Wireless Power Transmission

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Abstract

Wireless Power Transmission (WPT) has been an ongoing research area since 1873 when James Maxwell first theorized transferring power could be achieved through electromagnetic radiation. While microwave systems were first to be developed, in recent years the viability and demand for optical systems has grown significantly. In the space elevator contest sponsored by NASA in 2009, LaserMotive successfully demonstrated the potential of a laser based WPT system. The defense and space communities have started to recognize the impact that this technology could have given the multitude of battery-reliant unmanned systems that exist today. The current research is a study analyzing the background and benefits of laser based WPT systems, the system components, demonstrated/proposed WPT systems, and proposed research area needs within laser based WPT systems.

Keywords: Laser, Microwave, UAV, Photovoltaic, Concentrator lens.

1. Introduction

Military and Homeland Security personnel are becoming more reliant on the advancing technology in autonomous vehicles. Unmanned Aerial Vehicles (UAVs), Unmanned Combat Air Vehicles (UCAV), Unmanned Surface Vehicles (USV), Unmanned Underwater Vehicles (UUV), and Unmanned Ground Vehicles (UGV) are all being developed. Whether the need is to locate people after a natural disaster or to keep troops out of harm's way, the job of these systems becomes imperative.

UAVs are probably the most well known of the unmanned vehicles and commonplace in places like Afghanistan and Iraq. The troops feel a sense of security knowing that a UAV has already sent pictures and data about what type of obstacles lie ahead. Unfortunately, as more functionality is added to these surveillance systems, the endurance of the vehicles is greatly reduced. Many of the small battery powered vehicles have the ability to last an hour or two, depending on how much data they are collecting and transmitting. Larger gas powered vehicles are able to increase endurance to a few days.

Endurance is not limited to UAV's though; any of the unmanned vehicles run into the same problem. To get the most information possible, functionality is added to these systems, increasing weight and power demand. This results in a need to refuel periodically during a mission. In a natural disaster or war, time wasted to refuel can result in lives lost. The need to keep systems running 24/7 is a crucial one.

Efforts have been made to increase the endurance of these vehicles, by combining solar powered vehicles with small battery capacity. For QinetiQ's high altitude UAV, Zephyr, this has significantly increased the availability of the vehicle to two weeks [8]. While this solar powered system moves towards the ultimate goal, not all of the unmanned systems have access to solar power regularly, or the surface area to provide the needed power per cell. To accommodate these cases, another method that provides power transfer on demand is required. Wireless Power Transmission provides a viable solution for these needs.

2. Wireless Power Transmission

While Wireless Power Transmission (WPT) is not a new concept, it is one that is underdeveloped for its age. Transferring power through electromagnetic radiation was first theorized by James Maxwell in 1873. Thirty years later Nikola Tesla proved Maxwell's theory by transporting energy using electromagnetic waves through vacuum. Soon after, in 1918, Heinrich Hertz also validated the findings in principle. [6]

It was not until the Klystrom and Magnetron were developed that the next big step in WPT took place. William Brown used microwave energy to power a small tethered helicopter. In 1968, Peter Glaser proposed the first solar powered satellite systems based on work done by Tsickovski, Oberth, and Brown. Following in 1979, a study was done by the Department of Energy (DoE) and NASA about the potential of creating a solar power plant in space and beaming the energy down to earth. The "Solar Power System" report created by NASA and the DoE concluded that while the technology was feasible, the size and cost of such a system was too high to pursue [6]. Since the 1980's, several demonstrations and concepts have been proposed.

Wireless Power Transmission is typically considered using one of several methods: inductive coupling, microwaves, and lasers. Inductive coupling works well for two objects that can come into contact (or be relatively close) to each other, such as charging toothbrushes or medical equipment. For power systems over longer distances, microwave or lasers are the two options.

Since microwave systems have advanced more over the years than lasers, many more demonstration systems and designs have been created using microwaves. The first experiment was William Brown's helicopter following his invention of the rectenna in 1964. The rectenna, which is short for rectifying antenna, is the receiver that is needed to capture the microwaves and convert them into electrical energy. In 1975 the Jet Propulsion Lab (JPL) developed a system that transmitted 30 kW to a 26-meter diameter rectenna over a distance of 1.54 km. 85% efficiency was achieved. In 1985, N. Kaya was able to use microwaves to transmit power in space. A ground to plane transfer of power via microwaves was completed by the Canadians in 1987. In the early 90's Japan joined the WPT work by transmitting microwave power to a small airplane in 1993 and a balloon system in 1995. Radio Frequency Identification (RFID) systems would also be a smaller scale of proven wireless power technology using microwaves. [6]

Laser demonstrations, while not as prolific, are still another method that has been investigated over the years. In the 1980's there was some presumably classified work done in this area. Between 2002 and 2003, Steinsiek and Schäfer demonstrated a ground to ground transmission of laser power to a rover. This system used a green, frequency doubled Nd:YAG laser sending a couple of Watts to a rover 280-meters away.

The space elevator contest sponsored by NASA was a recent driver to get laser WPT developed. Contestants were provided a vertically suspended ribbon that teams had to create a laser powered mover to climb 1 km. This competition focused mostly on power level optimization and was not concerned with beam control or steering aspects of a WPT system. The competition ended in 2009 with LaserMotive winning. Since then LaserMotive has published a white paper specifically looking at the use of laser WPT to power UAV's [5].

3. Laser versus Microwave WPT

Both laser and microwave power transmission has been demonstrated and studied over the last 30 years offering different advantages for different applications. Table 1 provides a quick look at some of the positive and negative aspects of each approach. For applications where size and weight are limiting factors, such as small unmanned systems or space applications, laser systems provide a big advantage compared to microwave.

The systems differ in wavelength for operation to minimize atmosphere attenuation which drives the properties of the overall system. "Microwave frequencies of either 2.45 or 5.8 GHz (0.12-0.05 m; both in the industrial, scientific and medical (ISM) frequency band), laser energy transmission takes advantage of the atmospheric transparency window in the visible or near infrared frequency spectrum" [6]. Figure 1 highlights that atmosphere opacity by wavelength. As can be seen, laser systems in the visible range are attenuated slightly, while microwave systems are transparent to the atmosphere. These wavelength differences determine the size of the receiver and transmitter needed to operate. The laser system at 1μm versus the 0.12-0.05 m microwave system can be achieved using significantly smaller transmit and receive components.

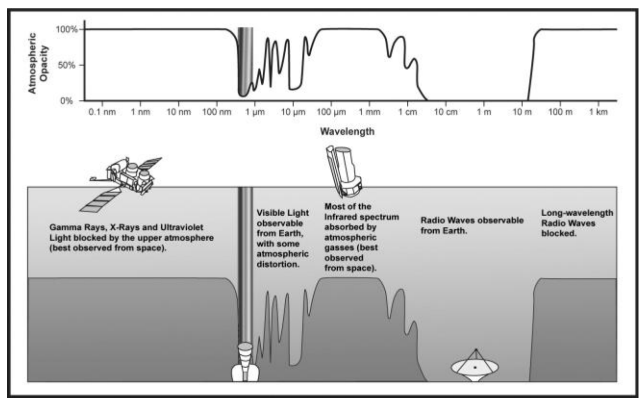

Figure 1: Transmission and absorption in Earth atmosphere (source NASA) [6]

Table 1: Laser versus Microwave Wireless Power System Advantages and Disadvantages (compilation of findings)

Type:	Microwave	Laser
Positives	- Little attenuation due to atmosphere - High efficiency rates - Electronic Beam Steering (well developed and implemented) - Ideal for terrestrial applications	- High Energy Density - Narrow, Focused Beam - Small receiver and transmitter system - Electronic Beam Steering (not very developed) - Ideal for space applications
Negatives	- Filtering needed to deal with side and grating lobes - Large transmitter and receiver (size and weight) - Low energy density - Safety systems necessary	- Atmosphere Attenuation - Low efficiency rates - High power systems require large cooling systems - Safety systems necessary

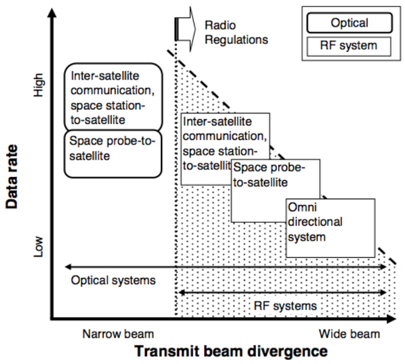

Figure 2: Classification of Satellite Communication Systems by Beam Divergence and Data Rate [6]

The energy density of the system also creates an advantage for laser systems. "Similar to the higher data rate achievable with optical data links (Figure 2), laser energy transmission allows much higher energy densities, a narrower focus of the beam" [6].

Electronic beam steering allows for minimal moving parts to be used in the system which increases overall system reliability. This was first developed for microwave antenna systems which was a clear advantage over laser based systems. A study done by "Schafer and Kaya demonstrated that a similar system is, in principle, also possible for laser based systems, by presenting a new concept for a retrodirective tracking system" [6]. This work, done in 2007, allows laser systems to have the same electronic steering capability as microwave systems.

The big drawback with laser systems is the reduced efficiency that comes from power conversions within the system. Where microwave systems can be created with an 80%-90% efficiency, laser systems are in the 10%-20% range. This low efficiency is attributed to many factors. Some factors can be improved with system design; others such as the atmosphere opacity of laser wavelengths cannot.

4. WPT System Components

A typical wireless power transmission system consists of several key components: transmitter, receiver, safety system, cooling, conversion electronics, power source, and pointing control system. Figure 3 shows these parts within a simple system. The two most important components being the transmitter and receiver that will be discussed more in this section.

The transmitter can be microwave or laser based. From the earlier discussion in Section 3, going forward it will be assumed that we are working with a laser system. A receiver in this case could either be, the traditional photovoltaic (PV) cells (convert the light into electric energy), or thermovoltaic cells (produce energy based on thermal gradient that is produced by the transmitter). Both receivers come with their own drawbacks when designing a system. Neither PV cells, nor thermovoltaics provide the highest efficiencies. To get better efficiencies, PV cells need to be optimized for the laser that is being used. The angle of incidence also needs to be taken into account in order to provide the maximum efficiency. Since thermovoltaic cells depend on the thermal gradient, its efficiency will be a factor of the environment. For lab settings this can be controlled, however applications like those discussed in Section 1 adds much uncertainty to the system if thermovoltaics are used.

As with any power system, safety needs to be integrated into the system. Some proposed designs desire to create a beam that is safe enough to walk through [4], while other designers prefer to have the beam turn off if an obstruction moves in the way of the beam [3]. Depending on the use of the system the power transmitted could range from a couple of watts to power a small vehicle to Megawatts to transmit power from a solar power plant in space to Earth. These safety concerns will introduce constraints on the overall system that need to be accounted for at all steps in the design process.

The power supply for the transmitter is an important design parameter within the system design. This power could come straight from the grid or from another power source (solar, battery, etc). An example of this would be a direct or indirect solar pumped laser. A laser system for a satellite would most likely be an indirect solar pumped laser. This indicates that the initial energy for the system is received via solar arrays, converted into electricity, and then converted into a laser beam. For many military applications or natural disaster scenarios, where electricity is not readily available, this might be the best choice for system design. Direct solar pumped lasers, on the other hand, is where the conversion to electricity is removed, and the collected solar energy converts directly to a laser beam. [6]

Cooling, pointing control, and miscellaneous electronics (data transmission, handshaking, etc) will be dependent on the specific design systems. The complexity of the cooling system will depend on the amount of power that is being transmitted through the system. A system of less than 100W can use something like Peltier cooling units [7]. As the output exceeds a couple of hundred Watts, a more complex and larger cooling system is necessary.

Pointing control is an important part of the system to increase the overall efficiency and safety of the system. Whether mechanically or electronically performed, the pointing accuracy will allow the laser to hit the receiver at the correct angle and avoid interference with other items in the environment around the receiver. As mentioned in Section 2 this is an area that has been neglected in recent work associated with the Space elevator contests.

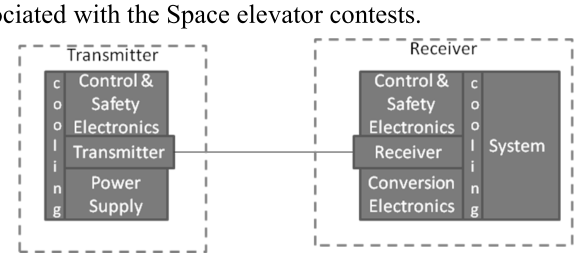

Figure 3: Simple Wireless Power Transmission System Using Laser Technology

4.1. Transmitter - Laser Systems

There are several types of lasers that exist for various applications. Trade-offs between the laser power (both average and peak), wavelength, propagation, and compatibility with the PV receiver need to be evaluated against system size, cost, and needed efficiency [1]. For example, the most common PV cells are Silicon (Si) and Gallium Arsenide (GaAs) with peak conversion efficiency at 900 nm and 840 nm respectively. Unfortunately, no laser has a high average power at either of these wavelengths [1].

Other lasers offer decent transition power levels with other parameters that are unacceptable. Chemical Oxygen Iodine Lasers (COIL) "demonstrated high power with moderately good beam quality (necessary for efficient propagation) but has high consumable costs and requires large infrastructures" [1].

The most common lasers for wireless power applications are Solid-State or Semiconductor (diode) lasers. The most popular solid-state laser is the Nd:YAG laser. The Nd:YAG laser uses neodymium-doped (Nd) yttrium aluminium garnet (YAG) crystal as the lasing medium and has a typical wavelength of 1064 nm. Studies by Steinsiek, Summerer, and Kawashima all use an Nd-YAG laser for theoretical and demonstration purposes [2, 6, 7]. Diode lasers, which are a subset of semiconductor lasers, operate using an active semiconductor medium that is similar to that of a light emitting diode (LED). Their frequency range most significant to WPT is the 795-830 nm range [6].

In addition to selecting the lasing medium necessary to meet requirements, the pumping process that the laser uses must be evaluated. Laser pumping is a process that raises atoms from a lower energy level to an upper energy level. Lasers can be pumped several different ways. Optically pumped lasers use light to perform the population inversion. A solar pumped, as mentioned before, can be done using sunlight directly or indirectly. Pumping can also be used to change certain attributes about the lasing medium. A Diode Pumped Solid State (DPSS) ND: YAG Laser can emit at 808 nm rather than the typical 1064 nm.

4.2. Receiver - Photovoltaic Cells

On top of optimizing the photovoltaic (PV) cells for the laser wavelength, the PV's overall conversion efficiency also has to be considered when developing a system. While cell material changes offer small advantages in efficiencies, adding an optical concentrator element to the PV cells can make a more significant impact.

The concentrator is a glass lens that allows the light to be more intense on each individual cell. "Higher light intensities enable higher efficiencies in converting sunlight to electricity, and greatly reduces the size of the PV cell required" [9]. At University of California, Merced it has been found that a Fresnel lens can be added as a concentrator on top of either, a silicon PV cell, or a multi-junction PV cell. The Fresnel Lens, by their experiments, have proven to be the best lens type for this application. They note, however, to keep the concentrator photovoltaic (CPV) cost effective the requirement of alignment needs to become less stringent, and a lens with a wider field of view needs to be used.

A Stretched Lens Area (SLA) architecture using Fresnel lenses was developed for space applications under NASA and Auburn University [11]. The Fresnel lens was used in combination with multi-junction PV cell receivers. Their design allows for 85% less PV material to be used per Watt of power produced. The "slope error tolerance of the symmetrical (Fresnel) refraction lens is more than 100 times better" than a conventional flat or reflective concentrator. The unique arch shape of this architecture is what produces the increased slope error tolerance. This shape would also provide an excellent aerodynamic surface if placed on a UAV.

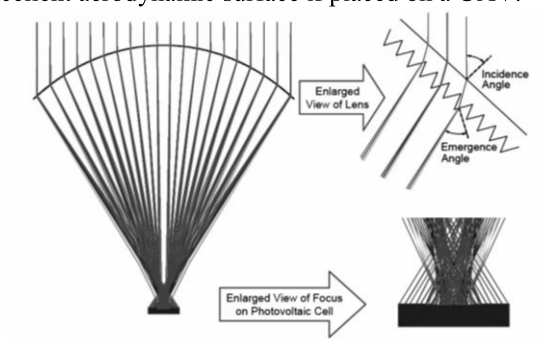

Figure 4: Symmetrical Refraction Lens with False-Color Rays Showing Wavelengths in the Photovoltaic Cell Response Range (0.36 µm to 1.80 µm for All Three Junctions of a Triple-Junction GaInP/GaAs/Ge Cell) [11]

The popular method of solar concentrators prior to O'Neill's work was mirror solar concentrators [11]. This design deploys mirrors at 60° to focus the solar rays as they hit onto the cell area. The problem that arises with this design is slope errors with the mirrors. The rays no longer reflect evenly on the cell area. Figure 5 shows the issues associated with these errors. The vibration environment on a small UAV would make it difficult for precise placement of mirrors like this.

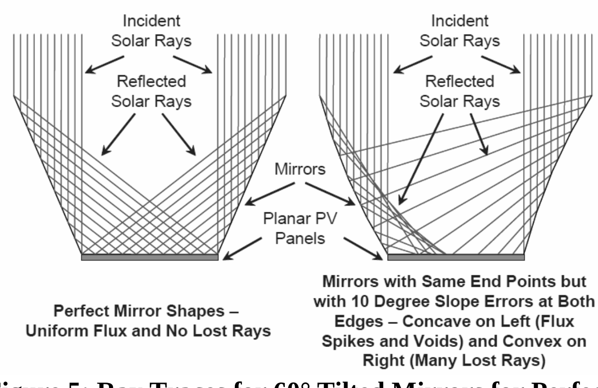

Figure 5: Ray Traces for 60° Tilted Mirrors for Perfect Mirrors (Left) and for Mirrors with Shape Errors (Right) [11]

In the early 90's the Photovoltaic Array Space Power (PASP) Plus Mission was the first deployment of this type of concentrator technology. The lenses were used on multi-junction cells (GaAs over GaSb). The design performed well and was able to withstand cell voltage excursions to 500V.

In 1998, Solar Concentrator Array with Refractive Linear Element Technology (SCARLET) launched with silicone Fresnel lens to focus sunlight with 8 times concentration onto triple-junction cells. The cells were able to produce 200 W/m^2, which was the best metric performed to date. The SCARLET was the basis for the O'Neill's SLA architecture development.

Figure 6 shows the deployment mechanism and the lens once deployed. The receiving cells in this design are triple-junction (GaInP/GaAs/Ge) cells. The efficiency found was approximately 27.5% when tested as NASA's Glenn facility. The lens efficiency for this design was near 90%.

Figure 6: Model Showing Basic Stretched Lens Approach [11]

Current products that exist in concentrator technology include panels by LightPath and 3M. LightPath has developed Gradium® glass solar concentrator lens. These cells were developed for space applications through a contract with AFRL. The product is said to offer a "wide field of view" to minimize the need for re-pointing [10].

5. Demonstrated or Proposed WPT systems

While demonstrated and proposed laser WPT systems are not as well refined as their microwave counterparts, several studies have been done advancing the technology and capabilities of such systems. Most of the studies focus on the overall system design and proof of concept activities, saving system performance improvements for follow-up activities.

5.1. PowerSphere (PS)

In Ortabasi's work, a device called a Powersphere (PS) is developed. The PS is "a high efficiency Photovoltaic Cavity Converter (PVCC) that is under development for Wireless Power Transmission (WPT)" [1]. The PS system, pictured in Figure 7, uses a "lamp pumped Nd:YAG laser operated in the CW mode, with a simple flat-flat cavity resonator" [1]. This design uses a near lambertian beam-diffuser to scatter the light onto the solar panels that reside around the cavity (Figure 8 shows half of the sphere). The properties of the lambertian diffuser allow the light to scatter such that the reflected light is of identical brightness, regardless of the viewing angle.

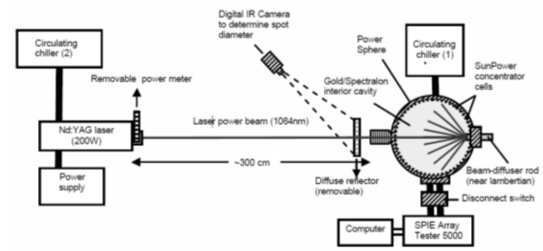

Figure 7: Experimental PowerSphere Setup at United Innovations in San Marcos, CA, USA [1]

Figure 8: The interior of the PowerSphere (one of the two hemispheres) [1]

The test system operated at about 14% efficiency using SunPower Silicon (Si) concentrator cells (HEDA312) [1]. The low efficiency was attributed to the fact that: "a) Si cells are not a good match for the 1064nm wavelength, b) the flux density inside the sphere is 30% less than one sun, though the cells are optimized for 500 suns, c) the standard AR coating for the test cells inside the PowerSphere have a reflectance of ~15% at 1064nm and, d) the cell population inside the cavity is only 24%" [1]. With corrections, Ortabasi believes 40% efficiency can be achieved, working towards 60% if better matched PV cell are used.

The PS design shows how optical methods and geometrical techniques can increase the efficiency of the PV cells. If pointing accuracy is a problem with the system, a reflective dish that concentrates the beam on a center disk containing PV cells (much like a satellite dish) could also be a technique worth exploring.

5.2. Powering of Remote Rover for Space Applications

In 2005 the European Aeronautic Defense And Space (EADS) Company developed a Space Power Infrastructure (SPI) project "aim(ing) at a commercial application of Power from Space in the long term, embedded in an international economical, political and legal network" [2]. EADS designed a system to power a rover from a distance of 30-200 m away. The application for this technology was looking at a rover that would be exploring a dark part of a planet, and a ground relay station that had access to sun. The ground relay station would capture the energy and transmit it to the rover. The paper investigates the development of a small demonstration system and analysis on how to build to a full scale model.

The test system was developed using a 5 Watt, Nd:YAG Solid State Laser. A 532 nm wavelength was used in testing for visibility purposes. The final system would be optimized to use a 1064 nm IR laser. Foil was placed around the cells to reflect light around the PV cells. This reflection provided feedback to the transmitter, allowing it to adjust pointing as needed. Gallium Indium Phosphide (GaInP) PV cells were used. GaInP has a 1.85 eV band gap and was "optimized with respect to the Gaussian laser beam profile" [2]. Based on the measurements made with the test system, it was determined that a 40% efficiency could be achieved.

Building on this initial test system, a second test system and third demonstration system were proposed. The second system would have a stationary laser transmitter with a relay airship, and a mobile rover. Its design would increase the power level, increase the transmission distance, try to improve the pointing accuracy, and potentially include data transmission capability. The demonstrator system could be run off the International Space Station and evaluate the ability to beam power to earth. This work was proposed to discuss the possibilities of WPT for remote powering of rovers on exploratory missions in space, and lay foundation for eventual Solar Power Plants.

5.3. *Powering of Unmanned Systems*

In Kawashima and Takeda's work, students developed a laser WPT system to power small autonomous vehicles [7]. Three systems were designed and tested at an indoor facility. The first was laser powering a rover. A 60 W laser diode was driven through a 400 µm fiber, transmitting to a 70 cm diameter solar panel receiver. The transmission was done at a distance of 1 km and produced a 20% overall efficiency.

The second setup used a small kiteplane. This system used a 200 W, 808 nm laser diodes driven through a 400 µm fiber to a 30 cm diameter receiving GaAs solar panel. GaAs provides 40% conversion efficiency per cell, to result in an overall panel efficiency of 25%. The average power measured on board was about 40 W. Figure 9 shows the system configuration for the kiteplane test. This system required a Peltier cooling system to be used due to the power levels.

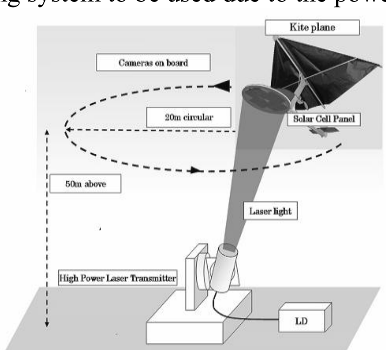

Figure 9: System configuration of a laser energy driven kiteplane [7]

A third test system was developed using a small helicopter shown in Figure 10. This system used a 530W laser and the same GaAs receiving solar array as the kiteplane. The array was placed under the propellers to provide the cooling needed for the system.

Figure 10: Helicopter with a vertical solar panel underneath [7]

5.4. *Current Product Development in WPT*

PowerBeam is a small company that has already started to explore the commercial options of WPT [3]. Using lasers, PowerBeam has developed small, safe transmitters and receivers to power things like speakers, computers, and televisions. Their system consists of a number of IR lasers on the transmitter side, and a PV cell detector on the receiving end. The laser operates at 1400+ nm with a collimated beam. This allows the beam to traverse relatively large distances (1 m to 100 m) with minimal loss in power or efficiency.

LaserMotive is another privately owned company, that is developing systems in WPT. While most of LaserMotives work was concentrated on winning the space elevator competition over the past few years, they recognize the importance of what they developed. LaserMotive released a white paper in March of 2010 about how WPT laser systems could be used to power or recharge small UAV's [5]. Figure 11 shows LaserMotives proposed systems.

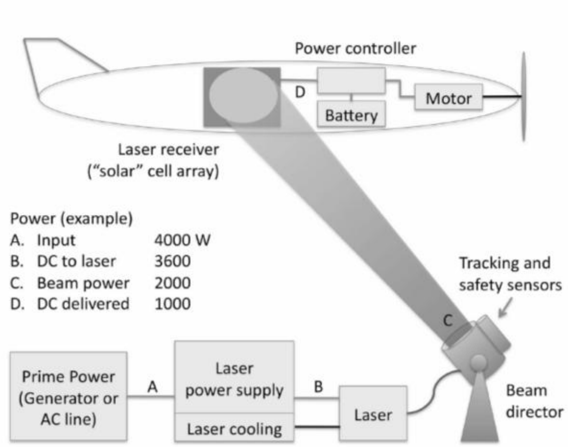

Figure 11: Schematic diagram of power beaming to UAV [5]

Initial concepts would look to use a near-infrared laser diode with >50% DC power into light efficiencies. For longer distances, a diode pumped fiber laser would need to be used. This change would create a lower divergence beam, smaller transmitter, but would increase the cost of the system.

PV cells would be the optimal receiver due to how developed the technology is currently. The cells for such a system would need to be matched to the laser wavelength and beam intensity to provide the best efficiency possible. [5]

LaserMotive highlights UAV applications of interest to be: station keeping, extended/multi-mission operations, and unlimited patrol. A safety system is also discussed that would shut the beam off if the path was blocked for any reason. The white paper provides the first real step towards laser recharging and identifies future steps that need to be taken.

6. Conclusion and Research Area Needs

While this study shows substantial research and test systems that have been completed in the area of WPT, all the authors' list similar future work opportunities.

The top areas of need include:

- Tests in increased power levels
- Tests with increased transmission distances
- Increase in Efficiency
    - On the front end, the electric to lasing conversion
    - On the back end, the beam to electric conversion using PV cells
- Improved Pointing Accuracy
- Development in efficient lightweight cooling systems
- PV cell development to better match lasing wavelength

While the first two areas are more suited for industry, the last four provide room for academic development. As mentioned, increasing the efficiencies of the PV cells can come from using optical techniques like concentrators on the cells, or methods such as the work being done for the PowerSphere. Pointing accuracy through electronic or mechanical steering seems to be an area not thoroughly explored by this community. This area might provide the most opportunity for discovery. Cooling techniques and PV cell matching are areas that will most likely need an element of academic and industry to get the most accomplished.

Wireless Power Transmission has felt a resurge in the last several years for a number of reasons. The military surge in investment for autonomous vehicles, will be a large driver for innovation in the area of WPT. Socially there is also a need for clean renewable energy. NASA continues to invest heavily in robotic missions, where power is always an important and limiting factor. Laser WPT provides an answer for all these needs, and has the proven potential to be extremely successful.

7. Acknowledgment

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