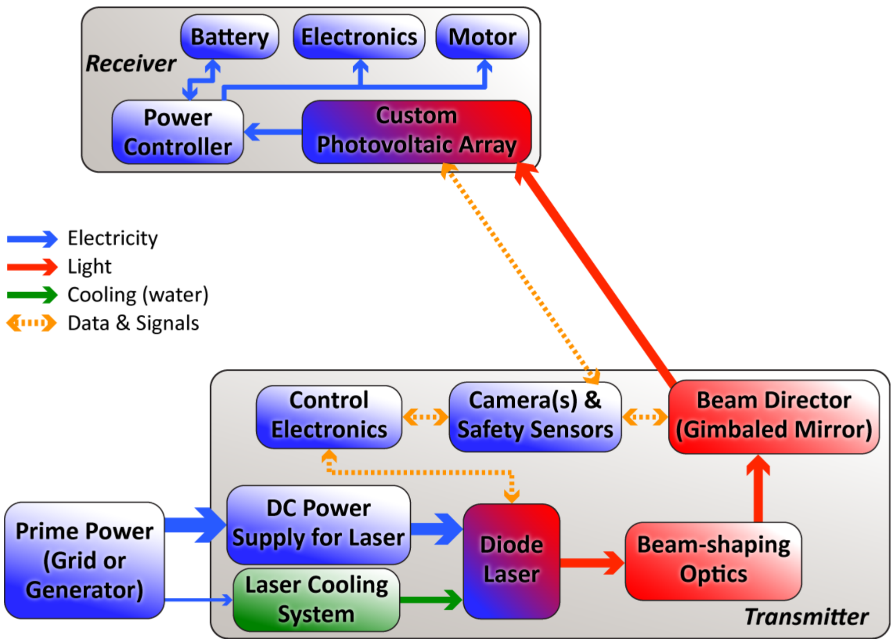
LASER POWER BEAMING FACT SHEET

I. What is laser power beaming?

Laser power beaming is the wireless transfer of energy (heat or electricity) from one location to another, using laser light. The basic concept is the same as solar power, where the sun shines on a photovoltaic cell that converts the sunlight to energy. Here, a photovoltaic cell converts the laser light to energy. The key differences are that laser light is much more intense than sunlight, it can be aimed at any desired location, and it can deliver power 24 hours per day. Power can be transmitted through air or space, or through optical fibers, as communications signals are sent today, and it can be sent potentially as far as the Moon.



The benefits of wireless power beaming include

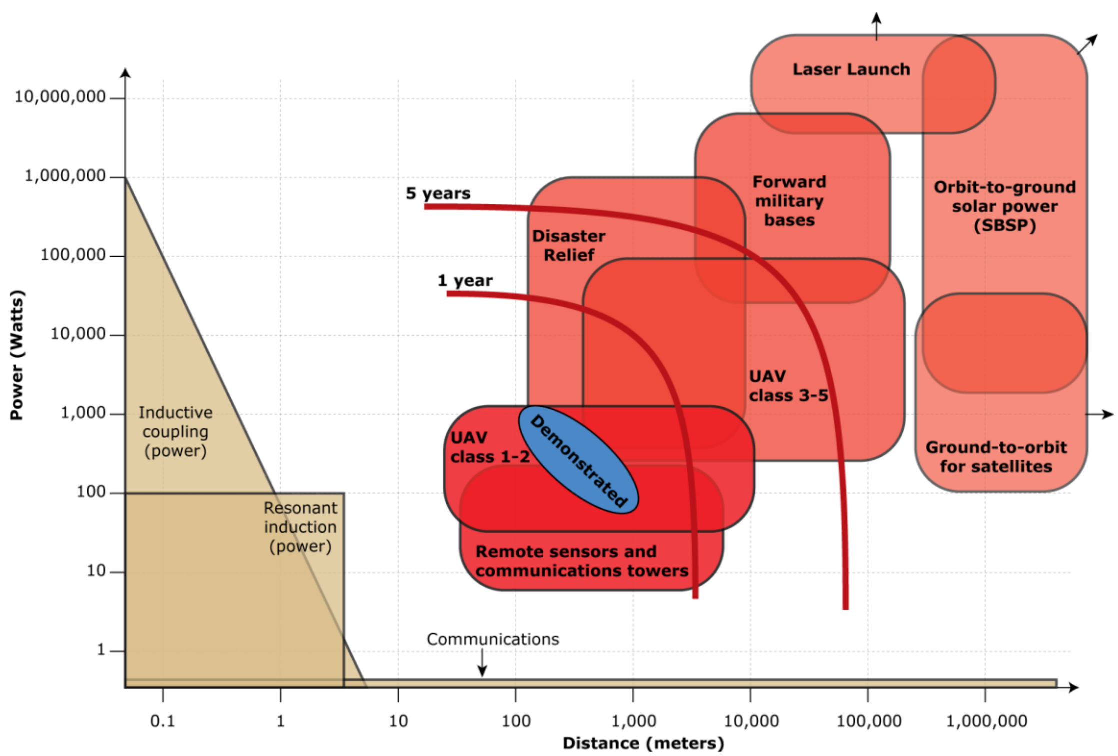
- The narrow beam allows greater energy concentration at long distances;
- The compact size of the receiver allows easy integration into small devices;
- Power is transmitted with zero radio frequency interference (e.g. to wi-fi/cellular systems);
- Electrical power can be utilized for applications where it was previously uneconomical or impractical to run wires, including aerial refueling of UAVs and other aircraft;
- Power beaming can use any existing power source to power the laser; and
- Power can be delivered through free space or over fiber optic cable.

II. What are the uses for laser power beaming?

Although still largely in the R&D stages, wireless power has many potential uses in the real world. These include powering air, ground, and underwater vehicles, replacing electric power wiring and transmission lines in difficult places, and even launching rockets into orbit.

Some specific applications in which wireless power will be the preferred power solution are:

- Small unmanned aerial vehicles (UAVs), whose users demand longer flights and power-intensive capabilities, yet prefer quiet, reliable electric motors. This is a high military priority.
- Unattended sensors, including underwater, increasingly used for military, border security, science, and industrial applications from oil exploration to agriculture.
- Unmanned underwater vehicles, such as those used for oil exploration and subsea structure inspection, where the weight of copper wire cables significantly impedes their usefulness.
- Telecommunication relay towers are often located far from roads and power lines, and frequently at sites where weather, terrain, or even appearance limit the use of solar panels.
- Disaster relief. Whether it is providing power for communications and hospitals after an earthquake destroys the infrastructure, like in Haiti, or powering water cooling pumps to prevent a nuclear meltdown, like in Fukushima, a Navy shipped anchored offshore of a disaster area could beam power in for emergency response.
- Forward military operating bases. Not only is fuel delivery expensive, but more than 1,000 Americans have died in Iraq and Afghanistan hauling fuel for forward military operations. Flying in fuel increases the delivery cost by a factor of 10.
- Low- or zero-pollution hybrid or all-electric aircraft, from personal air taxis to airliners, could be powered over most or all of their range by a network of laser stations. Boeing is targeting 2035 for an all-electric commercial aircraft.
- Electric power from space-based power plants can be delivered to the ground by laser.
- Cheap, routine space access, via rockets with inert propellants heated by ground-based lasers.
- A lunar base will require power other than solar to operate throughout the two-week lunar night. NASA has concluded that laser power delivered from Earth is preferable to building a nuclear reactor on the Moon.



III. History of wireless power

Although wireless power is a promising technology for the 21st century, the concept is not new. In fact, rudimentary tests demonstrating the transmission of electrical energy without wires were conducted more than 120 years ago by Nikola Tesla, a Serbian scientist whose patents and theoretical work form the basis of the modern alternating current electrical systems and the modern AC motor.

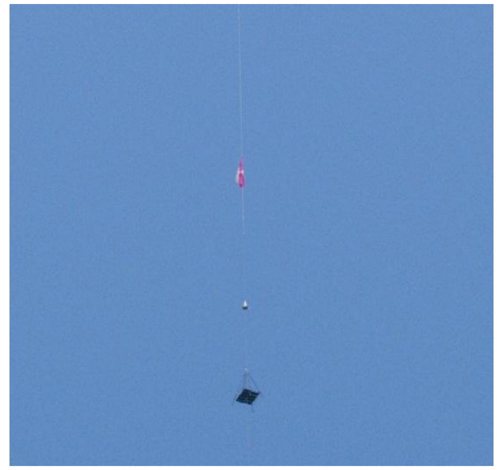
The first person to integrate all the elements of wireless power into workable system was William C. Brown, an American electrical engineer who helped to invent the crossed field amplifier in the 1950s. One of the pioneers of microwave energy for wireless power transmission, Brown published the first paper in on the topic in 1961 and later demonstrated the technology with a model helicopter powered by wireless microwave beam. Brown conducted additional developments in the field from 1969 to 1994 while affiliated with Raytheon. His achievements there include beaming 30 kilowatts of energy over a distance of one mile at 84 percent efficiency.

In 1968 American scientist Peter Glaser proposed using wireless power beaming to transmit solar power from space to Earth. Space-based solar power plants would be much more efficient than Earth-based, and they would generate power nearly 24 hours per day. Satellites with solar panels would be placed in space, and power would be beamed to the earth using microwaves, which would then be converted to electricity and transferred to power grids.

Throughout the 1970s, the idea was studied by NASA and the Department of Energy, which concluded at that time that the cost to do so was prohibitive. In the ensuing years and as technology developed, the concept had been looked at frequently, with both microwaves and lasers proposed as the energy transmitters. In the 1980s, researchers began looking at the technology both for space-to-space energy transmission as well as for space propulsion. In the 1980s, a multinational group of researchers conducted tests using microwaves to power model aircraft, although the energy loss as the beam spread over long distances would be impractical for large applications.

While researchers continued various experiments using laser power beaming, such as demonstrating the feasibility of the technology for powering unmanned aircraft, until recently the power and cost of laser diodes – necessary for power beaming – have been a key barrier to the practical application of the technology. With recent advances in technology, however, laser diodes are becoming sufficiently powerful, efficient, and inexpensive to make the commercial development of the technology feasible. In fact, in 2007, the Pentagon released a study recommending the development of space-based power systems using laser power beaming as the energy source. In the study, the Pentagon found that if placed correctly space power systems could provide enough solar energy in a single year equal to all known oil reserves on Earth, provide power for global U.S. military operations, and deliver energy to disaster areas and developing nations. In addition to the U.S., other nations studying the idea are Russia, China, the European Union, India, and Japan, which is working toward testing a small-scale demonstration in the near future.

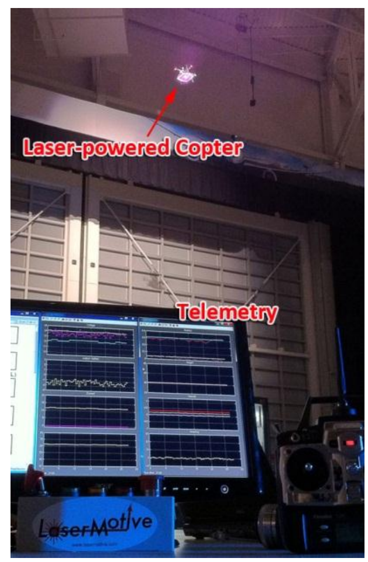
Between 2006 and 2009, NASA supported the development of wireless power technology through the Centennial Challenge Games, specifically the Power Beaming Challenge. Numerous teams competed to develop a wireless power system that could power a robotic climber to climb a cable one kilometer vertically with ground-based power. The final competition, held in November 2009, resulted in LaserMotive winning the competition and being the only team to successfully meet NASA's requirements (and actually doubling NASA's minimum speed requirement).



The records LaserMotive set in the 2009 competition include:

- Greatest distance for laser power beaming: 1 km (3280 ft., 0.62 miles)
- Most power transferred to a receiver: in excess of 1 kW
- Highest efficiency power beaming: more than 10 percent, DC power to DC power
- Fastest climbing speed up a cable at this competition: 3.97 m/s (8.88 miles per hour)
- Specific power in a laser receiver of ~500 W/kg

In October 2010 LaserMotive further advanced the technology by demonstrating wireless power delivery to an electric quadrotor helicopter (aka quadrocopter) in flight. The successful flight used a battery that would have enabled roughly five minutes of flight, instead, the vehicle flew for nearly 12.5 hours continuously, powered wirelessly by laser from the ground. This constituted 150x battery life. Multiple times during those 12.5 hours, the quadrocopter flew off the laser beam to demonstrate battery-only operation, then flew back within range of the laser beam and recharged its battery while flying.



The flight set the following records:

- Longest hovering flight duration for an untethered electric vehicle: Limited only by the venue; the Ascending Technologies Pelican quadrocopter and the LaserMotive power system were both capable of continuing indefinitely.
- Endurance record for any VTOL aircraft in this weight class
- Longest beamed-energy-powered flight of any type

In addition, the flight marked the following key milestones towards operational laser-powered UAVs:

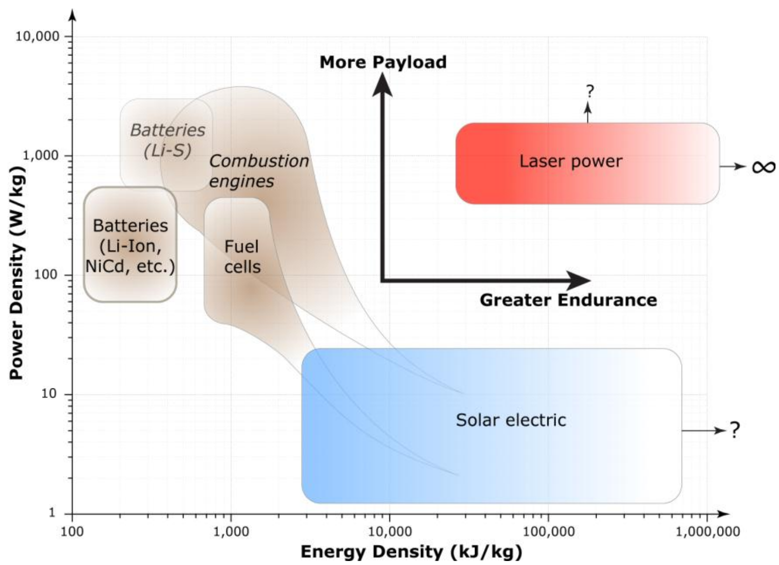
- Repeated fully automatic acquisition of UAV by laser tracking system
- In-flight battery recharging
- Automatic position hold in beam, with the laser tracking system controlling the UAV position
- "Class I" operation, meeting US and international laser exposure limits everywhere on the ground.

In the next significant step in the development of the technology, in August 2011 NASA issued three contracts for teams to investigate and design the architecture to use wireless power to deliver power from Earth to satellites in orbit and to use lasers to generate heat to launch rockets into orbit. LaserMotive is a member of all three teams. The results of this work, continuing through the second quarter of 2012, will advance the state of technology for a variety of uses of wireless power beaming.

The US Department of Defense is becoming increasingly interested in wireless power for a variety of applications across DoD, including powering UAVs, recharging soldiers' batteries in the field from an airborne transmitter, recharging sensors on the ocean floor, and delivering power to forward operating bases. It is likely that in 2012 DoD will begin funding laser power beaming technology development to make it commercially available.

V. Performance & Limitations

Both specific power (W/kg) and energy density (J/kg) are critical for many remote power applications, UAVs in particular. For a given power draw, greater specific power allows for more payload weight on a UAV. Similarly, higher energy density implies longer endurance, which is one of the biggest requests by users of UAVs. The figure below shows an approximate comparison of specific power and energy density for batteries, combustion engines, solar electric systems, and laser power receivers. Wireless power systems effectively leave the energy source on the ground, where power is easier and cheaper to generate.



LaserMotive has demonstrated wireless power systems with a receiver specific power as high as 800 W/kg. By comparison, lithium-ion batteries used in small UAVs are generally used with a specific power in the range of 200-500 W/kg.

Solar electric systems do not technically have an infinite energy density because batteries have a limited lifetime, so the endurance of a solar electric based system will depend on the number of charge/discharge cycles (daily, or more frequent, for sunlight-based systems) that the battery can support. In contrast, laser power does not need to turn off at night and can power the receiver continuously, with a battery required only during beam interruptions. Batteries or other energy storage are required at the receiver to handle beam interruptions.

With current laser cells, the deliverable power is limited mainly by cell cooling, and it can easily exceed 6 kW/m^2, or about 1 HP per square foot.

Range is also an important consideration and is limited primarily by source irradiance (W/m^2 sr) and source aperture size. Atmospheric scattering and absorption can degrade performance, but for many applications the beam has a strong vertical component or is at a reasonable altitude above ground level, either of which reduces atmospheric problems. Current diode laser technology and reasonable apertures can produce useful beam intensity at the receiver out to a range of ~10km. Longer distances can be achieved by switching to higher-quality sources (such as fiber lasers), although there is a penalty in cost and efficiency.

The biggest limitation of laser power beaming is that it requires a line-of-sight (either direct or reflected off mirrors) between the transmitter and receiver. Light weather can reduce efficiency and range, but heavy weather (heavy rain or snow, or fog) can block transmission altogether.

Overall system efficiency (DC power in through to DC power out) can be more than 25 percent, although in practice it is currently closer to 20 percent. Off the shelf diode lasers currently exhibit up to ~60 percent DC-to-light efficiency, and the DARPA SHEDS program demonstrated [http://www.nlight.net/nlight-files/file/technical_papers/SPRCS05_stanford.pdf] up to 85 percent efficiency. Current photovoltaics can achieve more than 50 percent light-to-DC efficiency, and monochromatic conversion efficiencies can theoretically go higher. We expect overall system efficiency to exceed 30 percent within several years, eventually approaching 50 percent.

V. Safety issues

While the word "laser" conjures up the idea of a death ray to many, the power density used in the LaserMotive wireless power systems is in the range of only 10 to 30 times sunlight. While this can certainly warm objects given some time, it generally will not burn anything that passes through the laser beam, such as vehicles, planes, or birds (and it took us 4.5 minutes to cook a hotdog).

The most efficient lasers currently operate at near-infrared wavelengths that are in the retinal hazard region, just beyond what ordinary human vision can see. Because these wavelengths are still focused by the eye, however, very low levels of stray or scattered light are potentially hazardous. Therefore special precautions are taken to eliminate eye hazards. Because stray light cannot be completely eliminated, LaserMotive will design systems to minimize stray light and protect animals from exposure to it.

Diode lasers are highly controllable. LaserMotive commercial systems will incorporate positive control systems that ensure the beam is disabled unless it is aimed at a proper receiver. They will also incorporate optical and other systems forming a “virtual enclosure” to prevent anything or anyone from entering the high-power beam.

For ground-dwelling and low-flying animals, a series of motion sensors around a laser transmitter can detect any motion and shut off the laser before the creature can get too close to the power beam. There is a need for protection from eye hazards for high-flying animals (including humans in aircraft) between the transmitter and receiver, and also those beyond receiver if it does not capture all the light. The multi-layered safety system will include hardware like a scanning LIDAR that will shut off the system as soon as an animal or aircraft approaches the beam, and then quickly reacquire the target when it is clear.

Longer wavelength light outside the retinal hazard region could be a better solution because it is not focused by the eye, and the safe exposure levels are 100 or more times higher than for visible and near-visible wavelengths. These longer-wavelength laser systems may be appropriate for some applications, and that list may grow in the future as their efficiency and cost improve. Such power beaming systems that are “eye-safe” (with respect to scattered light) can be built today, but with a real efficiency of only about 10 percent and at a much higher cost. As these component technologies improve with further development, more-efficient long-wavelength systems will open additional markets for power beaming.

VI. Current players

At present, there are a limited number of companies conducting research on wireless power. They fall into two categories: major aerospace companies such as Boeing, which are exploring the technology for powering UAVs and other large applications, and smaller privately held companies developing applications for specific, select applications. JDSU (a major laser and photonics manufacturer) offers power-over-optical-fiber systems commercially, but only for specialized very low power applications. LaserMotive is the first privately held company devoted exclusively to the commercial development of wireless power.

VII. Future directions

What can we expect to see in the future regarding wireless power? Certainly, as the technology evolves, costs for high power lasers are expected to continue to decrease, making the possibility of high power laser power beaming applications an increasing reality. Research will continue in the development of the technology for commercial use in several key areas, including unmanned aircraft and wireless electricity.

A tethered "instant tower," that is powered by laser over fiber optic cable, should be commercially available within a year. Commercial power systems for small UAVs should be available in about two years.

Whatever direction the market goes, LaserMotive plans to be a leader in the industry.