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Robots in ecology: welcome to the machine

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ABSTRACT

Robots have primarily been developed for warfare, yet they also serve peaceful purposes. Their use in ecology is in its infancy, but they may soon become essential tools in a broad variety of ecological sub-disciplines. Autonomous robots, in particular drones sent to previously inaccessible areas, have revolutionized data acquisition, not only for abiotic parameters, but also for recording the behavior of undisturbed animals and collecting biological material. Robots will also play an essential role in population ecology, as they will allow for automatic census of individuals through image processing, or via detection of animals marked electronically. These new technologies will enable automated experimentation for increasingly large sample sizes, both in the laboratory and in the field. Finally, interactive robots and cyborgs are becoming major players in modern studies of animal behavior. Such rapid progress nonetheless raises ethical, environmental, and security issues.

Keywords: Animal Behavior; Biodiversity Monitoring; Autonomous Vehicle; Drone; Cyborg; Population Biology; Robot Ethics; Robotics Network

1. WHY USE ROBOTS IN ECOLOGY?

Ecology as a scientific discipline dates back to Renaissance, yet it has only flourished over the past 50 years. Long considered second class “soft” science, it now enjoys strong support from society. This is due to the unequivocal impact of global change upon the biosphere, and to the anthropogenic “sixth extinction” which potentially threatens humankind itself. Professional ecologists across the globe are now pressed to: 1) provide complete censuses of the earth’s biodiversity, 2) understand the impact of ongoing global change upon the biosphere in end-to-end ecosystems, 3) predict future trends according to a series of scenarios conditioned by politics and socio-economic development. This in turn requires observing, experimenting with, and modeling the living planet with unprecedented completeness, accuracy, and rapidity. However, there are justified fears that progress in ecological knowledge might be far too slow to counter ongoing global environmental degradation [1]. Such a monumental task is not only limited by funding, which remains anecdotal in Ecology when considering the importance of the aforementioned issues threatening biodiversity on earth, but also by the available technology: numerous areas are too remote or too dangerous to be thoroughly surveyed, and essential experiments involving millions of repetitive tasks are not being conducted for lack of necessary manpower and time. For instance, species diversity is so high in tropical rainforests that researchers do not expect to ever obtain a complete biodiversity census: many species vanish in forestry clear cuts before having been identified by scientists [2]. Similarly, it is not yet technically possible to fully record the microorganism species diversity in one cubic meter of soil taken from any temperate woodland or pasture [3].

Successive technological revolutions have promoted economic growth and are ultimately leading to global change, including the current biodiversity crisis. Yet this technology also offers new tools for scientists investigating the ecological impact of such changes. It is an understatement that, as for the vast majority of scientific disciplines, electronics and computing have revolutionized Ecology in the last decades. Remote-sensing of continents and oceans from satellites, and high-performance computing running the most complex statistics and ecological models are two remarkable examples amongst the many scientific achievements permitted by new technologies.

However, much more may come. The rise of robots, which will soon modify our everyday lives (there are already an estimated 55.5 million personal robots around the world), may also fundamentally transform ecological research by allowing unparalleled endurance, accuracy, consistency and speed in scientific exploration, experimentation and modeling [4]. For professional ecologists, it is tempting to downplay the forthcoming role of robots and regard them as science fiction objects only operating in novels. Yet, amazingly, many "predictions" made by science fiction authors, such as Jules Verne or Isaac Asimov, have become reality, from nuclear-powered submarines to tactile screens.

Robots are spreading into ecological research even though they were not developed for this purpose. The automobile industry and space programs initially promoted robot development, in particular for the exploration of remote planets, yet the vast majority of modern, autonomous robots were designed and built to assist and potentially replace humans on the battlefield. Belligerent robotics long remained anecdotal but, since the beginning of the 1990s, with the third Balkan war, the September 11 attacks and subsequent Iraq and Afghanistan wars, their development has been booming. The US forces invaded Iraq without any robots on the ground, but are now estimated to use more than 10,000 of them. The US military also can deploy an estimated 5000 UAVs, almost twice as many as manned planes. American spending for UAVs and computer-guided missiles alone is estimated at $10 billion per year, over a third of the US Air Force budget [5].

Such a massive investment in robotics has brought about decreasing unit prices and increasing robot performance. A wide range of robots has become easily available, even to chronically under-funded ecologists; miniature drones can now be purchased for <400 US$ on the internet. This offer has been largely ignored by the scientific community working in Ecology. While approximately 100,000 scientific articles related to robotics have been published over the past 20 years, only 10 of these appeared in the top twenty ecological journals (Source: Web of Knowledge Sept. 2011). The aim of our review is therefore to enhance the awareness of Ecologists with respect to robotics, and discuss how such novel tools may help them tackle fundamental issues in Ecology.

2. WHICH ROBOTS FOR ECOLOGY?

Most robots to be used in Ecology are mobile, and can be classified according to: the equipment they carry, their size, where they operate, their mobility and autonomy.

2.1. Robot Anatomy

In terms of onboard equipment, scientific robots are designed with two distinct modules (**Figure 1**). The first set, which can be found in any robot, allows the unit to function more or less independently in its working environment. The core of this module is a positioning system, which is often a GPS receiver, except underwater where it might be replaced by acoustic signals. Such positioning is further refined by 3D motion sensors, and confronted with fine-scale mapping of the environment (for instance via RADAR or LIDAR) to yield decisions on where to and how to move. Beyond this navigation module which steers propulsion systems, robots carry tools designed for acquisition of ecologically relevant information [6]. These sensors include: 1) Optical sensors operating in a spectrum from infrared through visible to ultraviolet light. They are used to model the robot's environment, to identify and take a census of organisms of all sizes, and to record a variety of parameters such as surface temperatures, or underwater light attenuation. 2) Additional physical sensors, the most common being temperature, pressure, humidity and conductivity sensors. 3) Acoustic sensors, which are mainly used underwater to assess current features, but also to map organisms. 4) Chemical sensors, such as pH sensors or tools to detect a great variety of gases, especially O_2 and CO_2.

Figure 1. Morphology of an UGV (iRobot® 510 PackBot®). This small ROV (88.9 × 52.1 × 17.8 cm; 10.89 kg without batteries) can be used on a great variety of terrain (image courtesy iRobot®).

2.2. Robot Dimensions

Robot size currently ranges from nano-units (**Figure 2**) designed to operate at the molecular level [7] to the size of an aircraft: USA's largest military UAV, the Global Hawk (**Figure 2**) is approximately 35 m in wingspan, and can survey >100,000 km^2 per day [5]. Nevertheless, robots the size of a young or adult human prove most useful in land-based ecological research, possibly because they are analogue to research assistants.


(a) Nano-robot in blood vessel (b) AGV in desert (c) UGV in cave


(d) Quadricopter UAV (e) The world's largest AAV (f) Medium-sized UAV


(g) AUV in coastal water (h) Bio-inspired robotic bird (i) Cyborg insect

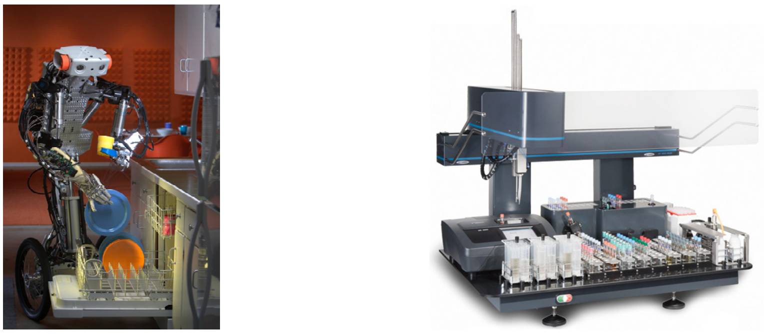
(j) Android (k) Lab robot

Figure 2. Which robots for Ecology? (a) Computer simulation of a nano-robot travelling in-between blood cells (Courtesy A. Cavalcanti); (b) Nomad AGV used to explore the Atacama desert. Approx. dimensions of a small car, mass 550 kg (Courtesy D. Apostolopoulos, Carnegie Mellon University and NASA, [48]); (c) TALON® UGV exploring a cave. Length ca. 0.9 m, mass 42 kg (Courtesy QinetiQ North America); (d) Quadricopter UAV used for <1 km exploration and surveying, Width 0.45 m, mass 4 kg (Courtesy of Inn & App, developing DroneA); (e) The Global Hawk is used by the US Air Force for continental-scale monitoring. Wingspan 35 m, mass 10 metric tons (Courtesy Northrop Grumman); (f) UAV used for medium-scale surveying over land and water. Wingspan 6 m (Courtesy J. Borges de Sousa, Porto Univ. [6]; (g) Seacon AUV for autonomous underwater exploration. Length 1.1 m, mass 18 kg (Courtesy J. Borges de Sousa, Porto Univ.); (h) Robotic reconstruction of flying bird. Wingspan 2 m, mass 0.4 kg (Courtesy Festo AG & Co. KG); (i) Beetle fitted with electronic equipment allowing remote-control of its flight movements (Courtesy H. Sato, Nanyang Technological University and M.M. Maharbiz UC Berkeley [12]; (j) Human-like robot (Courtesy Anybots); (k) Lab robot used for highly repetitive tasks on very large sample sizes (Courtesy Dublin Analytical Instruments).

2.3. Robot Habitat

Robots can operate more or less anywhere, from inside the human body to the deepest ocean basins [8]. Collected data and material can either be stored on board or transmitted using the many communication channels currently available, notably the internet. They most commonly work in dangerous, contaminated, confined areas: in April 2011, robots sent the first images and radiation recordings from inside the reactors of Fukushima power plant in Japan. Robots are of course also widely used to explore other planets, as well as in space. However, as this particular aspect of robotics and remote-sensing is well-known to the public, including researchers in Ecol-ogy, we will here only focus on robots operating in atmospheric, terrestrial, and aquatic environments. As we will see, robots can be used for ecological research in all three Earth system compartments. Furthermore, an essential recent development consists in using robots not individually, but within networks, also called robot swarms (**Figure 3**). Within such a network, which can stretch from local to global scale [9], robots communicate and their tasks are coordinated by a GCCS similar to that used by the US army. One major strength of such swarms is that all collected information (except biological samples) is transmitted to GCCS headquarters in real time.

2.4. Robot Mobility and Autonomy

A great variety of robots actually does not move at all, such as all laboratory robots developed in the biomedical sector to deal with highly repetitive tasks and very large sample sizes. Marginally more mobile robots are being used to a great extent in the car and the atomic industries: they move short distances on rails or racks built around their working area. In terrestrial habitats, AGVs currently move on wheels (**Figure 2**). They tend to look like Star Wars' R2D2, or like miniature cars (**Figure 1**), and they are strongly handicapped on rough terrain. It is widely acknowledged that bipedal motion is the ultimate solution (and androids the ultimate robot; [9]), yet, technically, designing legs is a major challenge in robotics, even if artificial muscle technology is already operational [9]. Autonomous bipedal robots including a wide range of androids are already on the market, yet it will probably take another decade before they become the norm [9].

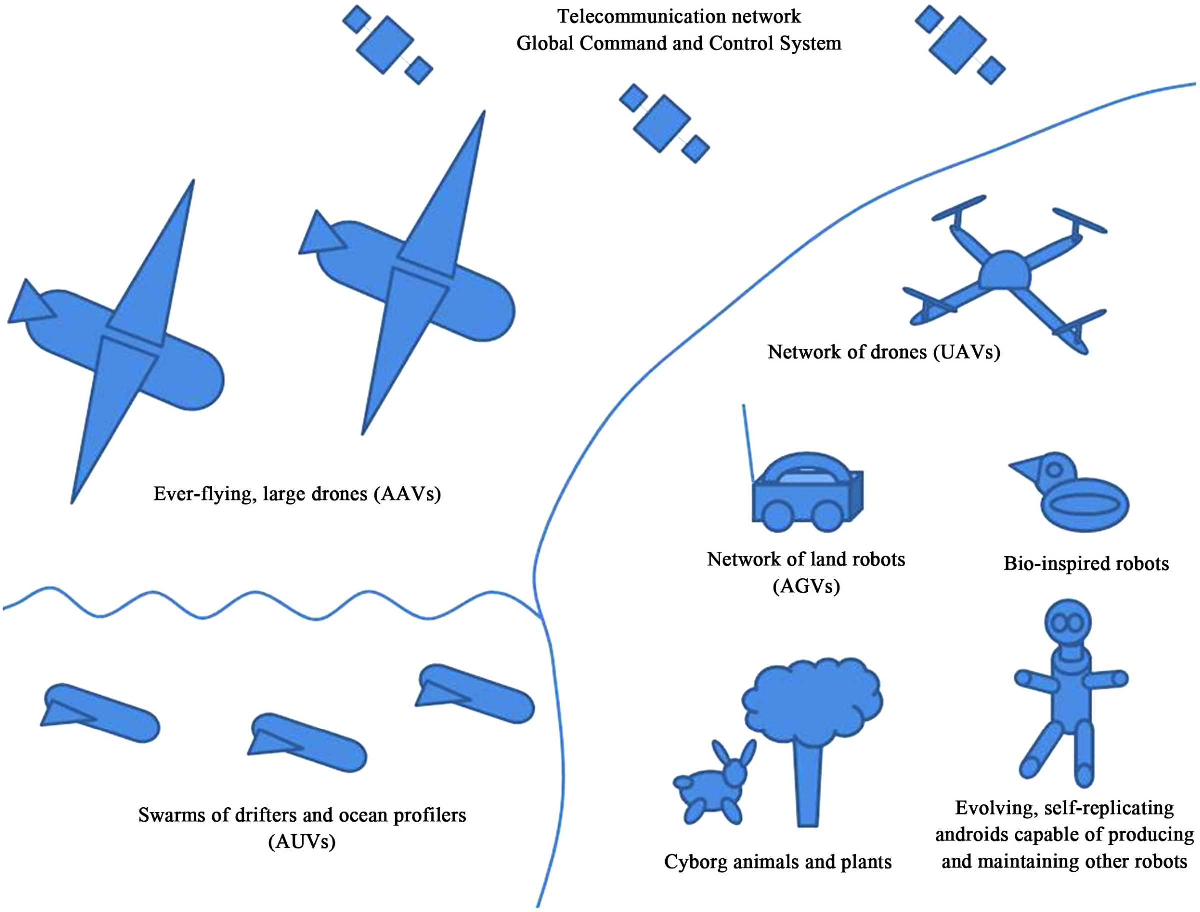

Figure 3. Robotics network: swarms of robots sampling the biosphere.

Operating robots underwater is much easier than on land in terms of propulsion; once launched they rarely meet obstacles when cruising the world's oceans. This is achieved using conventional propellers, pulsed water, or occasionally artificial fins, and these robots have the shape of torpedoes or deepwater submarines (**Figure 2**). However, since GPS navigation does not function underwater, AUV navigation remains a major challenge [10].

Curiously enough, flying robots (UAVs and AAVs) are the least difficult to operate: once airborne they can move more or less anywhere, flying, gliding, or hovering, and they have perfect reception of GPS signals allowing for easy guidance. This is why UAVs became popular so rapidly, and are already widely used in the form of unmanned planes, helicopters, or even artificial, bio-inspired birds and insects (**Figure 2**, [11]).

Finally, one particular type of robot mobility occurs in cyborgs. In this case, the robotic unit hooks onto a living creature and becomes part of it, thereby modifying its biological characteristics, including its behavior. This has not yet led to Terminator-like androids, but cyborg insects have already been created (**Figure 2**, [12]).

Beyond propulsion itself, what strongly limits the mobility and the autonomy of robots is power supply and artificial intelligence. Power supply is not a problem in large AAVs which can carry enough photovoltaic cells to fly for weeks [4], but it is critical for AGVs and AUVs. For instance, android robots powered by conventional rechargeable batteries are currently operational for a few hours at best [13]. In particular, the use of artificial legs requires substantial energy, which strongly constraints android autonomy [14]. The use of power by AGVs can be reduced by optimizing walking gaits, as well as on/off cycles, movement paths and deployment strategies of individual robots and robot swarms [13,15,16]. However, battery power also strongly varies according to environmental conditions. Specifically, low operating temperatures are still problematic, and hence strongly limit the use of AGVs in Polar Regions [17]. This is unfortunate since robots typically have their strongest potential in vast, unpopulated and inhospitable areas such as the Arctic and the Antarctic. A variety of novel fuel cells, including biological fuel cells allowing robots to "graze" *en route* are being developed, yet when they will be actually operational in autonomous robots is hard to foresee [9, 18]. Finally, artificial intelligence, machine learning, network transmission and robot autonomy technically depend upon computer power. Microchip technology is progressing so rapidly that the speed and size of embarked electronic systems is no longer a limiting factor; it is rather the size and the power requirements of servos enabling robot movements that constraint overall robot size and autonomy. Robot intelligence and learning is therefore primarily limited by human ethics, and how much autonomy mankind is ready to endow in the machines it has created.

3. WHEN USE ROBOTS IN ECOLOGY?

Just as computers, robots are likely to strongly transform all aspects of Ecology. We have identified a series of ecological subdisciplines which already benefit from robotics, or may do so in the near future.

3.1. Biodiversity Sampling

Monitoring plant and animal species while searching for all those unknown to Science is a major challenge and a target which seems out of reach with conventional sampling techniques [1]. This could be solved by the systematic use of man-guided and autonomous robots. These could cruise a great variety of habitats, and autonomously explore uncharted territory. Known species would be recorded by automatic image recording and processing [19]. New species could be sampled partly or as whole-organisms by automated arms and stored in onboard compartments for later morphological and genetic analysis. These units are the unmanned equivalent of current bathyscaphs, which helped discover oceanic hydrothermal vents and sampled endemic deep-sea ecosystems. For example, AUVs have been successfully used to automatically identify and sample zooplankton and phytoplankton, in the later case via an automated "gulper" system for the remote collection of organisms [20,21].

3.2. From Population Dynamics to Ecosystem Functioning

Beyond identifying species, robots may revolutionize all studies aiming at counting and mapping organisms. This second field of robotics applied to Ecology is certainly the most important, extremely far ranging and diverse. Crucially, robots allow the automatic identification of individuals in space and time. For instance, UAVs, mainly remote-controlled miniature helicopters carrying cameras, have been used to photograph colonies of waterbirds situated in remote estuaries. The UAV can be maneuvered over the colony without scaring the birds, whereas the presence of humans, or a low-flying prospecting plane would have chased them away. Such images are subsequently analyzed using custom-made software to extract species-specific population numbers and the spatial characteristics of breeding habitats [19]. Similarly, vegetation censuses have already been performed using UAVs in Mediterranean forests and North American steppe ecosystems [22,23], and UAVs have been used to automatically map benthic communities [24]. While such approaches are still in their infancy, it does seem that robots may replace human observers involved in the long-term monitoring of plant and animal populations (**Figure 4**), which is an essential input to demographic models.

3.3. Monitoring the Biosphere

Since sensors onboard robots can also record the entire range of biotic and abiotic environmental characteristics while studying a given population, the gathered data can be used for an ecological and evolutionary study of how targeted organisms function in their natural environment, without human disturbance. For example, AUVs have been used to track the thermocline and record oxygen concentrations in lake ecosystems [25], and to perform chemical measurements in ice-covered lakes [26]. Scaling further up, swarms of scientific robots may yield sufficient data to achieve a global visibility of entire ecosystem dynamics, integrating biophysical cycles of matter and energy, with a powerful, automated monitoring and forecasting of the impact of human activities (including robotics itself) upon the living planet [27,28]. Such robot swarms could become the ecological, mobile equivalent of weather station networks, or of the seismic networks used to monitor tectonic activity and warn for earthquakes and tsunamis. This would be an essential tool in conservation biology, ensuring early warning and allowing for the development of operational scenarios following environmental crises such as oil spills [6]. For example, they are being used to track the biological components of the global carbon cycle under the influence of global warming [29]. The best current example of such a network is the thousands of floats, gliders, and other autonomous units of the ARGO network, which are dispatched across the world's oceans to measure temperature, conductivity (as an index of salinity), and pressure [29]. These units have the capacity to adjust their operational depth, monitor the environment, to then float back to the ocean surface to transmit all recorded data. New chemical and biological sensors are now also being deployed on floats and gliders which are low power, small in size, precise and accurate, with long-term stability. Within recent years, sensor technologies for oxygen, CO_2, chlorophyll fluorescence (as a proxy for phytoplankton abundance), particles (as a proxy for particulate organic carbon), and nitrate have been refined [27,29,30], whose data are used to feed global general oceanic circulation and ecological models [4].

3.4. Experimental Ecology

Lab robots, which allowed sequencing the human genome, are also involved in ecological experiments which require several million repeated measurements [31]. These robots have not only been designed to perform laboratory tasks endlessly and with great precision [32], they have been built with sufficient artificial intelligence to independently design hypotheses, test them using their own empirical data [33], and eventually to design and replicate themselves [7]. Further, robots can be used to experimentally test evolutionary theory: robotics reconstructions of dinosaurs have helped assess how fast these extinct creatures might have run according to their putative morphological characteristics [34], and 500 generations of robots were used to test the importance of relatedness on communication performance [35]. Experimental behavioral ecology is also a surprisingly active field of ecological robotics [36]. Here, individual or

Figure 4. UGV deployed at Dumont D'Urville, Adélie Land, Antartica to perform observations of breeding Emperor penguins (*Aptenodytes forsteri*). Courtesy Yvon Le Maho.

swarms of robots are being "released" among truly biological organisms. For instance, researchers effectively used robotic cockroaches, and fooled their biological equivalents into seeing them as conspecifics [37]. Such model insects were used to test optimal foraging theory [38], and the consequences of behavioral rules in social insects [39], while robotic lizards were used to verify animal communication theory [40]. Robots therefore show a strong potential within the fields of behavioral and cognitive sciences that help understand personalities, decision-taking and learning, both in humans and animals [41,42]. To push this field even further, researchers also recently created cyborg insects, where electronic controllers were fitted to the live animal [12]. These radio-controlled micro units were used to send electric impulses to selected brain regions and flight muscles, allowing researchers to modify insect flight behavior. Such invasive experiments nonetheless raise clear ethical issues, which will be assessed hereafter.

4. ROBOT ETHICS IN ECOLOGY

It is currently not possible to forecast whether ecological research will move towards a global use of robots, when this move might occur, and whether robots will truly improve all research fields in Ecology. However, our review does indicate that robotics is already an essential aid in laboratory and cognitive studies. In any case, the use of robots in Ecology raises a series of environmental and ethical issues. Firstly, building robots, operating and trashing them use resources such as rare metals, energy, and ultimately generate electronic garbage. Beyond accelerating knowledge and the pace of life [43], the rise of robots will therefore accelerate the environmental issues which followed the advent of microelectronics, especially personal computers, as disused robots will add to the estimated 40 million tons of E-waste which are generated annually around the globe. These are mainly stored and partly recycled in developing countries, leading to very high levels of toxic compounds such as lead, polybrominated diphenylethers (PBDEs), polychlorinated and polybrominated dioxins and furans (PCDD/Fs and PBDD/Fs) in air, soil and water [44]. The ecological benefits of environmental research conducted using robots, and other new technologies, therefore have to be seriously weighed against the environmental costs (e.g. the carbon footprint) of building, operating, and recycling such tools [45].

Secondly, using robots and trusting that they will act as planned is a security issue, both for humans and for their environment. War robots have already opened fire on their human comrades on several occasions [5] and robots working in Ecology are bound to interfere with wildlife, potentially causing stress, harm and death: a drone flown too low over marshland could chase away entire waterbird colonies, causing a general breeding failure. A "smart" collar designed to modify the behavior of a large mammal via drug injection might kill the animal if it malfunctions. Wireless networks used for data transmission might interfere with avian cognition and migratory behavior. In this respect, using robots in Ecology raises the same ethical and environmental questions as the use of miniaturized biotelemetry tools attached to animals [46]: before using such tags in the field, researchers have to ensure that they have been sufficiently well-designed and tested to minimize (and possibly eliminate) their impact on the plant and animal species that they wish to study.

Finally, it is both striking and worrying that robotic developments are moving far ahead of law and ethics: robots are being massively used by the US army in Iraq and Afghanistan, on a very thin international legal background [5,47]. Ecologists wishing to use drones for census work are referred to air-traffic regulations, yet if the unit were to crash on wildlife it is unclear whether the programmer, the manufacturer, or the scientist would be liable. However, such issues will seem fairly minor compared to the ethical and legal issues as to whether, in the near future, cyborgs should be given the same legal status as humans [47]. There is indeed a large policy vacuum with respect to the use of autonomous robots in Ecology, which will probably take decades to respond to and will continue to lag behind the ethical questions raised by technological advances [43].

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GLOSSARY

Android: a robot designed to resemble a human
AAV: Autonomous Air Vehicle (also known as drone)
AGV: Autonomous Ground Vehicle
AUV: Autonomous Underwater Vehicle
Cyborg: an organism with both biological and electronic parts (Krause *et al.* 2011)
Floats and gliders: Robotic buoys widely used in oceanography
GCCS: Global Command and Control System used by the US army
LIDAR: Light Detection and Ranging system which uses a light source (e.g. laser) and radar to map the environment
Machine Learning: a programming scheme that allows a machine to elaborate its own behavioral response according to environmental characteristics
RFID: Radio Frequency Identification
Robot: an engineered machine that senses, thinks and acts (Lin *et al.* 2011). Robots can be autonomous, or partly guided by humans.
Servo: electronically controlled, mobile robot component.
UAV: Unmanned Aerial Vehicle. Unlike an AAV, this unit is remotely guided by humans on the ground. It is nonetheless also known as “drone”.
UGV: Unmanned Ground Vehicle. Unlike an AGV, this unit is remotely guided by humans. It is also known as ROV (Remote Operated Vehicle).
UUV: Unmanned Underwater Vehicle. Unlike an AUV, this unit is remotely guided by humans. It is also known as ROV (Remote Operated Vehicle).