Baker/Koob Endowments
Academic Affairs

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Baker/Koob Final Report: Solar Solution for Mini Mars Rover

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Title of Project: Solar Solution for Mini Mars Rover

Project Completion Date: June 3, 2022

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Cooperating Industry, Agency, Non-Profit, or University Organization(s):
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Executive Summary:

This project focused on designing, building, and testing a functional prototype of a collapsible solar array on the mini Mars rover being developed by client and sponsor, Mr. Rich Murray. Although many previous collapsible solar arrays have been deployed for space missions, the previous solar-powered Mars rovers only deployed their arrays once upon landing. This solar array will be able to collapse and deploy multiple times to allow for greater rover mobility and stability when the rover is not charging. This system is critical to the success of the rover project because it provides power without which the rover cannot take measurements, collect samples, or move on the Martian surface.

This report outlines the major accomplishments of the project, how the funds from the Baker/Koob Endowment were used to meet the project goals, and the conclusions from the team reflecting on the project's impact to each member's learning and career development. For a detailed description of the design process, see the project's Final Design Report, found on the Cal Poly Digital Commons under the title 'Solar Solution for Mini-Rover'.

Major Project Accomplishments

This section describes the detailed project requirements, final design, and major accomplishments of the project. Our team, known as 'The Sunny Company', successfully designed, built, and tested a foldable solar array to provide power for client Rich Murray's mini Mars rover. We exceeded the target on all but one of our engineering specifications (mass limit). The innovative folding design and mounting arrangement we developed allowed us to use only one motor to control multiple unfolding motions of the array with our passive cam-controlled side panels. In addition, our team added a tilting ability to the array to allow single-axis solar tracking for improved efficiency.

Expenditure of Funds

This section includes tabulated breakdowns of the original cost estimate, along with the actual cost for each of the two prototypes we manufactured. Of the requested $4600, approximately $650 were used for the first prototype, $1780 were used for the final prototype, $1250 were used for a custom extrusion, and the remaining $920 was spent on shipping costs and additional supplies that will be used on future rover projects.

Impacts to Student Learning

Finally, we offer our conclusions on what we learned during the project. Specifically, we discuss our increased appreciation for soft skills such as organization and communication, our experience gained interacting with vendors and purchasing administrators, and what we learned about the unique strengths of working on an interdisciplinary team.

Major Accomplishments:
This section gives an overview of the major accomplishments of the project. In order to understand the why aspects of the final design are relevant, we first explain the project requirements, then describe the final design, and finally explain which aspects of the final design are major accomplishments of the project. The formal problem definition for the project is as follows:

Mr. Rich Murray, Cal Poly lecturer, requires a compact, lightweight, foldable, rover-mounted solar collection device that will provide enough power to charge the battery on the Cal Poly mini-rover 'EXO' when the rover is deployed on Mars.

<u>Project Requirements</u>
This project was focused around providing power through a solar array for the mini-rover 'EXO' that Cal Poly professor Rich Murray is developing. After initial meetings with the sponsor to determine his requirements for the prototype, our team formulated a list of quantitative engineering specifications that governed our prototype development. The following table shows the list of requirements we developed during our critical design phase.

Table 1. Critical Design Engineering Requirements

Specification Number	Parameter Description	Target Value	Unit	Tolerance	Risk	Compliance Method
1	Folding/charge cycles	1000	cycle	MIN	M	A, S
2	Power production	55	W	MIN	M	T
3	Attachment Width	300	mm	MAX	L	A, I
4	Full Extension Deflection	25	mm	MAX	M	A, T
5	Battery charge time	70	hr	MAX	H	A, T
6	System Mass	2	kg	MAX	M	A, T
7	Deployment/Retract time	10	min	MAX	M	T
8	System efficiency	18	%	MIN	M	T
9	Clearance from rover	25	mm	MIN	L	A, I
10	Mounts to rear deck	YES	-	-	L	A, I

In addition to the target value and tolerance for each parameter, the table also includes the compliance method and risk associated with not meeting the requirement. The compliance method is categorized as one or more of the following methods: Analysis (A), Testing (T), Similarity to Existing Designs (S), or Inspection (I). The risk of not meeting the specification is divided into three levels: High (H), Medium (M), or Low (L).

The most important requirements are the number of cycles the solar array must be able to fold/unfold, the power that must be produced by the array, the allowable deflection under Mars-comparable wind conditions, the time the array takes to charge the battery, and the maximum mass of the system. Our progress in producing a prototype that met these requirements is explained below.

Design Process and Final Design Description

During the conceptual design phase, our team brainstormed various folding patterns and actuation methods for the mechanical design of our array. We then expanded on and improved our initial concept design through the critical design phase, including performing mass analysis and finite element analysis (FEA) of wind loading situations, until we had developed a prototype that would meet all of the listed engineering requirements. A brief overview of the final design is presented below.

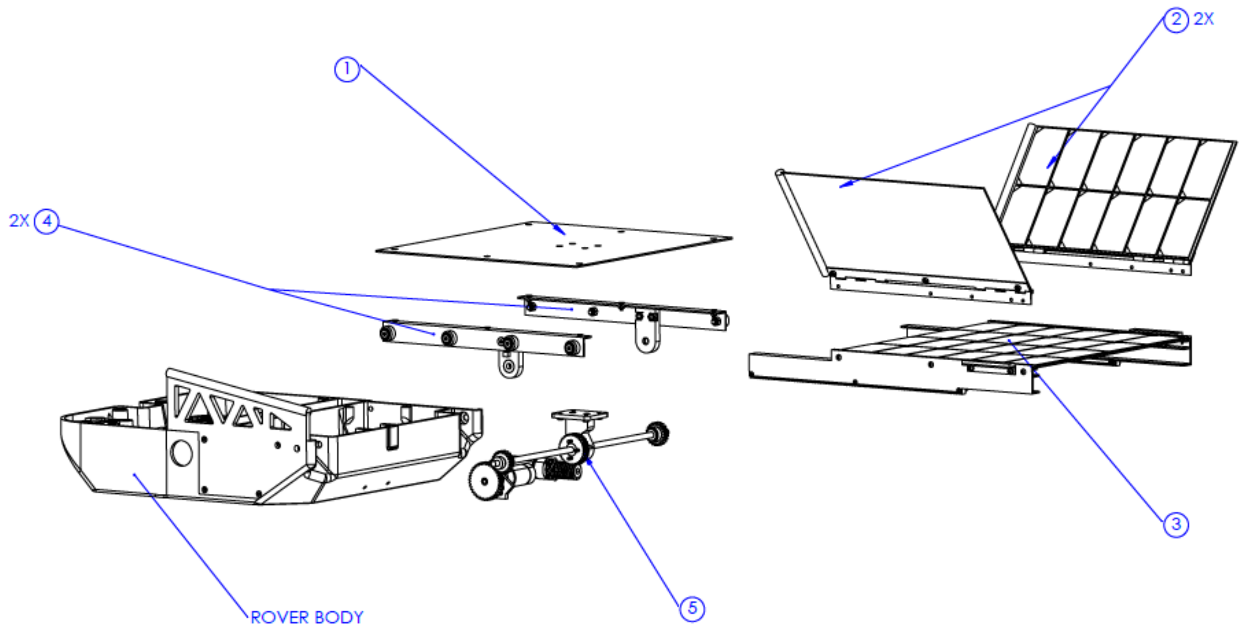

Figure 1. Final Prototype Exploded View

The five major subsystems of the design are as follows:

1. Base panel
2. Side panel
3. Sliding panel
4. Base rollers
5. Driveshaft/axle

The base panel subassembly consists of the 1/16-inch carbon fiber structural panel, Kapton insulation between the panel and cells, 24 space-rated solar cells, RTV silicone to attach the cells to the panel, and all associated wiring. Note that in the delivered final prototype, only 48 cells were provided by the sponsor, so the base panel did not include any solar cells. The panel still included Kapton tape insulation, but no cells were attached. The side panel subassembly is similar with the addition of Delrin 500 AF (self-lubricating Delrin and Teflon mix) rods to slide along the cams, along with the hinges used to attach the side panels to the sliding panel subassembly.

The sliding panel subassembly includes the same 1/16-inch structural carbon fiber panel with cells, Kapton, and RTV silicon as the base and side panel subassemblies. It also includes custom machined brackets which combine a U-channel for the wheels to roll in with L-brackets to attach to the carbon fiber sliding panel. This subassembly also includes the gear racks of the rack and pinion along with hard stops that prevent the side panels from folding out past horizontal. In the original final design, the custom machined part was designed as a custom aluminum extrusion which also included the hinge as part of the extrusion profile. However, this was replaced with a machined equivalent due to time constraints with the long lead time for the custom extrusion.

The base roller subassembly consists of structural aluminum L-brackets, rod supports and bearings that attach the panels to the driveshaft, Delrin rollers which facilitate the sliding, and all associated hardware necessary for attachment.

Finally, since all of the motor and shaft supports are included in the rover body, the driveshaft assembly simply includes the aluminum shaft, all gears, motors, bearings, and hardware necessary for attachment.

After settling on a final design and performing the necessary analysis, we used the on-campus machine shops to manufacture and assemble our final prototype. We performed testing along the way with our initial prototype and with the final prototype when all assembly was complete.

<u>Test Results and Major Accomplishments</u>

Overall, our sponsor was pleased with the final prototype we presented. During the fall, winter, and spring quarters of the 2021-2022 academic year, The Sunny Company successfully designed, built, and tested a compact, lightweight, foldable solar array that mounted to the Cal Poly mini-rover 'EXO' and provided enough power to charge the batteries of the rover. A picture of the final prototype is included below.

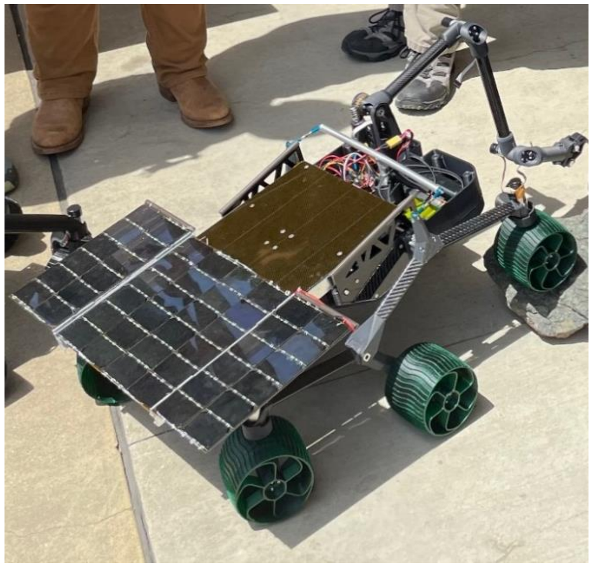

Figure 2. Final Prototype

One of the major accomplishments of our project was that we developed a novel folding pattern that allowed for compact transportation, simple actuation, and for 24 cells to be available for power production even when the array was in the retracted configuration. This T-shaped folding pattern only required one actuator (rack and pinion gear motor) to extend and retract the array due to the passive unfolding of the side panels on triangular cams.

Another major accomplishment was the successful addition of the tilting ability to the array. Using a worm gear and lever attachment, our team created a configuration that allowed the solar array to tilt up to 30° so the rover can track the sun to maximize power production. This feature was not originally required, but is very helpful for the client. In order to simplify the mounting and wiring for the motors, we designed the extension and tilting to happen about the same axis, which also allowed the two motions to happen simultaneously and independently if needed.

In addition to these innovative features, our team successfully met all but one of the customer requirements for our prototype. The test results and explanations are included below.

Table 2. Results of Significant Design Verification Tests

Test	Results	Target	Quantity	Units
Power Production	FAIL*	> 55	40	W
Folding Cycles	PASS	> 1000	1030	cycles
Full Extension Deflection	PASS	< 25	0.127	mm

Battery Charge Time	PASS	< 70	8.07	hr
System Mass	FAIL	< 2.0	2.5	kg
System Efficiency	PASS	> 18	21.5	%
Dust Mitigation	PASS	-	-	-

As the table shows, our final prototype met all of the siginficant requirements except the power production and mass requirement. Although the power production value is lower than the target value, our team determined that the target value should have been lower in the first place as the 55 W value is for perfect environmental conditions. In addition, our client informed us that the initial value of 55 W was calculated for a set of 70 cells in series, which would not have produced sufficient current to charge the battery, as our arrangement of 3 parallel banks of 24 cells in series does. Therefore, a value of 40 W is acceptable for the power production requirement.

The only requirement that our prototype failed was the system mass. However, this does not reduce the functionality of our system in any way and is not a major issue since this specific prototype will not be going to Mars (the main reason for a lightweight prototype is to reduce the cost associated with sending supplies to Mars). In addition, our team developed suggestions for how the mass can be reduced in future iterations of the solar power system. Overall, we consider our success in producing a prototype that surpassed most of the engineering requirements a major accomplishment of this project.

Expenditure of Funds:

Our team manufactured and assembled two prototypes for this project. The first prototype was used for most of the testing and design iteration and did not include the solar cells due to the high cost of each cell. The second and final prototype was manufactured for the Senior Design Expo with the improvements gained from testing and with two full arrays of solar cells (48 cells total).

The original projected cost breakdown for the Baker/Koob funding is presented in the following table.

Table 3. Operating Costs Breakdown for Funding

Operating Expenses		Subtotal:	$4,600
Non-computer Supplies & Materials:			
Item	Approximate Cost Per Item	Quantity	Total Cost
Refurbished Space-rated Solar Cells	$40	70	$2,800
Servo Motors	$150	3	$450

Structural Material (Ti, Al)	$1,000	1	$1,000
Servo Motor Controllers	$100	3	$300
Misc Hardware Components	$50	1	$50

As Table 3 shows, our budget consisted primarily of space-rated solar cells, material for constructing the support structure for the solar array, and devices to control and power the deployment and retraction of our array. Our client, Rich Murray, informed us that current leading-efficiency space-rated solar cells cost approximately $500 each. For our project, we planned to use older space-rated cells with lower efficiences that could be purhcased at significantly less cost. However, our team received a donation of about 50 solar cells from Professor Steve Dunton of the Cal Poly Electrical Engineering department. The remaining funds that were supposed to go to the purchase of the solar cells were instead used for other prototype materials, including the custom extrusion and replacement customed machined part used on the final prototype. The following tables display the actual cost breakdown and distribution of funds for each of the two prototypes our team manufactured.

The cost breakdown of the first prototype is shown below in Table 4. In total, the purchased parts cost about $545. The RoboClaw and motors were supplied by sponsor Rich Murray, so funds did not have to go to the purchasing of those parts. Additionally, the lithium-ion battery packs, RTV, and Kapton tape did not have to be purchased for the first prototype, since it was designed solely for testing the mechanical aspects of the solar collector.

Table 4. Prototype 1 Cost Breakdown

Vendor	Product Name	Qty	Price/Each	Total
Openbuilds	Delrin Mini V Wheel Kit	8	$4.49	$35.92
Openbuilds	Low Profile Screws M5 (10 Pack) - 20mm	2	$1.29	$2.58
Openbuilds	Low Profile Screws M5 (10 Pack) - 25mm	2	$1.39	$2.78
Amazon	CanaKit Raspberry Pi 4 Extreme Kit - 128GB Edition (4GB RAM)	1	$149.99	$149.99
Amazon	ReliaBot 2PCs 6mm x 400mm (.2362 x 15.748 inches) Case Hardened Chrome Plated Linear Motion Rod/Shaft/Guide - Metric h8 Tolerance	1	$13.49	$13.49
McMaster-Carr	Alloy Steel Cup-Point Set Screw, M3 x 0.5 mm Thread, 4 mm Long	1	$6.28	$6.28
McMaster-Carr	18-8 Stainless Steel Socket Head Screw, M4 x 0.7 mm Thread, 25 mm Long	1	$12.00	$12.00

McMaster-Carr	Nylon Plastic Washer for M6 Screw Size, 6.4 mm ID, 12 mm OD, Off-White	1	$7.11	$7.11
McMaster-Carr	Metal Gear - 20 Degree Pressure Angle, Round Bore, 24 Pitch, 21 Teeth	2	$29.02	$58.04
McMaster-Carr	Multipurpose 6061 Aluminum, 6 mm Diameter, 3 Feet Long	1	$2.81	$2.81
McMaster-Carr	Steel Piano Hinge without Holes, 1-1/2" Wide, 1/4" Long x 0.148" Diameter Knuckle, 1 Foot Long	2	$5.23	$10.46
McMaster-Carr	18-8 Stainless Steel Hex Drive Flat Head Screw, M3 x 0.5 mm Thread, 4 mm Long	1	$7.69	$7.69
McMaster-Carr	Architectural 6063 Aluminum U-Channel, 1/16" Wall Thickness, 1/2" High x 3/4" Wide Outside	1	$21.50	$21.50
McMaster-Carr	Architectural 6063 Aluminum 90 Degree Angle, 1/16" Wall Thickness, 1" High x 1" Wide Outside, 4 Feet Long	1	$13.50	$13.50
McMaster-Carr	Architectural 6063 Aluminum 90 Degree Angle, 1/16" Wall Thickness, 1-1/4" High x 1-1/4" Wide Outside, 4' Long	1	$16.86	$16.86
McMaster-Carr	White Delrin Acetal Resin Sheet, 1/4" Thick, 12" x 12"	1	$33.24	$33.24
McMaster-Carr	White Delrin Acetal Resin Sheet, 1/8" Thick, 12" x 12"	4	$20.54	$82.16
McMaster-Carr	18-8 Stainless Steel Hex Drive Flat Head Screw, M3 x 0.5 mm Thread, 6 mm Long	1	$5.42	$5.42
McMaster-Carr	18-8 Stainless Steel Thin Hex Nut, M3 x 0.5 mm Thread, DIN 439, ISO 4035	1	$11.61	$11.61
McMaster-Carr	Slippery Delrin Acetal AF Resin Rod, 1/4" Diameter, 1 ft	2	$2.84	$5.68
McMaster-Carr	Slippery Delrin Acetal AF Resin Rod, 3/8" Diameter, 1 ft	3	$6.34	$19.02
McMaster-Carr	18-8 Stainless Steel Nylon-Insert Locknut, M3 x 0.5 mm Thread, 5.5 mm Wide, 4 mm High	1	$6.94	$6.94
McMaster-Carr	Metal Gear - 20 Degree Pressure Angle, Round Bore, 24 Pitch, 36 Teeth	1	$46.08	$46.08
McMaster-Carr	Cast Acrylic Sheet, 12" x 12" x 1/4", Black	2	$10.78	$21.56

McMaster-Carr	Carbon Steel Set Screw Collar for 6 mm Shaft Diameter, DIN 705	6	$1.77	$10.62
123Bearing	Deep Groove Ball Bearing, 686-2Z	10	$1.50	$15.00
123Bearing	Deep Groove Ball Bearing, 676-ZZ	2	$2.80	$5.60
goBILDA	1301 Series Clamping Hub (10mm Bore)	1	$5.99	$5.99
goBILDA	Worm Gear Set (24:1 Ratio, 6mm D-Bore Worm)	1	$24.99	$24.99
Donation	RoboClaw motor controller	1	-	-
Donation	Metal gearmotor	2	-	-
			Total	**$654.92**

The final prototype cost significantly more than the first prototype, mainly due to the expensive custom extrusion and custom machined part that were used. Our client recommended we combine the U-channel, L-bracket, and hinge used in the extension of our array into one shape to decrease the amount of manufacturing needed and allow for easier mounting of the structural carbon fiber panels. The custom tooling needed for the extrusion and large minimum amount of material used (minimum extrusion length of 20 ft) contributed to the high cost of $1250. When our team realized this part would not arrive in time to incorporate in our final prototype, we had to quickly pivot to a custom machined part, which cost $1000 due to the complexity and short turnaround time.

Table 5 below shows the final prototype cost breakdown. The estimated cost of the final prototype is $1775.55. This cost does not include materials that were re-used from the first prototype and counts for materials that consist of "packs" with multiples of each item (for example, sets of 100 screws). The custom aluminum extrusion cost of $1250 was not included in this breakdown because it was replaced by a custom-machined aluminum part due to timing issues. This extrusion will be used by our client in future iterations of the solar array.

Table 5. Final Prototype Cost Breakdown

Vendor	Product Name	Qty	Price/Each	Total
The Model Studio	C-channel/L-bracket custom aluminum machined part	1	$1,000.00	$1,000.00
Donation	Space-Rated Solar Cells	48	-	-
Amazon	Permatex 80050-12PK Clear RTV Silicone Adhesive Sealant, 3 oz. (Pack of 12)	1	$55.80	$55.80
Amazon	CanaKit Raspberry Pi 4 Extreme Kit - 128GB Edition (4GB RAM)	1	$149.99	$149.99

McMaster-Carr	Distortion Resistant Ultra-Strength Lightweight Carbon Fiber Sheet, 12" x 12" x 1/16"	4	$75.00	$300.00
superbrightleds	Flat Power Cable - 4 Conductor - 10 mm	10	$0.95	$9.50
KHK Stock Gears	SUW1-R1 SUW Stainless Steel Worms	1	$44.33	$44.33
KHK Stock Gears	BG1-30R1 BG Bronze Worm Wheels	1	$35.39	$35.39
123Bearing	Deep Groove Ball Bearing, 686-2Z	10	$1.50	$15.00
Amazon	16 Ft (5m) 196 Inch Sliding sash Windows Doors Tape Pile Draught excluder Brush Seal Strip weatherstrip 7mm x 6mm (7/24 1/4 Inch, Gray)	1	$8.00	$8.00
McMaster-Carr	Music Wire Steel Extension Spring with Loop Ends	1	$11.94	$11.94
McMaster-Carr	Slippery Delrin Acetal AF Resin Rod, 3/8" Diameter, 1 ft length	4	$6.98	$27.92
McMaster-Carr	18-8 Stainless Steel Hex Drive Flat Head Screw	1	$7.12	$7.12
McMaster-Carr	Torsion Spring, 9271K599	1	$5.19	$5.19
McMaster-Carr	Torsion Spring, 9271K665	1	$5.19	$5.19
McMaster-Carr	Torsion Spring, 9271K645	1	$5.01	$5.01
McMaster-Carr	Torsion Spring, 9271K577	1	$5.01	$5.01
McMaster-Carr	Multipurpose Neoprene Rubber Sheet, Adhesive-Back, 6" x 6", 1/8" Thick, 50A Durometer	1	$14.62	$14.62
McMaster-Carr	316 Stainless Steel Button Head Hex Drive Screws 94500A261	1	$6.67	$6.67
McMaster-Carr	18-8 Stainless Steel Hex Nut	1	$5.27	$5.27
McMaster-Carr	316 Stainless Steel Button Head Hex Drive Screws 94500A221	1	$7.32	$7.32
McMaster-Carr	Steel Piano Hinge without Holes, 1-1/16" Wide, 1/2" Long x 0.174" Diameter Knuckle, 1 Ft Long	4	$2.06	$8.24
McMaster-Carr	18-8 Stainless Steel Hex Drive Flat Head Screw 92125A125	1	$3.89	$3.89

McMaster-Carr	Button Head Hex Drive Screw 92095A114	1	$4.88	$4.88
McMaster-Carr	Button Head Hex Drive Screw 92095A460	1	$8.51	$8.51
McMaster-Carr	General Purpose 18-8 Stainless Steel Washer	1	$2.99	$2.99
McMaster-Carr	18-8 Stainless Steel Nylon-insert Locknut	1	$8.86	$8.86
McMaster-Carr	Brass Heat-set Inserts for Plastic	1	$13.26	$13.26
McMaster-Carr	18-8 Stainless Steel Hex Drive Flat Head Screw 92125A128	1	$5.65	$5.65
			Total	**$1,775.55**

The team is very grateful for the Baker/Koob endowment which allowed us to purchase all the necessary materials for the project, as well as additional supplies which can be used on future iterations of the rover. The generous funding from the endowment also permitted us to purchase high-quality custom extruded and machined parts, which reduced our manufacturing time and increased the professional quality of the final prototype.

Impact on Student Learning:

This project provided an excellent opportunity for each of the team members to apply the engineering principles learned in our engineering courses to a ‘real-world’ application. Not only did we learn how our knowledge of mechanics, circuits, programming, and mechanical design applied to the task of creating a solar array to power a mini-rover, we also learned much more about the importance of ‘soft-skills’ in engineering projects.

The first quarter of the project focused primarily on project planning and research. While this phase of the project seemed tedious at the time, it taught us the importance of detailed preparation before starting work on the design and analysis. Our initial meetings with the sponsor to determine the precise needs and wants of the project were very helpful in focusing our research and future work. Throughout the year, we gained an appreciation for the value of organized communication. We realized the importance of having a designated team member to interact with our sponsor, using workplace messaging software to organize discussions and share files, and developing clear deadlines and expectations for dividing work. Without these organization and communication skills and tools, our project would not have been successful.

In addition to learning the importance of intra-team communication, our team also learned how to interact with outside vendors and other administrators. Much like in a larger engineering company, our project had different people and departments responsible for the finances of the project. We learned how to correctly complete and submit the necessary forms to our advisor and purchasing administrator who had control of our funding. After waiting too long to order materials for our conceptual prototype presentation, we learned to factor in both the administrative processing time and the lead time from the vendor when purchasing tools and parts. This knowledge will certainly be useful in our future careers when coordinating with other departments and procuring materials for projects.

Finally, we learned the value of interdisciplinary teams for projects. Instead of being a homogeneous group of all one major, our team was composed of mechanical, electrical, and general engineering students. We learned to delegate work according to each person's strengths, to elicit and incorporate feedback from different perspectives, and to patiently ask questions and explain answers to aspects of the project that someone was unclear about. While there were certainly challenges associated with working in a diverse team of students, we ultimately learned to appreciate our different skills and strengths. The successful final prototype we created is a testament to the capability of interdisciplinary teams to solve challenging problems, engineering or otherwise. Our team grew tremendously during this project, and each team member will certainly use the knowledge gained to succeed in future projects as engineers. Whether working in the solar industry, working on satellite communication, or working in the aerospace industry, members of The Sunny Company have been inspired and prepared by this project to make lasting impacts wherever they go.