A Solar-Powered Near Earth Object Resource Extractor

Thilini Rangedera, Ravi Vanmali, Nilesh Shah, Waqar Zaidi, Narayanan Komerath

Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology,
Atlanta, GA, 30332-0150, U.S.A

ABSTRACT

This paper is an offshoot of a project to study means of forming massive radiation-shielded structures using Near Earth Object (NEO) materials. The topic is the conceptual design of a solar-powered robotic craft to land on, attach to, and extract materials from, a typical NEO. A solar-powered trajectory to a candidate NEO is used to estimate requirements. A reconfigurable solar sail / collector is the primary propulsion and power source for the craft. Following a journey of nearly 5 years, the craft will use a unique pulsed plasmajet torque-hammer concept to attach to the NEO. The basic cutting tool element is a solar-powered Neodymium fiber laser beam sheathed in a plasma jet, expanded through a truncated aerospike nozzle. Two telescoping, rotating arms carrying a total of 60 such nozzles at the ends of "fingers" enable the craft to dig and "float" out NEO material at a rate adequate to build a 50m diameter, 50m-long, 2m thick, walled cylinder within 19 days. The system is also amenable to applications requiring excavation of a large mass of near-surface material for resource processing. The present design appears to close with a total payload to LEO of 37,500 kg, with a total mass of 30,000 kg including the sail/collector at earth escape. The primary consumables on the system are the plasma gas for cutting and maneuvering, and electrodes of the plasma cutters.

1.0 Introduction

Near Earth Objects (NEOs) offer convenient low-gravity sources of the resources needed to extend a permanent human presence beyond earth, and build a Space-based economy. In previous work[1], we have considered the concept of automatically forming closed wall shapes such as cylinders in Space from solid material of random shape and multidisperse size distribution, using "Tailored Force Fields". This concept opens the way to building stations with walls massive enough to provide long-term radiation shielding, and strong enough to operate as 1-G artificial gravity modules. In Vanmali et al[2], we laid out the requirements for such a mission to an NEO imagined to be at earth-sun L-4. Here we consider the conceptual design of a robotic machine to do surface excavation on a typical NEO.

Previous work on extraterrestrial resource exploitation has considered harpoons[3] to anchor a drilling craft onto the surface of a NEO in order to drill out material for mining. A nuclear-powered bucket-wheel excavator has been proposed[4] by the Colorado School of Mines, to roll along the lunar surface and scoop up material with a bucket wheel. This machine uses its own weight (on the lunar surface) to apply downward pressure to dig into the ground with the teeth of each bucket. Such a device is suitable for loose sandy material found on planetary surfaces, filling the role of a lifting machine rather than a cutter. The NASA Deep Impact mission demonstrated automatic adjustment of its navigation at high speed to intercept a comet. This demonstrates a solution to part of the problem of robotic NEO rendezvous.

Our interest is in developing a solar-powered solution that can then be used repeatedly away from earth for long-term resource exploitation. The craft thus considered has to be autonomous and versatile. The Rock Breaker described in Ref. 2 (see Figure 1) is a multipurpose robotic craft designed primarily to cut rocky material to construct habitats. The craft is to independently rendezvous with a NEO and attach itself. The craft would use plasma jets and laser cutters in order to cut out 20 cm cubic blocks and make them float into a helical cloud away from the NEO. The TFF craft would then form a resonator around the cloud of construction blocks in order to begin the shaping process. The design shares many features with a craft that will be required for any extra-terrestrial resource exploitation project that hopes to use low-gravity NEOs. In previous work, we conceptualized a trip to Earth-Sun L-4. In this paper, we specialize the mission to a 'typical' choice of Near Earth Object.

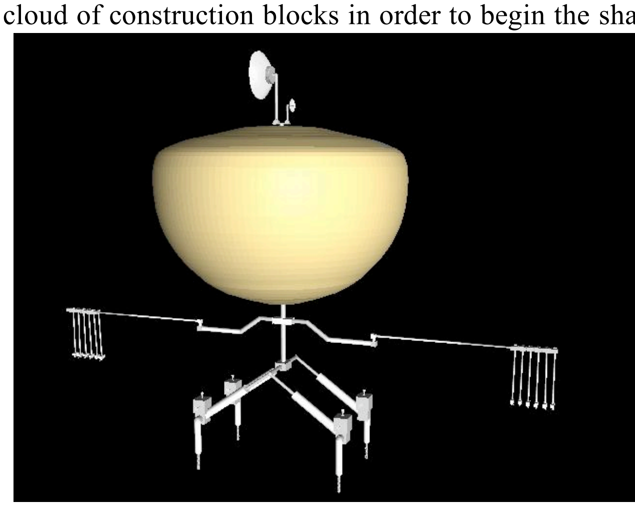

Figure 1: Conceptual Drawing of the Rockbreaker robotic NEO **resource extractor craft. From Ref. 2**

1.1. NEO Population

NEOs are classified by absolute magnitude, semi-major axis, aphelion/perihelion distance, and composition. The NEO population is composed of asteroids, active comets, and extinct comets. Subcategories of the NEO population are Atens, Apollos, and Amors. Their size range from dust-sized fragments to objects tens of kilometers in diameter[5]. The lower limit of detectability is generally on the order of a few hundred meters diameter. Roughly 1000 NEOs have been found, of which around 100 are accessible with mission delta-v comparable to that for lunar missions, though the mission time may be on the order of years[6]. Christou[6] provides guidance in selecting NEO mission destinations. Objects in orbits similar to that of Earth are the easiest and fastest to reach. An orbit eccentricity range of $0.3<e<1.2$, and an inclination limit of 5°, along with limits on object size, still leaves at least 27 possible NEOs. One possibility is 1996 FG3.

2.0 Requirements Definition for the Mission

The requirements for the Rockbreaker are given in Table 1, modified from Ref. (2).

2.1. Solar Sail

Given that most early NEO missions will be near the orbit of Earth, and these missions are not time-critical unlike human spaceflight, solar sail propulsion is an attractive choice. Since the solar sail is a low thrust spacecraft, it is difficult to find the best possible trajectories because it involves an in depth knowledge of numerical optimal control methods. Our approach at this conceptual design stage is to use trajectories calculated by other researchers, and scale the sail area needed using the payload-to-sail-area ratio.

Table 1. Mission requirements of the Rock Breaker

Requirement	Assumptions / choices
Single unit launch from Earth.	Avoid on-orbit assembly costs.
Travel to L-4 using solar propulsion	Minimizes launch mass and takes advantage of the 1 A.U. destination.
Rendezvous with a low-gravity NEO	NEO size is only a few kilometers.
Attach itself to the NEO in order stay anchored while cutting	Removable attachment means suitable for many sorts of surfaces.
Cut out a large amount of material in the form of discrete blocks, within a short time and loosen the blocks enough to float apart at controlled speeds.	Discrete blocks is a conservative choice; blasting is presumed to be unacceptable because of poor control on ejection velocity
Detach itself and move to another location on the same NEO, or leaving the NEO.	Craft used for repeated quarrying/ assembly/ resource extraction, with possible refill of cutting / maneuvering gas.
Use manipulator arms and power delivery systems to inspect cut pieces, and/or subject them to heating and gas jets for preliminary sampling and separation.	Plasma or laser heating, or microwave heating. Detectors and probes at arm tips.
Hold and guide large sintered pieces into position. Weld/ sinter them in place	Entire craft to maneuver, and robotic arm for precision.
Move to another NEO to quarry resources for future consumption	Redeploy solar sail.

Dachwald and Seboldt[7] used artificial neural networks (ANNs) along with evolutionary neurocontroller algorithms (EAs) to optimize for solar sail craft trajectories. We use their calculations of a solar sail mission to 1996FG3 "InTrance". A total sail craft mass of 148 kg (75 kg payload and 73 kg sail assembly) would have a 2500 sq.m sail area. Characteristic acceleration was on the order of 0.14mm/s^2. The transfer time was 4.15 years starting from earth escape. The characteristic acceleration is due to the solar radiation pressure (SRP) acceleration acting on the solar sail that is oriented perpendicular to the sun-line at 1 AU. Technology advances can be used to increase sail area for the same mass, thereby increasing the characteristic acceleration and reducing the transfer time significantly[5]. Alternatively, the total craft mass can be reduced. The Dachwald/ Seboldt design envisages total sail craft loading of 59.2 g/m^2. Scaling the sail area needed for the same trajectory, we see that the sail area needed for our mission would be 833,000 sq.m, and the total craft mass, for a 25,000 kg Rockbreaker craft, would be 49,333 kg. Recent experiments[8] have demonstrated a nested sail deployment concept, which promises area density of 0.01 kg/ m^2. With this technology, the sail mass can be reduced, and the sail area required is less than 510,000 sq.m. The total mass at Earth escape would be just over 30,000 kg, consisting of a 25,000 kg Rockbreaker craft, and a 5080 kg solar sail assembly.

3.0 Power Generation and Transmission

As the craft reaches its destination, its systems are "woken up". The 0.5 sq. km solar sail is formed into a solar collector, focusing sunlight directly to the power supplies of laser system, and on high-intensity solar cells to power other systems. In Ref. 2 we had proposed not locating power conversion systems on the Rockbreaker, since they were believed to be quite massive. Instead, they were to be located on the "Tailored Force Field" craft used to form the rubble cut up by the Rockbreaker into structures of desired shape. This posed challenges in beaming microwave power from the TFF craft to the Rockbreaker.

Recently, efficiencies of up to 38% have been achieved in the laboratory[9] in converting broadband sunlight directly to 1064-nm laser radiation using a Cr_2-doped Nd-fiber laser. This breakthrough is well suited to our application, since the primary tool used by the Rockbreaker is a Nd-fiber laser cutting tool. We can replace the Nd fiber laser with the Chromium-doped Nd fiber laser, and eliminate the need for conversion equipment to go from solar power to DC and then microwave. This is a huge mass saving, and it removes the argument in our previous work for tying the Rockbreaker to beamed microwave power from converters on the Force Field Tailoring craft.

4.0 Cutting System

The system conceived to cut material from the surface of the NEO is adapted from what Ref. 2 proposed for the mission to cut building blocks for a habitat module. It consists of six lasers each of 25KW, conveying pulsed beams to 60 nozzles arranged at the "fingertips", five to each arm, of 12 cutting arms, each laser beam sheathed in an annular plasma jet.

4.1. Laser Cutter

We propose evolved versions of the above laser to perform most of the cutting functions of the Rockbreaker. As described in Ref. 2, laser cutting tools have very low tool attrition[10,11], enabling maintenance-free operation for long periods with a variety of materials. The laser offers the highest power density available in the industry[12] and are two orders of magnitude faster than rotary drills for rock drilling[13]. The Nd fiber laser offers 10 w/kg and long operating lifetime[14,15] exceeding 100,000 hours[16], compared to 10,000 and 25,000 hours respectively for Nd-YAG and CO_2 lasers. A single fiber strand of a few microns can already generate and deliver over 1kW; this is expected to rise considerably[17,18,19,20].

A typical 700W fiber laser generates a beam intensity of more than 50MW/cm^2. A beam power density of less than 1kW/cm^2 sufficed[21] to cause thermal spalling of sandstone and shale, both of which have similar densities to silicon dioxide. The major uncertainty about NEOs is their composition. Given this uncertainty, the latent heat of melting of silicon dioxide was used in our calculations, assuming that 25% of the energy required for melting sufficed to crack the material. Fusion cutting, where laser energy melts and cracks the material, and a gas jet blows out the debris, requires only 10% of the power and 3% of the time for vaporization cutting[22].

4.2. Plasma Cutting Mechanism

A plasma jet sheath around the laser beam was proposed in Ref. 2, to blow away the material being heated and fractured by the laser, and expose fresh material to the laser beam[23]. Non-metallic NEO materials are amenable to a non-transferred plasma jet, where the torch nozzle becomes the anode. The pressures, standoff distance and nozzle expansion ratio are parameters used in optimizing the cutting trench width and the stagnation pressure exerted on the cut blocks (see Figure 2) to move them in desired directions (including the original objective of floating them away from the NEO for the construction application).

The electrodes are consumables that require periodic replacement; currently at less than 1000 hours. Generating a thin jet sheet in vacuum presents substantial difficulties, for which the aerospike nozzle provides some solutions. The storage volume and mass on the craft limit the amount of gas that can be carried for the plasmajet, so that minimizing the mass flow rate is critical. Electrode attrition and gas mass severely restrict use of the plasmajet.

4.3. Hybrid Aerospike Cutting System (HACS)

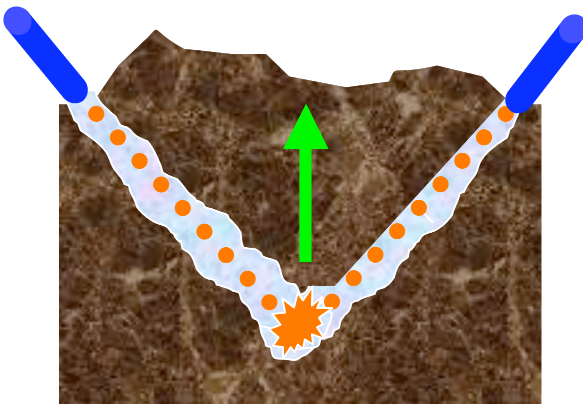

Figure 2: HACS operation, showing force exerted on the blocks by the plasmajet

A hybrid laser and plasma cutting system is proposed for the Rock-Breaker design. The main cutting tool that breaks up the surface material is the laser, while the plasma jet finishes the process by removing waste material from the trench and pushing the block towards the TFF craft. The HACS is lowered from the craft on a vertical pillar. HACS two main booms and can extend from the craft using its telescoping feature. At the end of each boom are 6 arms to lower 10 cutting nozzles each to the ground. Contained in each arm is a laser. The two arms rotate around the pillar in the vertical axis. The outcome is a spiral-cutting pattern. The rotor design, spiral pattern, and telescoping arms maximize the surface area covered by the HACS, and thus the amount of material that can be cut when the craft is anchored in one location. Ref. 2 described an optimized cutting sequence to generate the most cut blocks in minimum time. This is matched to the rotating/telescoping arm and multiple-fingers design.

4.4. Truncated Linear Aerospike Cutting Nozzle

A linear truncated aerospike nozzle[24] design is employed, similar in concept to that in the X-33 vehicle. The linear design stacks several modules to produce an effective “knife edge”. The laser beam is directed through the truncated base into the recirculation zone downstream, which adjusts itself to the pressure of the jet, forming a virtual spike. The laser beam is thus sheathed in a high-speed plasma jet, while the flow immediately in contact with the laser delivery lens remains at a low speed. The jet sheath and the recirculating base flow region protect the delivery lens from abrasion.

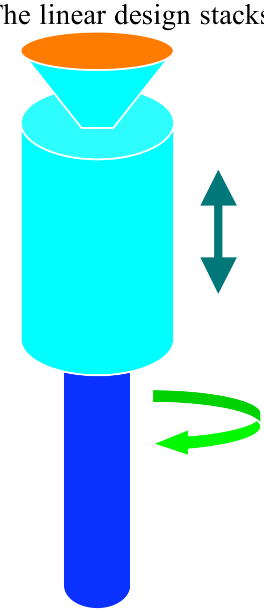

Figure 3: Impact Driver

5.0 Integrated Rendezvous-Anchoring Maneuver-System (IRAMS)

NEO rendezvous is complicated by NEO spin/tumble, which will demand considerable maneuvering delta-v. Reactions from any cutting operation must be absorbed by anchoring the vehicle on the surface of the NEO. We use a concept derived from the Impact Screwdriver that converts an axial, impulsive load to torque, matching the dynamics of the system to a pulsed solid-grained plasma thruster. Each leg of the vehicle is provided with an IRAMS pulsed plasma thruster which can be oriented in any direction for maneuvering. At the terminal stage of rendezvous, each leg approaches the NEO surface with a large-pitch, deep-thread screwdriver (or drill-bit) facing the surface. At impact, the inertia of the system translates into the first torque. Following landing, the plasma thruster operates in short bursts, with the reaction driving the solid fuel grain into the torque hammer groove, causing high torque on the spring-loaded threaded tool (Figure 3). Ten to twenty centimeters of travel into the surface, depending on its hardness and brittleness, will suffice to anchor the craft in place. Being a mass-spring system, the IRAMS can be optimized. We started by setting up a dynamical model of the IRAMS and then using this model to obtain the natural frequency combination that would produce the highest amplitude.

Pulsed, solid-grained plasma thrusters[25] offer precise pulsed operation, cold start, intermittent duty cycles and reliable, storable solid grain. They are thus the best choice for long-term operation. Again, the solid grain is a consumable, but it is not expected to be a limiter of the craft's lifetime. As shown in Ref. 2 the time between pulses depends on the natural frequency of the system, which should be matched with the thrust pulse rate to minimize power loss from thrust to torque output.

6.0 Auxiliary Systems

6.1. Active beam dynamics

The pulsed thrust of the plasmajets from the 60 independent nozzles will be phase-controlled to cancel out all but the lowest-order modes of bending of the Rockbreaker's arms during the cutting operation. This will also be used to control the arms during use as manipulators.

6.2. Sensor Systems

Sensor systems special to this craft, beyond those required for a standard spacecraft, include ground penetrating radar (GPR), which has been used on Earth to map geophysical properties[26] under the surface. Its role on the Rock-Breaker is to scout out favourable areas on the surface of the NEO before anchoring onto a location. The system to be used has an antenna frequency range of 0.5 - 1 GHz for medium to shallow penetration with a high-resolution radar survey. Optical sensors will be needed to control the temperature of the materials being heated by the Rockbreaker, as well as to see obstacles and samples.

7.0 Propellant Fuel Tank

The plasma jets feed off an argon[27] propellant tank. The tank structure mass is calculated at 5% of the total propellant mass. The plasma jet in its current application has an estimated power range of 1-10kW and current not exceeding 200A[28]. For these limitations, the mass flow rate range is 0.03-1.2g/s[29,30].

7.1. Robotic Manipulator Operations

The robotic arms have enough degrees of freedom to be ideal as manipulator arms. The four deployable legs with the IRAMS enables precise maneuvering of the craft.

8.0 Mass Estimation

In Table 2, the mass of the various components is estimated. The operating duration and mass excavation capability were calculated in Ref. 2 using the requirements for the Tailored Force Fields project, where each Rockbreaker was sized to cut up enough blocks of SiO2-class material to form a closed cylinder 50m diameter and 50 m long, with a 2m thick wall. The mass to be excavated was twice this amount, since 50% wastage was assumed. The number of nozzles, and the power delivery rate, were calculated to generate this amount of material with 19 earth-days of continuous operation at Earth-sun L-4. This time was considered appropriate because, with a 1cm/sec initial drift velocity after overcoming the gravity of the NEO, the mass generated could be collected in an approximately toroidal cloud a few kilometres away from the NEO in that time, to perform the shaping and sintering. These parameters are considered to be adequate as a starting design for a more general-purpose excavator/ resource extractor craft.

Table 2: Component Mass Breakdown

Component	Mass (kg)
IRAMS, Thrusters (propellant included)	1000
HACS	2000
Power conversion system (other than lasers) incl. high-intensity solar cells.	1200
Plasma/Laser Cutting System	15000
Propellant Tank (argon)	200
Argon gas	4000
Communications antennae	50
Sensor suite	300
Manipulator arms	500
Protective Covering	200
Thruster Propellant (for maneuvering)	500
Total payload	**24950**
Solar Sail	5080
Booster + auxiliary propellant	7500
Total propulsion package	**12580**

The majority of the mass is the laser/plasma cutting system, which is based on lasers currently available, assuming 10W/kg. The HACS is built with a network of hollow aluminum alloy rods strong enough to withstand the force of the plasma jets at the ends with active compensation as indicated above. Its weight is determined by its density ($2700 kg/m^3$) and the length of each section. The present Space Shuttle Manipulator Arm (Canadarm) has a mass[31] of 410 kg, and is sized to move the entire STS Orbiter (120,000 kg) at acceptable rates for rendezvous with the ISS, so the HACS estimate is reasonable and conservative. Solar sail construction is by the method mentioned at the beginning of the paper, and targets an aereal density of 10g per square meter. The mass of argon gas was found using the mass flow rate of 0.03g/s feeding to 60 nozzles over a period of 460 hours. The propellant mass required for drilling, anchoring and re-anchoring is included in the IRAMS component; the amount required for moving the Rock-Breaker from the rendezvous point to NEO surface and other maneuvering tasks is in the thruster propellant mass.

The mass estimate in Table 2 is broken into two packages. The first is the basic Rock-Breaker craft, which is the payload to be propelled by the solar sail. The second is the solar sail package itself, along with a 7500 kg boost package to take the craft and sail from LEO to a transfer orbit where the sail can be deployed. The boost package mass is ample for an electric thruster system to send the craft into an earth escape trajectory. It is seen that one of the new NASA launchers can lift the entire package to LEO or even into a transfer orbit, thereby making on-orbit rendezvous unnecessary.

9.0 Conclusions

This paper describes the approach to design a new kind of spacecraft for extraterrestrial construction and resource exploitation applications. Solar propulsion, beamed microwave power, and fiber laser and plasma jet cutting tools, and an Integrated Rendezvous, Anchoring and Maneuvering System are explored, and their issues considered. Conclusions are:

- Solar sail primary propulsion appears to be well suited to the NEO application.

- With direct solar-pumped Nd-fiber lasers, the solar sail of a single craft would suffice to act as a solar collector and provide continuous power for operations.
- With the new generation of launch vehicles announced under the Moon-Mars initiative, a Rockbreaker and the propulsion package for boost to an earth-escape trajectory, can be launched assembled in a single launcher to low earth orbit.

10.0Acknowledgment

This work is funded through a Phase 2 NIAC grant (Dr. Robert Cassanova, Technical Monitor), and through President's Undergraduate Research Assistantships from Georgia Tech (NS).

11.0References

[1] Wanis, S., Komerath, N., "Advances In Force Field Tailoring For Construction In Space". IAC05-D1.1.02, 56th International Astronautical Congress, Fukuoka, Japan, October 2005.
[2] Vanmali, R., Li, B., Tomlinson,B., Zaidi, W.,, Wanis, S., Komerath, N., "Conceptual Design of a Multipurpose Robotic Craft for Space Based Construction". AIAA Paper 2005-6733, SPACE 2005 Conference, Long Beach, CA, Aug. 2005
[3] NASA FACT SHEET: Asteroids, Comets, and NASA Research. http://meteorite.org/facts.htm
[4] Muff, T., Johnson, L., King, R., Duke, M.B., "A Prototype Bucket Wheel Excavator for the Moon, Mars and Phobos". Proceedings of STAIF 2004, Institute for Space and Nuclear Power Studies, Feb. 2004, p. 214.
[5] Bottke, W. F., Morbidelli, A., Jedicke. R., Petit, J., Levison, H.F., Michel, P., and Metcalfe, T.S., 2002. Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects. Icarus 156, 399-433.
[6] Christou, A.A., 2003. The Statistics of flight opportunities to accessible Near-Earth Asteroids. *Planetary and Space Science* 51, 221-231.
[7] Dachwald, B., Seboldt, W., "Multiple Near-Earth Asteroid Rendezvous and Sample Return Using First Generation Solar Sailcraft". Acta Astronautica, Pergamon Press, August 2004. http://www.sciencedirect.com
[8] Wilcox, B.H., "Nesting-Hoop Solar Sail". NASA Tech Briefs, Vol. 24, No.9, September 2000.
[9] Saiki, T., Motokoshi, S., "Development of Solar-Pumped Lasers for Space Solar Power". IAC-05-C3.4-D2.8.09, 56th International Astronautical Congress, Fukuoka, Japan, October 2005.
[10] Steen, W.M., *Laser Material Processing*, 2nd ed., Springer, London, 1998, pp. 104.
[11] Gahan B., Batarseh S., Siegfried R., "Improving Gas Well Drilling and Completion with High Energy Lasers," National Energy Technology Laboratory Strategic Center for Natural Gas & Oil, Argonne National Lab., DE-FC26-00NT40917, Des Plaines, Illinois.
[12] Steen, W.M., *Laser Material Processing*, 2nd ed., Springer, London, 1998, pp. 50.
[13] Gahan, B., Shiner B., "New High-Power Fiber Laser Enables Cutting-Edge Research," *GasTIPS*, 10,1, 2004, pp. 29-31.
[14] Trumpf Inc. North America. TRUMPF TLF Lasers.
[15] IPG Photonics. CW Industrial Fiber Lasers: 1kW to 20kW Output Optical Power. http://www.ipgphotonics.com/html/115_cw_fiber_lasers.cfm Viewed Aug. 6, 2005
[16] Shiner, B., "High-power fiber lasers impact material processing," *Industrial Laser Solutions*, 2003.
[17] Jeong Y., Sahu J.K., Payne D.N., Nilsson J., "Ytterbium-doped large-core fiber laser with 1kW of continuous-wave output power," *Electronics Letters*, Vol. 40, No. 8, 2004, pp. 470-472.
[18] Liem A., Limpert J, Zellmer H., Tunnermann A, Reichel V., Mörl K., Jetschke S, Unger S., Müller H.R., Kirchof J., Sandrock T., Harschak A., "1.3kW Yb-doped fiber laser with excellent beam quality," *Proceedings of Conference on Lasers and Electro-Optics 2004*, San Francisco, USA, May 2004.
[19] Jeong Y., Sahu J.K., Payne D.N., Nilsson J. "Ytterbium-doped large-core fiber laser with 1.3kW continuous-wave output power," *Optics Express*, Vol. 12, No. 25, 2004, pp. 6088-6092.

---

[20] Payne D.N., Jeong Y., Nilsson J., Sahu J.K., Soh D.B.S., Alegria C., Durpriez P., Codemard C.A., Philippov V.N, Hernandez V., "Kilowatt-class single-frequency fiber sources", Proc*eedings of SPIE – Fiber Lasers II: technology, systems, and applications: 24-27 January 2005*, San Jose, California, USA., International Society for Optical Engineering, Vol. 5709, Bellingham, 2005.
[21] Gahan, B., "Laser Drilling: Understanding Laser/Rock Interaction Fundamentals," *GasTIPS*, 8, 2, 2002, pp. 4-8.
[22] Steen, W.M., *Laser Material Processing*, 2nd ed., Springer, London, 1998, pp. 110.
[23] Ramasamy R., Selvarajan V., "Current-voltage characteristics of a non-transferred plasma spray torch," *The European Physical Journal. D, Atomic, molecular, and optical physics*, 8, 1, 2000, pp. 125-129.
[24] "Rocket Nozzle Shapes" from Huzel & Huang, 1967.
http://www.aerospaceweb.org/design/aerospike/shapes.shtml
[25] Pulsed Plama Microthrusters. http://www.mae.cornell.edu/ campbell/mppt/mppt.htm
[26] Olhoeft, G.R., "Applications and frustrations in using ground penetrating radar," *Aerospace and Electronics Systems Magazine, IEEE*, Vol. 17, No. 2, 2002, pp. 12-20.
[27] Venkatramani, N., "Industrial plasma torches and applications," *Current Science*, 83, 3, 2002, pp. 254-
[28] Hypertherm Inc. Manual Product Line http://www.hypertherm.com/manual/index.htm
[29] Bauchire J.M., Gonzalez J.J., Gleizes A., "Modeling of a DC Plasma Torch in Laminar and Turbulent Flow," *Plasma Chemistry and Plasma Processing*, 17, 4, 1997, pp. 409-432.
[30] Kelly, H., Mancinelli B., Prevosto L., Minotti F.O., Marquez A., "Experimental Characterization of a Low-Current Cutting Torch," *Brazilian Journal of Physics*, 34., 4B, 2004, pp. 1518-1522.
[31] Garneau, M., "CANADARM". STS97, Canadian Space Agency Website.
http://www.space.gc.ca/asc/eng/missions/sts-097/kid_canadarm.asp Viewed August 6, 2005.