Design considerations about a Photovoltaic Power System to Supply a Mobile Robot

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***Abstract*—It is desirable that robots would be, as much as possible, autonomous and self-sufficient. This requires that they can perform their duties while maintaining enough energy to operate. This paper presents the preliminary results for the design of a power supply system of an autonomous robot. Robot design is divided into four primary areas: energy storage, actuation, power and control. It is obvious that there are many relationships among these phases so as matter of fact they have to be analyzed in parallel to optimize a robot, especially from the energetic point of view. In particular, a power supply solution that utilizes solar cells and a microcontroller have been chosen to power and control an hybrid robot, named TriBot. Finally, initial tests with a probe-loaded robot prototype have demonstrated the feasibility of the solution.**

I. INTRODUCTION

A large variety of autonomous robots have been recently developed: these robotic systems can be classified according to their structure, dimensions, manoeuvrability, main tasks, and so on. In any case, every robot requires a power source to perform all its functions, like navigation, measurements, manipulations, to name just the most important. Different strategies can be used to guarantee energy autonomy to a roving robot: the introduction of recharge stations in the environment or embed in the robotic structure a power source generator. The latest solution increases the robot weight and consumptions, therefore, it is important to explore the added value, in terms of increased autonomy.

In [1], [2] and [3] Li-ion batteries and super capacitors are used as charge buffers for alternative power sources. On the other hand, batteries are not a recommended power source for robots that have to work in an isolated zone, since the power source would limit the lifetime of the system: in this case rechargeable batteries are a secondary power sources. Therefore, in the context of robot applications, another primary power source must be used. In order to account for all the objectives: lifetime, flexibility, simplicity, cost, the best compromise appears to be the use of micro solar power system with rechargeable batteries. Nowadays, solar energy harvesting has become increasingly important as a way to improve lifetime and reduce maintenance cost of portable appliances and stand alone power systems. In particular, the use of this strategy for supplying systems with limited size and mass, but nevertheless high-power requirements, such as a mobile robot, is studied. In this paper the attention is concentrated on the Photovoltaic (PV) technology, as well as on the possibility to use cells on a flexible support, increasing the adaptation to any surface shape. The paper is organized as follows: the state of the art of mobile robot's energy management and of the photocell application in robots will be first presented; then a description of the TriBot robot and its energy characteristic will be given; subsequently a description of the design of an autonomous photocell system to apply on the robot will be discussed.

II. STATE OF THE ART

Until now, batteries and/or capacitors have been used as power sources. Batteries are often used to provide power for mobile robots; however, they are heavy to carry and have limited energy capacity. Therefore power consumption is one of the major issues in robot design. Existing studies on energy reduction for robots focus on motion planning to reduce motion power [4] [5] [6]. However, other components like sensing, control, communication and computation also consume significant amounts of power. In [7] two energy-storage techniques are introduced: dynamic power management and real-time scheduling, that, together with motion planning provide greater opportunities to increase energy efficiency for mobile robots. Robots are, in fact, complex systems that include sensors, actuators, control circuits; for these reasons the energy request is quite high and the power supply management is an important aspect for robot design.

Concerning the recharge of batteries, there are two strategies for recharging batteries and capacitors: on board solar panels or off-board power stations. An example of a colony of hexapod robots, configured with both batteries and capacitors, whose behaviour depends on their power supply status, is presented in [8] [9].

Another example of the use of a power station is presented in [10]. They discuss about a system for resupplying power to self-contained mobile equipment, that includes a fixed station having an external power source.

Mobile robots often rely on a battery system as their main source of power. These systems typically produce a single voltage level, however the robot subsystems may require a set of different voltage levels. In [11] a battery system is used as main power source for a robot and then the power supply will consist of a combination of switched mode DC power converters. Experimental results show the converter efficiency and voltage ripple at rated load. Furthermore, solar harvesting

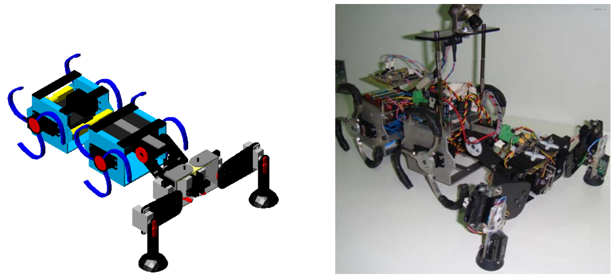
(a) (b)

Fig. 1. Robot TriBot. (a) AutoCAD design; (b) Physic realization.

circuits have been recently proposed to increase the autonomy of embedded systems. In [12], in fact, an energy scavenger system that exploits miniaturized photovoltaic modules to perform automatic maximum power point tracking at a minimum energy cost is presented.

One of the most important characteristic that an autonomous robot should have is to work for an extended period without human intervention. Therefore, our aim is to design a power system that makes the robot as much autonomous as possible, using solar cells to recharge batteries. This can allow the robot to have a high exploration capability in open spaces, and to test, on board, time consuming learning and swarming algorithms without the need to require a charging phase. Results show that, using PV cells, at the moment it is possible only to recharge batteries that power the control boards of the robot. There are components of the robot, such as motors and distance sensors, that involve a high power consumption, anyhow they can be deactivated in the case of low level batteries. Our aim is, in fact, to maintain a continuous communication of the robot with other robots and with a base station. Moreover, apart from PV solar cells, there are other power scavenging, such as temperature gradients and vibration [13], that can increase the energy generated on the robot. In fact, temperature variations and mechanical vibrations can also be used to provide energy to the system.

III. TRIBOT ELECTRICAL CHARACTERISTIC

In this section, we discuss about the electronic elements of the autonomous mobile robot developed. In particular, the robot design process and the energy consideration are shown.

In this paper, the robot used for energy consumption experiments is a bio-inspired hybrid robot called TriBot [14]; its 3D model and the real prototype are shown in Fig.1. The mechanical peculiar characteristic is the design of Whegs: each leg is in fact realized with a tri-spoke appendage and is actuated by a single electric motor. This solution tries to fuse together the powerful capability of wheeled system in terms of speed, payload and easy maneuverability and also includes the characteristics of legged systems able to adapt over rough terrains and to climb obstacles. The robot is composed of three modules. Two of them are identical and they are inspired to Whegs; a passive joint, based on a spring, is used to connect the two wheeled modules. This degree of freedom allows a fine adaptation of the robot posture in cluttered environment and this characteristic is extremely important during obstacle climbing. Moreover, a manipulator is connected to the two wheel-legs modules by an actuated joint. It consists of two legs with 3 degrees of freedom respectively. The standard legs module has been added to increase the climbing capabilities and to use it as manipulator. To control the robot, two boards based on ATmega128, a low-power CMOS 8-bit microcontroller [15], connected using a serial bus and a graphical user interface (GUI), have been developed. Besides, the computer oversees and controls the robot through a RF wireless XBee module, that uses the standard ZigBee. This communication technology was chosen because of its much less energy demanding compared with other technologies [16]. As all autonomous vehicle, the robot needs a storage energy system, in this context to select an appropriate battery type, different kind of batteries based available on the market have been evaluated. Several parameters are used to compare the commonly used battery, anyhow they can be clustered in five categories: Costs (battery and required electronics), Efficiency, Freedom in the design, Durability, Environmental issues. Among the different battery types: Nickel-Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium Ion (Li-Ion), Sealed Lead Acid (SLA), Rechargeable Alkaline Manganese (RAM) and Lithium-Polymers (Li-Po); NiMH is the only battery type that does not have great disadvantages in any of the categories. Although it requires additional electronics to protect against overcharge and over-discharge, a further disadvantage is the high self-discharge rate (15-25% per month). The NiMH battery is available in different shapes and capacities, and voltages are multiples of 1,2V.

Li-Ion is also a very good candidate except for its costs (although prices show a decreasing trend), and temperature dependent aging (durability). The significant advantages of Li-Ion batteries are size, weight and energy density (the amount of power the battery can provide). Li-Ion batteries are smaller, lighter and provide more energy than either nickel-cadmium or nickel-metal-hydride batteries. Additionally, Li-Ion batteries operate in a wider temperature range and can be recharged before they are fully discharged without creating a memory problem. An alternative to Li-Ion batteries is the Li-Po cell. These two technologies are extremely similar, but one advantage of Li-Po batteries is that they are more resistant to physical trauma, and moreover they can be easily shaped to fit many different devices. For these reasons they have been chosen to power the control boards of the robot. Furthermore, to obtain the maximum torque and so better performance for the robot, motors used to actuate the robot need a 6 V power supply. This value has been reached using NiMH batteries. It is important to take into account that, while in most applications the need is to have batteries as much light as possible, but at the same time with a high capacity, in this application the weight of batteries allows to increase the stability of the whole structure. As matter of fact, at the moment, the robot is equipped with two different battery packs:

TABLE I
TECHNICAL CHARACTERISTICS OF TRIBOT.

Robot size (manipulator up) (manipulator down) (length, height, width)	36cm x 23cm x 13cm 28cm x 12cm x 25cm
Weigh	1,95 kg
Velocity	46 cm/s
Spoke length	6 cm
Body flexion	$\pm 30^o$
Wheel-legs and joint motors	Hitec HS-985MG
Manipulator motors	Hitec HS-82MG
Average Power for moving on flat terrains	9W
Average Power for control, sensing and transmission	1.628W
Higher obstacle overcoming	1.8 times wheel radius

- 10 rechargeable 1.2V, 3000 mAh type Ni-MH AA stylus batteries;
- a rechargeable 1345 mAh, 7.4V, Lithium-Polymers battery.

A scheme of the power system of the robot TriBot is shown in Fig.2. The flow chart shows as the Ni-MH battery pack power supplies all the motors that actuate the robot, while the Li-Po battery is regulated to 3.3V and to 5V to power supply the wireless module and the control board together with the robot sensory system (i.e. tactile sensors and infrared distance sensors). Experiments show as, using these kinds of batteries, the lifetime of the robot is about two hours. In order to increase the autonomy of the robot a small PV system will be added (gray part in Fig.2). Our aim is, in fact, to use these PV cells to recharge the Li-Po battery. The DC/DC block represents the conversion circuit needed to adapt the voltage coming from PV cells to that required to recharge batteries, and the Maximum Power Point Tracker (MPPT) that allows to extract the maximum power available from a cell.

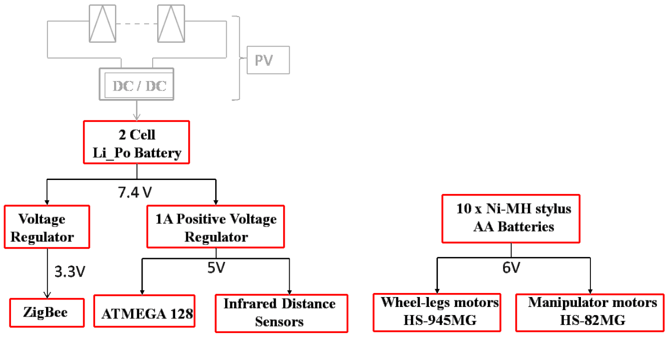

Fig. 2. Flow chart of the TriBot power system.

The relevant technical information concerning the robot are summarized in Table I.

In order to built an efficient autonomous power supply system, we measured instantaneous current absorbed by the motor system in two different typical scenarios: movement at maximum speed on a flat terrain and obstacle climbing. Moreover, we measured an instantaneous current observed by the control system. The results have been obtained using a current transducer LTS 6-NP and an U2300A Series Multifunction USB Data Acquisition board by Agilent [17].

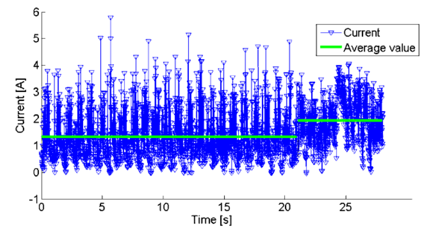

Fig. 3. Behavior of the instantaneous current absorbed by motors. Data have been acquired at 100 Hz (triangular markers). The continuous line represents the average value. The first parte represents the movement at maximum speed, while the second one an obstacle climbing.

Data have been acquired with a frequency of 100Hz and then the average value was evaluated. Fig.3 shows that the behavior of the current relative to the motor system, where in the first 20 seconds the robot is running at its maximum speed in a flat terrain, and the current changes in a fixed interval; after 20 seconds the velocity of the robot was decreased for stability reason and the robot has overcome an obstacle of 8cm. As we can see, in this second part the current has a peak while the robot is overcoming the obstacle and then it decreases. Since motors have been powered at 6 V, the average power consumption for the motors results to be about 9W when the robot runs, while it is about 12W during an obstacle climbing.

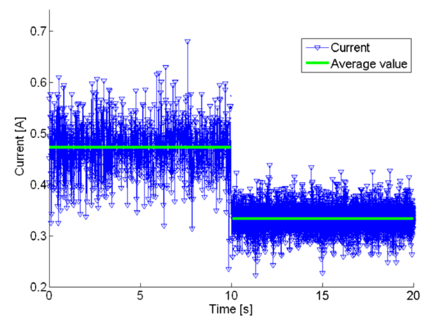

Fig. 4. Behavior of the instantaneous current relative to the control board (triangular markers). The continuous line represents the average value. In the first 10 seconds the infrared distance sensors are activated, while they are deactivated in the second period.

Fig.4 shows the behavior of the current, analyzed in an interval of 20 seconds , relative to the two boards that control wheel-legs and manipulator modules and that includes the microcontroller, the ZigBee module and, only in the first 10 seconds the sensory system. Data have been acquired during a task that needs a continuous exchange of data from robot to a base station and vice versa. Therefore, the average power consumption relative to the control boards is about 3.5W when sensors are activated, in so far the control board is powered at 7.4V. This high power consumption is due to the four infrared distance sensors, in fact each of them have an average dissipation current in the range of 33-50 mA. These sensors are needed for autonomous navigation, but they can be deactivated when the batteries of the robot are discharged. In this case the robot can continue to communicate, for example, with other robots or with a base station. Therefore, the second part of the Fig.4 (from 10 sec. to 20 sec.) represents measures about the control board without sensors and it shows as the power consumption decreases considerably (2 W) if the four infrared distance sensors are deactivated. Moreover, actually the regulator used in the control board is a linear one. These kinds of regulator have an efficiency less than 0.7. Therefore it is possible to further reduce the power consumption using switching regulators which have an efficiency greater than 0.9.

After having measured the power consumption of the robot, it is necessary to analyze the energy that the solar power system can generate. Obviously, it depends on the dimension of the cells used and on their technology. The robot has a limited available surface where to place the cells, therefore it is important to carefully design the whole structure. In the next section, in fact, some possible structures that will be placed on the robot to incorporate the PV cells are discussed, considering only outdoor applications.

IV. Placement of PV panels analysis

The PV-cell is a relatively large part of the external encasing of the robot and it needs to be mounted in such a way that it receives as much light as possible. For the studied application, basically three ways of incorporating the PV-cell exist:

- placement in the encasing, under a transparent cover;
- placement directly against a transparent cover;
- placement outside or as a part of the encasing.

All alternatives include one or more interfaces between media, so that additional reflection occurs. In order to tackle this problem, the reflection effects need to be understood. The selected PV cell type should be feasible from both energetic and economic viewpoints. For an economical evaluation, two different PV technologies can be identified, namely thin film technology providing encased modules, and crystalline cells (c-Si) with the need for further module assembling. In photovoltaic (PV) energy systems c-Si technology is always been predominant because of its proven reliability and acceptable cost. This kind of cells have efficiencies between 12% and 17% and represent about 90% of the market. Another technology which has recently advanced in the market is the Thin-Film. Thin-Film cells on foils have the advantage to be bendable and thereby allow higher freedom in solar cell integration into the products encasing, but show a bad energetic performance. That is, a-Si cells show efficiencies at determined standard testing conditions around 7% maximum, compared to a 13-17% range efficiencies of commercially produced crystalline cells, with cells up to 20% efficiency commercially available at relatively low costs. Solar cell efficiency, however, decreases towards lower radiation, and if the robot will be used in indoor environments, this effect should be taken into account.

Nowadays, the market offers various PV solar panels technologies and, it is clear that, the shape of these structures depends also on the technology that will be used and, vice versa, the choice of the technology depends on the energy consumption of the robot and on the available surface for the installation of the panels. Since the chassis of the robot consists of two modules with wheel-legs and a manipulator, it is obvious that, if we want to exploit at maximum the available surface of the robot, the PV cells have to be embedded on the two wheel-legs modules. Each of these two modules is 57mm long, 68mm thick and 54mm tall; therefore, at most, it is possible to use two 10x10 cm PV cells. Using AutoCAD, some examples of covering structures have been designed. The different proposed solutions depend on the technology that will be used. The first possibility is to use two 10x10cm cells put on the two wheel-legs modules. Using this technology, the covering structure is rigid and flat; the proposed solution is shown in Fig.5(a).

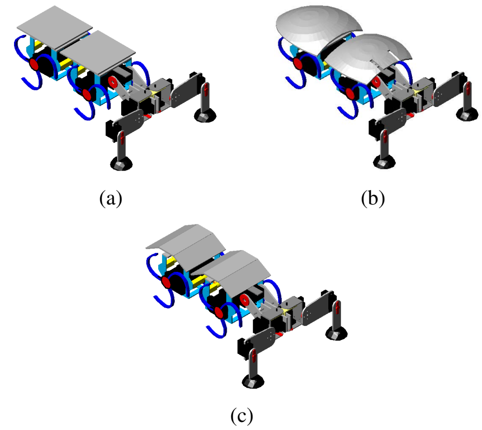

Fig. 5. Proposed covering structure using different PV technologies. (a) Two 10x10 cm^2 cells that use the crystalline-silicon (c-Si) technology; (b) Two cells that use the Thin Film technology; (c) Six 3x10 cm^2 cells that use the crystalline-silicon (c-Si) technology.

Fig.5(b) shows another possible solution. The idea is based on the low profile and flexibility of thin film cells that allow them to be incorporated with innovative straight or curved mechanical structures in this case an optimal fit with the robotic structure can be reached. In this case the covering surface is bigger than the previous one (about 330 cm^2), but it is not an advantageous solution because of the low efficiency of the considered technology. Finally, using poly-crystalline silicon, it is also possible to obtain 3x10 cm^2 cells connected in series; this would allow to have a greater flexibility in realizing the structure that has to contain the cells, optimizing the available space. Fig.5(c) shows another possible shape of the surface that should contain the PV cells. Solutions (a) and (c) will increase the weight of the robot of about 5-10% due to the presence of protective glass layer over the crystalline silicon cells.

Considering these three solutions, the third one, up to now, appears to be the most appropriate, since it uses the crystalline-silicon technology that has a greater efficiency than the thin film one and it allows to have more flexibility in the body flexion of the structure. This solution, considering that the power consumption of the control boards with sensors deactivated is of about 2W, allows to increase the autonomy of the robot of four and an half hours (considering that the average daily solar radiation in Catania (latitude $37^o34^{'}$ N longitude $15^o10^{'}$ E, Italy) is 4÷5 kWh/m^2/day [18]), if the energy harvesting process optimized. Therefore, in this context the main objective is to developed an electronic board that allows to exploit as much as possible the solar energy and to manage correctly the batteries, as illustrated in the next section.

V. The photovoltaic charger

Long-term operation is an important goal of many mobile electronic systems. One may attempt to achieve this goal in three ways: reduce energy consumption of the system, increase energy capacity of the battery and replenish battery energy over time. Energy reduction can be done by improving hardware design and more intelligent power management, which entails turning off unused components or slowing down during idle periods. Unfortunately, batteries are limited by both their energy capacities as well as their number of recharge cycles, even if the system already consumes very low power. As a result, it is necessary to harvest energy efficiently from the environment. Among energy harvesting methods, photovoltaic (PV) sources have the highest energy density [19] and, consequently, represent, at present, the best way to gather energy from the environment. Nonetheless, partial shading and rapidly changing shadow conditions are particular problems in portable and mobile applications. Indeed, the optimization of the energy harvesting process under varying light irradiance conditions is certainly one of the major design challenges for PV systems. In fact, the optimal working voltage of the PV cells depends upon the specific load, which fix the output working voltage. Harvested power can be maximized if the cells and the load are impedance matched in every light irradiance and temperature condition. To this aim, in most photovoltaic systems a particular technique, namely maximum power point tracking (MPPT), is adopted. MPPT techniques are very common in the world of large-scale solar cells. The extra energy that is consumed by the maximum power point (MPP) tracker is easily offset by the much higher amount of energy that can be harvested from the environment. In contrast, in those applications where few solar cells are employed the gain in input energy is not always higher than the additional losses that are caused by the MPP tracking operation. Therefore, an MPPT controller for small devices must maximize net power transfer mainly by minimizing MPPT overhead, while it can afford to sacrifice MPPT accuracy. The energy consumption and efficiency of the MPP tracker are, therefore, very important design criteria in energy scavengers for solar-powered mobile applications. The optimization of the energy harvesting process under varying light irradiance conditions is certainly one of the major design challenges. In particular, maximizing harvester circuit efficiency becomes fundamental at low light irradiance [19] [20]. In literature there are several methods and algorithms to track the MPP voltage [21] [22]. The most popular ones are Perturb and Observe (P&O), Incremental Conductance (IncCond) and Fractional Open-Circuit Voltage (FOCV). The P&O and IncCond methods are widely used with medium-high power PV modules, since it allows accurate MPP calculation [21]. However, they require complex control actions that are often implemented using microcontrollers or DSPs and several current/voltage sensors. Consequently, the major drawback of these methods is the relatively high power consumption required to implement the MPPT circuit, which is not affordable in very low power PV applications. Moreover, these approaches have been effectively used in stand alone and grid-connected PV solar energy systems and work well under reasonably slow and smoothly changing illumination conditions mainly caused by weather fluctuations. However, it is not easy to directly apply these approaches into portable PV applications due to low tracking speeds or complex implementations [23].

The main constraint of the solar power system is the limited amount of area that can be used to place the PV cells on board. This lead to a maximum available peak power for the adopted PV cells of about 1.4 W. In this context, a very efficient charging system is mandatory. In order to minimize complexity while optimizing energy harvesting, $FOCV$ method is efficiently used in small-scale PV systems for portable applications [24], [25]. This method exploits the nearly linear relationship between the operating voltage at MPP, V_{mpp}, of a typical PV module and its open-circuit voltage V_{OC}, i.e., $V_{mpp} = K_{FOC} \cdot V_{OC}$. K_{FOC} is a constant that ranges from 0.71 to 0.78, which slightly depends on irradiance conditions. Considering KFOC as a constant under different irradiance conditions leads to small errors in the V_{mpp} evaluation but strongly simplifies circuit solutions adopted to implement MPPT. The main drawback of this method is the dependence of the MPP voltage with temperature. The temperature MPP voltage is a linear function of temperature, while it slightly depends on irradiance conditions, therefore, in order to get rid of the temperature dependence of the MPP voltage, a temperature sensor is exploited.

Fig.6 shows the block diagram of the proposed solar power harvesting system and it has been designed to accomplish the future development of the robotic structure.

An high-efficiency switching step-down battery charger constitutes the heart of the system. The charger accommodates Li-Ion/Polymer chemistries and provides a constant-current/constant-voltage charge characteristic, with maximum charge current externally programmable up to 2A. The circuit employs an input voltage regulation loop, which reduces charge current if the input voltage falls below a programmed level (i.e. the MPP voltage), set with a simple resistor divider. The adopted architecture allows a compact and efficient implementation, while ensuring a very fast MPP tracking, since no digital processing is necessary. As the temperature characteristic for a typical solar panel MPP voltage is linear, a simple solution for tracking that characteristic can be implemented using an LM234 3-terminal temperature sensor.

The system comprises an high performance battery monitor

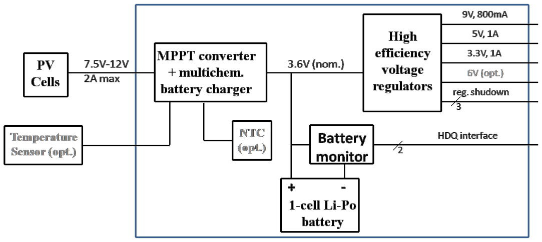

Fig. 6. Block diagram of the solar power system.

IC which measures the coulometric charge/discharge current (with automatic offset compensation), battery voltage and temperature. These data, transmitted through the HDQ interface to an intelligent host controller, allow an accurate evaluation of the battery state of charge (SOC) which, in turn, permits the implementation of power-saving strategies for the robot. The board also implement the voltage converters supplying the control board (3.3V for the processing unit, 5V for the sensors and auxiliary 9V). Additional control signal which allow an external host controller to shutdown each voltage regulator are also implemented.

VI. CONCLUSION

A preliminary analysis of the feasibility of a photovoltaic system with batteries to supply a mobile robot has been presented. By analyzing both the power drawn by the robot during the movement at various speed rates and the efficiency of the most used PV cell technologies, it is clear that the PV system can supply only the control and wireless transmission systems.

Therefore, using PV panels it will be possible to maintain the communication of the robot with other robots, a charged station or the supervisor also if batteries are discharged. However some qualitative evaluations on the possibility of using less power consuming motion system and at same time the presence on the market of very efficient PV cells forecast the feasibility to extend the photovoltaic power to supply to whole robot. Further investigation is therefore needed in these directions.

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