Power Beaming techniques for NASA's 2009 Centennial Challenge

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Abstract: *We present concepts for power beaming (wireless power delivery using light) as applied to the 2009 NASA Centennial Challenge and our specific approach. Extending our design to alternate power beaming is presented, extending to longer distances and other beam characteristics such as divergence, power, and wavelength of operation.*

Keywords: Power beaming, high power laser, optical beam, photovoltaic cells, wireless power

Introduction

The concept of powering devices wirelessly through the use of a beam of energy has existed for many decades. Realistic devices have been demonstrated as long ago as the early 1900's with the work of Nikola Tesla. However, most of these devices have had efficiencies so low that they have had very limited applicability. Most of the transmitted energy tends to be "broadcast" (i.e. the beam is relatively wide) such that the device receiving the power intercepts a very small fraction of the transmitted power. Possibly due to this problem, power beaming applications have historically been applied mostly to short-ranges (within tens of meters).

With the advent of lasers and microwave resonators, power beaming is capable of reaching longer ranges and delivering higher power to the intended recipient. Although the applications are still rather limited, the technology now exists to reach out to ranges of many kilometers rather than merely meters. For some applications, no other viable alternative for power delivery exists. For these applications, the receiver is typically so constrained in terms of size and weight that it cannot have power on-board.

Applications

We present here a couple of example applications for power beaming to illustrate why this technology can be an enabler of special capabilities. One example might be a persistent surveillance system on a high-altitude balloon (HAB). For HABs operating at altitudes in excess of 20km, recent technology has shown that it is possible to loiter in regions for many days or possibly months. However, such balloons may be overly limited in payload and power for some applications. If the HAB does not need to carry as much power, it can carry more payload. However, if the power is compromised, so is the duration of the mission. Power beaming could in this case offer a means of delivering power to such a payload, extending its mission duration and increasing the payload sensor suite on-board.

Another application might be a special type of sensor that must be ultra-light and/or non-invasive (covert). Consider a sensor for monitoring illicit activity near a border crossing, mounted on a tree. If the sensor was powered by wire or battery, it would be easier to defeat or require more service, significantly decreasing covertness. However, if power was delivered wirelessly (not necessarily continuously, but at regular intervals), then detecting and defeating the device would be much more difficult.

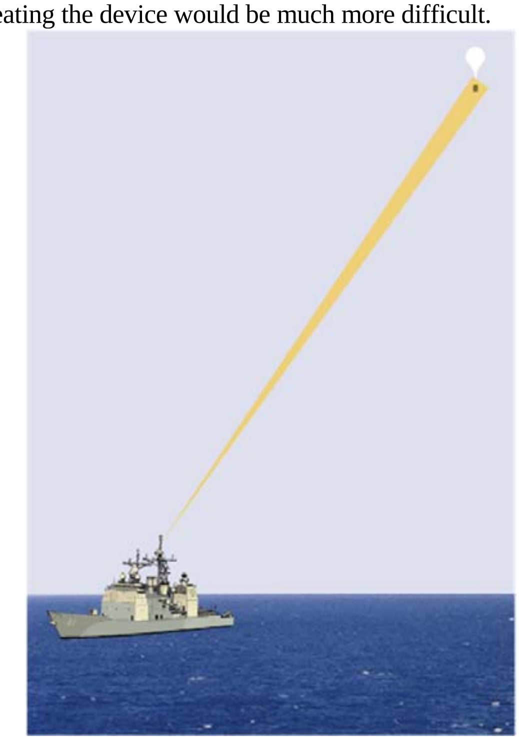

Figure 1. A possible use-case of power-beaming: sending power to a payload on board a high-altitude balloon gondola.

The Transmitter

The transmitter arguably has the most stringent requirements placed on it. It is responsible for getting relatively large amounts of energy to propagate across free space to a location far in the distance. It must do so while ensuring the beam has a sufficiently small divergence so that the receiver will be able to harvest enough of the energy that reaches it. To create the beam, there are numerous trade-offs involved, and the trade-offs exist not only in selecting the wavelength(s) of operation, but also the method of forming the beam shape (divergence). In selecting the wavelength, in general, the longer the wavelength, the less expensive the optics will be because the tolerances are commensurate with wavelength for “diffraction-limited” systems: longer wavelengths mean looser tolerances. Diffraction-limited beams are typically necessary because these are the tightest beams possible (i.e. smallest divergence). However, the diffraction-limited beam divergence is directly proportional to the wavelength; longer wavelengths mean greater beam divergence. Divergence is also a function of aperture. Tighter beam divergence can be attained through the use of an aperture that is larger (if properly designed). Ultimately, selecting the wavelength of operation is a consideration for both the transmitter and the receiver, as the receiver needs to be able to convert the energy into useful power, but generally these rules are still important to consider when weighing the cost of the system. Many times, however, the determining factor for the wavelength is the availability of a source of sufficient energy, whether that be a laser or a microwave source.

The energy density of very high power sources (many thousands of watts or more) tends to be spread out over an area that is not a point source: it is not a single-mode beam source. These extended sources make use of additional volume in gain media to create the added power. This is a very important consideration for beam forming! When a source is no longer a point, its extended size adds to the divergence of the beam. For an optical system, the only way to reduce the divergence of an extended source is to increase the focal length. This tends to also increase the needed aperture, however, because the source has its own beam divergence: the lenses or mirrors used to collimate the source must be large enough to capture all of the light from the source in order to be efficient.

The Receiver

In general, the receiver can act in a mode of either scavenging or harvesting the energy incident on it. The distinction is whether the receiver is able to normally optimally orient itself to receive the maximum amount of energy or not. In scavenging mode, it is designed to capture some energy (but usually not all) regardless of its orientation because the orientation is not predetermined. In harvesting mode, it normally does not significantly change its orientation needed to capture the maximum amount of energy or there is a built-in method of optimizing the orientation (for the case of moving systems). Converting the power from the beam into useful energy typically requires conversion to either electricity or heat. Each of these sources of power come with trade-offs for system design in terms of size, weight, and efficiency.

The NASA Centennial Challenge: Power Beaming competition

For this competition, teams needed to build an end-to-end system for beaming power to a vehicle that would climb a tether to an altitude of 1km. The winning team would be the one demonstrating the best combination of speed (time to climb) and payload capability. So, to compete effectively, both a transmitter and receiver (the vehicle) needed to be built by each team. Trumpf Laser donated access to their Tru-Disk 8002 laser to any team wishing to use it as the power source for the competition. This is an 8kW laser operating at 1032nm and coupled to a fiber. Teams could then connect the fiber to their transmitter. Our team chose to take advantage of the use of this laser.

Methods

The design for a power-beaming system requires careful consideration of the methods of forming the beam as well as the methods of converting the beam energy into useful power at the remote end, whether that power is ultimately in the form of electricity or heat. For the most efficient system, it is important to also consider how the power is going to be used. For instance, if the remote system needs the power to move, then it ultimately needs mechanical energy, and whether the receiver converts the beam into heat or electricity can have a sever impact on the overall system requirements to ultimately generate motion. For example, there are motors that run on heat (e.g. Stirling engines) and there are motors that run on electricity (e.g. electromagnetic motors).

The conversion of light into heat is well understood and requires little technology to achieve conversion efficiencies in excess of 80%.

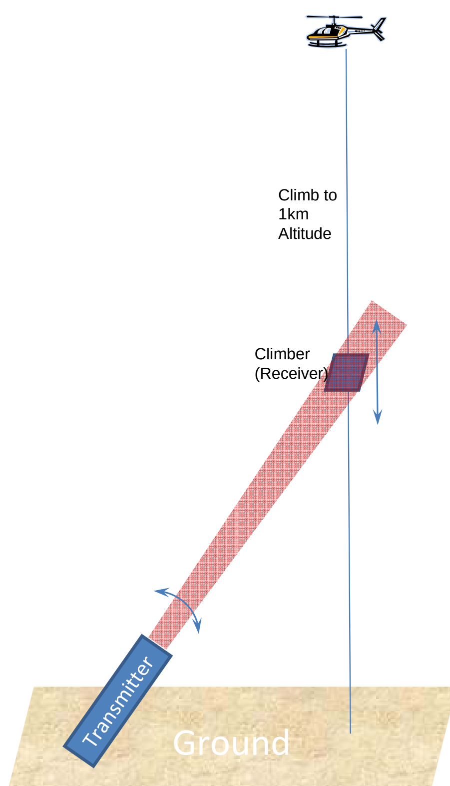

Figure 2. Depiction of the power-beaming Centennial Challenge. The transmitter sends power via laser beam to the vehicle climbing the tether.

<u>*Optical Design - Transmitter*</u>

Upon evaluating acceptable methods of creating a beam from the Trumpf laser, our initial approach was to use a reflective design, involving just one mirror, an off-axis parabola. The fiber tip would be placed at the focal point of the parabola, thereby creating a collimated beam with diffraction-limited quality. An off-axis design is desirable when using mirrors because this allows the fiber tip (and its connector) to remain outside of the path of the reflected beam. There are a couple of manufacturers offering such mirrors but the cost became prohibitive for our team, which was lacking adequate financial sponsorship.

To mitigate the issue of cost, alternate designs were investigated, especially involving inexpensive off-the-shelf lenses from manufacturers such as JML or Edmund. The result of this effort was fruitful, producing an optical design with acceptably small amounts of wavefront error: less than ¼ wave peak-to-valley over 90% of the beam diameter, less than $^{1}/_{20}{}^{th}$ wave rms. The layout of the optics is shown in Figure 3. The design uses just two lenses, one meniscus and one plano-convex (PC), both catalog lenses from JML. The meniscus lens is the critical lens, accomplishing many benefits:

- it serves to modify the focal length of the system (shortening the overall length)
- it corrects most of the spherical errors of the PC lens
- it allows focusing: small movements of this lens (while keeping the fiber-tip to PC lens spacing constant) maintains low wavefront error
  - o this also mitigates small errors in the spacing from fiber tip to the PC lens
  - o mechanically, this is the easiest item to move in order to achieve focus

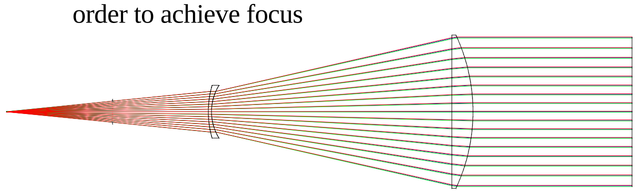

Figure 3. This shows the layout of the Beam Forming optical design. Both lenses are catalog off-the-shelf available through JML Optical, and produce a nearly diffraction-limited beam at 1032nm. Although rays are shown here to the edge of the lenses, approximately 95% of the laser energy resides within the central 112mm of the outgoing beam.

The PC lens sets the effective aperture for the system, with a diameter of 145mm. The effective focal length is 655mm. The laser that will interface to the optics is a Trumpf Tru-Disk 8002, which provides 8kW of continuous-wave (CW) energy at 1032nm through a fiber having a 200µm core diameter. All lenses were coated with anti-reflection coatings for less than 0.25% reflection per surface at 1032nm.

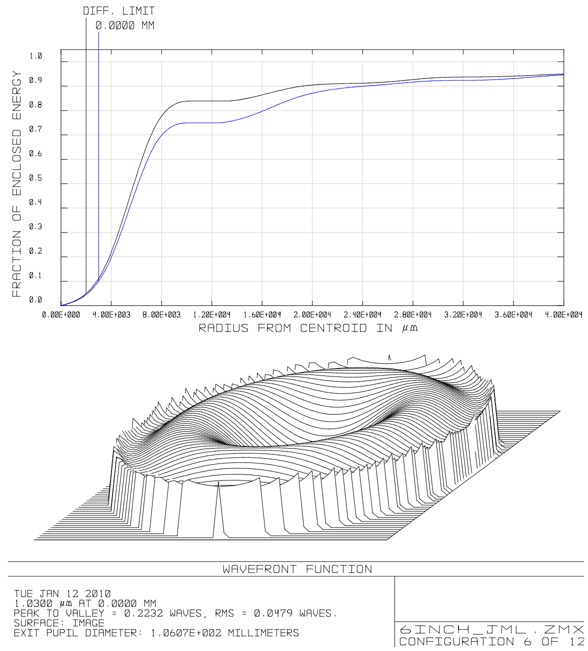

Figure 4. The fraction of encircled energy (top) is shown with respect to the diffraction limit. The wavefront error map is also shown (bottom) to convey the nature of the residual design error. These are shown for the optics set to focus at a distance of 3km, where the beam size is approximately 1.2 meters in diameter (due to the extended size of the fiber source, this is larger than a point source).

<u>*The Receiver*</u>

The main problem that our team faced in this effort was how to make effective use of the wavelength of the laser that Trumpf Laser, Inc. had offered for the competition. Since our sponsorship financing was small, we could not afford to use another power source. Therefore, the receiver must be capable of harvesting power at a wavelength of 1032nm as well as dissipating the incident unused energy which gets collected as heat. Conventional photovoltaic cells are not good for this, because they are made of silicon, which has relatively low efficiency of converting photons to electricity at this wavelength: efficiencies less than a few percent are common. An additional problem with photovoltaic cells is the phenomenon of saturation. Photovoltaic cells generate current that is directly proportional to the incident flux, but only up to a certain flux. If the incident flux exceeds the saturation point, the current starts to be less than the linearly extrapolated value, and for fluxes much higher than saturation, the current output reaches an asymptotic value. Our team chose to use the technology of a Gallium Antimonide (GaSb) ThermoPhotoVoltaic (TPV) cell. These cells make use of the incident energy that gets converted to heat and uses the heat to aid in the generation of carriers (electricity). Additionally, the cells were advertised to have much higher efficiency at 1032nm (approx 60%, see Figure 6) than alternate cells. These were tested for saturation and determined to be effective at up to 1W/cm^2 irradiance. Considerable space between cells was needed to accommodate wiring and structure, and upon testing it was determined that considerable heat buildup results at the frame. If this heat was not dissipated, it would lead to solder joints melting.

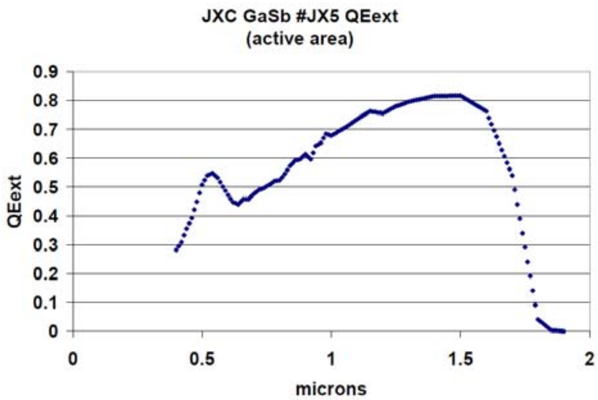

Figure 6. Quantum Efficiency curve for the TPV cells. Data provided by the manufacturer.

To address the problem of heat buildup, a lightweight heat dissipation system was devised that works similar to a heat pipe. This involved a polyethylene bag containing just enough acetone to keep the TPV cells and frame immersed in liquid. This bag (seen in Figure 7, left) was shaped similarly to a conventional finned heat sink, with several sections of the bag protruding vertically upward (and supported with wire from a lightweight frame) to allow acetone vapor to rise into them. These vertical sections of the bag provide large surface areas for the acetone vapor to re-condense and then drip back down the bag to the bottom where the cycle starts again.

The Stering Engine

Our team seriously considered an alternate method of mitigating the issues of the wavelength of operation at the receiver: converting the photons to thermal energy and then using a Stirling engine to propel the vehicle. This approach is desirable when looking at the overall efficiency of power transfer. Optical designs for transferring the received light into the heater of the engine revealed that transfer efficiencies in excess of 75% should be possible. Testing of the heater cell of the engine indicated that a temperature of 400°C could be achieved. Given an ambient temperature of 30°C, this suggests a Carnot cycle efficiency of 60%. Even if our Stirling engine was only 50% efficient, the resulting overall efficiency of the receiving end would be about 22%. For an 8kW laser, this provides nearly 2kW of power from the engine. Despite these promising numbers, we abandoned the Stirling engine because its fabrication could not be completed by the middle of May 2009, a date reported to us at the time to be the date of the competition (the actual competition was held in November).

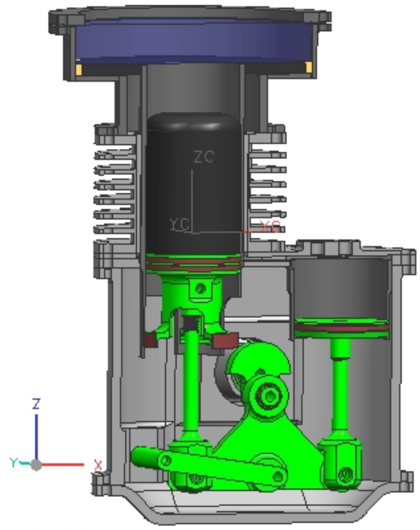

Figure 5. A cross-sectional view of the Stirling engine design that was developed for this challenge, however schedule complications led to the design being abandoned. It is currently being reconsidered for a future competition.

Results

The beam forming optics and TPV array for this Centennial Challenge were tested at the Trumpf Laser facility in Plymouth, Michigan on the 12th and 13th of October 2009. The TPV array needed to sustain 10 minutes of continuous illumination by a beam that was considered to have the maximum irradiance at the operational altitude. Since the laser for the Challenge was intended to be 8kW, but the Trumpf facility only had a 4kW laser on-site, the beam was tightened by a factor of 1.4 in diameter (2x in area) to increase the effective irradiance to that expected while using the 8kW laser. The array was then centered in the beam and tested at 4kW for 10 minutes. Within seconds, the acetone started to boil. The vertical sections of the bag showed visible condensation of the acetone, which then fell by force of gravity back to the TPV cell array. The climber lasted the full 10 minutes and passed the melt test. This test validated the use of the acetone-bag method of creating a "heat pipe" and using it to cool the array.

The optics for the transmitter also sustained a "melt" test whereby the optics were subjected to 10 minutes of 4kW transmitted power (again, the maximum available at the facility). This testing revealed a small amount of stray light that needed to be baffled, but otherwise showed the lenses could handle the power of the laser. The lenses were cool to the touch immediately after shutdown of the test.

Conclusion

Our efforts indicated that effective methods could be used to mitigate the issues that developed. The TPV cells offer a viable method of harvesting energy from the transmitted beam, despite its wavelength being less than ideal for commonly available photovoltaic cells. The use of an acetone bag having a series of vertical chambers such that the TPV array stayed immersed in liquid acetone proved to be an effective and lightweight method of dissipating hundreds of watts of heat.

This effort also showed that the use of a Stirling engine applied to this type of problem could potentially offer significant advantages by avoiding the conversion to electrical power (and the associated losses from converting the electricity to motorized movement).

Power beaming as a means of delivering kilowatts of power to a remote system was demonstrated to be viable. This may be an enabling technology for use cases in which a system needs power but cannot be wired for power nor can it afford the weight or service schedule required of a battery powered system.

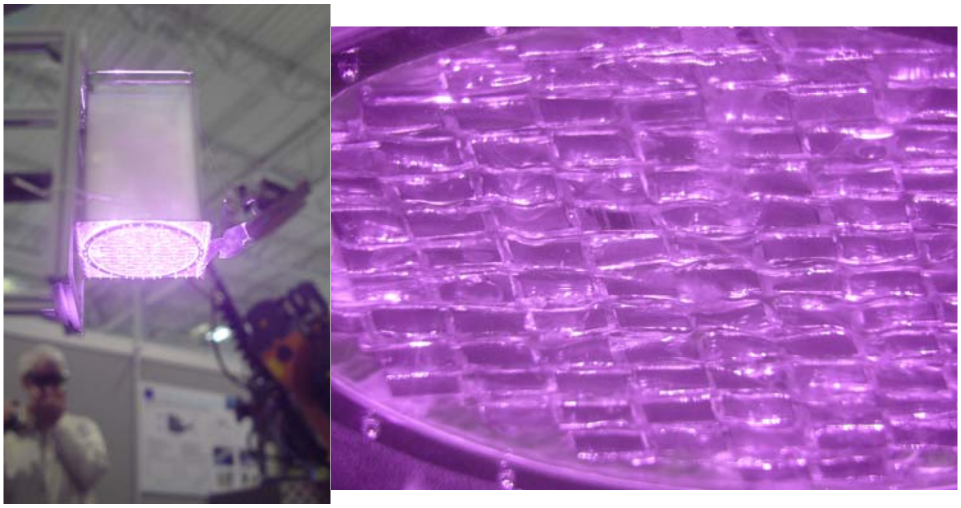

Figure 7. The TPV array being "melt" tested at Trumpf Laser, illuminated from below. A close-up view (right) shows the bubbling acetone maintaining the cells at a constant temperature of 56°C.

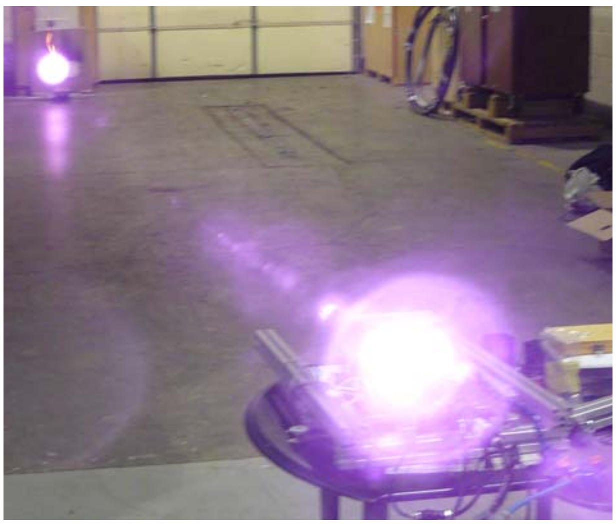

Figure 8. A picture at a time of approximately 10 seconds after the transmitter optics "melt" test commenced. The beam dump is a series of gypsum boards, the paper of which ignites (seen here) and burns away, leaving the bare gypsum for the beam to dump into.

Discussion

Our efforts on this project were continuously and heavily limited by funding as well as an unpredictable competition schedule. Many times our efforts were compromised due to being informed that the competition for the Challenge was just a few weeks away, and so we abandoned some efforts only to find out that the competition would be delayed. Our team suffered from this condition that lasted over a year: the competition always seemed to be just a couple months away. Yet, our best ideas would require 2-3 months to test, so most of them we did not pursue. Although our team had many ideas for methods that could further increase efficiency, the time and money was not available. We continue to work on this technology problem in a more limited capacity now that the competition has occurred. We are currently considering revisiting our Stirling engine design for the 2010 Centennial Challenge.

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The design for the Stirling Engine was the brainchild of Rick Topf.