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ULISES: AUTONOMOUS MOBILE ROBOT USING ULTRACAPACITORS-STORAGE ENERGY SYSTEM.

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Abstract. Recent technology improvements enabled ultracapacitors (UCaps) to be an interesting option for short-term power applications, such as in industry, automotive and traction drives, regenerative energy system, telecommunication and medical equipment. UCaps are being developed as an alternative to pulse batteries. To be an attractive alternative, ultracapacitors must have at least one order of magnitude higher power and a much longer shelf and cycle life than batteries. UCaps have much lower energy density than batteries and their low energy density is, in most cases, the factor that determines the feasibility of their use in a particular power application. The main advantages of UCaps are that they can provide high power capability (60-120s is typical), excellent reversibility (90-95% or higher) and long cycle life (>10^5 cycles). Thus they exhibit 20-200times larger capacitance per unit volume or mass than conventional capacitors. In this paper, an autonomous mobile robot was converted from a conventional lead-acid or lithium-ion battery to an ultracapacitors as the power source. The integration of UCaps as element of energy storage on the robot was studied with the main of optimizing the energetic solution. The design of the ultracapacitors based power supply system is outlined.

Keywords.
Ultracapacitor, electrochemical double-layer capacitors EDLC, mobile robots, energy/power density, capacitive energy-storage.

1. State of the Art.

Ultracapacitors (UCaps), also known under colloquial names such as Electrochemical Double-Layer Capacitors (EDLC), power capacitors or supercapacitors, are energy storage devices with high power capability and long life. UCaps achieve capacitances several orders of magnitude larger than conventional capacitors. So referring these capacitors as electrochemical capacitors ECs is more appropriate, which is similar to a battery, they both require two electrodes (anode and cathode), an electrolyte and a conducting charge path in order to operate -see figure 1-. ECs also have an additional component, the separator that electrical isolates the two electrodes. Electrochemical capacitors have been known since many years (first patents date back to 1957, Becker U.S. Patent 2 800 616 to General Electric). Today several companies such as Maxwell Technologies, Panasonic, EPCOS, NEC, NESS and several others invest in electrochemical capacitors development. The beneficial characteristics of ultracapacitors are possible due to their composition and construction. Actually UCaps are available in sizes up to 10000F per unit today with typical voltage ratings of up 2,3-2,7V per cell using carbon activated. Cell voltages up to 3,5V/cell have been reported with structured carbon using ionic liquid electrolyte. Desirable characteristics for use in low power applications include: fast charge, wide operating temperature ranges, low weight, flexible packaging, zero maintenance, long life and environmental friendliness [1, 2].

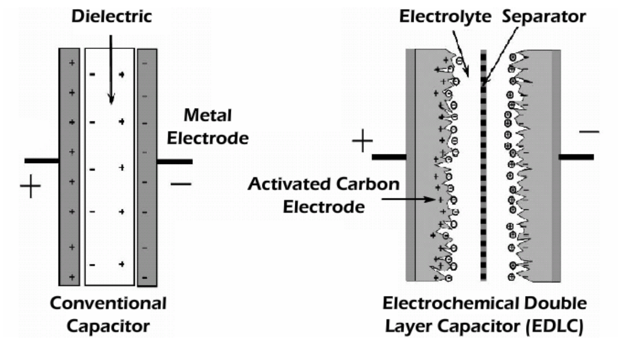

Figure 1. *Structure of aluminium electrolytic capacitors versus ultracapacitor EDLC.*

Conventional capacitors consist of two conducting electrodes separated by an insulating dielectric material, see figure 1. The surfaces on each electrode accumulate opposite charges when a voltage is applied to a capacitor. The dielectric keeps the charges separate producing an electric field. Thus allows the capacitor to store energy. Capacitance "C" is directly proportional to the surface area "A" of each electrode and inversely proportional to the distance "d" between the electrodes. The dielectric constant of free space is ε_o (8,85×10^{-12} Farads/meter) and ε_r is the dielectric constant of the insulating material -dielectric- between the electrodes [3].

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \qquad E_C = \frac{1}{2} C V^2 \qquad (1)$$

Where the energy stored "E_C" in a capacitor is directly proportional to its capacitance. Therefore to increase the capacitance is need to maximize the surface area A or to minimize the thickness dielectric d.

Ultracapacitors are governed by the same basic principles as conventional capacitors. However, they incorporated electrodes with much higher surfaces area and much thinner dielectrics that decrease the distance between the electrodes [2, 3]. The maximum voltage of the capacitor is dependent on the breakdown characteristics of the dielectric material. Thus from (1) this leads to an increase in both capacitance and energy. UCaps store the electric energy in an electrochemical double layer formed at a solid-electrolyte interface. Positive and negative ionic charges within the electrolyte accumulate at the surface of the solid electrode and compensate for the electronic charge at the electrode surface. In order to achieve a higher capacitance the electrode surface area is additionally increased by using porous electrodes with an extremely large internal effective surface. Combination of two such electrodes gives an electrochemical capacitor of rather high capacitance.

Due to the micropores in the activated carbon material used in the electrodes, the UCaps has a specific high surface area up to $3000m^2/g$. This property combined with a short distance between the opposite charges (the thickness of the double-layer depends on the concentration of the electrolyte and the size of ions, which is in the order of 5-10Å Angstrom for concentrated electrolytes) allows an increase in both parameters: capacitance and energy. As indicated Burke [2], the specific capacitance of activated carbon can vary over a wide range (100-250F/g) depending on how it is processed and the electrolyte used in the cell [4].

Ultracapacitors have no mechanical moving parts as in a flywheel -eliminating all maintenance- or chemical bonds maintain life cycle goal well in excess of 500.000 cycles. Moreover they have a large modularity with respect to voltage and capacitance, ultra-low internal resistance, low self-discharge and can be produced at low cost. All these characteristics have been demonstrated with a minimal degradation. UCaps also withstand temperatures ranging from -40ºC to +65ºC (or even higher for short durations) due to the high conductivity low freezing point electrolyte.

Lead-acid battery is the oldest and the more common electrical energy storage device because is cheaper and simple to use. Batteries have been the technology of choice for most applications, because they can store large amounts of energy in a relatively small volume and weight and provide suitable levels of power for many applications [5, 6]. These utilize a chemical process or oxidation-reduction state change, which is not completely reversible. Shelf and cycle life has been problem with most types of batteries but people have learned to tolerate this shortcoming due to the lack of an alternative. In general, lead-acid batteries present a cycle life of around 700, specific energy about 35Wh/kg and 150W/kg of specific power [6]. In recent times, ultracapacitors are being developed as an attractive alternative, due to they have much higher power, and much longer shelf and cycle life than batteries, at least one order of magnitude higher. Thus Ucaps have much lower energy density than batteries and their low energy density is in most cases the factor that determines the feasibility of their use in a particular application. In general, for a particular set of materials, a sacrifice in energy density is required to get a large reduction in the time constant and thus a large increase in power capability.

Ultracapacitor can be discharged or charged faster than batteries -in matter of seconds it can be recharged again for use- and can deliver 10-25 times more power e.g. UCaps typically have a specific power of around 2000W/kg [7, 8], as well as a much lower charge time when compared to lead-acid batteries. Double-Layer Capacitor also offers 10-100 times the energy density (Wh/kg) of conventional capacitors. Moreover its life expectancy is superior to batteries. In terms of energy and power density, ultracapacitors can therefore be placed between batteries and conventional capacitors [2, 6, 9], see figure 2.

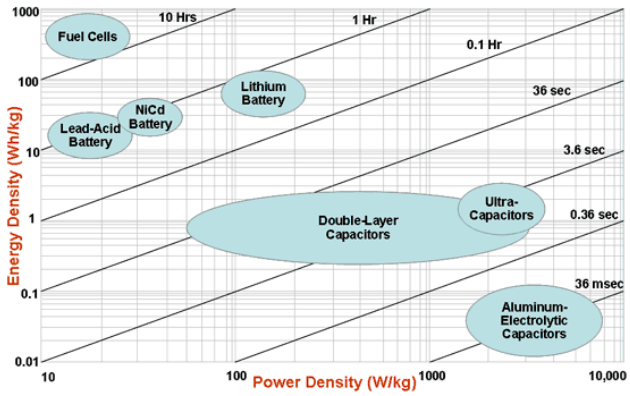

Figure 2. *A Ragone chart storage device energy density versus power density on a log-log coordinate system, with discharge times represented as diagonals.*

The reason why electrochemical capacitor were able to raise considerable attention are visualized in figure 2, where typical energy storage and conversion devices are presented in the so called "Ragone diagram" in terms of their specific energy (Wh/kg) and specific power (W/kg).

Ultracapacitors are becoming the component of choice for engineers and designers with applications requiring short-term or peak (burst) power [3]. They are ideally suited as stand-alone solutions for short-term power requirements ranging from a few seconds to minutes. The charge in these devices is realized in seconds whereas lead-acid batteries often require hours, thus potentially benefiting quick-charge applications. Moving toys, such as miniature racing cars or mobile robots, also benefit from the fast-charge properties of the UCaps which can be charged just before use.

2. Ultracapacitors Power-Supply Design.

Ultracapacitors are power devices with excellent performance over a wide temperature range including both hot and extreme cold conditions. As compared to lead-acid or lithium-ion batteries, UCaps have an extremely long cycle life, but they also have a very low energy density. The ultimate energy storage system solution for commercials vehicles or transportation applications is to combine UCaps in active parallel with lithium-ion batteries. Table 1 provides a useful comparison of an ultracapacitor rated (2,7V; 350F) with a representative lithium-ion cell (3,6V; 2,1Ah) and a typical lead-acid cell (2,1V; 4Ah). For approximately the same capacity in Amp-hour (Ah) the mass y volume of the lithium-ion cell are substantially less than the ultracapacitor. However, the peak power and cycles life of energy throughput for the ultracapacitor dramatically overshadow these same metrics for the lithium-ion cell. Formula used to calculate performance attributes are included in the table; where V_{OC} is the open-circuit voltage of the battery and R_{int} is its internal resistance.

Table 1. *Comparison of Ultracapacitor with Lithium-ion cell and Lead-acid cell Batteries.*

Attribute	Ultracap BCAP0350	Lithium-ion 18650 cell	Lead-acid NP4-6 cell
Capacity	350F	2,1Ah	4Ah
Voltage	2,7V	3,6V	2,1V
Resistance	3,2mΩ	75mΩ	30mΩ
Mass	63g	70g	290g
Volume	0,053dm^3	0,017dm^3	0,115dm^3
Cycles	>500000	<2000	<750
Energy	$W_{UC} = \frac{CV^2}{7200}$	$W_{Li} = C_b V_{oc}$	$W_{Pb} = C_b V_{oc}$
Pk Power	$P_{pk} = \frac{V^2}{4ESR_{dc}}$	$P_{pk} = \frac{2V_{oc}^2}{9R_{int}}$	$P_{pk} = \frac{2V_{oc}^2}{9R_{int}}$
Energy	0,354Wh	7,56Wh	8,4Wh
Power_pk	569,54W	38,4W	32,7W
En. density	5,62Wh/kg	108Wh/kg	29Wh/kg

The equivalent circuit used for conventional capacitor can also be applied to ultracapacitors. The first-order circuit model is represented in the figure 3. It consists of four circuit elements: a resistor R_S in series with an inductor L and a capacitor C with a parallel resistor R_P. R_S is called the equivalent series resistance (ESR) and contributes to energy loss during capacitor charging and discharging (I^2R). R_P simulates energy loss due to capacitor self-discharge and is often referred to as the leakage current resistance. The inductance L is usually small and can be neglected in most applications. It has a significant role especially at high frequencies. Resistor R_P is always much higher than R_S in practical capacitor. The capacitance of the complete ultracapacitors module is based on the number of individual capacitors cells connected in series or parallel. In this way, if "n" is the cells number in series and "m" is branches number in parallel, the capacitance of the module can be calculated according (2).

$$C_{Total} = C_{Cell}\frac{m}{n} \qquad R_{Total} = R_{Cell}\frac{n}{m} \qquad (2)$$

Where, R_{Total} and C_{Total} represent the total ESR and capacitance of the ultracapacitor bank, respectively. Just, R_{cell} and C_{cell} represent the internal resistance and capacitance of individual ultracapacitor cell [10]. Note also that RC time constant in ultracapacitors is usually too long τ_C = ESR×C (capacitors response time, seconds polymer-film or ceramic electrostatic ≅ 10^{-9}s; aluminium electrolytic ≅ 10^{-4}s; electrochemical ultracapacitor > 1s).

As mentioned in the previous section to guarantee an adequate life expectancy of the module, differences in cell voltages have to be minimized by cell equalization circuits, see figure 3. The cells can be added in series and/or parallel combinations to form a string or bank. The number of cells to be used is determined by the design requirements. Care must be taken when connecting the ultracapacitors in string due to the need for individual "cell balancing", [4, 11]. Each individual cell voltage cannot exceed the maximum design cell voltage to avoid permanent damage. This can happen in strings of UCaps due to the differences of the capacitance manufacturing tolerances and self-discharge rates (leakage resistance) of individual cells.

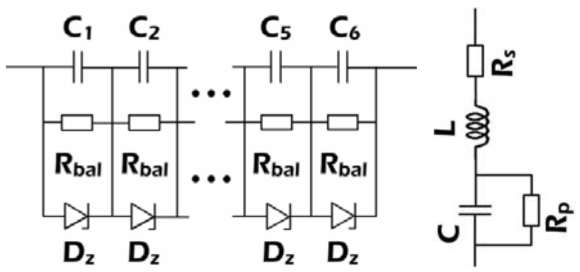

Figure 3. *Voltage self-balancing circuit together the first-order circuit model of an ultracapacitor.*

There are basic types of cell balancing techniques [4, 12], these circuits bypass are composed by passive or active components. The simplest and the most cost effective method are to add series resistors in parallel with each cell (R_{Bal}), [11]. This method is effective to reduce the cell voltage by increasing the leakage current from ultracapacitor. It however also reduces the efficiency due to higher losses. Another idea to equalize the cell voltage is to use zener diodes D_Z in parallel with the cells, see figure 3. On this occasion the maximum cell voltage for the ultracapacitor is limited to the zener voltage V_Z, by protecting the cells from dynamic overvoltages (3).

$$R_{Bal} < \frac{V_{Cell}}{10 i_{leakage}} \qquad V_{Cell} \cong V_Z \qquad (3)$$

Figure 3 represents the circuit schematic employed in the power supply of Ulises as passive balancing technique to regulate the cell voltage. In our case the circuit is formed by a bypass resistor and zener diode in parallel with each cell, these elements are sized to dominate the total cell leakage current, (3). This leakage current has the effect of self-discharging the cell and varies from a few milliamps to tens of milliamps in large ultracapacitors (in the case proposed BCAP0350, $i_{leakage}$ = 0,3mA). The numbers of cells required are determined by the system variables, such as allowable change in voltage (maximum and minimum voltage), current or power and required duration time. The aim when sizing any string of UCaps is to minimize the mass, which implies using the least amount of capacitors [12, 13].

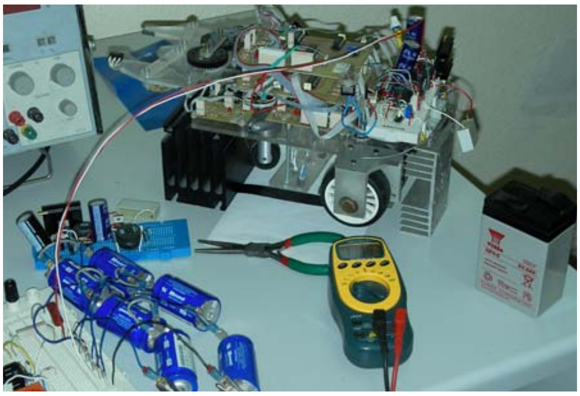

Figure 4. *Mobile robot prototype together with the new supply system formed by ultracapacitors + SEPIC converter.*

Figure 4 illustrates the simplicity of the design. It shows the MicroBot prototype during an experimental test (charge/discharge cycles). In this particular design, six cells were used in series (C_{Total} = 58,34 Farads) to obtain a maximum voltage in the UCaps of +16,2V (2,7V/cell). The energy extracted "ΔE_{UCap}" from an ultracapacitors string depends on the voltage variations in the cells, (4).

$$\Delta E_{UCap} = \frac{1}{2} C(V_{max}{}^{2} - V_{min}{}^{2}) \quad (4)$$

The minimum voltage value "V_{min}" allows estimating the energy extracted of the UCaps during the discharge (4), ΔE_{UCap} = 7392,84J or ΔE_{UCap} = 2,05Wh. Moreover the operation time "$time_{MBot}$" can be calculated, if we have into consideration his consumption ($Power_{MBot} \cong$ 9,50W), in this way $time_{MBot} \cong$ 12,5minutes approximately.
The voltage variation "ΔV_{UCaps}", represents the change during the discharge of the ultracapacitor. This is determined by knowing the maximum voltage (V_{max}) and the minimum allowable voltage (V_{min} = +3V). Often the present minimum voltage specification is limited by a component of the system. In our case, the variable to consider is the maximum current value through the MOSFET transistor in the converter, -Switch Current Limit, i_{max} = 4A-. This calculation assumes a constant power during the discharge. Therefore, at lower voltages a constant power requires higher current as the voltage decreases $i_{UCap}|_{max}$ = Power/V_{min}, in same way the lower current is $i_{UCap}|_{min}$ = Power/V_{max}.

Power electronics can be used between the UCaps and the MBot, keeping a constant voltage value in the robot. It should be noted that the use of a DC/DC converter is optional but it permits to increase the system efficiency (decrease the discharge voltage value in the UCaps without to expose the robot to excessively low voltage). Therefore in some applications, the use of ultracapacitors together with a DC/DC converter reduces the number of cells required in the power supply. The rating of the low power electronics interface is influenced by the choice of operating current and voltage of the UCaps. However using different topologies for low power electronics could reduce the power rating. Boost, Cuk and Flyback converters at boundary of continuous-conduction mode -CCM- are generally accepted for low power applications.

The SEPIC converter (Single-Ended Primary Inductor Converter), figure 5, can both step up and step down the input voltage, while maintaining the same polarity and the same ground reference for input and output. The input to the converter will be the wide operating voltage range of ultracapacitor. This allows the UCaps to be deeply discharged while providing a relatively constant voltage to the MBot. The input current in the converter is continuous and thus it needs smaller volume of input filter. Unfortunately, the SEPIC topology is difficult to understand and requires two inductors, L_1 and L_2. The two inductors can be wound on the same core since the same voltages are applied to them throughout the switching cycle. Using a coupled inductor takes up less space on the PCB and has lower cost than two separate inductors.

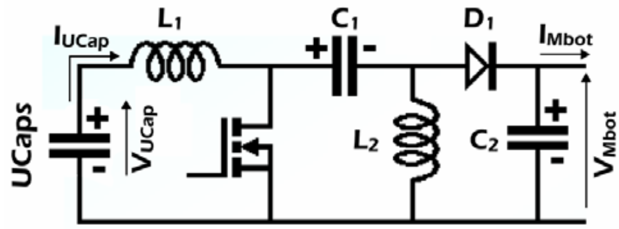

Figure 5. *Proposed simple SEPIC circuit. The converter allows the output voltage to be greater than, less than or equal to the input voltage (UCaps) in DC-DC conversion.*

When the power switch is turned "on", the first inductor L_1, is charged from the UCaps voltage source during this time. The second inductor L_2, takes energy from the capacitor C_1 (L_2 is connected in parallel with C_1). Diode D_1 is reverse bias and the output capacitor C_2, is left to provide the MBot current. No energy is supplied to the out capacitor C_2 during this time. The fact that both L_1 and L_2 are disconnected from the load when the switch is on leads to complex control characteristics.

During the power switch is turned "off", the first inductor, L_1, charges the capacitor C_1 and also provides current to the MBot, as shown in figure 5. The second inductor L_2 is also connected to the load during this time. The current in L_2 also flows into C_2 and the MBot, ensuring that C_2 is recharged ready for the next cycle. During this period the voltage across both L_1 and L_2 is equal to V_{MBot}. The output capacitor sees a pulse of current during the off time, making it inherently noise than a buck converter.

The voltage drop and switching time of diode D_1 is critical to a SEPIC´s reliability and efficiency. The diode switching time needs to be extremely fast in order to not generate high voltage spikes across the inductor L_1, L_2, which could cause damage to components. Fast conventional or Schottky diodes may be used. Thereby, higher efficiency and simpler implementation are obtained.

The output voltage of the SEPIC is controlled by the duty cycle "D" of the control transistor (5). This converter is similar to the buck-boost converter, but has advantages that the isolation between its input and output (provided by a capacitor in series). It has become popular in recent years in battery-powered systems that must step up or down depending upon the charge level of the battery.

$$D = \frac{V_{OUT}}{V_{OUT} + V_{IN}} \qquad V_{OUT} = V_{IN}\frac{D}{1-D} \qquad (5)$$

Thus operating in continuous conduction mode (the current through the inductor L_1 never falls to zero), D_{MAX} occurs at $V_{IN}|_{min}$ and D_{MIN} occurs at $V_{IN}|_{max}$. This type of converter is natural when the designer uses voltages from an unregulated or variables input power supply (UCaps).

Unlike batteries, ultracapacitors may be charged and discharged at similar way. This is very useful in the electronics application design. A DC/DC constant current regulator is the simplest form of active charging. An UCaps with zero charge looks like a short circuit to the charging source. The RC time constant of passive charging networks is usually too long. Therefore, linear regulators are inefficient components during this process. The charger used is a switch-mode boost converter operating as current source (CSI) that removes energy from a DC bus to charge the ultracapacitors. The power losses or ultracapacitors heating is proportional to current squared times the duty cycle. Charging UCaps is one of the simpler aspects of power management. During a charge process the voltage must be controlled to ensure that it does not exceed the rated voltage of the cells. A constant current charge process is particularly useful to check this parameter. The assumption is that the UCaps will never be charged above the combined maximum voltage rating of all the cells. Having voltages above rating will reduce the life of UCaps cell proportionally to the overvoltage value. If the excess is high enough, cell failure may occur rapidly.

Other main characteristic is the low impedance cell, ESR (Equivalent Series Resistance). When an UCap is fully discharged it will appear as a small resistance to many charges and will draw as much of the source current as is available unless limited. Therefore, a constant current or constant power charger will need to be used. When charge time is critical, constant power charging provides the fastest method [14, 15].

3. Application Example: Logistic Centre.

Power-supply here described has been implemented in "Ulises", a small autonomous mobile robot -colloquially called MicroBot-. This unit forms part of a robot group with a logistics orientated purpose, where each of them has different systems of energy storage (e.g. lead-acid or lithium-ion batteries, ultracapacitors and hydrogen fuel-cells). This distinguishing characteristic has allowed us to compare the goodness and deficiencies in the different energy sources applied to low-power robotic devices. As example to comment that "Teseo" (the first MBot constructed, see figure 6) has a lead-acid battery, which introduces a deadweight motivated by the battery size ($mass_{LA}$ = 870g) in relation to the Ucaps used in "Ulises" ($mass_{UC}$ = 360g) or Lithium-Polymer batteries used in "Hefesto" ($mass_{LP}$ = 190g). This overweight involves an increase in the energetic consumption and a minor efficiency in the vehicles.

The specific activity developed by the mobile robots consists of moving small objects or pieces between different points or stations of a warehouse. From a pre-established position, every MBot is capable of coming to a destination, previously selected by the user among the possible destinations in the warehouse (called stations). Once reached this one, MicroBot will capture the piece and will transport it to the destination or final point. That way the example of logistic application simulates a small automated warehouse or factory, where the robot makes a complete cycle of search and location. At present, the importance that acquires the automatic warehouse management has caused that the industry develops great quantity of commercial devices destined to the traffic of goods in logistic centres.

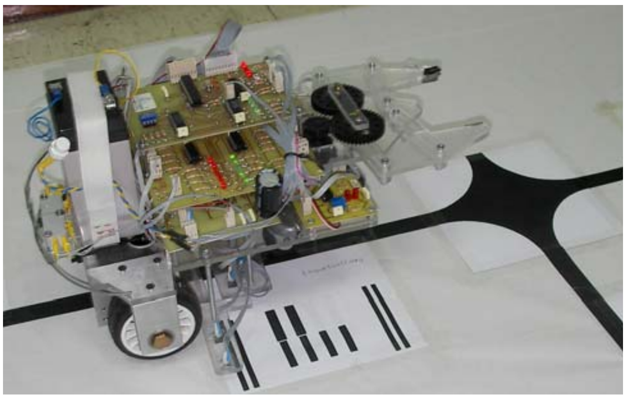

Figure 6. *MBot's prototype developed in the proximities of an intersection in the logistic application.*

Figure 6 shows a small detail of the environment in the logistic plant taken as reference and its structure has a shape of grid. In our case it has been considered a black line on white background as indicator of possible paths along which the different MBots drive. The grid is formed by 16 intersections or crossings, which simulate the different path of a warehouse. Every robot has a set of sensors and actuators that allow its navigation and orientation of an autonomous form. Material delivery place remains pre-established for the PC by means of wireless communication. Navigation system has is able to rectify the way if during the displacement he finds some obstacle in his way. Moreover it can calculate alternative routes (orientation and navigation algorithm) to reach the destination with the load.

At the logistic centre, Ulises has the use of two energy charge stations for the ultracapacitors. This motive allows increasing the autonomy in the robot. UCaps can be charged in seconds whereas batteries often require hours, thus potentially benefiting quick-charge applications.

When the ultracapacitors voltage decrease below a minimum value (marked as reserve value), MBot goes to one of the energy charge stations. In this case, the robot considers the proximity to each of them. The quick electrical-charge is carried out of autonomous way by the MicroBot. This process is developed of mechanical form (by contact between two conical terminals placed at the back part in the MBot and the points created at the service station). Once finished the electrical charge of the ultracapacitors, the robot returns again towards its destination.

The use of wireless communication technologies allow to share (MBots $\leftrightarrow$ PC) at all time information as: position of the different vehicles inside the logistic centre, cut routes physically, identification of troubled zones by means of information analysis -traffic analysis-, transmission of orders from external devices as mobile phones, etc... The knowledge of this information allows to effect optimization algorithms in the navigation of the mobile robots, being fundamental in the development and execution of collaborative work.

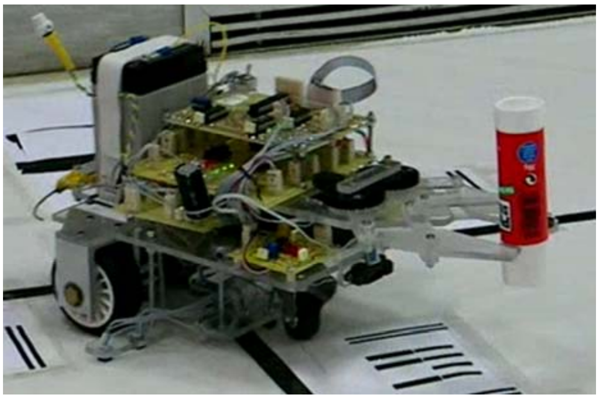

Figure 7. *Mobile robot "Teseo" moving a small object to the destination station.*

4. Conclusions.

The paper described some of the most conventional methods to store energy for mobile robot, such as chemical battery systems and ultracapacitors, showing the advantages and disadvantages of each one of them. Although the energy to power ratio of electrochemical capacitors is often more adequate, batteries or capacitors are chosen for commercial reasons. The influence of several design parameters on the lifetime of the ultracapacitor system can be analyzed and evaluated. A reason for considering UCaps for a particular application is their long shelf and cycle life. Higher-voltage ultracapacitors technology arises on the horizon and the implications are enormously far-reaching.

In this paper an autonomous mobile robot has been proposed as an efficient design tool for a system approach. Ulises was converted from a conventional lead-acid or lithium-ion battery to an ultracapacitors as the power source. The integration of UCaps as elements of energy storage on the robot was studied with the main of optimizing the energetic solution. In particular emphasis is given to the role of low-power electronics as the enable for a correct decoupled power and energy.

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