WIRELESS POWER TRANSFER TO A MOVING VEHICLE: EXPLORATIONS WITH THE KANSAS CITY TEAM FOR THE NASA/SPACEWARD POWER BEAMING CHALLENGE

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The Kansas City team recently took the silver medal in the 2009 NASA power beaming competition. The task this time was to move a climber up a vertical tether of 1km length at either 2m/s or 5m/s average speed for two different prize levels. KCSP, as one of only two teams, successfully climbed several times to over 500m on automated power-tracking with an 8kW Laser. For the Kansas City team the term "pirates" stands in the time-honored tradition of privateers. They take risks executing tasks on special funding, that their government is not willing to take, may it be catching merchant ships for booty or researching innovative concepts for space exploration. The talk tells about the road travelled developing for the power beaming competition, solutions discovered and issues encountered, from a personal perspective.

I. INTRODUCTION

Wireless power transmission using induction or capacitive transfer at proximity, in a near field mode, is increasingly popular even for consumer electronics. Power transfer at a distance was experimentally validated by Tesla[1] as early as 1891 and by W.C. Brown[2] with microwaves over 1mi in 1964 claiming an efficiency as high as 84% (but ignoring divergence). Power transfer at a distance is also called power beaming, since it typically involves power conversion to electromagnetic waves and back. Power beaming has had few applications so far due to some inherent limitations in the sender/receiver technologies but is becoming more interesting as power sources such as lasers gain efficiency.

The power beaming competition managed by Spaceward, one of the NASA centennial challenges, introduced additional constraints: the receiving apparatus has to be light and mobile, in principle following a development path enabling future aerial and space applications such as good potential to power UAVs for broadcast, networking, or surveillance. The space elevator community sees it as a test ground for climber technology suitable for a space elevator.

This paper describes in some detail the approach taken by the Kansas City Space Pirates team for the 2009 competition, including some information about the setup for the power source, optical design, tracking system, telemetry, PV array, competition results and lessons learned.

II. CLIMBING TASK

The task of the 2009 Power beaming challenge, as held by Spaceward/NASA at Edwards Air Force Base, offered a real world testbed for new approaches to power beaming.

A detailed description of the task and rules can be found in the competition manual[3].

This round of the competition solar power was explicitly excluded. On board power sources were as before restricted to power the control system and telemetry, but not the climb itself. Climber weight was restricted to 50kg but open at the low end. KCSP decided to build as small a climber as possible because the rating formula including payload favored small climbers.

After evaluating several other ideas Spaceward settled on providing the required 1km vertical race track by lifting a steel wire rope with a helicopter. Each team had to provide power source, climber, and end-stop.

Climb performance required to win a prize was 2m/s or 5m/s for $900k or $1.1M respectively.

III. POWER SOURCE AND CONVERSION

The company TRUMPF kindly sponsored a near infrared TruDisk 8002 disk laser for all it's teams, of which USST and KCSP made it to the final round.

Fig. 1: KCSP Tracking Box with exit lens, tracking mirror, and sheeting air tips.

The TRUMPF laser has 160µrad full divergence according to specs and 8kW output power delivered in a sub-millimeter fiber end at unspecified elliptical polarization housed in a standardized plug. It creates the 8kW from four active mirror disks in the laser cavity. The beam quality of the TRUMPF laser is truly remarkable.

Unfortunately the laser was only available for testing on less than a handful of occasions. The costs of those tests ran up quickly: each required availability of a large laser of the specified type, support from TRUMPF personnel, substantial range rental fees, and cost the team several thousand dollars to make a trip to the test location in Michigan or Mojave.

These full-up tests were therefore extremely limited, especially imposing limits on testing the configuration over the full distance of 1km, including specifically the optics, tracking, and power conversion components at distance.

At the climber, beam power was converted back to electrical with premium grade silicon cells. Calculations showed that from a power perspective the tradeoff using commercial cells with lower efficiency was viable for the climbing task at substantial savings over the $50k+ cost of custom solar cells. The motor, electronics, and drive mechanics were carefully optimized to operate with the tether at the given power and speeds.

IV. OPTICS

Cost constraints were always imperative for KCSP, especially in the beginning when sponsors like BARR with capabilities for expensive optics were not on board yet. Quartz lenses or large optics were impossible to fund. That restricted the minimum distance where the optics could start from the power laser. At 8kW only a diameter of 3cm or higher was considered acceptable for short term use of standard, affordable optic materials such as BK7. The beam had to diverge sufficiently, approximately 50cm from the fiber exit, to reach a power density low enough not to cause issues.

The optical design was conceived as bi-directional: a power path, the laser beam (NIR) from the bottom to the climber target, and a sensor path, returning from the active target on the climber (red) to a focal plane array split out for tracking.

Optica, a design tool based on Mathematica donated by Optica Software, was used to evaluate different one- and multi-lens designs, including zoom lens arrangements. Optica is very versatile, fully integrating the symbolic and high precision numeric capabilities of the Mathematica platform. Customizations, e.g,, to simulate material changes due to heating are also possible. The simulations showed that within the confinements of the box a divergent path through the beam splitter combined with a one lens arrangement offered the best combination of cost and result. The simulation also provided data on the adjustments necessary when switching wavelengths in the power path between a green pilot laser and the TRUMPF NIR power laser.

A well designed quartz lens that collimated the diverging laser beam into the beam splitter obtained from TRUMPF had to be removed. The power beam was then permitted to diverge through the beam splitter and only collimated at the exit lens, then deflected by the tracking mirror.

This 6” enhanced gold tracking mirror was optimized by BARR for high reflectivity at a 45 degree incident angle and two wavelengths, TRUMPF’s IR and the red beacon diodes of the active target, achieving 99.96% and 98.94% tested reflectivity respectively (Fig.2)

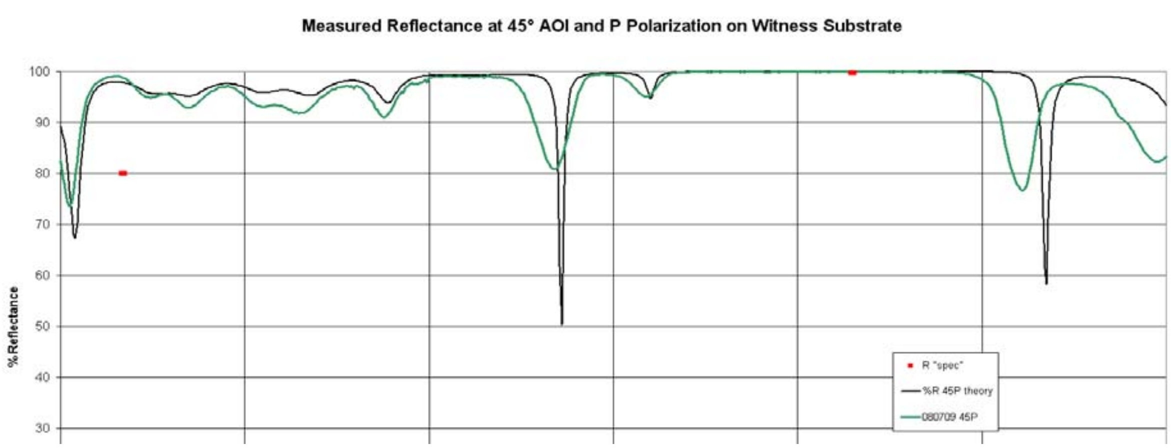

Fig. 2: Reflectivity of enhanced gold tracking mirror over wavelength, red bars mark wavelengths used, left for the red active target LEDs and right highest reflectivity for the NIR power laser)

Aspects of turbulence and several related concepts for active optics were considered and calculated but appeared to offer limited value over the relatively short distance of 1km. The practical environment at the competition later showed that dirt and dust of the desert posed more severe challenges. Often the dust significantly clouded power beaming capabilities and visibility given the amount of particles suspended in the air. The salty dust particles precipitating on any exposed optics also posed additional chemical challenges.

In the only laser test that was possible in Detroit for the full 1km distance an uneven power profile was noticed. The sub-millimeter fiber end of the TRUMPF laser was magnified to more than a meter diameter at the full range. This configuration was far outside of the usual designs for the TRUMPF laser normally used for welding. The apparent nonlinear donut profile consisted potentially of a mixture of several effects, including spherical aberration, uneven divergence from the beam splitter, and issues in the laser modes, e.g., caused by a potential misalignment of the laser fiber. To obtain the best possible options, KCSP and Asphericon worked out an aspheric lens design with 10cm diameter that corrected the spherical aberration component. The upgraded aspherically corrected non-imaging power beam was used in the competition.

V. TRACKING

Tracking systems typically consist of a sensor detecting a present value, e.g., position of a target, a control system that calculates updates and corrections from a previous value to the present value, and an actuation that adjusts the system to reflect the present value. Often other useful information such as time-derivative terms in first and higher order is added, enhancing the accuracy of the control system or substituting for lack of speed in the control loop.

Computer vision, which includes industrial machine vision, an area the sponsor National Instruments is known for, demonstrates capabilities of high speed input suitable for tracking. However, the option was discarded due to insufficient software development experience in the team and perceived complexity. KCSP's analysis showed however that a high frequency LED beacon, implemented as 16 red LEDs on a climber, could provide sufficient signal-to-noise ratio for a direct tracking signal at 1km under daylight conditions on a small focal plane array. A tracking beacon signal was implemented with LEDs blinking at high speed, optically split out from the in-line return path with a beam splitter, and selected with filters against the NIR laser background. Then the sensor signal was further processed via a small focal plane array, down-mixing and amplification implemented in custom hardware and further in the embedded real-time Labview environment using an FPGA.

Labview offered several canned options for control loop modules such as PID that could be adapted by KCSP to implement a high speed control system. We achieved 11ms updates at the competition. For the actuation component the main mirror was moved in two angles at a coarse level by motors capable of full range and a high speed voice coil system with smaller range. This was the only fully automated functional tracking system at the competition. And delivered a performance not typically seen outside of military applications.

VI. COOLING

With all the high power components cooling was essential.

In the ground setup, several components were water cooled to offset the heating by the 8kW laser. Some of the larger optical components did not require water cooling due to their high efficiency (reflectivity or transparency) but were cooled by sheeting air nevertheless. This also helped in the dusty competition environment. Cooling is one of the most stringent limitations of a climber, even in the atmosphere as in the competition. Anything but air cooling is prohibitively heavy for climbers. Good air flow was essential to keep the climber operating since PV array performance degrades with rising temperature. The climber can of course also radiate heat but at the high laser energy flux of the competition radiation alone is insufficient for a stable operating environment. A Space Elevator climber will have to rely on radiation only once it leaves the atmosphere and efficiency will have to be improved.

VII. CONTAINMENT

The whole setup was "double boxed" in the form of a portable box as shown in Fig. 1 for the laser and tracking arrangement and then again in a full trailer for further containment.

VIII. RESULTS

The tasks of the power beaming challenge appear deceivingly simple. Even school classes have participated in the past. The tasks however escalated quickly over a few years to a complexity level where only three teams participated in the final round at Edwards 2009. This complexity level always brought more issues for newcomers and made hybrid systems, that offloaded some of the complexity to human skills successful. That includes KCSP's helio-beaming from 2007 and LaserMotive's winning approach in 2009 with manual tracking.

Integration remained the number one challenge for most teams since all up testing of the full setups is prohibitively expensive outside of the competition. LaserMotive proves this point with a win, already using a laser setup in 2007 and full access to long range testing at their home base for 2009.

KCSP finished second with a 750 m best climb, and reaching 4.5m/s speed, with a well working tracking system and optics that could manage the full distance, by far the lowest overall funding, ~$100k including ~$35k entry fees and the lightest climber of all teams, 1.2kg vs 5.3kg and 8+kg. Some hang-ups that went undetected prevented better final performance. That included a hard stop imposed by the Laser Clearing House in the focus setting, which prevented the system from focusing as designed and tested, failing to deliver sufficient climb power at over 700m.

Another limitation is certainly the PV array. Only custom PV cells permit the intensity of ~10 suns to be used efficiently. Such an array would have required us to raise $100K in the first few months of the competition but probably it would have more than doubled our performance.

KCSP including anchor sponsors such as TRUMPF, Thorlabs, BARR, National Instruments certainly proved itself as a world class team to be reckoned with and I am thankful for the opportunity to participate.

IX. WHAT'S NEXT

Despite a challenging funding situation at NASA, the competition for this new technology is not done yet. $1.1M NASA prize money is still available. Spaceward contemplates to organize a rematch for the 5m/s prize component in Spring 2011. KCSP is therefore looking for funding or sponsorship for a high-efficiency PV array to compete in this task with a high likelihood of success. We can also offer expertise for power beaming and tracking applications. Please contact us at http://kcspacepirates.com or the author per email.

Fig. 3: A lit climber rising into the sky on the power beam on the left and team captain Brian Turner carrying the MaryAnn climber in the desert at Edwards on the right.

[1] Tesla, 1891, History of Wireless Energy Transfer, http://en.wikipedia.org/wiki/Wireless_energy_transfer, e.g., patent 454622.

[2] W.C. Brown, http://en.wikipedia.org/wiki/William_C._Brown

[3] Manual, Power Beaming Competition 2009, http://www.spaceward.org/documents/elevator2010/Handbook-pb2008-0.97.pdf