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Power System and Drive-Train for Omni-Directional Autonomous Mobile Robots with Multiple Energy Storage Units

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ABSTRACT

In this paper power system and drive-train for omni-directional autonomous mobile robots with multiple energy storage units are presented. Because in proposed system, which is implemented in soccer robots, the ability of power flow control from of multiple separated energy storage units and speed control for each motor are combined, these robots can be derived by more than one power source. This capability, allow robot to diversify its energy source by employing hybrid power sources. In this research Lithium ion polymer batteries have been used for main and auxiliary energy storage units because of their high power and energy densities. And to protect them against deep discharge, over current and short circuit, a protection circuit was designed. The other parts of our robot power system are DC-DC converters and kicker circuit. The simulation and experimental results show proposed scheme and extracted equations are valid and energy management and speed control can be achieved properly using this method. The filed experiments show robot mobility functions to perform the requested motion is enough and it has a high maneuverability in the field.

Keywords : Drive-Train, Mobile Robots, Omni-Directional, Autonomous, Multiple Energy Storage Units, Robocup

1. Introduction

Due to recent maturity of robotics technologies, It is predicted new generation of mobile robots accomplish a wide range of new tasks and play a wide range of new role [1] from filed and service application [2] to assistance for the disable and elderly and from entertainment applications to surgical devices [3-4]. So that, there is prediction that, after analog TV, VCR, personal computer and digital consumer, robots, will cause a rising new wave in electronics industry [5]. Furthermore it is expected the intelligence and mobility functions of robots will dramatically increase in coming decades employing new technologies, and thus they can do sophisticated tasks. For example the goal of Robocup foundation is to develop a team of fully autonomous robots that can win against the human world soccer champion team by mid-21st century [6-7].

As the complexity of robots increases, because they should get more information from environment, more sensors are required. As well to increase robot mobility functions, number of motors and other actuators should be increased. Thus more powerful microcontrollers are becoming essential to poll sensor's reading and send

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commends to motors and sensors. On the other hand, to increase the intelligence of robots there are need for more powerful embedded computers [8]. And because in a robot all these devices consume power, these high performance robots need sufficient energy to perform their tasks and the management of this energy will be essential. Especially for any autonomous mobile robot that carries its own energy source, design of power and drive-train systems present a great challenge for researchers [9-10]. Since the mobile robots total power consumption is limited in the range of several watts to several tens of watts it is predicted that robots become the next driver of low power electronics and they provide the biggest challenges for this industry in the future [8], [10-12].

In this paper, our effort is to develop the power system and drive-train for autonomous mobile robots. The proposed system is implemented in soccer robots for the RoboCup middle size league because robots soccer are considered a benchmark for the progress of robotics by providing standard problems where a wide variety of technologies can be integrated and examined [6-7]. The mechatronics architecture design, vision system and behavior control of our robots have been explained in [13] and [14] previously. In our design because of the car-like locomotion poor mobility functions, we have used an omni-directional mobile platform which employs 3 omni-wheels .And to control these wheels, propulsion system utilizes three permanent magnet DC motor with their motor drives and a system for power flow control.

Because in our proposed system the ability of power flow control from of multiple separated energy storage units and speed control for each motor are combined, this robot can be derived by more than one power source [15-16]. This capability, allow robot to diversify its energy source by employing hybrid power sources. The other parts of our robot power system are batteries, DC-DC converters, protection systems, and kicker circuit. In addition to energy of propulsion motors, the batteries provide the required energy of micro controller, USB-Hub, USB-RS232 converter, and kicker. The simulation and experimental result shows the energy management and speed control can be achieved properly using proposed method. The robot omni-directional movement is achieved using proposed power and propulsion systems. And robots have high maneuverability in the field.

These robots are made by “Hibikino-Musashi” which is a joint RoboCup middle-size league soccer team. Members of the team are from three different research and educational organizations [1] located in the Kitakyushu Science and Research Park, Kitakyushu, Japan. These robots could get the 1st and 2nd place at RoboCup Japan in 2006 and 2007 respectively and was ranked among the best 4 teams at world championship in 2007. As well our team can get award from Robotics Society of Japan.

2. Robot Component Architecture

In this Common component architecture of a mobile robot is shown in Fig. 1. [10] . As shown in this figure, this architecture includes five major parts, sensors, actuators, microcontroller, embedded computer and energy storage unit. Usually robots use rechargeable batteries as energy storage unit and motors as actuators. In an omni-directional robot, sensors include an omni-directional camera and motor encoders. Micro controllers perform low level control and computer is in charge of high level controls, such as motion planning and coordination.

Usually in robots, motors and other actuators consume major part of total energy. Therefore in our proposed component architecture, shown in Fig.2, actuators are supplied by multiple energy storage units, and the amount of energy utilization of each unit is determined by power flow control unit. By using proposed component architecture, robot can be supplied by different kinds of energy sources, thus robot life-time can be increased effectively. For instance, the main storage unit can be rechargeable batteries and auxiliary units, ultra capacitors which is utilized when actuators energy demand is high. Or as another alternative, main energy storage unit can include photovoltaic cells or fuel cells, and auxiliary units include rechargeable batteries. In this case, usually only main energy source is utilized. And when actuators need more energy, auxiliary batteries will be added to main energy unit. However in this paper, rechargeable batteries with high energy and power densities have been used as main and auxiliary energy units.

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[1] The three organizations are: Kyushu Institute of Technology, The University of Kitakyushu, and Kitakyushu Foundation for the Advancement of Industry Science and Technology.

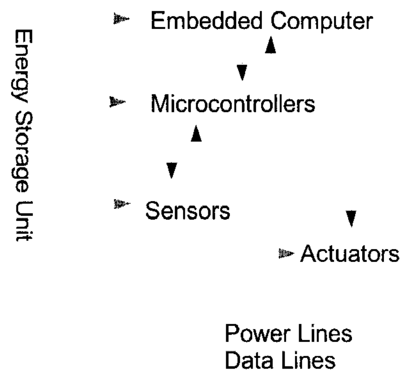

Fig. 1 Robot component architecture for common systems

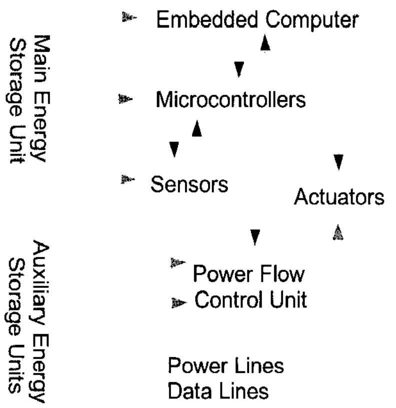

Fig. 2 Robot component architecture proposed system

3. Control of Power Flow

In our robot one rechargeable battery has been used as main storage unit and two other batteries as auxiliary unit. While the main battery is used permanently, auxiliary batteries is utilized when robot needs high acceleration and speed during catching and carrying a ball. Because the power flow between these batteries and motors and also motor speeds should be controlled at the same time, we proposed a two cascaded cell modules consisting motor speed control and power flow control modules. Power flow control using cascaded converters has been used in multilevel inverters previously [17-19].

In proposed system ,shown in Fig.2, for each forward motor, there are two cascaded modules, one module which consist of main battery and a PWM inverter, control the motor speed and the another one manages the delivered energy from auxiliary battery. Although in this robot two energy storage units are utilized these system can be extended to more energy storage units by adding extra cascaded modules.

For this cascaded modules the output power of each auxiliary battery (P_{BB}) and output mechanical power (P_{mech}) are calculated in (1) and (3) using (2).

$$P_{BB} = V_{BB} i_a \tag{1}$$

$$V_T = V_{BB} + V_{inv} \tag{2}$$

$$P_{mech} = (V_T - R_a i_a) i_a \tag{3}$$

Where V_T , V_{BB} and V_{inv} are motor terminal, battery and inverter voltages respectively, is motor, battery and inverter current, and i_a is armature resistance.

And then the relation of P_{BB} and P_{mech} is achieved in (5) using (1)-(4).

$$\omega = K_\omega (V_T - R_a i_a) \tag{4}$$

$$P_{BB} = P_{mech} \frac{K_\omega V_{BB}}{\omega} \tag{5}$$

Where K_ω and ω are speed constant and angular speed of motor respectively.

Because the robot moves with maximum speed (1.9 [m/s]) during utilizing auxiliary batteries, the motor speed and motor power is almost do not change and they could be assumed constant. Therefore the delivered energy from battery with constant speed (E_{BBc}) is calculated as follows.

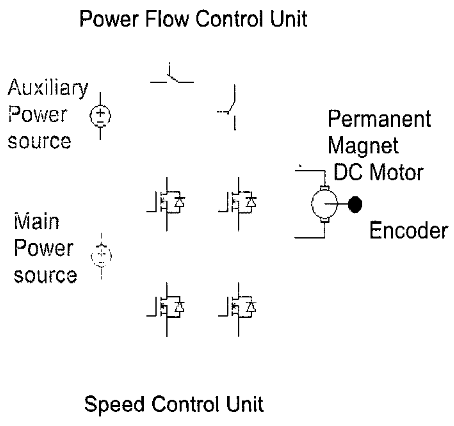

Fig. 3 Proposed Power flow and speed control system

$$E_{BBc} = \int_{T_{on}} P_{mech} \frac{K_\omega V_{BB}}{\omega} dt = P_{mech} \frac{K_\omega V_{BB}}{\omega} \Delta T \tag{6}$$

$$E_{mechc} = \int_{T} P_{mech} dt = P_{mech} T \tag{7}$$

$$E_{BBc} = \frac{V_{BB} K_\omega}{\omega} E_{mechc} \times \frac{\Delta T}{T} \tag{8}$$

Where ΔT, T and E_{mechc} are the time interval of auxiliary batteries utilizing, total time of robot movement with speed and mechanical energy produced by motor respectively.

When the motor speed changes with constant acceleration, the robot acceleration and consequently the motor torque (τ) and motor angular acceleration (α), are constant. Therefore mechanical energy produced by motor when speed changes (E_{mechv}) is calculated as follows.

$$E_{mechv} = \int_{T_1}^{T_2} \tau\omega dt = \tau \int_{T_1}^{T_2} (\omega_1 t + \alpha) dt = \tau(T_2 - T_1)\left[\omega_1 + \frac{1}{2}\alpha(T_2 - T_1)^2\right] \tag{9}$$

Where ω_1, ω_2, T_1 and T_2 are primary motor speed, secondary motor speed, start time of the speed change, and the time that motor speed reach to ω_2.

In this condition the delivered energy from auxiliary battery (E_{BBv}) is calculated as follows.

$$E_{BBv} = \int_{\Delta T} \tau\omega \frac{K_\omega V_{BB}}{\omega} dt = \tau K_\omega V_{BB} \Delta T \tag{10}$$

And finally the relation between E_{BBv} and E_{mechv} is calculated as follows using (9) and (10).

$$E_{BBv} = \frac{2 V_{BB} K_\omega}{\omega_1 + \omega_2} E_{mechv} \times \frac{\Delta T}{(T_2 - T_1)} \tag{11}$$

In start up condition, our robot acceleration is constant. Therefore for time interval of motor startup (T_s) equations (12) - (14) can be written.

$$E_{BBs} = \int_{\Delta T} \tau\omega \frac{K_\omega V_{BB}}{\omega} dt = \tau K_\omega V_{BB} \Delta T \tag{12}$$

$$E_{mechs} = \int_{T_s} \tau\omega dt = \int_{T_s} \tau\alpha t dt = \frac{1}{2}\tau\omega T_s \tag{13}$$

$$E_{BBs} = \frac{2 V_{BB} K_\omega}{\omega} E_{mechs} \times \frac{\Delta T}{T_s} \tag{14}$$

Where E_{BBs} and E_{mechs} are delivered energy from auxiliary battery and motor mechanical energy in startup condition respectively.

As seen in (8), (11) and (14) the delivered energy from of inverter supplied by main battery and auxiliary batteries can be controlled by adjusting the time interval of auxiliary batteries utilizing.

4. Energy Storage Units and Their Protection Systems

Like as energy storage requirements for electrical vehicles which are expressed in [20] and [21], the robot electrical storage unit must be sized by an energy storage and power requirement. Therefore the robot battery performance characteristics (Energy/weight Energy/size and Power/weight) should be enough to store sufficient energy and to provide the necessary peak power. After calculation of necessary power and energy for our robot we chose Lithium ion polymer batteries because these batteries have high power density (2220 W/kg), high energy density (185 Wh/kg) [22], a slow loss of charge when not in use and no memory effect [23]. The nominal voltage of each cell is 3.7 volt. One 7 cell (25.9 V) and one 2 cell (7.4 V) batteries have been used in this system. This battery should not be discharged to a level below 3V per cell under load, because deep discharge below 3V per cell can deteriorate battery performance [22]. As well these batteries need protection against over current and short circuit conditions.

Therefore to achieve a safe operation for robot and to avoid of battery damage, a battery pack with protection function has been designed. This protection include, over discharge protection (ODP), short circuit protection (SCP) and over current protection (OCP). In proposed circuit the load is removed from battery as soon as the voltage drops below lower permitted level, or current goes over permitted level.

As another feature of proposed circuit, switch-on voltage level is larger than switch-off voltage level, thus when the battery voltage is higher than a certain chosen threshold, the relay switch is closed; while when the battery level is below lower permitted voltage level, the relay switch is opened and when the input is between the two, the relay switch retains its previous situation [24]. The benefit of inventive circuit with is greater stability (noise immunity).

5. Power System

Fig.4 shows the flowchart of the whole robot power system including a main Li-Polymer battery (25.9 [V]) and two auxiliary Li-Polymer battery (7.4 [V]). As seen in this figure, two front motors, which are considered as main energy consumer actuators, are supplied by both batteries to achieve high acceleration and speed during catching and carrying a ball. In this system kicker and rear wheel motors which consume less energy only is supplied by main battery.

The necessary voltage for robot sensors, communication devices, microcontroller and micro computer power supply are converted from main battery voltage level using DC-DC converters. Total power consumption of the robot is approximately 40 [W] and the operation estimated duration of the robot is 0.5 [h].

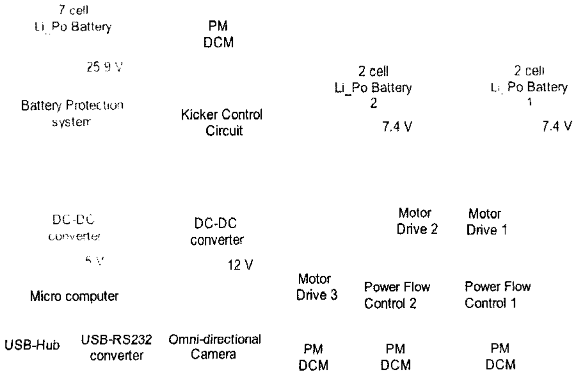

Fig. 4 Flow chart of our robot power system

6. Experimental System Setup

Each robot is equipped with 3 omni-wheels, each of them driven by a permanent magnet DC motor which its specification is shown in Table 1.

Table 1 DCPM Motor Nominal Parameters

Rated Power	70 W
Rated Torque	88.2 mNm
Rated Current	2.25 A
Torque Constant	36.4 mNm/A
Rotor Inertia	67.7
Speed Constant	263 rpm/V
Terminal Inductance	0.201 mH
Terminal Resistance	1.11
Nominal Voltage	24.0 V
Max Continuous Current	2.44 A

Gearboxes with reduction rations of 18:1 are used to reduce the high angular speeds of the motors (7000 rpm) and to amplify the wheels torque. Each motor has a 540 [ppr] digital incremental encoders. A laptop PC sends the motor control commands (target and velocity) to the motor drivers. The robot can move with maximum speed of 1.9 [m/s] and acceleration of 2.5 [m/s2]. The major parts of robot power and drive-train systems are shown in Fig.5, and Fig.6 shows developed autonomous omni-directional mobile robots.

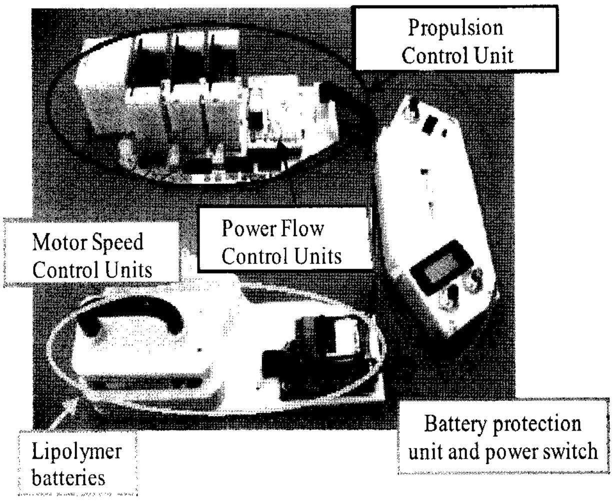

Fig. 5 Robot power system

Fig. 6 Our autonomous robots

7. Simulation

7.1 System Simulation

To analysis the validity of proposed control method, the system was simulated using MATLAB-SIMULINK, and its results were evaluated. The simulation of system which is shown in Fig.7 includes PWM inverter, current limiter, energy management system, PI speed control and dynamic model of permanent magnet. In this simulation, which saturation effect is not considered, dynamic modeling of PMDC motor is proposed based on (15)-(18).

$$e_a = K_T\omega \tag{15}$$

$$i_a = \frac{1}{L_a}\int(V_T - e_a - R_a i_a)dt \tag{16}$$

$$\tau = K_T i_a \tag{17}$$

$$\omega = \frac{1}{J}\int(\tau - \tau_L - B\omega)dt \tag{18}$$

Where e_a , L_a ,B, J, K_T and τ_L , are armature back emf, terminal inductance, damping coefficient, Rotor and load Inertia, torque constant, and load torque respectively . And B and τ_L were extracted from experimental tests.

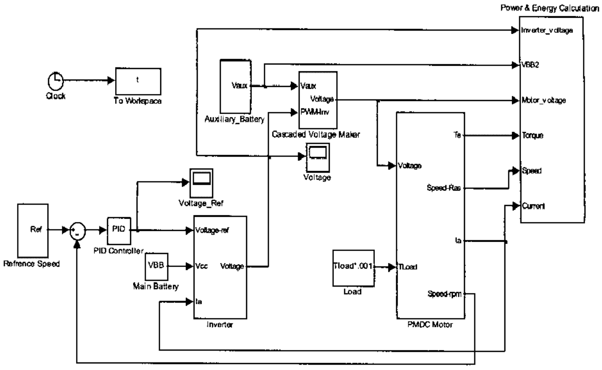

Fig. 7 Our autonomous robots

7.2 Simulation results

To evaluate extracted equations, results of mathematic calculations are compared with simulation results. When the motor speed is 5000 rpm and auxiliary battery is utilized in the whole time interval ($\Delta T = T$), the calculation result from equation (9) shows ratio of auxiliary battery energy and mechanical energy is about 39% ($E_{BBc} = 0.3892E_{mechc}$). The simulation result for similar condition is shown in Fig.8. As shown in this figure not only the motor speed control is achieved but also the energy ratio is same as mathematical calculation. Therefore the equation (8) is valid. As shown in this figure the terminal voltage include two parts, one DC part witch is from auxiliary battery and another part which is a PWM voltage and is created using main battery. The PWM wide is changed when reference speed is changed.

8. Experimental Results

As well, the validity of our extracted equations is evaluated by experimental results which are shown in Figures 9-11. To study the equation (8), same condition with simulation condition is considered ($\Delta T = T$, ω =5000 rpm). The motor speed reference set to 5000 rpm and auxiliary battery is utilized in whole time. The experimental resulted which is shown in Fig. 9, prove experimental and simulation results are same and the equation (8) is valid. It can be seen that, the speed control unit changes the output voltage to set the motor speed to reference speed. Thus speed control and power flow control can be achieved.

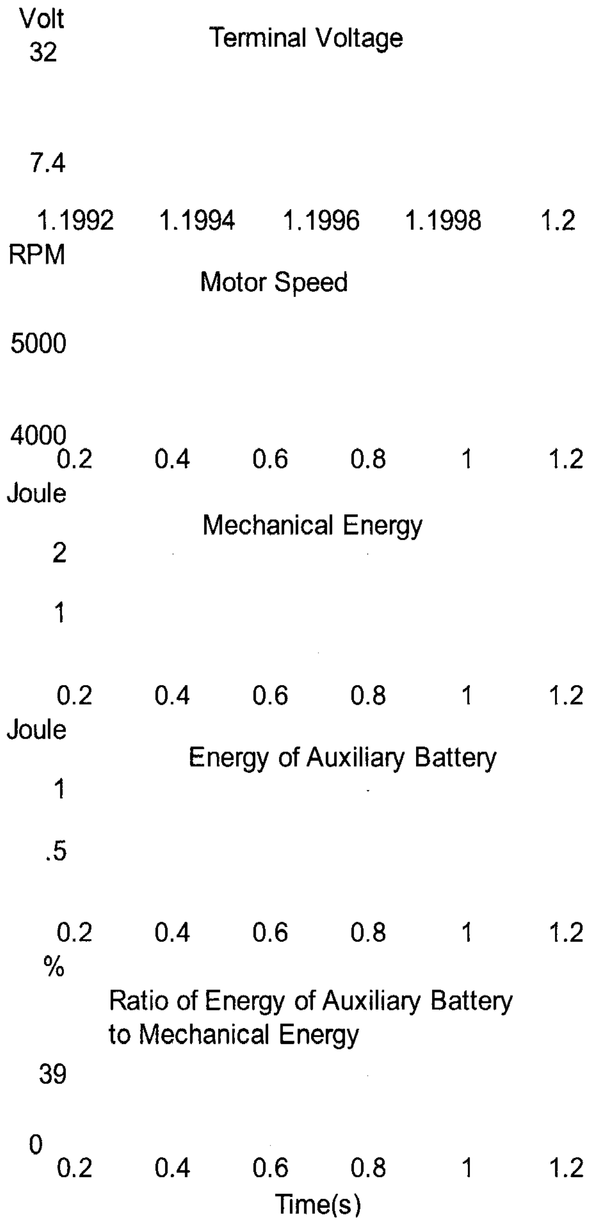

Fig. 8 Simulation results for $\Delta T = T$ and 5000 rpm

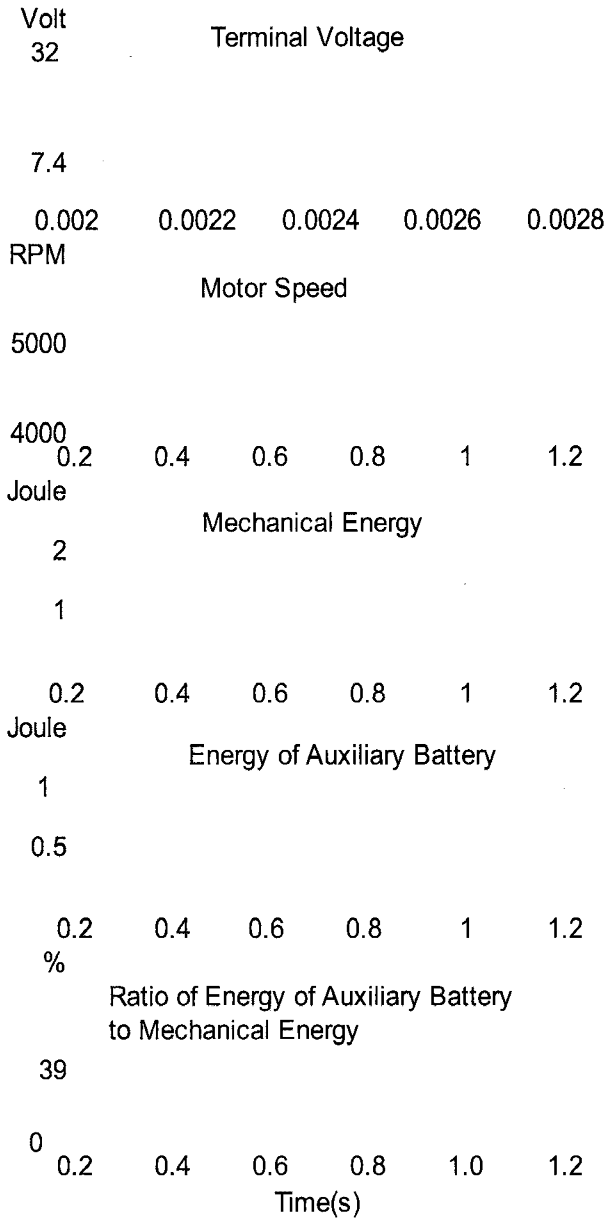

Fig. 9 Experimental results for $\Delta T = T$ and 5000 rpm

In Fig. 10 experimental results, when auxiliary battery is switched on and switched off, is shown. As shown in this figure the delivered power from auxiliary battery is zero when it switched off, and in this condition the energy ratio decreased. Again when it switched on, the energy from auxiliary battery fellows to motor and thus energy ratio will be increase. This figure shows the experimental energy ratio matches with mathematical calculation using equation (8).

The validity of equation (11) is proven in Fig. 11. In this test, the motor speed is changed from 2000 rpm to 5000 rpm with constant acceleration. As seen in these figures the energy ratio for experimental tests and mathematical calculations based on (11), are same and this ratio will decrease when motor speed increases. So that for 2000 rpm this ratio is about 97% and for 5000 rpm it is about 56%.

9. Conclusions

In this paper power and drive-train systems design for autonomous omni-directional mobile robots is presented. In this system the ability of power flow control from of multiple separated energy storage units and speed control

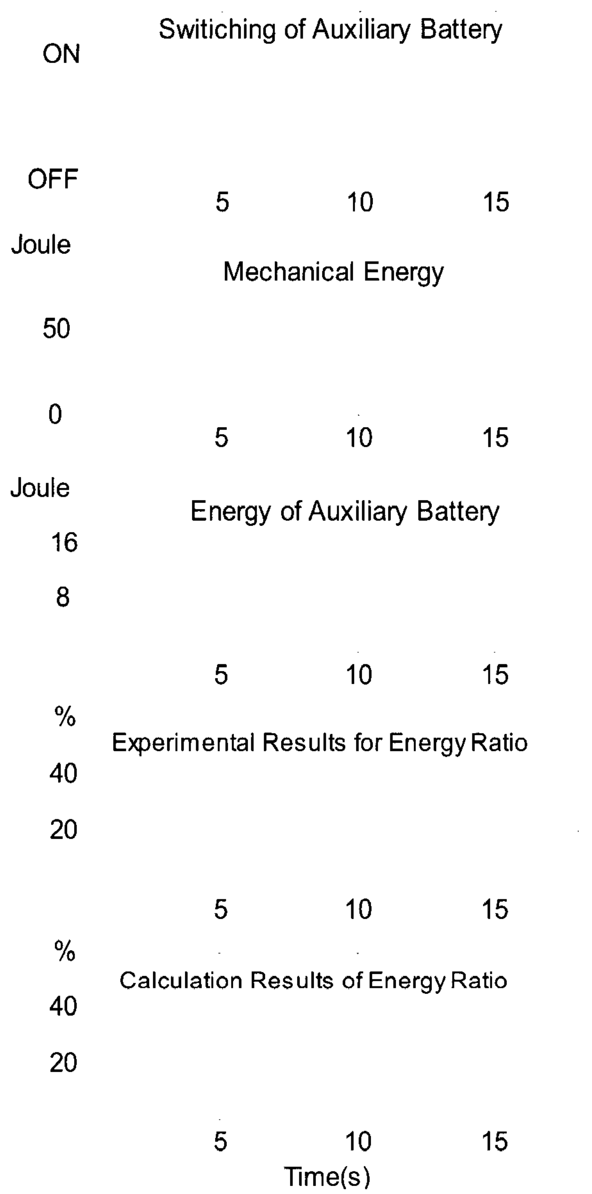

Fig. 10 Experimental results when auxiliary battery is switching

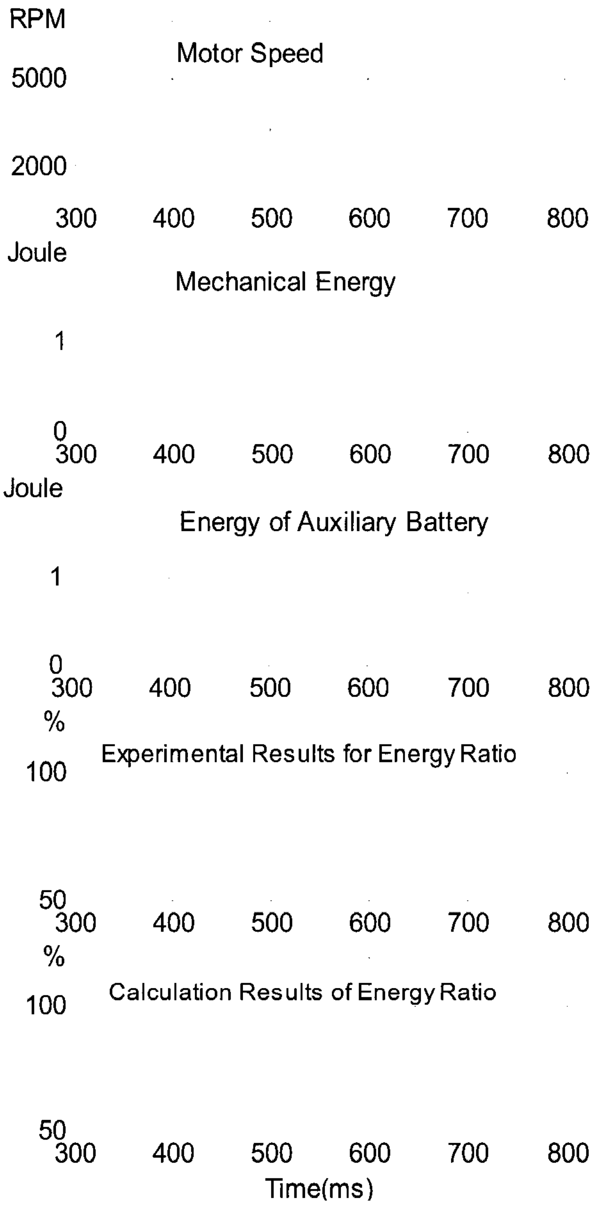

Fig. 11 Experimental results when motor speed changes

for each motor are combined. To avoid of Li-Polymer batteries damage a protection system against deep discharge, short circuit and over charge, is designed. The simulation and experimental result shows the energy management and speed control can be achieved properly using proposed method. And the filed experiments show robot mobility functions to perform the requested motion is enough and it has a high maneuverability in the field.

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