Performance Monitoring in UMR's Solar Car

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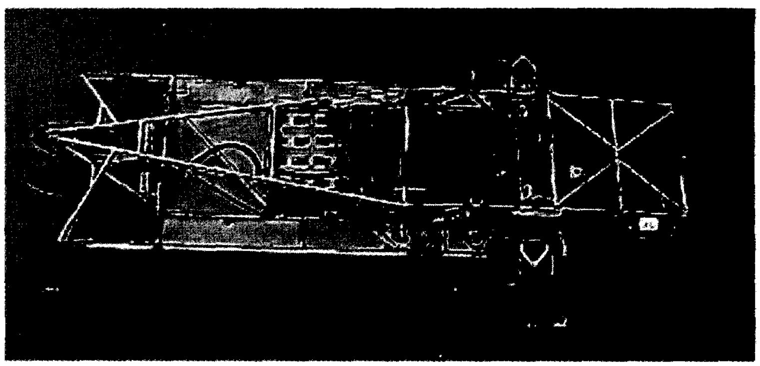

Photo: Aaron Rues

A solar car, essentially an electric vehicle with solar cells that recharge the batteries, is one of the more exotic kinds of transportation. The array of solar cells typically covers less than 8 m^2 in area; consequently, the power of the array is limited. Under a bright sun, an array can generate about 1000 W, which is slightly less than what a hairdryer draws. Therefore, a solar car must be extremely lightweight and energy efficient.

Solar car races are endurance events; the focus is efficiency and reliability. For example, the World Solar Challenge is a ten-day event in which teams cross the entire continent of Australia from north to south. Solar cars are driven from 8:00 a.m. to 5:00 p.m., with the few extra daylight hours used to recharge the onboard batteries. As a result, these vehicles must also be fast and reliable. Numerous tests and simulations help calculate reliability, while the close monitoring of energy used in the car's systems determines efficiency.

A solar car's monitoring system measures the voltage, current, and temperature of the essential components, such as the motor, solar cell array, and batteries. Weight and power limitations restrict the instrumentation in a solar car, so the monitoring system continuously transmits data to a support vehicle. Those data are then analyzed and used in planning race strategy.

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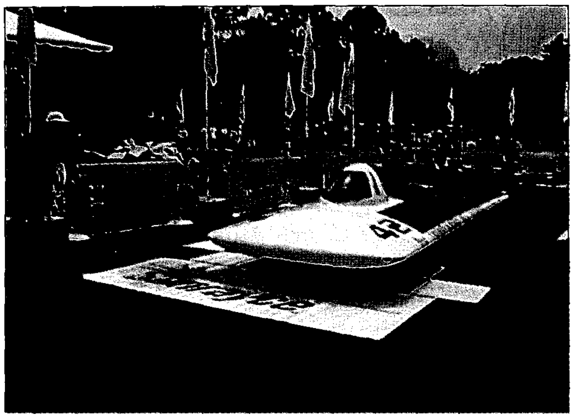

Fig. 1. Solar Miner II winning Sunrayce99.

The Solar Car Team at the University of Missouri-Rolla (UMR) designed the winning entry for the 1999 American Sunrayce (Fig. 1). This race covered the distance between Washington, D.C. and Orlando, Florida in nine days of driving. In this article, we describe the instrumentation in UMR's solar car.

Current Field of Expertise

Every team strives for low power consumption and high reliability. Saving 1 W in standby power can mean finishing a race 15 minutes ahead of the competition. Reliability is equally important because one breakdown that consumes 15 minutes can cancel any gain made in power savings.

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Accurate knowledge of the operating parameters inside the solar car is crucial to maintaining high efficiency and reliability. Race teams base their decisions, such as whether to speed up or slow down, on the power the car is using over the particular terrain and on the power produced by the solar array. A good telemetry system can often identify failures hours before they occur by watching for irregularities in a specific parameter.

A monitoring system can also help during design. By measuring performance under different conditions, design teams can improve the aerodynamics and handling characteristics of the car. Furthermore, they can improve the car's efficiency by track testing it while manipulating different factors, such as the vehicle's ride height and tire alignment. These test runs provide a library of data for comparison during the race. We tested the UMR solar car for approximately 2000 km before the race. During the initial testing stages, we prepared a mathematical model of the car from the measured parameters. The model allowed us to predict the performance of the car during the race.

Every team has some way to measure battery voltage, whether it is an automated system or a multimeter strapped within view of the driver. The majority of cars also have some way of measuring the current produced by the solar array. Race teams can determine performance parameters during the race from carefully designed prerace experiments that involve these two variables.

More elaborate data-acquisition systems exist. Many teams also monitor the individual voltages of each battery cell and of subsections of their solar arrays. For example, a car that has a battery with temperature-sensitive chemistry may monitor the temperature of each battery cell. The efficiency of solar cells depends on temperature, so sensors placed behind the solar cells are useful.

Instrumentation

Fig. 2 shows the general layout of the car's electrical system. Fig. 3 shows the placement of components in the chassis of the Solar Miner II. Solar cells generate all of the car's energy. The Solar Miner II uses solar cells made of single-crystalline silicon, rated at 14% efficiency. Our array produced about 900 W at 120 V under full sun. The array divides into three subarrays. Two of them produce 144 V at approximately 3.1 A, and the third subarray produces 144 V at approximately 1.5 A. Each subarray drives a dc/dc converter, called a maximum-power point tracker (MPPT in Fig. 2). The outputs from the power trackers connect in parallel to a main bus at 96 V.

The power trackers keep the solar array operating at its highest efficiency by conditioning the input and maintaining the maximum power point of the solar cells. The output is tailored to the batteries' state of charge to ensure a maximum power transfer to the battery pack. We used models manufactured by Australian Energy Research Laboratory.

A 150-kg pack of Delphi lead-acid batteries supplies a 96-V bus to run the motor and various electrical components. New Generation Motors, Inc., manufactured the motor and motor controller. The motor is an axial flux, three-phase, dc brushless machine that operates at a nominal 96 V. The air gap between the rotor and the stator is adjustable to allow for torque and speed optimization. The motor controller can reverse the motor for regenerative braking.

We used smaller dc/dc converters by Vicor to convert 96 V to 12 V for the horn, ventilation fans, gap-adjust motor, and digital signal processor (DSP). A Texas Instruments DSP is the central processing unit on the car. It monitors the electrical systems and computes power consumption. It also sends the data out through a radio modem to a remote computer in the support vehicle. Dual, eight-channel, 10-bit A/D converters integrated on the DSP read the hall-effect sensor to measure current. Four 8-bit D/A converters set the speed of the motor and run the driver's LCD speedometer display.

A 25-A hall-effect sensor, model IHA-25, manufactured by F.W. Bell, measures the current from the solar cells to the batter-

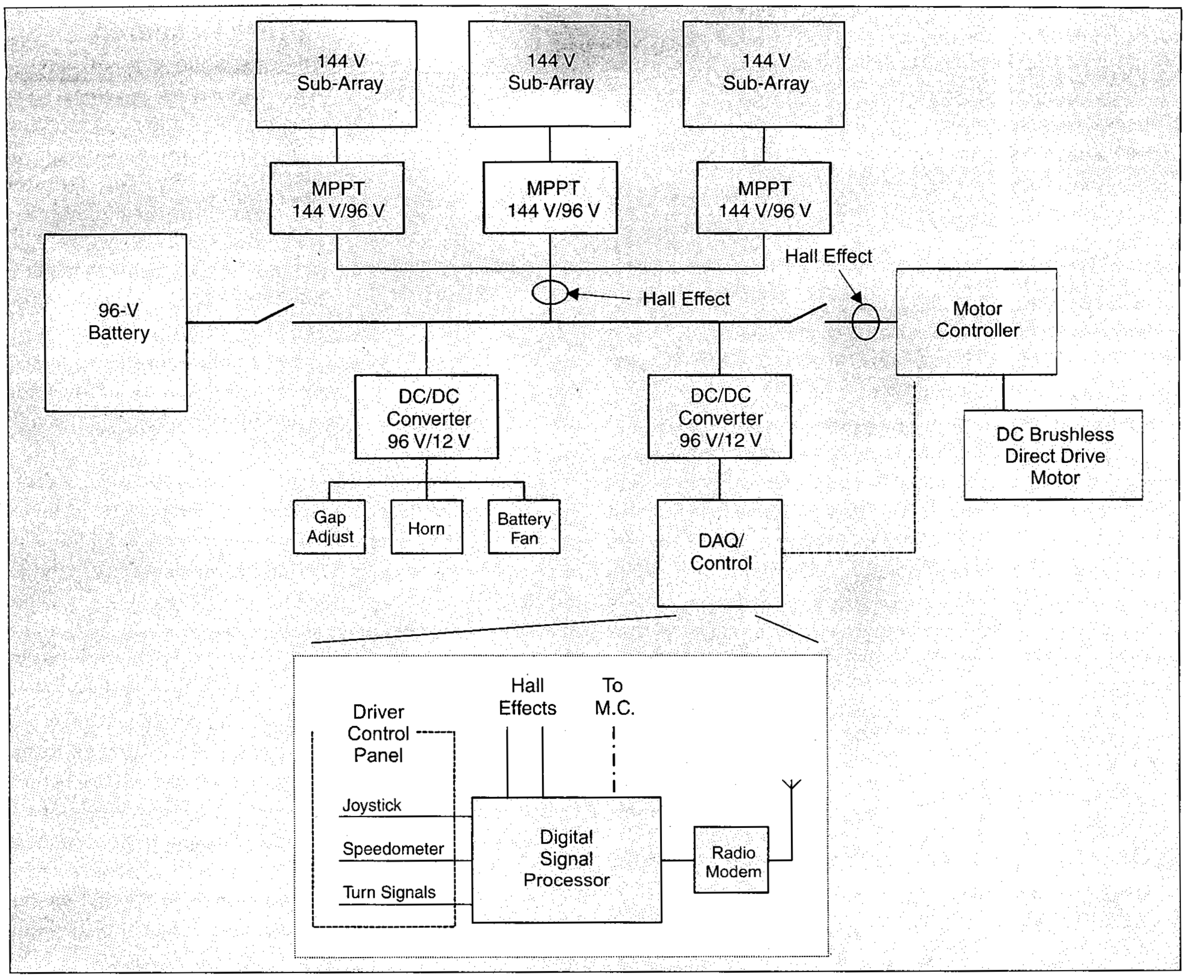

Fig. 2. Layout of the Solar Miner II electrical system.

ies. It measures the total current of the solar array, but not the individual subarray currents. We wrapped the array wires twice through the current sensor to decrease error and double the accuracy. The DSP's 10-bit A/D converter converted this signal with a resolution of 10 mV that represents 100 mA in sensing current. Fig. 4 shows large amplitude noise (±0.2 V representing ±2 A) from current spikes in the motor during hard acceleration. A similar hall-effect sensor, F.W. Bell model IHA-100, rated at 100 A, measures the motor current to 500-mA resolution.

We measure many of the parameters in real time through the motor controller. The motor controller's integrated 8-bit A/D converter samples the voltage on the battery bus at 10 times/s. It is accurate to about 1 V. Fig. 5 shows the data on the bus voltage collected over the first four days of Sunrayce99. The motor controller also measures the wheel's revolutions per minute, temperature of the motor, and its own temperature. These values communicate digitally to the DSP and are either used in calculations or relayed directly to a computer via a radio modem. Fig. 6 is a screen shot of the posted data on the remote computer in the support vehicle.

The car's DSP calculates distance and speed in real time. It also calculates the power from the solar array and the power

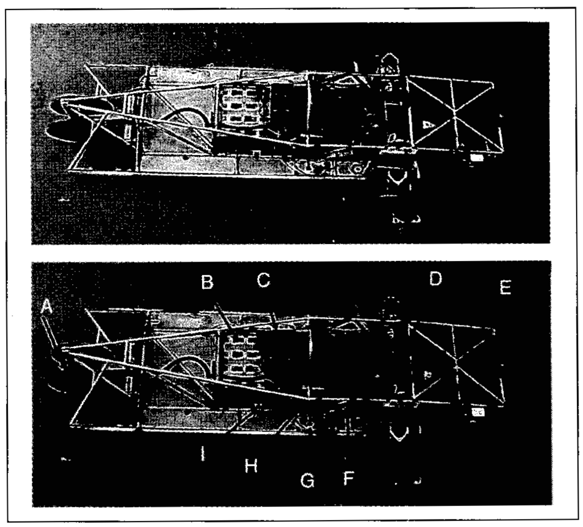

Fig. 3. Components in the chassis of Solar Miner II: A) brushless dc motor; B) lead-acid batteries; C) brushless dc motor controller; D) LCD speedometer; E) radio modem; F) digital signal processor (DSP); G) solar array umbilical cord that connects to the three power trackers which are housed in the body of the car; H) hall-effect sensors, both sensors for the motor and solar array are located within this region; and I) dc/dc converter.

to the motor from the respective currents and bus voltage. Then, it integrates to find the total energy generated and used.

The power trackers also measure current and voltage and drive LCD displays. During periods of stationary charging, the race team read the LCD displays to orient the solar array to the sun with an adjustable stand so that it generated the maximum amount of power. The team also calibrated the hall-effect sensor by using values from the LCD displays.

We divided the array into 20 modules to detect errors. Each module comprises approximately 36 cells (generating 18 V). A switching device, shown in Fig. 7, selects the voltage from the 20 modules to be measured by a multimeter. It allows the race team to determine where cracked or nonfunctioning solar cells are located. The switching device has small sense wires to save weight, which prevents the measurement of the short-circuit current (approximately 3.5 A).

The power trackers keep the solar array operating at its highest efficiency by conditioning the input and maintaining the maximum power point of the solar cells.

Future Research

The next solar car will have a data-acquisition system that will provide more information to the race team, enhance problem diagnostics, and monitor potential problem areas. We plan additional sensors, reorganization of data-collection methods, and faster update rates. Newer hall-effect sensors will convert their outputs to a digital format near the location of the measurement, rather than running an analog line through high noise areas.

Measuring short-circuit current and open-circuit voltage provides incomplete data on the state of the array. A device that measures the entire current-voltage curve from the solar array would be useful in determining problem areas in the array. It could give clues to the source of the problems, whether they are broken cells, internal resistance caused by poor solder joints, or overheating.

Draining a battery below its lower cutoff voltage results in permanent damage to the battery. A bad cell in a battery limits the effectiveness of the entire battery pack. If we monitor the individual cells of each battery, we can avoid the potential problem of total failure in the battery pack.

Though UMR won Sunrayce99, the car has room for improvement. We have described some of the instrumentation used on that car and ways that we would like to improve it.

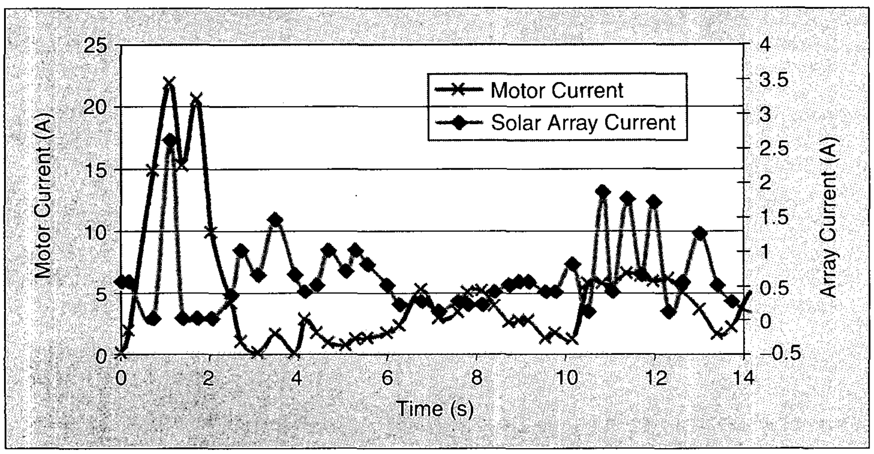

Fig. 4. Hall-effect noise. During hard accelerations, the high motor currents induced noise into the solar array and motor current sensors. This data was taken from the first day of Sunrayce99, where weather conditions hampered energy generation.

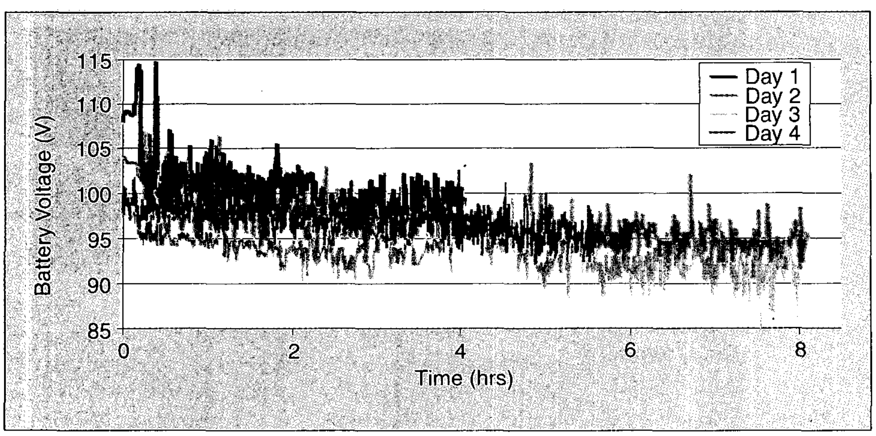

Fig. 5. Continuous measurement of battery voltage from the first four days of Sunrayce99.

Louis McCarthy is a junior majoring in computer engineering at the University of Missouri-Rolla. He has participated in Sunracye97, Sunrayce99, and the 1999 World Solar Challenge. During the second year of the Sunrayce99 project, he served as the Vice President of Manufacturing and the Array Group Leader for Solar Miner II.

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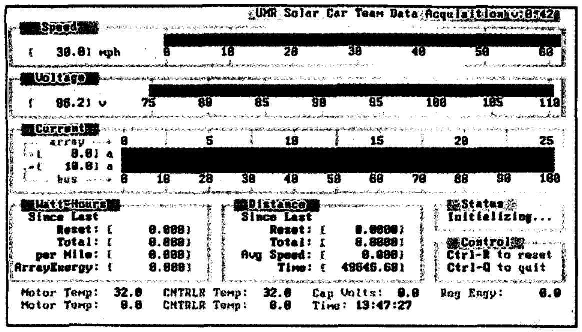

Fig. 6. Data posted remotely via the radio modem to a computer in the support vehicle.

Missouri-Rolla. He has been a member of the solar car team since the fall of 1998 and participated in the 1999 World Solar Challenge. He is currently serving as the Director of Electrical Systems.

Aaron Rues is a senior majoring in electrical engineering at the University of Missouri-Rolla. He has been with the solar car team since 1998, serving as Assistant Electrical Engineer on Sunrayce99 and is currently serving the team as Vice President of Race Logistics.

Cheng Hsiao Wu is a Professor in the electrical and computer engineering department at the University of Missouri-Rolla and is an Advisor to the UMR solar car team on electrical and solar-array systems. His research in semiconductor devices has covered a wide range of solar cells, from GaAs on Ge, silicon to amorphous silicon cells. In addition, he is a pioneer in wave computing for future computers.

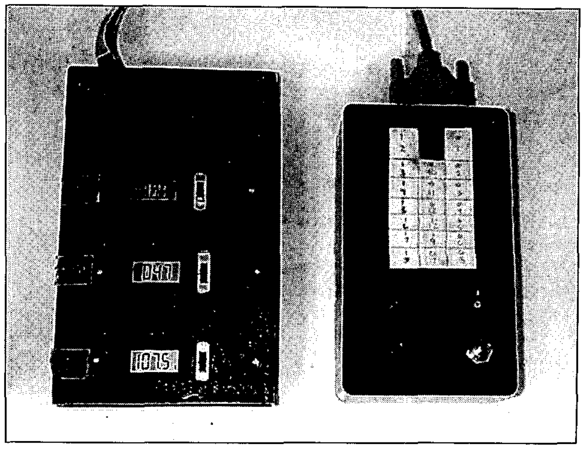

Fig. 7. Array measurement devices. These devices are used during nonracing periods. The device with three LCDs on the left connects directly to the maximum-power point trackers. There are four measurement settings: solar array voltage, solar array current, battery voltage, and battery current. A multimeter connected to the box on the right allows for measurement from all 20 modules.