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Some Considerations on Robotics for Environmental Friendliness *

François G. Pin
Autonomous Robotic Systems Group
Oak Ridge National Laboratory
P.O. Box 2008, Bldg. 6025, MS-6364
Oak Ridge, TN 37831-6363, U.S.A.

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Abstract

This paper presents a series of considerations regarding the use and potential of robotic devices for supporting humans in a variety of tasks, while maintaining, if not improving, environmental friendliness. One of the main considerations brought forward here relates to the type of human-support functions which the robots are, or will be, expected to perform, and from this, a clear differentiation appears between robots designed to replace humans in environments that were engineered in the past for best human functionality, and robots designed to take functions in the future, in environments which could be better engineered for large-scale human-robot synergy. Other considerations discussed involve the "life-cycle" cleanliness of robotic systems, including the materials needs for their construction, their operation, their disposal and, more importantly, their energy consumption which will impact the cycle of natural resources utilization. These considerations are discussed using a variety of possible robotic systems applications in contexts varied as manufacturing, energy recovery and production, emergency situations handling, traffic improvement, waste management, agriculture, and space exploration. In all these applications, the operation costs and complexity of the robots seem to vary in inverse proportion to the amount of engineering that is feasible to make the task environment more robot-friendly, but with no seemingly direct impact on the potential for environmental friendliness of the robots.

1. Introduction

Since its inception, the field of robotics has had the goal to develop systems that could support, supplement, aid, or replace humans in some specific activities. In what follows, we will make the basic assumption that the prime function of robots has been and will be to *facilitate* the work and existence of humans and that, in all foreseeable future, humans will maintain ultimate supervisory and override capabilities over robots. The wording "autonomous robot" should therefore be understood as denoting not a human-being-equivalent, capable of independently pursuing an existence, but as an electromechanical system with specific perceptive and electromotive capabilities, programmed to accomplish given tasks with high levels of autonomy. Analogies with the animal world or with the delegation of tasks in a command hierarchy

(e.g., business, military, etc.) can be utilized to "visualize" degrees of autonomy under supervisory commands (e.g., in a hierarchy) or under preprogrammed operation (e.g., animals' genetic heritage).

In their role as support devices for humans, robots can be categorized according to the objectives they are designed or expected to fulfill. The most significant category involves the "replacement" of humans in tasks that constitute a health hazard for humans, either because the task itself is hazardous, or because the task is mundane in nature but has to take place in a hazardous environment. In this category are applications such as, for example, battlefield robotics, fire fighting, radioactive material handling, deep subsea operations, nuclear plant monitoring, chemicals processing, and space exploration. For most of these systems, the environment is not only hazardous, but the "hostility" typically is a direct result of the unpredictable nature of the surroundings. The challenge in developing these robots therefore is in providing them with means to detect and cope with unforeseeable (and thus not handled through direct programming) occurrences.

A second category of automated systems involves devices aimed at aiding, supplementing, or replacing humans in tasks that are routine, tedious, or fatiguing, in which human performance tends to degrade very rapidly and may lead to errors that could have significant consequences. In this category are systems such as industrial or manufacturing robots, monitoring devices, construction and assembly robots, driver's aids, flaw detection in assembly line or manufacturing processes, and in general, systems performing highly repetitive processes. Due to the more structured nature of the environments in which they operate, improvement to these systems is typically equally obtained by further augmentation of the robotic devices and by further engineering and structuring of the environment.

The third category of automated devices includes what we will call here general support systems, i.e., systems that perform simple or complex functions but whose failure would not result in serious injury to humans and/or damage to the natural environment, or to a costly process. Few robots exist in this category as yet, but their number is anticipated to grow significantly with the growing trend for increased leisure time and minimization of day to day chores in our society. Automated home appliances, mail delivery carts in companies, autonomous vacuum cleaners, hospital meal delivery robots,

recreational or amusement robots are examples of systems falling in this category. The fact that the environments in which they function can be structured, and even modified, to alleviate some technical or implementation difficulties, allows great flexibility in the design of these robots. This possibility to structure and/or adapt the task environment to the capabilities technically achievable for the robot, as well as the less stringent constraints of the task, would appear to make systems in this category the most likely candidates for playing a significant role in, and having a major impact on, improving or preserving our planet's environment and/or demonstrating the potential for environmental friendliness of our growing automated devices population.

Severe economic and human factors conditions however, may interfere with such expectations. Other considerations such as energy consumption, waste generation, material recycling capabilities, etc. may also upset the presumed imbalance among the categories mentioned above. In the following sections, we attempt to discuss some of these considerations in the context of a few of the applications listed as examples of the categories, and offer some thoughts on possible systems that could improve the environmental friendliness of robotic devices and/or help preserve our natural resources and our planet's environment.

2. "Human-Replacing" Robots in Hazardous Environments

As mentioned in the previous section, this category of robot systems may not appear as the best candidate for environmental friendliness improvement, however several applications could be envisioned in this category which would provide significant gains with respect to preserving natural resources.

Battlefield Robotics

We will not pursue the area of battlefield robotics in our investigation here, since the context of war and/or conflict implied by this area does not support the concept of environmental friendliness, and indeed swamps any other consideration but that of destruction. On the other hand, it is important to recognize that defense-related research activities have, and will continue to provide a significant technology base, upon which advances in other areas can be built; robotics being one of these areas, as experienced in several countries. Thus an eye needs to be kept on these defense-related developing technologies so that the most rapid and cost-efficient developments can be made in other areas such as the environment preservation and the environmentally conscious design of future robotic systems.

Robots for Nuclear Energy Support

This field has included some of the very first applications of modern robotics for the obvious reason

that high levels of radioactivity can seriously affect humans' health, and even be lethal, through only proximity to a source or through ingestion, inhalation and/or consumption of contaminated material or suspended dust. The resulting desire (requirements) to (1) remove and shield humans from radioactive material proximity; and (2) isolate, with ideally sealed-tight containment, the *entire* energy producing process, from uranium mining to plant operation, to waste disposal; has provided a fertile ground for application of robotics. We are far, however, from having fully succeeded in these goals, and there are no doubts that the nuclear energy producing cycle brings a significant potential for serious impact on the natural environment, be it only with respect to long-term disposal of the produced waste.

For goal (1) above, teleoperation has been the robotic technology most employed to date, and to some extent has been fairly successful within the confines of nuclear plants or processing facilities. Its application is doubtful, if practical at all, in the other components of the cycle, such as mining, transport, or waste disposal, which all require large-scale mobility, or monitoring during long institutional periods (typically 100 years). In these areas, advanced autonomous robots combining mobility and manipulation capabilities could greatly enhance the safety and environmental friendliness of operations. For example, robots capable of autonomously mining uranium ore under or within sealed-tight "cocoon," immediately (i.e., within the cocoon) separating it from the tailings through a leaching process, drying the extracted ore and tailings, recycling the leachate by-products, and relocating the tailings at the extraction site, would significantly decrease air emission of radioactive dust at the site, virtually eliminate contamination of nearby fauna and flora, and reduce potential groundwater contamination by the leachate by-products.

With respect to plant operation and monitoring, and waste disposal and management, the potential of robotic systems is quite different according to the surroundings in which they have to operate, and a clear differentiation appears between operation in yesterday's plants and disposal areas, and what could constitute such nuclear facilities in the future: anyone who has walked through the incredibly complex network of flow pipes, valves, and other control devices that exist in a nuclear plant will have no problems realizing the very advanced perception, mobility capability, and dexterity that would be required of robots to perform simple repair, inspection or even monitoring tasks in such surroundings. In a similar fashion, tasks involving surveying, detecting, safely retrieving, sealed-tight repackaging, and redispersion of waste materials improperly disposed of in the past would require very advanced sensing, manipulation, and material handling systems which remain a challenge today. These "self-inflicted" challenges, due to poor previous engineering, are what is often referred to as the "legacy of the past" in the nuclear community. It seems clear that success may be very hard to reach for robotics in such esoteric environments designed principally for humans. These challenges

however should retain some of our research and development focus, as significant environmental gains can be achieved through safer plant operations and through environmental restoration with proper decontamination and decommissioning of the facilities and waste of yesterday.

On the other hand, it seems like the majority of the challenges for robotic systems in such nuclear environments could be greatly decreased if the facilities and surroundings were engineered in a more robot-friendly manner. For example, a nuclear plant in which a conventional wheeled robot would have full accessibility (no stairs to climb, no flow pipes to step over, etc.), in which all monitoring devices were standardized, and in which valves and other simple control devices were designed to be operated by robots (e.g., a robot could much more easily turn a screw bolt with an arm-mounted drill and socket than it would operate a steering-wheel-type handle) would allow many inspection, monitoring and/or simple repair tasks to be performed by robots, which otherwise would not be feasible with today's technology. In other words, to allow robots to be more useful in certain surroundings, the surroundings themselves need to be made more robot-friendly. This is particularly true for surroundings which may become the exclusive domains of robots (i.e., no human entrance). If this is accomplished, then not only will robots be made more utilizable, but they implicitly will enhance the environmental friendliness of the entire process or plant in which they operate by helping fulfill goal (2) mentioned above. For example, consider that entire sections of a nuclear plant have been made robot-friendly so that one or a set of specialized autonomous robots, equipped only with the currently existing state-of-technology in perception, mobility, and manipulation, could perform all the monitoring and maintenance tasks in these sections; then these entire areas (with their included robots) could be fully sealed, therefore facilitating the task of isolating and shielding them from the outside environments. The same concept could be envisioned for future low-activity waste disposal areas (and even for high activity wastes with improved radiation hardening of the robot components) which could be fully sealed and isolated. Only a few areas would require research and improvement to achieve such a goal, including improved robot mechanical and electronic component reliability, long life rechargeable batteries (through "docking" and "plugging-in" of the robots at a recharge station, for example) and remote maintainability of the robots.

The few examples of possible future improvements given here are only representative and by no means constitute an exhaustive list, however, we believe the above considerations would translate very similarly in other areas dealing with hazardous materials, such as chemical processing plants, chemical waste handling and disposal, etc. One of the major points we brought here is that to allow robots to effectively and rapidly support environmental friendliness in such esoteric and hazardous surroundings, a lot can be gained through some compromise in which the surroundings are made more robot-friendly

(as opposed to being designed for human motion capabilities and human operation alone), so that the entire system (plant plus specialized robots) can be made more environmentally sealed and therefore less environmentally risky.

Fire Fighting Robots

The area of fire fighting is definitely one with great potential for future robot applications because of the hazard it represents for humans. Very little has been done in this area as of yet, and this is mainly due to the complexity and very unstructured (unpredictable) nature of fire-stricken buildings and areas, in addition to their potential lethality. Many robotic applications, however, could be envisioned to help neutralize devastating fires. Typically, fires in buildings are hard to extinguish from the outside of the buildings where firemen are usually confined, because the major source of the blaze which produces the heat and propagates the fire is inside and unreachable by humans. Fire-shielded robots could be developed to enter and/or navigate through buildings on fire, look for sources of the blaze and, using on-board fire extinguishers, attempt to put out the fires (or at least minimize their spread).

On a much larger scale, forest fires can also be quite devastating. Autonomous (smoke, debris, etc. would make visual or remote control very slow or impractical), all terrain, fire-shielded robots could be envisioned as support equipment in outdoor fire fighting, for example, to dig fire-cut trenches, or move to the inside of the blaze area to deliver extinguishing agents. The sensor-based intelligence and robotic technologies to realize these types of specialized systems may not be far, indeed, from current state of technology, and actual implementation may only necessitate focussed multidisciplinary engineering teams. It is clear that, here too, significant gains in both the time before actual realization of such robots, and the overall efficiency of these systems, can be achieved with some improved (robot-friendly) engineering design of the surroundings, particularly for in-building fire fighting. For example, it would make little sense attempting to design a robot capable of performing the complex tasks of grasping and operating fire extinguishers that have been specifically designed for handling by humans. A modified type of extinguisher designed in a robot-friendly way (i.e., compatible with current robot handling capabilities) and engineered for as easy an operation as possible by a robot, would bring much closer to reality this application, which otherwise would seem elusive.

Subsea Operations

A lot of concepts and devices, both teleoperated and autonomous, have been developed and extensively used in this area (e.g., Titanic inspection, autonomous shore-following torpedoes, pipeline repair systems, etc.). There is still, however, lots of room for more advanced concepts and, in particular, for more environmentally friendly exploitation and

preservation of the marine environments. For example, autonomous robots wandering around the shallow continental shelf in search of toxic or hazardous waste matters could help detect abusive releases of toxic substances and/or old sources of hazardous materials previously discarded which are today leaking or spilling in the oceans, lakes, or rivers. Miniaturized chemical, organic, and non-organic, substance sensors (sometimes also called "sniffers") exist today to detect a wide variety of toxic and/or hazardous substances. These could readily be integrated in such applications.

It is expected that subsea environments may see large numbers of a variety of robots in the future, and one consideration to have today is that the robots themselves should not become polluters of the very prime marine environments, i.e., particular attention should be placed in the design of future aquatic robots so that no oil spills and waste materials are left behind after a robotic operation. In other words, the robots need to be designed to be environmentally clean themselves.

Space Exploration Robotics

This is by far the area where the most advanced type of robotics, from the standpoint of autonomy, intelligence, and reliability, will be required; but it is also the area where environmental awareness today may have the most significant impact on the environmental friendliness of the world in which we will live tomorrow. The various space agencies of many countries have proposed a great variety of space robots for exploration, future exploitation and even colonization of nearby planets, and it is not our intent to review or discuss these here. On the other hand, several considerations can be brought forward on this topic. There is no doubt that the same argument made in previous sections with regard to the need for and definite gains obtainable with a more robot-friendly, or robot-compatible design and engineering of the "robot workplaces," also applies here; in particular, if construction of structures, mining operations, energy production, or mineral resource exploitation are envisioned on other planets. Since there is very little "precedence" in this area of space robot design, this philosophy of improving the robot-friendliness of some task environments to allow more efficient and environmentally friendly use of robots, should be adoptable without requiring much mentality change. It will however require awareness and environmental consciousness on the part of the *human* designers!

This latter point cannot be emphasized enough, particularly considering the following: space flight and exploration activities are in their infancy stage, probably comparable to what aviation was in the early 1900s. Large and fast developments are expected in the next few decades. At this point, space flights are still occasional and only a handful of landings on other planets have taken place. But the earth's orbit is already crowded with "dead" satellites for which no retrieval and/or disposal has been planned, and all landing missions have left

behind them non-functional carcasses and structures with no reusable value. Are those the precursors of what will be the space pollution age? In any case, they are definitely indicative of the shameful trend of our society for carelessness about waste or recycling, and in general about preserving the natural (and in this case pristine) environment. Indeed, despite all of the robots that we can envision to create for environmentally friendly functions, we humans, as ultimate supervisors and designers of those robots, must first accept to change our methods, thought process, and attitude toward the environment, if any results at all are to be obtained.

3. Robots for Human-Support Functions

For those applications in non-directly hazardous environments, the justifications for use of robotics have varied from a need for improved precision and quality, to purely economic reasons. These justifications typically do not "mix well" with environmental friendliness. In fact, gains in the conventional primary objective areas have typically resulted in loss in the environmental area: all automated devices use energy of some sort, and energy production has proven to be one of the most detrimental for the environment, be it with respect to resource recovery (e.g., coal or uranium mining, timber cutting, drilling for petroleum) which deteriorate the sites, the air (with fumes) and the subsurface water (leachate migration, well leaks, etc.), or raw material transportation (oil spills from tankers), energy production facilities (smoke stacks, cooling water discharge) or waste disposal. Thus, as a very first consideration, the field of robotics in its entirety could be made more environmentally friendly by placing some focus on minimizing energy consumption of the robots, and by emphasizing research on and use for robotics of renewable energy, such as solar, whenever feasible. Besides providing some gains in environmental consciousness, the local nature of renewable energy collection, such as solar using solar cells for example, would allow an alternative energy supply (or resupply) to be carried on-board the robots, thereby enhancing their autonomy potential (e.g., for space exploration, etc.). Even a gain of 0.1% of the world's energy consumption would represent a globally enormous environmental gain and, more importantly, would hopefully constitute the start of a trend for future applications.

Another consideration can be developed with respect to the global proliferation of robotic devices: just like space exploration, the field of robotics is probably in its infancy, and large numbers of robots may be expected to be commonplace in the not-too-distant future. If we take as reference, for example, how "unrecyclable" today's automobiles are, one may wonder if the time is not right to initiate research programs to ensure that the large majority of the future population of robots is highly recyclable.

Waste Recycling and Waste Handling Robots

There is no doubt that one of the major sources of environmental problems is the increasing amount of waste produced by our societies. There are really only two ways to deal with this problem: generate less waste and recycle the waste. With respect to the former, the solution resides within each of the millions of processes and specific plants that generate a different set of waste materials; and therefore it is very unlikely that a single (or even a few) robotic concepts would generically resolve or improve the vast variety of individual process problems. The solution therefore in this area of waste generation minimization, is essentially an individual one, on a plant by plant basis, and even process by process basis.

With respect to waste recycling, on the other hand, several improvements of a generic nature could be envisioned to remove some of the hurdles encountered today with recycling. The first consideration relates to the fact that all waste is essentially "dirty," and that consequently humans are reluctant to perform the sorting of the waste materials which is necessary for proper recycling. This, in my opinion, is a very fertile ground for many applications of robotics. Robots could sort through piles of waste, separating materials, compacting as appropriate, and packaging the sorted waste for shipment to recycling plants. Of course, the argument developed in the previous section about gains in efficiency and applicability realized through improved robot-friendliness of the robot's workplace and robot tools, would directly and strongly apply here: it would be senseless, for example, to envision robots sorting waste through visual perception only, like humans do. Sets of sorting systems and/or tools such as magnets, centrifuges, sieves, etc. would of course need to be considered and incorporated within the overall system.

Another hurdle encountered in recycling is the difficulty of separating materials that are agglomerated or tied together within a single waste mass (e.g., plastics, metals, and rubber in a discarded car). The task of disassembling these waste masses so that the various materials can be separated is often considered much too tedious for humans to perform, but would be an ideal task for a specialized set of robotic systems. Breakage of parts would be of no importance, and the mechanical strength of robots over humans could be exploited, while tediousness is a non-issue in robotics. This type of disassembly robots would of course build upon the very large amount of research and development that has taken place in the area of robotic assembly.

Agricultural Robots

One of the main characteristics of agricultural robots is that they will operate in direct contact with the natural environment, performing tasks that, for centuries, have been performed by humans as an essential part of human life and survival without, in most cases, exhibiting significant, long-term deterioration of the environment. Several systems

have recently been developed for tasks such as citrus fruit or tomato harvesting, and even strawberry picking, with specialized end effectors for not bruising the fruits, and vision systems capable of estimating if a fruit is ripe. Overall, it is conjectured that plowing robots, sowing robots, and many types of harvesting robots, although feasible or close to feasible with today's technology, have not been widely developed and used to date because of lacking economic incentives. We expect, however, that they will appear rapidly as soon as economic, demographic, and/or geopolitic factors will justify their utilization.

Large numbers of robots are expected to be developed in this area, and a consideration to bring forward here is that these robots should not be conceived, designed, or operated in such a way that they result in a lesser production and/or harvest per acre of land. Today's cotton picking machines, for example, can leave behind up to 50% of the cotton on the plants, and in wineries using automated equipment, the spacing between the rows of grapevines has typically been doubled, if not tripled, to allow the passage of the machines. It is hoped that such examples of automation resulting in lower efficiency per acre of land would not represent a trend for the future agricultural robots. Thus, a major consideration should be given to the optimization of production per acre ratios in the design of future agricultural robots. This will be significantly complicated considering the observation made in the previous section that the operative efficiency of robots is typically improved when the surroundings and/or "robot workplaces" can be adapted and made more robot-compatible. The resolution, trade-off, and/or compromise between these two considerations will be key to gains in environmental friendliness which future robots can contribute in the field of agriculture. The other considerations made earlier regarding energy utilization (e.g., solar), cleanliness (no pollution or materials left behind), and recyclability also apply to robots in this area.

An interesting consideration relates to the use of robots with respect to fertilizers in agriculture. Fertilizing is a common and natural process in which decomposing materials eventually enrich the soil. For centuries, human and animal wastes were used as fertilizers in agriculture. There still are today many gardens with compost piles. In this century, some societies have moved away from fertilizing with only natural elements and have accepted the addition of chemicals to the natural fertilizers, mainly because fertilizers are wastes and wastes are intrinsically "dirty," and because the chemicals allowed a "cleaner" processing, storage, and distribution of the fertilizing materials. As mentioned in previous sections, robots are ideal devices to replace humans in tasks that are "dirty" or that may constitute a health hazard (robots do not catch typhoid or other diseases). It could therefore be envisioned in all seriousness, that robots could be developed to perform all the "dirty tasks" involved in collecting compostable waste, be they human wastes, animal wastes, or household trash, transport that waste to "sealed" processing plants in which

other autonomous robots would process, package, etc. these wastes to be distributed as fertilizers. The overall environmental gains of such a concept, would involve less chemicals, less societal wastes to be disposed of otherwise, better recycling ratios, less sewer discharge, etc. and the technology required to develop the waste-collection robots may not be far off in the future, if it does not exist today.

Vehicles and Traffic Management Robots

This area is one that lends itself to a variety of applications of robotics, in particular, sensor-based mobile robotics. Many countries have issued plans and concepts for mobile robotic systems to serve as the advanced highway vehicles of the future, and it is not our intent to review all these plans and concepts here. However, it should be noted that besides the safety, time saving, and economic justifications brought forward in these plans for intelligent vehicle and highway systems, each also include very strong environmental awareness statements. The main considerations for improved environmental friendliness revolve around a potential decrease of toxic emissions by automobiles due to more fluid and better managed traffic. Little in these plans actually focusses on the raw consumption of vehicles. The consideration given in previous sections concerning the desire to design future robots with energy supply depending on, as much as feasible, renewable energy particularly applies in this case. The compromises which will take place between such a consideration and, for example, the acceptance of a lower speed of transportation, may be very different in each program, and quite illustrative of the relative environmental consciousness of the people in the countries or regions covered by the various programs.

General Support Systems

As discussed in the introduction, there is a great variety of robots that can be envisioned for the future. Each type will have a "triggering" point at which time they will become deployable in large quantity. The major triggering factor will be economic but, as pointed out in the previous sections, other factors such as demography or health hazard may come into play. For household robots (e.g., vacuum cleaners), which may become the most common of the future general support systems, factors such as reliability and liability (they will work near children, pets, valuable property, etc.) may decide when they will make their massive entrance into homes. For each of the envisioned systems, much will be gained by adding an environmental factor with a large weight (is a weight greater than that of the pure economic factor acceptable today?) in the decision making process. Since such an environmental factor exists and is utilized today (e.g., see the most recent programs such as IVHS), then the considerations brought forward here may be useful in conceiving/designing future concepts. In the immediate future, it is my belief that the wide variety of waste-related problems and/or waste-related activities offer the most fertile ground for development of environmentally friendly

and environmentally useful robots. Without doubt, wastes of any type, i.e., materials that are not directly reused or recycled, are at the source of our next serious environmental problems. In many other areas, the state-of-the-art technology today would soon allow emergence of robotic systems that could enhance the environmental friendliness of our activities, however, a modification of the weights we associate with the environmental and the economic (and other) factors in our decision making process may be necessary for such systems to be deployed in an environmentally friendly way in the not-too-distance future.

4. Concluding Remarks

A series of considerations with respect to the use of robotics for improved environmental friendliness have been brought forward. These considerations have been discussed through a variety of contexts and applications that are most commonly associated with the area of robotics, with no intent however to exhaustively survey all potential applications. A few areas less familiarly encountered or considered for robotic applications have also been discussed to present possible concepts and/or modifications to existing processes with some potential for improving their environmental friendliness. Examples of past engineering where little consideration has been given to either robot operability or environmental friendliness in the design of task areas or surroundings, have been used to point out the "legacy of the past," i.e., problems of such significant magnitude and complexity that their resolution will require the most advanced technologies, including those related to robotics. On the other hand, much less complex robotic technologies would appear necessary if proper considerations were given at the design phase to both the robot-compatibility or robot-friendliness of the task surroundings, toolings, and environment, and the overall robot-process-system's environmental friendliness. It would seem that the comparison of this with the "self-inflicted" and paramount challenges of our "legacy of the past" would induce us to modify our approach and philosophy with respect to environmental considerations. Some examples related to developing fields or areas, in particular space exploration, have been presented to point out that in most respects, our design practices and philosophy with respect to considering the potential impact of our activities on the natural environment are not much different today than they were a few decades ago. This is very disappointing, and clearly brings to light the fact that *human awareness and environmental consciousness* are essential prerequisites, and indeed the key, to the environmental friendliness of future robotic systems (or any other activities as a matter of fact). A few examples of possible systems more focussed on environmental friendliness have also been brought forward as a very small contribution to this area, and in the hope that a positive trend initiates in the very near future.

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