ECE 445 SENIOR DESIGN LABORATORY FINAL REPORT

Custom MPPTs for Illini Solar Car

Ву

Alex Chmiel (achmiel4) Alex Lymberopoulos (alexdl2) Akhil Pothineni (akhilp3)

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TA: Matthew Qi

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Abstract

The goal of this project was to develop custom and low-cost solar Maximum Power Point Trackers (MPPTs). These MPPTs use a boost converter to optimize power output from the solar array to charge the battery efficiently. With the array divided into three sections for reliability, each MPPT gives redundancy to the system. Customization gives simple integration with the vehicle's electrical systems, allowing for plug-and-play functionality. This cost-effective solution takes away the need for expensive off-the-shelf components and provides access to schematics for easy maintenance and upgrades.

Contents

1. Introduction
1.1 Problem1
1.2 Solution
1.3 Visual Aid2
1.4 High Level Requirements2
2. Design
2.1 Block Diagram
2.2 Logic Board Subsystem3
2.2.1 Overview
2.3 Power Board Subsystem5
2.3.1 Overview
2.4 Tolerance Analysis9
2.5 Enclosure Design
3. Design Verification
3.1 Sensor Validation12
3.2 Boost Verification12
3.3 Tracking Validation13
4. Costs14
4.1 Parts14
4.2 Labor
5. Conclusion
5.1 Accomplishments15
5.2 Ethical considerations15
References
Appendix A Requirement and Verification Table17

1. Introduction

Briefly describe the science or engineering problem to be addressed in the report, as well as the purpose and usefulness of the device or system you have built. Summarize the contents of the upcoming chapters as well as the main conclusions of your project, to be elaborated in the last chapter.

1.1 Problem

Illini Solar Car is manufacturing their 3rd generation vehicle to race at the American Solar Challenge this coming summer. The team has recently installed their array and is looking for easyto-use, configurable, and efficient solar maximum power point trackers (MPPTs). MPPTs are used to control power output of a solar array. In this case, it will precisely control power into the vehicle's battery pack to charge the battery. Off-the-shelf models are very expensive and will take time to integrate into the vehicle's architecture. Additionally, if off-the-shelf components have a failure, we will not have access to the schematics to replace the component.

1.2 Solution

The idea is to create custom, efficient, and low-cost boost MPPTs built for the team's electrical system. These MPPTs will function by utilizing a boost converter to step the voltage of the array to charge the battery. It will use an algorithm to vary the switching duty ratio of the boost converter to control the power output. For context, as the battery charges the voltage will increase and therefore the requested duty ratio will vary as a result.

For some background, the vehicle has the array wired in three separate sections. The goal behind the 3 sections is better resilience to shading and redundancy built into the system. We would make an easy to move enclosure with three MPPTs inside that can be mounted in the vehicle. If one of the MPPTs fails, we would still have 2/3 of the solar array producing power.

By making the MPPTs in house lots of problems could be solved. We could drastically reduce the cost, make it plug-and-play with our vehicle's electrical systems, and be able to debug issues quickly.

1.3 Visual Aid



Figure 1: Visual Aid for MPPTs

1.4 High Level Requirements

- 1. Logic Board can send information via CAN and control the power board using a perturb & observe algorithm.
- 2. The power board can successfully boost input voltage from 20V 90V to a range of to a range of 77V-120V. It should have a tolerance of +/-1.5%.
- 3. The size of a single power board should be less than 272mm x 164mm in order to fit in the space allotted for the MPPTs in the vehicle.

2. Design

2.1 Block Diagram



Figure 2: Block Diagram of MPPT

2.2 Logic Board Subsystem

2.2.1 Overview

The logic board will be the main control board for our system. The logic board will collect I-V characteristics from the power board. Using this information, It will be tasked with running a perturb and observe algorithm to vary the switching signals to a separate power board. The board will send data over a CAN bus to communicate with the rest of the car. The plan is to have the switching frequency at 200kHz.



Figure 3: Main Sheet of Logic Board

The main things of note for the high-level design is how the subcircuits connect to each other and the power board. The first thing to note is that the low voltage power for the logic board is received from a connection to the car's 24V bus, and then the 24V along with a stepped down 3.3V is sent to the power board. The PWM signal from the microcontroller is also included along with the power.

The sensor communications also come in from the power board. There are two connections, one for SPI communication and another for ADC communication. This is due to us being uncertain about the sensor choice for the power board at the time the logic board was designed. Eventually we decided upon using the ADC sensors, but the SPI connections are left there as they can be repurposed into spare MCU pins if needed.

To provide the low voltage power from the LV bus to the rest of the logic board and to the power board, it is run through a power protection circuit along with a DCDC converter to provide 3v3 logic power for the MCU. This subcircuit is shown in Figure 4.



Figure 4: Power Protection of Logic Board

The design for the power circuit is mostly taken from the general power protection circuit used on all solar car boards that provides over and under volt, reverse polarity, and over current protection. The 3.3V DCDC is simply an off the shelf RECOM DCDC.

The MCU used on this board is the LPC1549 from NXP, specifically the 48-pin version. This controller was chosen as the LPC1549 series is used on the rest of the solar car boards, and so therefore there are already common libraries written for standard functions like CAN, PWM, and so on. This subcircuit also contains the JTAG header for the debugger, and an ISP and reset button for programming and resetting. Capacitors were also added to the power input pins of the MCU as requested by the datasheet [5].

The rest of the pin assignments were determined by their purpose. The datasheet requested specific pins for CAN, and the ADC sensors from the power board had to go to the pins that had ADC functionality. The temperature sense and fan tachometer also needed ADC pins. A 12MHz crystal was used for the MCU clock, this is a much higher frequency than we are taking our measurements and running the boost converter at, so it should be more than enough for this board.



Figure 5: MCU Sheet of Logic Board

2.3 Power Board Subsystem

2.3.1 Overview

The power board will be a high-power boost circuit controlled by the logic board to take in the input power and vary the output power to charge the battery. Each module should handle power up to 400W. MPPTs should be able to output in the range of 77V-125V. Max charge current is ~25A.

The idea behind the circuit design is to keep the low voltage and high voltage separate for safety and functionality purposes. The main sheet can be seen in Figure 6 below.



Figure 6: Main Sheet of Power Board

The main sheet shows connectors to and from the logic board, facilitating communication. Five sensors send signals to the logic board, along with 3.3V and 24V lines. As there's no power protection on this board, reliance is on the logic board for voltage regulation.

Here, the boost converter is visible on the high voltage side of the schematic. Additionally, an isolated DCDC feeds into a gate driver, regulating MOSFET switching. The presence of extra components caters to faults or errors during simulation.

The below sheet shows the sensors utilized in the power board. The sensor sheet can be seen in Figure 7 below.



Figure 7: Sensor Sheet of Power Board

To preserve isolation, isolated amplifiers were used to sense voltage and current. Resistor dividers were used to create a voltage reference for the amplifiers to send to the logic board. The resistors were sized according to the equations below. Equation 1 was used to size the voltage sense resistor. Equation 2 was used to size the current sense resistor. These were found from references [2] and [3].

$$R_{VOLT} = \frac{V_{IN}R_{TOP}}{V_{source} - V_{IN}}$$
[1]

$$R_{CURR} = \frac{V_{sens,MAX}}{I_{MAX}}$$
[2]

Temperature sensing was added to verify conditions and regulate fan speeds for cooling the power board, ensuring correct performance.

To find the correct transfer function for the sensors. We used Excel to map V_{in} to V_{sense} . This let us have an easy linear trendline output the sensed value. An example of the graph can be seen in Figure 8 below.



Figure 8: Battery Voltage Transfer Function

The layout design is shown below in Figure 9. The notable feature is the isolation between the low voltage and high voltage sides on the right side of the board.



Figure 9: Layout of Power Board

2.4 Tolerance Analysis

High power MPPTs can have a few different tolerance challenges. To verify our design would meet specifications, we used a simulation to validate the operating conditions. The first simulation that was run was using our nominal case. If we vary the duty cycle, we can get the current down to an acceptable value. This simulation doesn't consider the real characteristics of solar cells, which have an I_{sc} of 6.46A. In this case, we are modeling the solar cells as a voltage source.



Figure 10: Nominal Power Board Operating Condition

With the nominal simulation complete, we simulated the worst case. This included the tolerance present in the inductor($\pm 20\%$) and capacitor($\pm 5\%$). With this addition, the current ripple and voltage ripple increases. This is still within the specifications.

$$L_{worst \ case} = 1.2 \mu H * 0.8 = 0.96 \mu H$$

$$C_{worst\ case} = 470\mu\text{H} * 0.95 = 446.5\mu\text{H}$$



Figure 11: Worst Case Power Board Usage Operating Conditions



Figure 12: Output Voltage and Current at Worst Case (Blue: Output Current | Green: Output Voltage)

As shown above in Figure 12, the ripple voltage and ripple current still stay within acceptable ranges even in the worst-case scenario.

2.5 Enclosure Design



Figure 13: Initial Enclosure Design

During the development process we determined that enclosures would be necessary to secure and isolate the boards from each other as well as other components in the car. Separate enclosures were designed for the logic and power boards. The power board included mounting for a fan as we determined that certain components could rise in temperature.

The enclosures shown in figure 13 were designed to be 3D-Printed. Due to issues with resource allocation, we were unable to get access to a 3D Printer and had to redesign the case for other

manufacturing methods. The redesigned case is shown in figure 14. The initial two cases are now combined into a single case that was cut using a laser cutter and the fully assembled case can be seen in figure 15.



Figure 14: CAD of Redesigned Case



Figure 15: Assembled Final Case with All Components

3. Design Verification

3.1 Sensor Validation

The team has had to deal with noise issues in the sensors throughout the project. To reduce the effect of noise, the team included a low pass filter and local averaging to make the sensors more readable. The first sensor that was tested was the voltage sensor. The table below, Table 1, shows some data gathered from testing.

Measure Voltage (V)	ADC Sensor Voltage (V)
9.98	9.6
15.01	14.9
19.98	20.1

Table 1: ADC Voltage Sensor Verification

The table below, Table 2, shows some data gathered during current sensor verification. This shows that the sensor cannot distinguish low currents. This was an issue during the demo as we used a 40 Ω power resistor to model a solar cell's MPP. This limited the current too much. Once we changed to a 1 Ω resistor, the current sensor worked as expected.

Measure Current (A)	ADC Sensor Current (A)
0.08	0.5
0.6	0.55
0.86	0.89

Table 2: ADC Current Sensor Verification

3.2 Boost Verification

To test boost, we used a simple signal generator at a 20% duty cycle and a load to view the output. The full setup can be seen in Figure 16 below.



Figure 16: Boost Test Setup

The load was set to 300Ω , and the input voltage was at 15V. With the duty cycle of 0.2 we got an output voltage of ~25V. This allowed us to move onto the tracking portion of our project.

3.3 Tracking Validation

Tracking validation was relatively limited. We couldn't use a solar array, so we couldn't map the IVcurves and verify the MPP. The way we validated tracking was by engaging/disengaging the MPPT. To try to have some semblance of a power curve, we added a large power resistor in series with the input. This can be seen in figure 17.

When tracking was engaged the power would steadily increase, because the voltage was constant, and the current would increase. When tracking was disengaged, the power would go back to a lower value. We also used our telemetry application to validate the tracking. When the MPPT was engaged the CAN message that showed duty increased steadily, same with the power input.



Figure 17: Tracking Test Setup with Power Resistor

4. Costs

4.1 Parts

Listed below are the bill of materials for each of the boards. Costs are pulled from the source they are bought (Digikey).

Reference	Value	Footprint	Datasheet	DNP	MPN	Note	Qty	Uni	t Price	Tota	al Price
C1	10uF	Capacitor_SMD	~		CAP CER 10uF 50V X5R 0603		1	\$	0.24	\$	0.24
C2	1nF	Capacitor_SMD	~		CAP CER 1nF 50V X5R 0603		1	\$	0.10	\$	0.10
C3-C6	1uF	Capacitor_SMD	~		mixed values		4	\$	0.10	\$	0.40
C7, C8	470uF	Capacitor_THT	https://www.chemi-con.co.jp/products/relatedfiles	mixed va	EKXJ201ELL471MM40S		2	\$	3.76	\$	7.52
C9	0.1uF	Capacitor_SMD	~		CAP CER 0.1UF 10V X5R 0603		1	\$	0.27	\$	0.27
C10, C13	1nF		~			Place Ne	2	\$	0.10	\$	0.20
C11, C14	100nF		2			Place bet	2	\$	0.24	\$	0.48
C12, C15	1uF		~				2	\$	0.10	\$	0.20
D1	Blue	LED_SMD:LED_	~		LED BLUE CLEAR 0603		1	\$	0.55	\$	0.55
D2, D3	0.83V	Package_TO_S	https://www.rohm.com/datasheet?p=RB098BM150	mixed va	RB098BM150TL		2	\$	1.19	\$	2.38
J1	Inputs	Connector_Mol	~		43650-0400		1	\$	1.66	\$	1.66
J2	Sensors	Connector_Mol	N		43650-0800		1	\$	2.49	\$	2.49
J3	Vin Solar	layout:Anderso	https://www.andersonpower.com/content/dam/app	o/ecommer	3-5912P1		1	\$	0.91	\$	0.91
J4	Vout Battery	layout:Anderso	https://www.andersonpower.com/content/dam/app	o/ecommer	3-5912P1		1	\$	0.91	\$	0.91
JP1	SolderJumper_2_Open	Resistor_SMD:	N				1	\$	0.10	\$	0.10
L1, L2	1.2 μH	Inductor_SMD:	https://www.we-online.com/components/products/	mixed va	744325120		2	\$	4.27	\$	8.54
Q1, Q2	IXTT220N20X4HV	Package_TO_S	https://www.mouser.com/datasheet/2/240/Littelfus	mixed va	IXTT220N20X4HV		2	\$	18.54	\$	37.08
R1	10	Resistor_SMD:	~		RES SMD 10 OHM 5% 1/10W 0603		1	\$	0.44	\$	0.44
R2	0	Resistor_SMD:	~		RES SMD 0 OHM 5% 1/10W 0603		1	\$	0.44	\$	0.44
R3	10k	Resistor_SMD:	N		RES SMD 10K OHM 5% 1/10W 0603		1	\$	0.44	\$	0.44
U1	RO-2412S	Converter_DCD	https://www.mouser.com/datasheet/2/468/RO-171	.1124.pdf	RO-2412S		1	\$	8.11	\$	8.11
U2	STGAP2SMTR	Package_SO:SO	https://www.st.com/resource/en/datasheet/stgap2	s.pdf	STGAP2SMTR		1	\$	2.26	\$	2.26
U3	MCP9700AT-ETT	Package_TO_S	http://ww1.microchip.com/downloads/en/DeviceDe	oc/21942e.	MCP9700AT-ETT		1	\$	0.36	\$	0.36
U4, U5	AMC130M02DFMR	SOIC20_DFM_T	https://www.ti.com/lit/ds/symlink/amc130m02.pdf	ts=170861?	4190529&ref_url=https%253A%252F	-%252Fwv	2	\$	8.27	\$	16.54
Total Power Board Component Cost \$							92.62				

Table 3: Power Board BOM

Reference	Value	Footprint	Datasheet	DNP	MPN	Note		Quantity	Uni	it Price	Tot	al Cost
C1	0.047u	Capacitor_SMD:C_0603_			CAP CER 0.047UF 50V X	7R 0603		1	\$	0.28	\$	0.28
> C2-C5	0.1uF	Capacitor_SMD:C_0603_	~		CAP CER 0.1uF 10V X7R	10V X5R 06	503 20%	4	\$	0.31	\$	1.24
> C6, C7	18pF	Capacitor_SMD:C_0603_	~		CAP CER 18pF 10V X7R	10V X5R 06	603 20%	2	\$	1.88	\$	3.76
D1	Q_SCR_KAG	Package_TO_SOT_SMD:S	https://ww	w.littelfuse	S602TSRP			1	\$	0.86	\$	0.86
D2	20 V	Diode_SMD:D_SOD-123F	-		DIODE ZENER 20V 500M	IW SOD123	F	1	\$	0.20	\$	0.20
D3	28 V	Diode_SMD:D_SOD-123F	-		DIODE ZENER 28V 500m	W SOD123	F	1	\$	0.39	\$	0.39
> D4, D5	LED	LED_SMD:LED_0603_160	~		mixed values			2	\$	0.55	\$	1.10
F1	5A	layout:Littelfuse_154_4.2	~		FUSE BOARD MNT 5A 12	25VAC/VDC	32V 125°C	1	\$	2.95	\$	2.95
J1	JTAG_Header	layout:IDC-Header_2x05	Pitch1.27	nm_Straigh	3220-10-0100-00	JTAG_head	ler	1	\$	0.61	\$	0.61
J2	24V In		~					1	\$	0.61	\$	0.61
J3	Comm		~					1	\$	0.61	\$	0.61
J4	Power		~					1	\$	0.61	\$	0.61
> Q1, Q2	Q_PMOS_GDS	Package_TO_SOT_SMD:1	https://ww	w.mouser.	FQD11P06		30Vgs 9.4/	2	\$	1.09	\$	2.18
R1	1k	Resistor_SMD:R_0603_1	~		RES SMD 1K OHM 5% 0.	1W 0603	0.1W 1% 0	1	\$	0.10	\$	0.10
> R2-R4	10k	Resistor_SMD:R_0603_1	~		RES SMD 10K OHM 5% 0	.1W 0603	0.1W 1% 0	3	\$	0.20	\$	0.60
> R5, R6, R9	10k	Resistor_SMD:R_0603_1	~		RES SMD 10K OHM 1% 1	0.1W 5% 0	603	3	\$	0.20	\$	0.60
> R7, R10	1k	Resistor_SMD:R_0603_1	~		RES SMD 1K OHM 5% 1/	0.1W 5% 0	603	2	\$	0.20	\$	0.40
R8	0	Resistor_SMD:R_0603_1	~	DNP	RES SMD 0 OHM 5% 1/4	0.1W 5% 0	603	1	\$	0.20	\$	0.20
SW1	ISP	layout:RST_STM_PTS_820	https://ww	w.mouser.	ADTSM31NV			1	\$	0.59	\$	0.59
SW2	~RESET	layout:RST_STM_PTS_820	https://ww	w.mouser.	ADTSM31NV			1	\$	0.59	\$	0.59
TP1	24V IN	TestPoint:TestPoint_THT	~					1			\$	-
TP2	24V OUT	TestPoint:TestPoint_THT	~					1			\$	-
TP3	GND	TestPoint:TestPoint_THT	~					1			\$	-
TP4	VGSThreshold	TestPoint:TestPoint_THT	~					1			\$	-
U1	LPC1547JBD48	Housings_QFP:LQFP-48	https://ww	w.mouser.	LPC1547JBD48			1	\$	10.37	\$	10.37
Y1	12MHz	layout:Crystal_SMD_TXC	http://www	v.mouser.c	7V-12.000MAAE-T			1	\$	0.79	\$	0.79
Total Logic Board Cost \$							\$	29.64				

Table 4: Logic 4 BOM

4.2 Labor

To estimate the labor cost associated with this project we began by looking at the average salary for a UIUC Electrical/Computer Engineering graduate. The average yearly salary is \$98,472, when combined with the fact that the average working hours per year is 2080, the result is an hourly rate of around \$47. We anticipate that we will spend 10 hours a week for the duration of the project (10 weeks) resulting in the following calculation: \$47 * 10 hrs. * 10 weeks * 3 people = \$14,100 in labor costs.

When combined with the component costs the total is: \$14,222.26.

5. Conclusion

5.1 Accomplishments

This project was very rewarding and taught us many skills. Some of these skills include how to design a boost converter from scratch, details on how MPPTs work, and good sensing practices. Overall, we are proud of the product that we have produced, it accomplishes the tasks that we set out to do at the beginning of this semester.

The main thing that we are proud of is the MPPTs low-cost. The solar car team currently uses COTS (commercial off the shelf) MPPTs and these cost \$1500 each. The car has three subarrays which means to fully integrate these MPPTs with the car the team would have to spend \$4500 without even considering spares. We were able to make our MPPTs with a budget of \$150, just 1/10 the price of the competitors.

There is still potential for future work with this project and gives the Illini Solar Car team a starting point for a future project.

5.2 Ethical considerations

As MPPTs are high power devices, there are safety issues that may arise when working with high voltage electronics. For example, when working with a solar array there will always be a voltage present, especially in strong light. This means that we should take caution when connecting the MPPTs to any solar array, or when handling solar array connections. When testing, we will also be using a high voltage power supply to test the power converter. When testing, care should be taken to ensure that there are no unwanted connections, and everything is properly connected and covered so that there is no risk of accidental contact with the test setup. For safety for the LiPo battery that will be used, a battery management system that was previously manufactured will verify everything is in good operating condition. Also, the team will take the high voltage training to make sure everyone is safe while working on the project.

The MPPTs should also have an enclosure that will prevent any accidental touches or any debris from getting inside and damaging the electronics or causing a short. Since these will be used inside our solar car, extra care will have to be taken with the construction of the enclosure to ensure there is no way for the driver or another person doing maintenance on the car to accidentally encounter the electronics. The enclosure should also be in a safe place inside the car and built correctly so that any possible debris

getting inside the car or other mechanical components becoming loose or damaged will not cause damage to the electronics. The enclosure should also comply with the American Solar Challenge regulations regarding labeling, mechanical structure, and wiring.

The MPPTs will be used to charge the car's batteries, which introduces additional safety concerns. We must ensure that the MPPTs are thoroughly tested with a load and power supply before connecting them to batteries to avoid any possible overvoltage or overcurrent issues. The battery itself already has a BMS with automatic monitoring and shut off, and the BMS should always be used and in working order whenever working with the batteries. Campus policy regarding batteries will be followed, which includes rules about battery storage, bringing batteries into buildings, and training for working with batteries. If any work is being done with batteries safety equipment such as fire extinguishers and sand will be present.

In terms of ethics, as this product is being built for a single specific application for our battery and solar array, there are minimal ethical issues with this product. This product will not be sold or used in any other situation and will remain with the team. There is little to no risk beyond the high voltage safety concerns.

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Appendix A Requirement and Verification Table

Table 5: Power Board R&V

Requirement	Verification
The boost converter handles inputs up to 90V at 400W, and is able to boost the voltage to an output range of 77-125V	We will make sure to test the converter at maximum and minimum inputs and verify that the output is boosted correctly when tested with a load.
The duty cycle input adjusts output voltage of the boost converter.	We will test the MCU control loop with inputs from the sensors. We will test the PWM duty cycle output and make sure it is logical for the desired output

Table 6: Logic Board R&V

Requirements	Verification				
MCU sends PWM gate signal requests to the power board.	Scope the PWM gate signal output to verify its voltage range(0V- 3V3) and frequency(200kHz).				
MCU receives temperature data and is within Actual Temperature ± 10°C.	We will use an infrared digital thermometer to verify the actual temperature and compare with our sensor readout using CAN telemetry application.				
MCU receives voltage data from solar array and boost output. The reading is within Actual Voltage ± 10%.	We will use a multimeter to verify the actual voltage and compare with our sensor readout using CAN telemetry application.				
MCU receives current data from solar array and boost output. The reading is within Actual Current ± 10%.	We will use a current sense probe to verify the actual current and compare with our sensor readout using CAN telemetry application.				
MCU sends a fan request rpm message and spins the fan.	The fan spins and a noticeable RPM change will be felt. Also scoping the PWM input to the fan can verify the speed request.				
Can send and receive CAN data at 500kHz	Using the brain battery management system we are able to receive CAN information. By scoping the CANH and CANL signal, we view the frequency of data. Using the telemetry application made by Illini Solar Car we can verify the message integrity.				
The bus voltage(24V) is stepped down to 3V3 ± 5%	We will use a multimeter to verify the actual voltage from a test point on the board and compare with $3V3 \pm 5\%$.				