the Uncanny Valley effect introduced by Mori (1970) is perhaps the most serious issue. Based on folk experience, he argued that close, but not 'perfect' resemblance to humans does not increase likeability, rather it leads to even stronger aversion. Since then, studies were conducted to investigate this hypothesis, both with morphed pictures (faces: MacDorman, Green, Ho, & Koch, 2009; Seyama & Nagayama, 2007), videos of real robots (MacDorman, 2006) or actual interactions with them (Bartneck, Kanda, Ishiguro, & Hagita, 2009). Although the results are mixed and the debate is not over, the issue is worth considering during the design of experiments. Interestingly, a similar effect can be found in animals (long-tailed macaques, *Macaca fascicularis*; Steckenfinger & Ghazanfar, 2009). However, there is also some data suggesting that such aversion toward artificial agents may be modified during development, and that this issue may be circumvented by a different robot building strategy (for details see Miklósi et al., 2017).

Probably the most prevailing approach in HRI is when the embodiment and behavior of the robot contain a mix of human-like and machine-like features (Kanda, Shimada, & Koizumi, 2012; Ogawa et al., 2011; Tahir et al., 2014;). This can cause misunderstandings about the robots' actual abilities (Miklósi & Gácsi, 2012; Rose, Scheutz, & Schermerhorn, 2010) and can lead to disappointment from the users' perspective. The mixture of human- and machine-like attributes can also strengthen the Uncanny Valley effect. Saygin, Chaminade, Ishiguro, Driver, and Frith (2012) used fMRI to measure responses in the brain areas of the action perception system, while the subjects watched videos with three agents performing actions: a human (human embodiment, biological movement), an android robot (human-like appearance, machine-like movement) and a robot with visible mechanical parts (machine-like embodiment and movement). The discrepancy between the seemingly biological embodiment and the machine-like motion in case of the android resulted in higher activation, as it contradicted the predictions formed about the agent. This prediction error might contribute to the Uncanny Valley (Saygin et al. 2012). A mismatch between voices (human or synthetic) and embodiment can also increase perceived eeriness (Mitchell et al., 2011).

Levels of Autonomy

We can consider three levels of autonomy from the controlling perspective (see also Krause et al., 2011) (Table 1):

1. *Remote controlled robots* are controlled externally by an experimenter (Patricelli et al., 2006).
2. *Semi-autonomous robots* display some forms of autonomous behaviors or behavioral sequences activated by a human via a remote control system (Mutlu, Yamaoka, Kanda, Ishiguro, & Hagita, 2009).
3. *Autonomous robots* make decisions and execute actions based on inputs that originate from the environment (via specific sensors) or that are generated by the controlling software, and they function (mainly) without any external human control (Halloy et al., 2007).

Note that, in human-robot interaction studies, the utilization of remote controlled and semi-autonomous robots is called metaphorically the 'Wizard of Oz' method (Riek, 2012). The main idea behind this application is that the human subjects are usually unaware that a human experimenter is at least partially controlling the robot's actions.

Table 1

Specific Features of Robots Based on their Level of Autonomy

	Autonomous locomotion	**Autonomous execution of behaviors/ behavior sequences**	**Sensory input**	**References**
Remote controlled robot	No	No	No	Patricelli et al., 2006
Semi-autonomous robot	Yes/No	Yes/No	No - limited	Mutlu et al., 2009
Autonomous robot	Yes	Yes	Yes	Halloy et al. 2007

Remote controlled robots. The main advantage of r*emote controlled robots* is the possibility to control every aspect of the behavior displayed by the robot at any moment; the human experimenter decides when, where and how to act. This provides an opportunity to investigate more complex behaviors and interactions that may require accurate and well-timed behavioral actions (e.g., Abdai et al., 2015; Bonnet, Kato, Halloy, & Mondada, 2016; Patricelli et al., 2006). In the case of modelling, the greeting behavior of dogs by remote controlled robots, an experimenter can control, for example, the length of contact seeking and orientation towards the owner and align it with the changes of the position and behavior of the human at any time. However, studies using remote control also face limitations especially with regards to the methodology:

1. The observation (test) period is rather limited because of the limited capacity of the experimenter to focus on the interaction.
2. The robot behavior is directly controlled by a human experimenter who introduces subjective elements into the interaction. The robot's behavior may be influenced by the observer's momentary perception and understanding of the situation.
3. If only one experimenter controls the robot during the whole study, then this brings in the problem of pseudo-replication that, apart from being methodically questionable, also restricts generalizations of the results.

Semi-autonomous robots. Semi-autonomous robots represent a transition between remote controlled and autonomous robots for which researchers pre-program specific behavioral elements or behavior sequences that are initiated manually by an experimenter, but displayed by the robot autonomously (e.g., Mutlu et al., 2009). The robot can be controlled by the experimenter, who initiates the behavior (sequences) after each other throughout the experiment. Alternatively, the robot displays some autonomous behaviors until its actions are interrupted by experimenter-initiated behavior commands. In semi-autonomous robots, the experimenter needs to control not the behavior itself, but only its onset and offset. Such robots also facilitate the standardization of the experiments as the pre-programmed sequences are reliably repeatable (and reproducible). Further, by the means of an editing program it is possible to generate new sequences from simple pre-programmed behavioral elements. However, compared to the autonomous robots, an important disadvantage is that the parameters of the behaviors are usually fixed, and thus input from the social and physical environment does not have an effect on them. Due to this missing feedback loop, the behavior may become irrelevant from the perspective of the animal partner. In our example this would mean that all parameters of the greeting behavior are programmed into the robot; however, if the human moves away, the robot is not able to maintain proximity and contact. One solution to this issue is taking a step towards autonomous control with the integration of feedback elements in the behavioral sequences. In this case, some environmental cues are actively searched for as part of the sequence itself. In the previous example, this would mean a 'searching for the partner' element, in which the robot would try to follow its partner's movements in space and orientate toward it before displaying the rest of the behaviors in the sequence. Another solution could be if the experimenter was able to modify certain elements of the sequence when the behaviors were being displayed, e.g., he or she could take control of the head movements of the robot while the other behaviors were being displayed according to the original sequence.

Autonomous robots. The use of autonomous robots may open up new prospects in behavioral research. Longer running time without human control provides a unique opportunity to place these animats into animal/human social groups for longer periods, of which they may become full members [e.g., cockroaches (Halloy et al., 2007); eastern grey squirrels (*Sciurus carolinensis*, Partan et al., 2009); rats (del Angel Ortiz, Contreras, Gutiérrez-Garcia, & González, 2016); chicken (Jolly et al., 2016); zebrafish (*Danio rerio*, Butail et al., 2014)].

By using well-programmed autonomous robots, the objectivity of the behavioral interaction increases as the behavior displayed by the robot depends on its own control system, and the experimenter is freed from problems of subjectivity and pseudoreplication. However, such robots are difficult to program, as they need to be able to process and react to stimuli from the social and physical environment 'live' without any possibility of human involvement. Sensing abilities should be complemented by skills to move in the physical space (e.g., obstacle avoidance, path planning) and to recognize social agents and their behavior with some precision. In addition, such systems have to be able to correct errors that may occur frequently at this level of complex interactions, and there is also a requirement for learning to adjust the social skills of the animat. A fully autonomous robot has to overcome the issues of easy and fast maintenance and repair, as well as having a reliable energy source (autonomous battery charging is difficult to design and program, while being physically connected (wired) to an electrical grid limits the movements of the robot). Although these features are constantly improved by engineers and programmers, the commercial utilization of such robots capable of meaningful social interactions is still not widespread, although there are some examples of autonomous or somewhat autonomous robots, e.g., Rovio.

A specific approach within autonomous robotics is embodied cognition. Embodied cognition in connection with robotics examines the interaction of morphological and neural systems with behavior (Anderson, 2003), and can be an important tool for developing the autonomous behavior of robots, while taking into account the evolutionary aspects of behavior. It represents an approach in which the actual specific behaviors are not pre-programmed but are the result of learning processes that are designated to specific goals (e.g., learning new ways of locomotion). Bongard and Lipson (2014) used evolutionary algorithms to create a robot system capable of learning its own embodiment without prior assumptions. They used a four-legged, star-shaped robot that had no internal model of its own structure, only sensory information from vestibular sensors located on its main body. By moving and creating evolving models it was able to learn not just its structure, but also means of locomotion.

Behavioral Skills

Successful interaction between robots and animals requires the robot to have a set of appropriate behavioral skills. Ethorobotics envisages that the study of (social) behavior by using robots is possible only if the human or nonhuman partner considers the interaction with the animat as functional ('meaningful'). This may pose a huge burden on these robots, as they need to show behavioral skills under challenging environmental conditions on the basis of receiving and processing sensory inputs. It is no wonder that such animats are most successful in situations when both input and output requirements are minimal. The following argument about the necessary behavioral skills is primarily true to the design of autonomous robots, but it should also be considered in case of remote controlled and semi-autonomous robots.

Swarm robotics is such an area where robots need 'only' to move/swim/fly and they need to process information only about the position of the group members in space. The deployment of robots in animal groups (e.g., fish schools, cockroach groups; Bonnet et al., 2016; Halloy et al., 2007) could reveal how interaction among individuals leads to group-level changes in behavior. This knowledge can be used to predict group behavior in specific situations (e.g., predator avoidance, group panic) but also to construct artificial swarms of autonomous robots that are able to coordinate their activity simultaneously (e.g., Rubenstein et al., 2014; Sahin, 2005; Sahin & Winfield, 2008;), and develop models using computer simulations (e.g., Garnier, 2011; Mitri, Wischmann, Floreano, & Keller, 2013).

Even seemingly simple skills are not easy to implement. In the case of following behavior, animats need to be able to both recognize when they are being followed (or not followed) and when to follow (or not follow) an individual according to the specific situations. As a demonstration, some of these features are easy to implement (Gribovskiy et al., 2010), but the skills of such robots are still many magnitudes away from those shown by the respective biological systems.

The main promise of social robotics is that animats may engage with species, especially humans (Fong et al., 2003), in which social interaction is regulated by complex rules of communication. This poses a so far unsolvable problem for robotics because communicative exchange relies on diverse perceptual (e.g., recognition of signals) and motor (e.g., displaying signals) skills in addition to abilities like turn taking, mutual attention, etc. Different animal species utilize such skills to various degrees, but there is an overall positive association between communication and social complexity. Although human subjects in experimental situations may be tolerant toward a social robot with very poor communicative skills, this is not the case with animals. Neglecting the precise details of animal communication (e.g., multimodal visual and vocal alarm behavior in squirrels; Partan et al., 2009) terminates the interaction prematurely (see also Frohnwieser, Willmott et al., 2016; Frohnwieser et al., 2018). Nevertheless, the deployment of animats to study human or animal communication can also bring some insights even at this rudimentary state of technical level. Communication often relies on a stereotypic and redundant signaling system. This offers the possibility to investigate what is the minimum number of parameters that still allows for communicative exchanges between the animal and the animat. For example, a wagging tail of an animat may overshadow the absence of other communicative signals, just as humans focus also on this behavior when greeted by their dog (Konok, Dóka, & Miklósi 2011).

Thus, behavioral skills of the animat can be important from two points of view. On one hand, animats can be useful for studying which parameters are important for the maintenance of the interaction, as we can change these systematically (see Frohnwieser et al., 2018, who applied a similar method to test the effects of different visual features on the recognition of the robot as conspecific). On the other hand, it is important that the animat shows the proper behavioral skills when these behaviors are required for studying other phenomena. In the second case, engineers can have two sources of information to design the behavior of an animat: (1) researchers can pretest thoroughly these parameters by using different approaches (see above); or (2) they can use the results of previous research on the phenomenon that was carried out in a natural environment (see also Frohnwieser, Willmott, et al., 2016, who used marker-based motion capture to develop the motion of an animat). For example, in case of an out-of-reach object, we can use the behavior of dogs as a model to program the behavior that the animat should show toward the human (e.g., duration and number of gazing at the target, number of gaze alternations). However, it is easy to see that there is no one good solution for all options; engineers and ethologists need to work together to find out the best solution for the specific problem.

Implications of Ethorobotic Concepts for Future Research

Ethogram

Ethograms enable researchers to create a comprehensive catalogue of behavior patterns displayed by the studied species (Jennings, 1906; Makkink, 1936; Tinbergen, 1959). Ethograms are used for the general or partial description of nonhuman animal or human behavior (Nishida, Kano, Goodall, McGrew, & Nakamura, 1999) and to describe behaviors exhibited in specific situations (Espejo & Mir, 1993), e.g., human behavior observed in operating rooms (Jones et al., 2016). Ethograms are created by observing the continuous behavior of the studied species and defining discrete behavioral elements that comprise the behavior repertoire of the animal, based on their form and sometimes their presumed function. These elements can be described on different levels, relating to only a muscle, a body part or the whole body.

Ethograms usually contain a detailed description of position and form (e.g., limb raised at a certain angle), spatial position (e.g., behavior element occurring near conspecifics), orientation (e.g., head orientates towards food), and intensity (e.g., loudness of vocalization, speed of locomotion) for all behavioral elements. Simplified ethograms can contain only a short verbal description of the behavioral elements and their functions (for an example see Schleidt, Yakalis, Donnelly, & McGarry, 1984).

For successful ARI and HRI research, ethograms of the subject species, as well as of the animat, are needed. Cataloguing and providing detailed description of form for each behavior element can help engineers and programmers to implement them and enables researchers to study which exact behavior form is best in specific cases (e.g., gazing behaviors in HRI). Creating such a catalogue should be the first step in the development of an animat. There is also a need for standardization to increase the comparability of the namely same behaviors in different experiments.

Creating an ethogram for the studied animal species can serve as the basis for designing the necessary behaviors of the robot in advance and assures that no possibly important aspect is overlooked. Here are some criteria for constructing a useful ethogram for an animat:

1. The position and form have to be described in relation to angles of articulations, directions of movements, the necessary degrees of freedom, and the intended kinematic chain of the motion.
2. The spatial position and orientation has to specify proxemics parameters in compliance with the navigational limitations of the robot.
3. Orientation has to be defined according to either the coordinate system used by the robot (e.g., in World Coordinate System), or the function of the behavior (e.g., orientates toward human face).
4. Intensity has to account for the speed, dynamics, duration, and if applicable, exerted force or other specific parameters (e.g., measures of sound strength of vocalizations).
5. Variability of the behavior parameters can be important in certain studies: while the observed behavior elements of animals have discrete forms, a small variation usually occurs between multiple cases of the same element. If we want to implement this aspect in robots, we have to specify the range and probability of these variations.
6. To make the development of the robot control system easier, we should also establish which behavior elements can be overlapping, and which are mutually exclusive.

The Use of Animat in Research: Practicalities

One of the first problems that a researcher has to face when starting an investigation in ARI, is how to obtain a robot; is it possible to buy one, or is collaboration with engineers necessary? There are three types of animats regarding their origin: (1) off-the-shelf robots with features (physical and behavioral as well) that cannot be changed; (2) off-the-shelf robots with open source code, or multiple interchangeable physical modules (e.g., detachable parts), thus, researchers can modify at least some of their features; and (3) robots developed by the researchers/engineers for a specific set of studies.

The first two options can be good choices if the research does not require very specific behaviors and a perfect physical appearance, or the off-the-shelf robot already has the important features. Gergely and colleagues used a simple remote-controlled robot (small toy car) as an interactive partner to study the social behavior of dogs, where the shape of the robot was less important (it only had to move around on wheels) (Gergely et al., 2013; Gergely, et al., 2015). Thus, researchers could rely on the robustness of a commercially available agent.

Off-the-shelf robots with open source codes may offer new extended possibilities because researchers can modify them to be a better fit for their requirements (see e.g., TurtleBot (Open Source Robotics Foundation, Inc., n.d.)). The use of these robots is still easier than the most difficult and challenging version, which is building a completely new robot, in which all elements should be designed or selected and implemented by the research team constructing the robot.

Robot development is a complex process with creative use of technological solutions and frequent setbacks, which can result in a hard to follow building and upgrade history for each unique robot.

This could be a problem when the technical details of the robot are described as part of a publication, or when a new modification should be made on the robot, but it is not clear whether it could be installed into the already existing complex system. Documenting the robot building process is essential, and we advise anyone starting this complicated (and often long) process to keep logs from the very beginning (see Landgraf, 2013 for details).

To make the comparison of robot attributes and capabilities easier, we advise the development of a standardized fill out form which would be freely available to all engineer teams and researchers and could be attached to publications as supplementary data. This form should include data on the initial research goals and design objectives of building the robot, hardware and software specifications (e.g., information on the drive system, maximum locomotion speed, sensor range information, software architecture layout), a chronological account of modifications or upgrades, and a general ethogram cataloguing all behaviors feasible with the robot. Although the development of a universally accepted and comprehensive form requires the work of multiple teams of engineers and researchers, with time, these forms could be the basis of a research robot database that would lead to higher unambiguity and could promote research collaborations.

In case researchers choose to build a robot, both hardware and software modularity should be considered as a basic design concept. With a modular robot construction, the basic robot platform could be enhanced with easy to install components, for example, actuators, sensors, or parts that affect embodiment, e.g., covers or variants of parts that emulate animal characteristics. The robot's software has to be able to accommodate these hardware changes and additions. Moreover, the programming of complex behaviors can also benefit from a modular approach, in which sequences are created from simple behavior elements (see also *Behavioral Skills* and *Ethogram*). This enables researchers to compare the effects of various components of the embodiment and behavior on the social interaction. A step by step development also makes it easier to go back to the basic robot setup at a later point, or to create multiple complex behaviors or embodiments of the same robot by using the different augmenting parts.

Robot Nomenclature

According to the ethorobotics approach, robots that are not designed as mimics for existing animal species, but rather represent novel forms and interaction capabilities, should be recognized as new species (relying on an evolutionary analogy, Miklósi et al., 2017). Each particular robot model could be considered as one, with a unique set of behaviors and embodiment features that is specific to all individual robots of the same model. These new robots could be given a scientific name, following the nomenclature rules first proposed by Linné (1735). Since then, the phylogenetic aspect of scientific names became evident (de Queiroz & Gauthier, 1994; Garrity & Lyons, 2003), calling for universal, stable and explicit names for species and clades (de Queiroz & Gauthier, 1994). Although evolution in the biological sense is not applicable to robots, technological developments and inventions can be viewed in an evolutionary framework (Ellul, 1964), as an evolution of ideas. This approach has already been applied e.g., with mobile phones (Faragó & Miklósi, 2012) and emergent synthesis (Kampis & Gulyas, 2006). Whereas the relatedness of the robots can be mostly based on feature similarities and cultural aspects, noting this concept may be an interesting acknowledgement of the interdisciplinary nature of this field.

Robot models can be distinct from each other by major or minor (only in technical parameters and configurations) differences; however, sometimes these distinctions are not clear. Naming robots as species may force researchers and engineers to define robot models along these differences (in analogy to intra- vs –inter-species variation). Directions of development in social robotics could be indicated with a phylogenetic-like approach, grouping robots created by the same research team or project, similarly to the creation of higher taxa. This would make it easier to follow what types of robots are used in research, and in which projects. Especially in HRI, this approach could clearly suggest that robots are not aimed at replacing humans in any way; instead they represent a specific group of agents that are able to engage in beneficial interaction with humans.

As an example, we created species names for the robots we have worked with, and which were specifically developed for our studies by engineers (see technical details in e.g., Szayer, Kovács, Korondi, & Tajti, 2013; Tajti et al., 2014). The four robots belong to the family *Ethonidae*, referring to the strong ethorobotics approach followed by our research group. Currently there are two genera, *Mogi* and *Ethonis*. The two genera are separated by substantial morphological differences, as well as by the level of similarity they have to existing animals. The one robot belonging to the *Mogi* genus, which we named *Mogi caniformis* (Figure 1B) resembles mammals, especially dogs, in some features (layout and form of head, ears, eyes and tail), even though it moves with wheels and has no otherwise movable limbs. In contrast, the *Ethonis* genus is comprised of robots that do not resemble specific animals and are assigned to a distinct species and two subspecies. The subspecies, *Ethonis vulgaris rubrum* (Figure 1C) and *Ethonis vulgaris caeruleus* (Figure 1D) are identical in embodiment, but the robot belonging to *Ethonis vulgaris rubrum* was developed for autonomous operation, therefore its software and sensorization is more enhanced. The fourth robot belongs to a distinct species, called *Ethonis longicollis* (Figure 1E). It differs from the other members of the genus due to morphological (embodiment, sensorization) and software reasons, e.g., it is much taller than the two subspecies, with a long internal column that continues into a slender neck. In our case, all robots are a representative of a different taxa, but if e.g., the individual robot belonging to the subspecies *Ethonis vulgaris rubrum* would be mass produced, those robots would become a population of the same subspecies. The names listed above are only examples, with the intention to encourage the adoption of this concept, and to serve as inspiration for other research teams. In case the concept gains support and robots with scientific names become a regular occurrence, we advise the creation of a comprehensive quasi- taxonomic system.

Dog-Robot Interaction as a Case Study

The practical approach of ethorobotics can be shown in the studies on dog-robot interaction. From the dogs' perspective the animat is just as likely a social partner as a human, because both differ in embodiment and behavior from conspecifics. This situation has the advantage of enabling dogs' social behavior to be studied by separating the embodiment from the behavioral skills of the agent.

In a series of experiments, it was shown that well-socialized adult family dogs regard the artificial partner (UMO) as a social being, and show similar behaviors toward it as to a human under comparable conditions (e.g., Gergely et al., 2013, 2015). After a short social interaction (e.g., the UMO provides food for the dog), the UMO was able to change the dogs' preference in a food choice task (Abdai et al., 2015). These results indicate that dogs are able to rely on their social behavior patterns deployed during the interaction with humans and utilize it in a novel social situation. Thus, one may hypothesize that after getting engaged in functional (beneficial) interaction, dogs may make a specific mental representation about the behavior of the UMO, and adjust their social behavior accordingly.

Importantly, the same concept can be applied to HRI, in which case the social robot is in an analogous position to a family dog. One can argue that similarly to the case above, the social robot does not need to be a mimic of a human; instead, it can take up a position of a different species. This would not constrain the effectiveness of HRI if the robot is equipped with human-compatible social skills, just as dogs do (Miklósi et al., 2017).

Conclusion

Technological advancements in robotics will continue to encourage the use of robots in ethological research, providing more tools to study animal-robot and human-robot interactions. Here we aimed to provide a guide to those who are only starting to conduct research using animats, and also to present important issues, concepts, and methods that can contribute to the transparency of the field and facilitate collaboration between research groups. Selection of the proper animat and its features is crucial for all studies conducted in ARI and HRI and should be considered thoroughly before implementing the ideas. On a larger scale, this is valid for the entire field. Thinking in advance of the general steps in research and the possible issues arising on the way is important at an early stage. We suggest that the application of ethograms, standardized fill out forms for robot descriptions, and the use of scientific names can facilitate the communication in an increasingly complex field with more and more animats present in both ARI and HRI.

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