Solar Panel Integration as an Alternate Power Source on Centaur 2 (SPIAPS)

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The dream of exploration has inspired thousands throughout time. Space exploration, in particular, has taken the past century by storm and caused a great advance in technology. In this project, a retractable solar panel array will be developed for use on the Centaur 2 Rover. Energy generated by the solar panels will go to power the Centaur 2 Robot (C2) or Regolith & Environment Science & Oxygen & Lunar Volatile Extraction (RESOLVE) payload, an in-situ resource utilization project. Such payload is designed to drill into lunar and Martian terrain as well as be able to conduct other geological testing; RESOLVE is slated for testing in 2012. Ultimately, this project will fit into NASA's larger goal of deep space exploration as well as long term presence outside Earth's orbit.

Nomenclature

A	=	Ampère
C2	=	Centaur 2
C2's Back	=	Relatively flat, exposed area of Centaur 2's body situated between the two suspension systems
Centaur	=	For the purposes of the paper, Centaur refers to Centaur 2 and not its predecessor
DC	=	Direct Current
Encoder	=	Electric device that converts the angular position of a device into digital information
GRC	=	Glenn Research Center

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High Efficiency Solar Cells	=	Solar cells with an efficiency over 15%
ISRU	=	In-Situ Resource Utilization
JSC	=	Johnson Space Center
MPPT	=	Maximum Power Point Tracking
NASA	=	National Aeronautics and Space Administration
RESOLVE	=	Regolith & Environment Science & Oxygen & Lunar Volatile Extraction
RPM	=	Rounds Per Minute
R2	=	Robonaut 2
SEV	=	Space Exploration Vehicle
Solar Cell	=	Relatively small device that transforms light into electricity
Solar Panel Efficiency	=	Ratio comparing amount of electricity created to the potential energy that could be collected should all exposed light it is exposed converted into energy
Solar Panel	=	An array of solar cells wired together in series and in parallel
SPIAPS	=	Solar Panel Integration as an Alternate Power Source on Centaur 2
W	=	Watts
W/ft^2	=	Watts per square foot

I. Introduction

Solar energy has become more practical as a means of energy as the technology has improved. When applied appropriately, solar cells can provide a mobile and flexible source of energy; examples include the solar panels on the International Space Station, as well as solar cells to improve C2's battery life as it carries the Regolith & Environment Science & Oxygen & Lunar Volatile Extraction (RESOLVE) payload, an ISRU project that serves as a mobile laboratory. RESOLVE is designed to study the surface of both the moon and Mars. Ideally, the solar panel array will allow the robot and payload to function all day; consequently, the solar panel array will have to be sturdy enough to be deployed as the robot works, yet agile enough to track the sun and integrate into the robot's current design.

NASA's Glenn Research Center, which has helped create payloads for C2 previously, has designed two different solar panel arrays for C2. SPIAPS seeks to build off their designs and provide another option for testing in 2012. This project seeks to create a new design that will better function with Centaur's current design both aesthetically and electronically. With an unspecified budget for the project, designs ranging from the cost of roughly $3,000 to $300,000 were considered.

II. Initial Design

In order to fully integrate the solar panel array into the design of Centaur, the project team took several steps in the initial design process including:

-Understanding the requirements of the project
-Initial design
-Concept review

A. Understanding the Requirements of the Project

Project objectives for SPIAPS remained very fluid at the beginning; many requirements had not yet been defined and the project team was at first uninformed about C2's design and how to appropriately integrate into it. Furthermore, many entities were involved in the project including Johnson Space Center, Glenn Research Center, the Canadian company Neptec, and several other companies in the private sector. Consequently, requirements for this project did not come explicitly stated. C2 and RESOLVE engineers initially requested the solar panel to only power RESOLVE, requiring an output of 28V and a minimum of 240W from the solar panels; however, it has been deemed that solar panels may charge C2's internal battery and the RESOLVE payload will draw power from the same battery. Electronics to control the mechanisms of the array will also have to be mounted securely, but cannot be placed inside of the robot's current body unless absolutely necessary. Such integration also includes mounting the solar panel array to existing attachment points on the robot. Mounting structures consist of eight bolts on the top of Centaur's back and eight additional structures on the back of the robot. As an example of fluid requirements, the aforementioned requirement was only discovered during a concept review after the initial design. The design will therefore have to attach at no more than the sixteen available points on the back and aft faces of Centaur. It is preferred that the attachment only use the eight bolting points on C2's aft face.

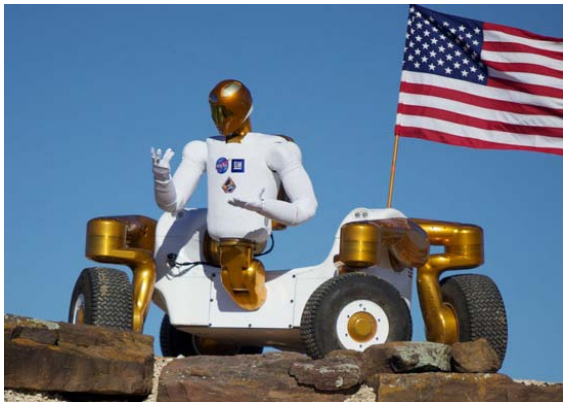

Figure 1. Centaur 2 with Robonaut. *C2 is pictured here as it carries Robonaut at the JSC rock yard.* [5]

Figure 2. Centaur 2 with Glenn Research Center Bucket and Space Exploration Vehicles in background. SPIAPS draws inspiration from the GRC bucket, SEVs, as well as C2.

Centaur is designed to be a very versatile robot. Beyond its main body, the robot can integrate with not only the RESOLVE payload but also with Robonaut 2 and the Glenn Research Center bucket. Future plans for payloads to attach to Centaur's back are in development. In order to optimize the utility of the solar array, the design must not interfere with other payloads. However, a critical requirement is that all actuation avoids other areas of motion such as that of the wheels and suspension area of the robot. Furthermore, the array should be capable of being deployed while C2 is moving at a rate of 10 cm/sec. Weight also is a large factor; the array must be as light as possible to minimize its impact on the functionality of the robot.

B. Initial Design

Once the initial requirements were understood, the design process began. Primary focus

was on the mechanics of the array with less focus on exactly what solar cells would be used. This was done in order to approximate the surface area available for solar cells and to find dimensions for the solar cells. The original design featured two panels (see figure 3). Both panels measured about 40" x 24". The thickness was set as an arbitrary dimension which would be defined when specific solar cells were chosen. The design included two axes of motion: the first lies at the joint where the first solar panel attaches to the motors near the aft face of Centaur. The second axis of motion lies at the joint where the inner panel attaches to the outer panel. The two axes of motion, combined with the size of the panels and support structure allow for the whole system to fold completely onto C2's back while allowing one panel to remain facing upwards, allowing for almost constant exposure to available light (see figure 4).

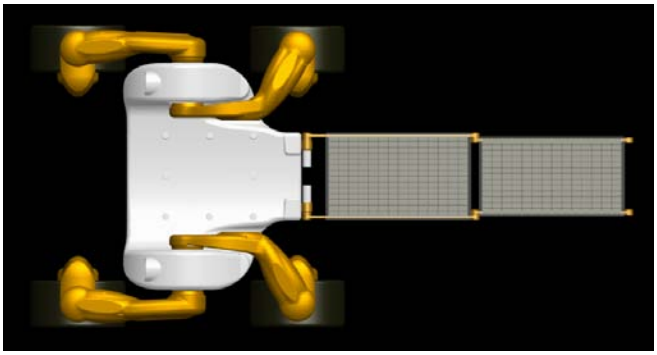

Figure 3. Original Dual-Full Panel Design. *With two axis of motion as well the ability to fold onto Centaur's back, the original design proved to be a launching point for future improvements.*

This design is powered by four custom brushless Magmotors, all of which are mounted to C2's back. These motors were chosen because of their accessibility as well as for their ability to be regulated down to lower speeds. Actuation is achieved by two motors controlling the first axis near C2's back while two more motors that run to a belt encased in aluminum tubing control the second axis located where the two solar panels are connected together. However, a large gear reduction was necessary because the Magmotors have a very high RPM (~6,000RPM with no load), and the desired rate of rotation is (~3) RPM. To lower the RPM and increase torque, the motors will be connected to harmonic gear boxes with a gear ratio of 100:1. This large gear ratio combined with regulation of the brushless motors will allow for the reduction needed. Harmonic gear boxes with this specific gear ratio were chosen primarily for availability; however gear ratios of 160:1 are also available.

Originally, the four motors were mounted two apiece in modular casings. Modularity was very important in this design because of C2's numerous functions; depending on the robot's payload, the solar panels could be positioned appropriately. Furthermore, at the time of the initial design, engineers were still moving mounted cameras around the body of the robot. Motor housing could be mounted to the back of the robot using a simple mounting plate or be mounted directly to the side into the fiberglass body. The initial motor housing also incorporated room for the harmonic gear boxes as well as a cover for the actuated joint. The front of the motors, shafts, and harmonic gear boxes would all be housed together, while the end of the motors would be covered in fabric

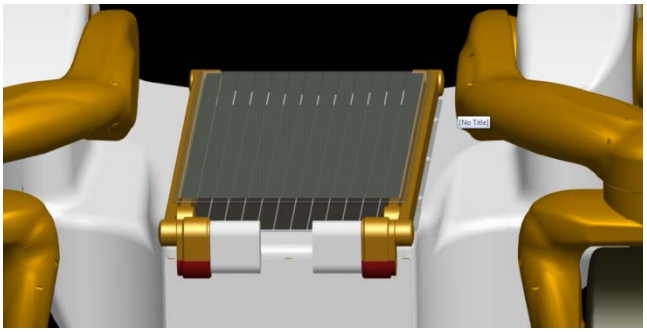

Figure 4. Solar Array Folded Back. *When not in use the original design of the solar array would fold back compactly. Simultaneously, the top panel faces upwards to collect some energy.*

similar to the design of the Space Exploration Vehicle drive motor mounts (see SEVs in figure 2).

The mechanics driving the system were designed to be lightweight as well as durable. The joint nearest the body is connected directly to the harmonic drives. The second joint is controlled by one of the two motors in the casing. Thus, each joint is controlled by two motors. To actuate the second joint, two belts and three sprockets per on each side of the panel: a sprocket attached to the output of the harmonic gear box drives a belt that rotates a second sprocket on a floating axle concentric to the shaft of the other motor. This sprocket, when actuated, drives another belt that runs the length of the aluminum tubing supporting the first panel and actuates a sprocket that is attached to the second joint, thus driving the two joints independently of each other.

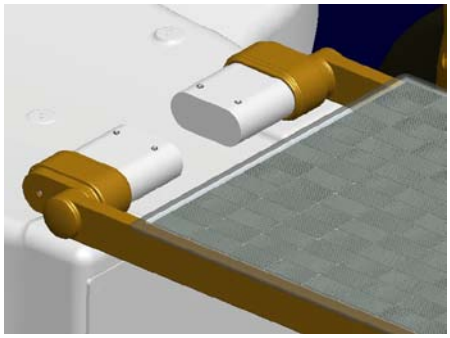

Figure 5. Topside Mounting. *Original design had both motor casings mounted directly onto the fiberglass.*

Furthermore, in order for the solar panels to track the sun without affecting the movement of C2, a turret was implemented in order to rotate the solar panels. This alteration affected the original modularity; however, it presented another design option. While stationary motors offered greater modularity, the turret allowed for greater autonomy in operation. With the turret, all of C2 is not required to rotate in order to tack the sun. The turret is actuated by a motor attached to a gear which drives a very large gear (approximately 18" in diameter) floating in a stationary mount attached to Centaur. The solar panel array is mounted to a plate attached to the large gear. Therefore the plate must be very strong to withstand warping.

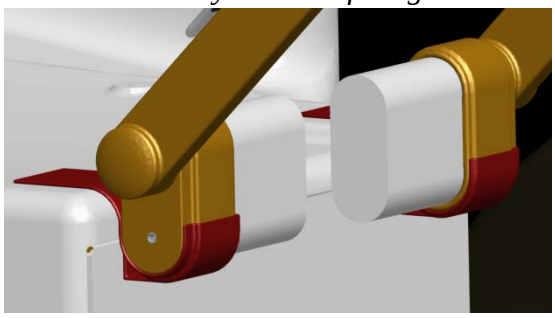

Figure 6. Aft Face Mounting. *The original modular design allowed for mounting two different locations*

Solar panel size was based on calculations that were later found to be incorrect. However, because solar cell selection proved to be a challenge, array size was not changed in anticipation that it would remain similar when the final solar cell provider is chosen. If panel size does change because of the chosen solar cells, the design of the array is flexible enough to integrate any size solar panel smaller than 26" x 50" due to the area onto which the solar panels must fit folded on Centaur's back.

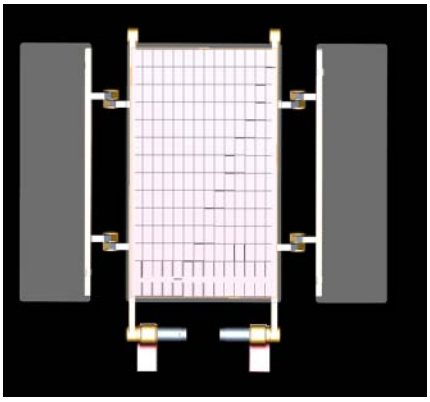

Figure 7. Tri-fold Design. *The tri-fold lowered torque at the expense of redundancy.*

In addition to the primary dual-panel design initially developed, a tri-fold was also developed as a way to reduce the torque exerted on the system by shortening the lever arm formed by the two panels. Though more mechanically complex, the tri-fold design provides a more compact area in which solar panels would be deployed. Side panels are actuated by a similar belt system; however the belts will actuate worm gears that fold the side panels under the main panel.

Because there is a panel on each side of the primary panel, only one motor controls each side panel, resulting in a loss of redundancy. When the entire array folds back onto C2's body the side panels will face upward. This allows the system to collect some light even when it is not deployed, as with the original panel design. Like the initial design, the tri-fold design is also capable of being mounted on a turret or with the initial modular design.

C. Concept Review

Once initial designs were transferred into three-dimensional animations a concept review was arranged with C2 engineers. The presentation allowed the engineers to comment on the designs. Critique mainly focused on the need for a plan to integrate the solar array with C2's current electrical infrastructure. It was decided that a separate electrical box would store motor controllers as well as other necessary hardware to minimize changes to C2's electrical system. However, the solar panel array will be controlled via C2's computer. Such integration will allow the solar array to be controlled from the same console as Centaur. Furthermore, it was suggested that electric brakes be integrated into the drive assembly between the motor shaft and harmonic drive. Such integration would reduce the energy needed to hold the solar panels' positions. Additionally, it was said that mounting directly to C2's fiberglass body would be impossible, and any solar panel array would be bolted to the exposed mounting wells located on C2's back or aft face. The turret design was preferred by the engineers because of the increased power generation without the need to move the entire robot.

III. Secondary Design

Secondary design followed concept review. The original design of two, long panels was abandoned in favor of the tri-fold design. Ultimately the original design was too gangly and unrealistic if C2 was to conduct work while the array was deployed.

A. Solar Panel Selection

The issue of choosing solar panel provider remained daunting. A consumer study was conducted to find out what was commercially available. Data collected showed that commercially available solar panels averaged about 12 W/ft^2. However, with the current surface area in the tri-fold design, roughly $18W/ft^2$ would be needed to reach the desired 240W. The only way to achieve such wattage would be through high efficiency solar cells. Through collaboration with Glenn Research Center, contact was made with SunCat Solar LLC. After preliminary talks, the company proved promising. An original budget of $10,000 had been given for the whole project with the chance of increase once promising designs had been accepted. SunCat's pricing for the necessary high efficiency solar cells would raise the budget over $10,000.

Before committing to SunCat Solar, it was determined that a number of solar panel options would be explored. These options would allow for a range in budget and mechanical designs to be made available once funding was set. To improve organization a solar panel database was created; this database allowed the team to compare available solar panels and consider all options. Once the database was compiled, panels that did not meet our needs were weeded out and prospective panels were explored further. Panels not considered were eliminated for being too large, not meeting power criteria, or being too heavy. Those that remained were put into another database: the options database. Once in the options database, each panel was further

evaluated on numerous traits including expense, whether it would power RESOLVE directly or power C2, and surface area. Furthermore, various panels studied allowed for a variety of budget ranges but required different mechanical systems. Some panels needed a tri-fold design with two or three hinges on each side, depending on length, while others required that motors be mounted closer together, because of relatively narrow panels. Though computer aided designs were not made of all options in the options database, the database served to illustrate the number of mechanical and electrical solutions that are possible when the project goes into final design stage.

Through research of various solar panels in our solar panel databases, it was determined that a solar panel with a built-in bypass diode is needed. Because solar cells are connected in series, the same amount of current must pass through all the cells. When one or more cells are shaded, its current output is less than the current going into it from the better producing cells and creates a "hot spot." A bypass diode will allow the shaded areas to be isolated and allow current to go through. This is especially important because shading caused by C2's suspension is unavoidable.[6]

Figure 8. Glenn Research Center Bucket. *Mounting to C2's aft face was inspired by the GRC Bucket.*[7]

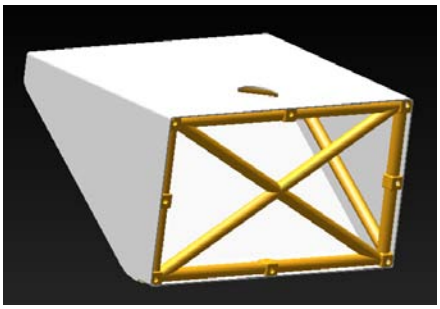

Figure 9. Mounting Box. *The box will house SPIAPS electronics and mount to C2's aft face as well as serving as the base for SPIAP.*

B. Fine Mechanical Integration

During secondary design, a limiting factor in light collection that had been previously overlooked was caught. Because of the suspension and steering system of C2, motion of the solar array's turret and solar panels would be limited. Consequently, a design that would solve numerous problems at once was conceived. A box would be mounted to Centaur's aft side and serve as housing for electronic hardware as well as an extension of C2's back. The turret could be mounted on this extension to avoid some motion limitations caused by the protruding suspension system. Because all SPIAPS electronic hardware will be mounted in the box, the original idea of modularity reemerged. Beyond a few plugs, SPIAPS would be completely removable within a matter of minutes. This mounting system was inspired by how the Glenn Research bucket attaches to C2 (figure 7). While the system would still have some restricted motion caused by C2's body, limitations would be greatly reduced. The inside of the housing would be supported by a structure similar to the truss found inside C2's body; ideally, it will be nearly identical in coloring. Furthermore, the motor protruding from the bottom of

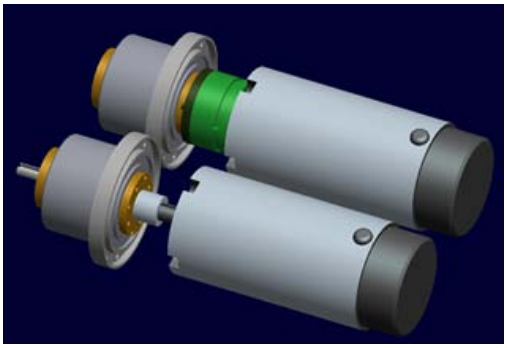

Figure 10. Brake and Coupling Integration. *The green models the brake's placement in the drive system. Brake is hidden in left motor to show coupling (grey) also hidden is housing that will attach and stabilize all mechanisms to turret.*

the turret will be able to be mounted in the metal housing.

As suggested during the concept review, brakes were integrated into the drive system. To create a mounting plate for the brakes, the housing of the drive system had to be changed. The brakes were integrated by adding a plate on which the motor mounted on one side, and to which the brake attached on the other. During the redesign of the drive housing, it was realized that a coupler would be needed to connect the motor shaft to the brake.

D. Electronics

Integrating solar panels into either C2's current electronic infrastructure or directly into the RESOLVE payload means more than just plugging in panels. Several vital pieces of electronics are required. To control the custom Magmotors (B23-150), Advanced Motion Control Digiflex Motor Controllers are suggested for use. Five controllers will be needed to control all the motors: one to control the turret and four to actuate the tri-fold. The motor controllers will be housed in the mount box and wired into C2's cPCI so that a single console can be used to control both C2 and SPIAPS.

Specialized electronics for the solar panels will also be used to harness energy from the solar panels. A consultant at SunCat Solar recommended that GenaSun solar charge controllers with maximum power point tracking (MPPT) be employed to allow the solar panels to run at their most efficient voltage, allowing them to produce the highest wattage possible. MPPT serves the function of tracking the solar panel's output and applying appropriate resistance to obtain maximum power output from the solar cells. GenaSun solar charge controllers are unique because of their MPPT characteristic. However, other MPPT charge controllers should also be explored.[8]Dependent on the chosen cells; numerous GenaSun charge controllers may be needed.

DC to DC converters have also been discussed. Because the solar panel has not been finalized, a converter may be needed to boost output voltage to the 310V needed to charge C2. However, if a DC-DC converter is used, a ~13% loss of power is created, a loss that can be avoided if a custom solar panel is made. If the solar panels feed directly into RESOLVE, a regulator might be needed to decrease voltage to the 28V maximum RESOLVE runs on. While this is dependent on which solar panels are chosen, avoiding power loss through inefficiencies should be considered when choosing a solar panel.[9]

Though the solar panel has the range of motion to track the sun, light sensors will be needed to track where the optimal position of the solar panels will be. This is achieved by placing a cluster of four light sensors on the main panel. With appropriate programming, sun tracking can be fully automated.

E. Programming

The initial phases of this project were based on mechanical and hardware aspects of SPIAPS. Programming was not explored beyond its correlation with hardware. However several major aspects have been considered.

One major programming consideration is that the brushless Magmotors will need to be regulated so that the solar array will rotate at a slow, reasonable speed. Because of the use of worm gears to actuate the side panels, a gear reduction is implemented in addition to motor regulation and the harmonic drive. This should be taken into consideration when programming the speed at which the motor runs so that the tri-fold does not open too slowly, but the main panel does not open too fast. Furthermore, limitations on rotations should be placed so that arrays will not risk hitting C2's body. This limitation will have to take into account whether the

tri-fold is open or closed. However, either way, limitations must be put into place to avoid damage to the SPIAPS or C2. To help with this, the Magmotors come equipped with encoders.

F. Change of Mechanics

Because of the challenges faced with finding panels that met power requirements and size constraints, a tri-fold design was formed in which three commercially available panels would be deployed from C2's back. Unlike the previous design where both side panels folded closed onto the same side of the main panel, the "swirl" design flipped the hinges on one side forcing that panel to rotate the opposite direction.

IV. Final Suggestions and Possible Changes

After going through initial designs, consumer studies, and various consumer reviews, options and suggestions have become apparent and should be explored.

- If harmonic gear boxes prove to be too expensive, planetary gear boxes stacked together may be an option as well.
- Langley Research Center is currently conducting experiments with solar panel efficiency, contacting them may allow access to highly efficient custom panels for low prices.
- Consulting a solar panel expert to check wiring and electronics chosen to handle variable power output of solar panels.
- Testing solar panels is needed before integrating into either C2 or RESOLVE electronics to ensure that power output is known.

V. Conclusion

Much work remains to be done on SPIAPS. A final budget will be needed before choosing a solar panel or starting construction. The power the solar array will create is almost directly correlated to the budget. Whether custom panels or commercial panels are utilized, a more rigid set of requirements is needed before the decision is made. SunCat solar continues to be a promising vendor for solar panels.

Mechanically, the tri-fold design is versatile enough to incorporate numerous commercial panels as well as custom panels. More specifications will need to be found on the Magmotors because of their custom nature, but the motors seem to be capable of supporting the array.

Electronically, much work remains to be done, integrating five motors into C2 is no small task. The task, though made easier through the modularity of the hardware, will require serious thought. It is undecided whether output power will go back into C2 or power RESOLVE directly. Furthermore, special electronics are needed to ensure that the variable power source does not cause problems with the C2 or RESOLVE electric infrastructure. Ultimately, SPIAPS serves as the future of robotics and an exciting addition to NASA's robotic fleet.

VI. Acknowledgements

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