ADVANCES IN FORCE FIELD TAILORING FOR CONSTRUCTION IN SPACE

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Long-term human habitation in space requires the ability to use extraterrestrial materials to build massive radiation-shielded artificial-gravity stations. The technology of Tailored Force Fields promises to enable formation of desired shapes from multidisperse construction material in microgravity. This paper reports the status of adapting this new technology to a mission plan to build a 5-module, 1-G radiation-shielded station. Theory and experiments using acoustic, optic and microwave fields have been used to generalize this observation into a unified general force field fabrication technology. Engineering estimation showed that the solar energy requirements to form rubble in space into cylindrical habitat modules are quite within reach. Long wavelength radio waves would be appropriate for this application. A 50m diameter, 50m high cylindrical module, shielded to 2m depth, was selected as an extreme test case. Preliminary design estimates show that the input power needed to a radio-wave resonator in order to form such a module within a few hours from a cloud of 20cm-diameter rocks, could be provided by 2 square-kilometers of solar collection with 10% conversion efficiency.

INTRODUCTION

Long-term human habitation in space requires the ability to use extraterrestrial materials to build massive radiation-shielded artificial-gravity stations. The Tailored Force Fields (TFF) technology offers the capability to automatically form walls of specified shape in microgravity from loose, random-shaped objects automatically. As futuristic as this may sound, the breakthrough potential of such a technology is in removing the fundamental obstacles to building massive infrastructure in space. This would transform the priorities of space technology, and open the way to a large Space economy. The complete validation and refinement of the technique for large-scale construction in deep space is certainly a complex process requiring several years. It is essential meanwhile to have a reference mission architecture and engineering solutions to the other issues in building large-scale habitats. This paper summarizes work aimed at the automatic construction of a 1-g, radiation-shielded space station using solar energy and extraterrestrial material. It documents the state of validation, the remaining challenges and prospects for their solution, and the state of thinking on the peripheral issues.

BACKGROUND

Acoustic Shaping

The principle behind the technology is that the interaction of particles with a periodic potential field generates net forces. The forces can be magnified using a standing wave field in a resonator. The force expressions in acoustics were developed by King (1934)[1]. The technology has generally been used to manipulate a single particle in a carefully tailored ultrasonic field. However, an undergraduate experiment[2] in 1997 on the NASA Reduced Gravity Flight Lab (a.k.a. "Vomit Comet"), asked the question of what would happen if a myriad particles of random shape were placed in a resonant acoustic field, in microgravity. The hypothesis was that the particles would drift towards the nodal surfaces of the field and form walls, and this hypothesis was proven true. By tailoring field geometry, one can thus form particles into walls of different shapes in an acoustic resonator. Subsequent work[3], [4] has explored various aspects of this "acoustic shaping".

Electromagnetic Analogy

The original formulation of the acoustic equations by Rayleigh[5] noted the similarity to electromagnetic waves. Thus, when the question came up on how to apply this technology to large-scale construction in vacuum, it was natural for us to seek analogues in electromagnetics. The literature shows that the basic principle of particle/wave interaction is common to the phenomena of acoustic levitation[6], laser microscopy and optical "tweezers"[7]. In the case of nano-particles, where optic tweezers are used, there are recent demonstrations of nano-rods being assembled[8]. However, we know of no published evidence of wall formation (particles coming together in a single-particle-thick sheet and self-adjusting to fill gaps) in electromagnetic fields. This remains today the biggest source of remaining uncertainty.

In 2003, we showed[9] that the force generation mechanism in acoustics bears strong similarity with the force generation in optical fields such as those used in laser optic tweezers. A general prediction method was sought, linking observations in acoustics, optics and long-wave electromagnetics. Initially, an estimation method was developed for silicon dioxide particles in different types of resonant fields, for the acceleration induced per unit intensity, as a function of the size parameter, i.e., the ratio of particle effective diameter to the wavelength. The estimation was confined to the Rayleigh regime, where the size parameter is less than 0.1. In this regime, the scattering of radiation by the particle is essentially omnidirectional, simplifying the prediction. In subsequent work, the analogy has been tied back to first principles, thus providing a clearer idea of the various issues needed for accurate prediction and fine control.

Large Orbital Habitats

In the 1970s, several visionaries argued that the best habitats for humans living away from earth to conduct space-based manufacturing, repair, supply and exploration, would be orbiting cities, rather than on or under planetary surfaces which were "gravity wells" that imposed prohibitive delta-v requirements on commuters, exports and imports. In-depth studies were conducted[10] in the late 1970s. Contemporary humans need a gravity level near that at Earth's surface (1G) for long-term living. Habitats built along the inner circumference of a rotating wheel or cylinder can simulate gravity to a desired extent. However, a current thumb rule is that rotation rates must be below 1RPM to spare most people from disorientation. Thus a wheel with 1G at the rim at less than 1 RPM, has a radius on the order of a kilometer. Building such a structure in space is a daunting undertaking.

Radiation shielding is the other show-stopper to plans for human exploration and development of space. Again, a thumb rule is that roughly 2m thickness of lunar regolith, or about 0.5m of water, is needed to effectively stop all forms of space radiation to the level needed to avoid limiting human tenure in space. The O'Neill and ASEE Habitat designs stumbled on the issue of constructing the large structure, and were completely lost on how the massive radiation shield might be built.

In previous work[11] we showed that with coherent infrastructure planning, and taking advantage of modern concepts such as telepresence and automobile assembly robots, the O'Neill habitat construction problem could be solved. We showed how a 2km diameter, 2km long, spinning cylinder with 2m-thick walls could be built essentially without any human on-site presence other than telepresence, at a lunar Lagrangian point, over a period of 10 years. The engineering for this was further refined during a NIAC Phase 1 study[12]. This certainly required a massive effort on the Moon, including construction of a continuously-growing power plant by the Ignatiev robotic concept, lunar mining, metal fabrication and the construction of a large lunar electromagnetic launcher sized to launch rail-car-sized containers filled with regolith. The cylinder shell construction was reduced to a repetitive operation. We showed how intelligent up-front coordination between various resource exploitation concepts would make all of them feasible. This demonstration removed the notion that large projects had to be impossibly expensive in taxpayer dollars. The line of thought started by this demonstration has led to recent work on the process of global collaboration needed to develop large space infrastructure[13,14].

TFF REFERENCE CASE

Beyond cislunar distances, construction must be amenable to fully robotic operation. The first stations to host serious exploration and exploitation of Near Earth Object resources will have to provide long-term radiation shielding and generous living space. Here, the TFF method offers a way. The extreme test case we chose is a 50m dia, 50m long cylinder, shielded by 2m thick walls, made from silicon dioxide class rubble using a radio wave resonator. The walls would be formed from blocks of nominal 20cm effective diameter, with sufficient force to move them at an averaged acceleration of 1 micro-G towards the desired wall shapes. This power could be provided by a 2 square-kilometer, 10% efficient solar cell array or equivalent collector and converter. The power needed was much lower than that used by the Arrecibo radio telescope in the 1970s to beam a 3-minute signal into space as part of the SETI program.

Example: Construction of a 50m dia cylinder at Earth-Sun L-4 from NEO material radiation-shielded, 1-G Station at Earth-Sun L-4:

Particle diameter: 0.2m

Wavelength: 100m

Particle acceleration: 10^{-6} g

Resonator intensity: 328 MW/m^2

Resonator Q-factor: 10,000

Beam diameter = 100m

Power input: 258 MW

Active field time: 13 hrs

Solar Collector efficiency: 10%

Collector area w/o storage: 2 sq.km

Fig. 1: Construction System Parameters.

In the current phase of this project, we are refining this to the design of various subsystems for this mission. We estimate that the construction can be done, using NEO material extracted by robotic plasmajet/laser cutters, with a roughly 3 year mission time. It takes several Earth-days to quarry enough material for a single station module with our present design of the "Rockbreaker" craft discussed later – limited by the cutter mass of the Rockbreaker and not by power. The actual formation and hardening of each cylindrical module using the TFF resonator takes only a few hours. The subsystems are being sized for launch on Boeing DeltaIV Heavy class vehicles to LEO, and by solar propulsion to the eventual construction location.

Relevance of Earth-Sun L-4

Earth-sun L-4 was chosen as a reference location, although there are no known NEOs there. The reason is that it provides a good reference solar intensity (same as Earth's), and a firm mission time and delta-v.

So far, only a "dust ring" has been detected at L4/L5, although the 5km-wide "Cruithne" was discovered in Earth's orbit in 1986. In the long term, L-4 is a good candidate to locate large-mass resource-exploitation stations, and perhaps even to park resource-rich NEOs powered by mass-drivers. Thus missions to L-4 would have all the features of actual missions to build habitats near candidate NEOs. There is no dearth of candidate NEOs as. As Professor O'Neill pointed out, the construction material could well be a by-product of the resource extraction operation itself. There are reports that nearly 100 of the 900 to 1800 NEOs are in the kilometer size range[15], with rendezvous mission delta-v on the same order as that for lunar missions. The composition of the NEOs is less certain; however, we postulate that some must be sources of the silicon dioxide material that we assume for force calculations.

Design Convergence for L-4 or Asteroid Belt: Solar Collector/ Sail Size

The construction system parameters are given above in Figure 1. For missions in the general vicinity of 1 A.U. from the Sun, travel time is not a major issue, and solar sail propulsion is a viable option. This is particularly interesting because the radio resonator for the TFF construction operation requires large solar collector area. A reconfigurable sail/ collector appears to be an excellent candidate solution. We see that a 1.2 sq-km sail operating for 23 months would provide the impulse needed for a mission to L-4 with a standard 25000kg payload. The optimal combination is likely to be a solar/gas thruster "tug" which provides the initial and final maneuver thrusts, with the solar-sails providing cruise thrust. This design is extremely conservative. It is based on combining two disjointed facts: firstly, that a continuous-thrust mission generally takes about 2.7 times the delta-v needed for the same mission performed with impulsive Hohman transfers. However, this is because of the inefficiency of spending energy accelerating fuel mass which is to be expended later as opposed to using it all up in an impulsive fuel burn. The second fact is that solar sail propulsion can be used for several segments of this mission. Six TFF craft, each with a 1.2 sq.km solar sail / collector would provide thrice the power needed to construct the station, without need for energy storage.

Thus, to a first iteration, the collector area is dictated, albeit very generously, by the propulsion requirement, not the construction power requirement.

Given this fact, one realizes that the same system could perform resource extraction and construction at locations where solar intensity is greatly reduced. In fact the size is sufficient to operate the process at the orbit of Mars, and perhaps beyond to the vicinity of the asteroid belt itself, with few modifications. An optimized system design may be more restrictive, but at first glance, there is little to be gained by greatly reducing solar sail area since the mass saving is small.

There is no pressing need to arrive at an accurate propulsion requirement to L-4, beyond getting to an acceptable conceptual design. More detailed calculations using this system are underway to reach Mars orbit and specific selected NEOs.

VALIDATION OF WALL-FORMATION USING TAILORED FORCE FIELDS

The idea that light can exert a weak force on a totally absorbing surface, which can be doubled if the surface is made reflective, is well known. Lord Rayleigh was searching for an acoustic analogue to that phenomenon when he studied acoustic radiation pressure. A particle in a sound field smaller than the wavelength by 1 order of magnitude will experience a force due to radiation pressure if its mechanical material properties are such that its impedance is different from the surrounding host fluid. This is simply due to the momentum change in the wave as the particle scatters a portion of that wave. King (1934)[1] solved for the momentum transfer that results from the scattering of a rigid spherical particle placed in an inviscid fluid which hosts a stationary sound wave. Keeping the particle small relative to the wavelength (the Rayleigh scattering regime) enables a simple analytical expression for the radiation force on spherical particles, where only the monopole and dipole terms need be retained in the scattered field[16]. For a field where the variables are varying only in the x-direction, the force expression for a particle of radius a, wavenumber k, wave amplitude P_o, sound speed c_o, density ρ_o, and relative particle-fluid density δ, can be written as:

$$F = \frac{P_o^{\,2} \pi k a^3}{3 \rho_o c_o^{\,2}} \left(\frac{5\delta - 2}{2\delta + 1} \right) \sin(2kx)$$

Wang[17] mapped out the force exerted on a small particle in a standing acoustic wave in the audible range. Others have also demonstrated the same thing at ultrasonic wavelengths as long as the particle-wavelength ratio is maintained.

Acoustics-Optics Analogy

Similarly in electromagnetics, when an electromagnetic wave is incident on a particle of different impedance than its surrounding medium, part of the wave scatters. The radiation force exerted by a laser beam onto a small dielectric spherical particle was derived by Ashkin[18]:

$$F_{\sigma} = \pi \varepsilon_o E_o^2 k a^3 \left(\frac{m^2 - 1}{m^2 + 2} \right) \sin(2kx)$$

for a particle of radius a, wavenumber k, electric field strength E_o, surrounding permittivity ε_o, and relative index of refraction μ.

The above expression has been validated by several experiments in the optical part of the the electromagnetic spectrum[19,20]). An extension of wavelength to microwave frequencies was demonstrated by Barmatz[21].

The primary shaping forces in each field have been classified as either a scattering force or a gradient force. For both fields the scattering force is a result of the rate of momentum change in the otherwise-undisturbed field due to the presence of the particle. An analytical expression for scattering cross-section is available in the Rayleigh regime[22]. The force is a function of wave intensity, ratio of particle-to-medium impedance, wavenumber to the fourth power and particle radius to the sixth power.

The gradient force is generated from physically different mechanisms in the acoustics and electromagnetics cases. In electromagnetics, the electric field component of the wave polarizes the dielectric particle and consequently the external field interacting with the induced dipoles yields a Lorentz type force. In acoustic standing fields, it is believed[23] that the phase difference between the incident and scattered fields produces a different wavenumber and particle radius dependency from that found in the scattering force due to a traveling acoustic wave interacting with a particle in its path. The gradient force in both fields also has equivalent dependency on gradient of field intensity, ratio of particle-to-medium impedance, wavenumber, and particle volume.

Thus, both force fields are analogous in their scalability with field variables: wavenumber, intensity (or its gradient), speed of wave propagation, characteristic impedance of host medium; and on particle properties: particle radius and impedance. This is being used to develop a generalized force field theory for flexible fabrication as schematically shown in Figure 2 below.

Microwave Regime: Experimental validation

Comparison with experimental results obtained by Barmatz et al at NASA JPL[23] has demonstrated that the equations governing Rayleigh particles in optic fields can be extended to microwave frequencies. The experiment placed a sphere of known dielectric properties in a microwave resonator. The sphere was held in place by a sting attached to a sensitive microbalance. in the weight of the sphere as the relative position of the sphere and the field was changed. Excellent agreement between our prediction and the experimental results validates our claim that the force mechanism remains scaleable from nanoparticles and optical tweezers to microwave frequencies and millimeter-sized objects. Although this experiment was only for a single particle in the field, adding multiple particles to the field is expected to behave in analogous manner to the acoustic experiments we have conducted. The reasoning is that the secondary attraction forces found in acoustics is similarly found in electromagnetics since we can regard the particles as electric dipoles and attraction forces are a result of the interaction of several dipoles. Current work is being done on this issue of modeling the effect of multiple particles on each other and on the overall primary field.

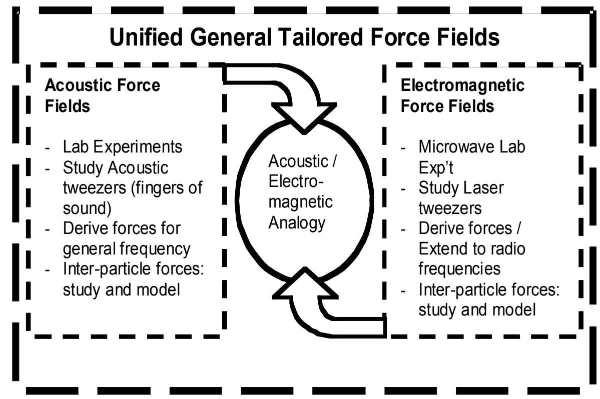

Fig. 2: Development of the TFF logic

MISSION ARCHITECTURE

In our architecture, the TFF craft are separate from the resource-extraction "Rockbreaker" craft. The architecture is modular. Extensive use is made of solar power, as well as solar sail propulsion. Beamed microwaves are used to power some of the craft. Beamed microwaves / infrared waves are used to sinter NEO material to form hardened structures. The outer shells of the station modules are assembled by the TFF technique, with sealed interior structures being deployed as inflatables from inside the cylinders.

Requirements are summarized below:

1. Propulsion to get the rock breakers and radiowave resonator crafts to the desired position
2. Provide power levels adequate to construct the structure and to generate the construction material required.
3. High conductivity radio-wave resonator at least 100m x 100m x 100m.
4. Ability to deconstruct large rocks into the size needed for construction
5. Fully robotic operation
6. Ability to fuse the rocks when they reach the desired position

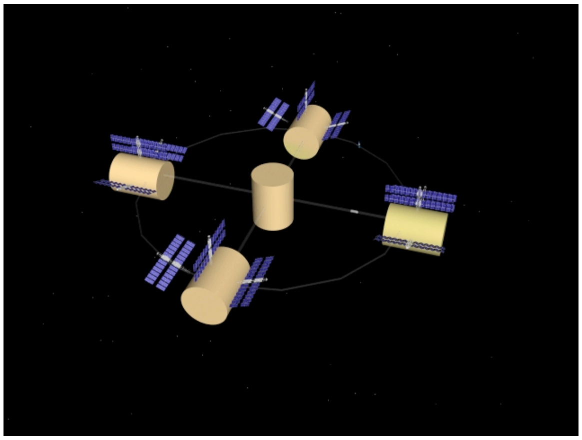

Fig 3: Completed 5-Module 1-G Station

At present, the mission architecture to satisfy the above requirements is as follows:

1. Six TFF craft and four Rockbreaker craft are to be launched into LEO in quick sequence using Delta IV Heavy class launchers. Each payload is less than 25000 kg. In the case of the TFF craft, the entire package can be built under 25000 kg given some improvement in the mass of the conversion electronics from solar energy to radiowave. In the case of the Rockbreaker, it makes sense at present to send separate booster packages with a disposable rocket and a solar sail package, two in each payload, for rendezvous in LEO. Thus the four Rockbreakers require six 25000 kg launches. With the heavy-lift boosters recently announced for the NASA Moon initiative, it appears that the payload to LEO can be increased substantially.

2. Each craft is boosted into a transfer orbit towards the destination (L-4 in the test case, or towards Mars). Once away from the g-jitter and drag of LEO, solar sails, each 1.2sq. km in area, will unfurl and drive the craft with continuous thrust for the duration of the journey.

3. Arriving at the NEO, the first Rockbreaker performs a rendezvous with the NEO. We asume a non-spinning NEO, or one that has been slowed down by the harpoon / sling angular momentum bleed technique. The Rockbreaker's power antenna locks into the beam from one of the TFF craft, and start powering up its own rock-breaking operation.

4. As discussed below, the Rockbreaker generates a cloud of blocks cut out of the NEO and set floating gently into the cage formed by four TFF craft that move with the cloud. The cage forms a Fabry-Perot resonator and is energized to start forming the cylindrical shell. As the first cylinder wall is formed, the Rockbreaker (or the TFF craft) sends focused beams to sinter the surface of the cylinder.

At this stage it is left open whether there is any merit in building successive layers of rock walls, sintered each time. This is expected to require a switch to a different mode of the standing wave field. This aspect is being studied using a finite element model. It may be that a single layer of rocks is sufficient for the structure, with other radiation-stopping internal walls being created from inflatables delivered from Earth. In the latter case, the additional radiation protection would come from the hydrogen fuel or water that is brought to the station for long-term habitation.

The TFF craft would have to change to a different mode to form the end-caps of the cylinder, which would then be manipulated, transported and fixed to the cylinder by the Rockbreaker robot.

SYSTEMS

Antenna Design for full-scale TFF Craft

The field inside the resonant cavity has to be excited with an RF transmitter. The power requirements are dictated by the losses in the resonator. Work by our colleagues John Magill, William Agassounon and Mike Read at Physical Sciences Inc. shows that transmitting vacuum tubes are probably the best source of RF power to use as a source for this application, in view of the high power rating needed. Since the shaping will be done using discrete frequencies that drive specified modes of the resonator, and since the resonator walls can be moved or even deflected to make small needed corrections, it is possible to use oscillators with very narrow bandwidth. This provides large savings in mass per unit power over broad-band amplifiers. A triode device is proposed as a simple first design, given the single-frequency advantage. For the 100m wavelength of our test case, the resonator walls are proposed to be of 58micron-thick aluminum sheet, with wire loops providing the power input to the resonator cage. The theoretical "Q" factor of the resonance in such a cage is about 300,000. However, that does not take into accound the losses due to scattering off the object being formed, or the cloud of construction material. To keep the input power specification conservative, we estimate that the actual resonator Q will be no more than 10,000. This appears achievable. This is used to size the power input, and thus the size of the collector needed for continuous operation (smaller collectors would force design of a system with storage and discharge).

Construction System Elements

The construction system has two primary elements. The first is a "Tailored Force Fields Craft" (TFFC) (Figure 4). This includes a 200m x 200m x 58 micron-thick aluminum sheet radio-wave reflector and its support structure, along with a high-intensity radio-wave transmitter and microwave beaming antennae. The craft obtains power from a 1.2 sq.km reflective solar sail, reconfigured into a solar collector, with high intensity solar cell arrays or direct-conversion system. Other significant mass items are the power conditioning electronics and oscillators for selected radio frequencies, thermal control system, the maneuvering propulsion system. Given some improvements in the mass per kilowatt of power conversion electronics and heat rejection systems at very high power levels, the mass target of 25,000 kg for the payload arriving at L-4 appears feasible. Additional mass to be included in the launch from earth includes the propulsion to transfer from LEO to the L-4 transfer orbit.

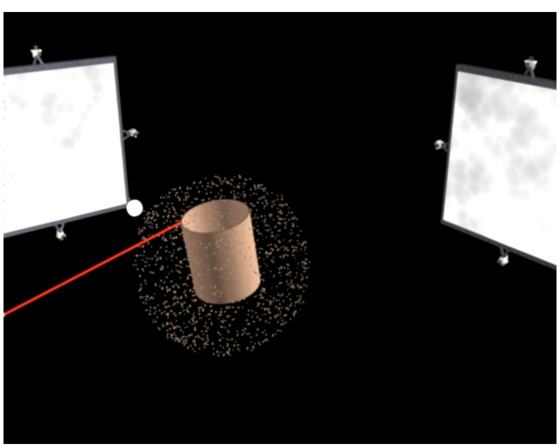

Fig. 4: TFF craft forming cylinder out of NEO rubble. A sintering beam is shown schematically, fusing the structure after a wall has been formed.

Obtaining NEO Material: Engineering a Space Based Construction Robot

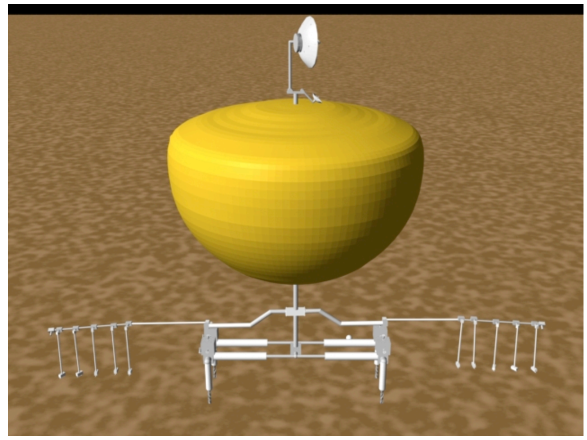

Fig. 5: Rockbreaker robot craft quarrying NEO

When the sails of the four TFF craft, are reconfigured into solar collectors, a great deal of power is available beyond what is needed to power the TFF craft. This power is available to operate the machines that generate the construction material, perform the sintering, position and assemble elements, and eventually serve as resource extractors. These latter machines (Figure 5) are called "Rock Breaker Craft" (RBC), and are again sized to a 25,000 kg mass to use similar solar sail/collectors for transport. Since the power conversion electronics are the major mass item on the TFFCs, these are not duplicated on the RBCs. Power is beamed from the TFFCs to the RBCs. The RBCs as presently conceived are craft that can attach themselves to NEOs using impact-torque-hammer pulsed plasmajet systems on their legs. They then deploy two to four revolving, telescoping arms, each carrying 15 to 30 rock-cutters. Each cutter incorporates a truncated-base external acceleration nozzle (truncated aerospike concept) with an Nd-fiber pulsed laser as the primary cutting tool acting through the truncated base. These are to cut spiral trenches and use the pressure of the hot plasma jets to break and lift out blocks from trenches, sending the floating away at very low velocity for capture and shaping by the resonator cavity. The parameters of the system concept are summarized in Figure 1. The design of the Rockbreakers is detailed in Vanmali[24].

SUMMARY OF TECHNOLOGIES

Figure 6 summarizes the status of the various technologies critical to the implementation of TFF. The technologies along the top branch of the fishbone diagram are ones which are special to TFF in the space program. The ones along the bottom are technologies that are central to other concepts/ fields related to Space endeavors, and may thus be expected to develop independent of the need for TFF.

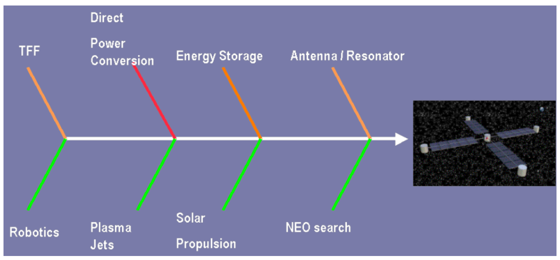

Figure 7: Technologies needed for TFF

The above discussion shows that the systems required to implement construction of large, massive habitats are surprisingly within reach. The focus needed is on the refinement and validation of the core technology of force field tailoring. We note that this technology has come a long way since the initial flight test results of 1997. The formation of walls in the acoustic experiments was first shown to correspond to predicted mode geometry. Problems cited in the literature using single particles in the Mie regime, such as particle rotation or segregation by size or density did not materialize, thus proving the hypothesis that they should not occur in the Rayleigh regime. A fear was developed based on previous experiments using single-particle acoustic levitation (again in the Mie regime) that the generation of thermal gradients would negate the force field, and prohibit wall formation. This was disproven in our Rayleigh regime ground experiments[4] where we showed that walls could be maintained through the cooling of a wall formed from hot particles, provided the field frequency was adjusted to maintain resonance.

Experiments and theory from the optics regime have provided increasing evidence that there are no surprises in developing the acoustics-electromagnetics analogy. While there is much to be done on modeling multiple-particle interactions with the force field, there is so far no evidence against wall formation. The recent success in matching our predictions with the JPL microwave single-particle force measurements, is a major step in showing that the electromagnetics predictions are scaling as we postulated. Long-wave RF still remains to be explored.

Another concern was that either the RF field would heat up the materials being pushed (and also result in large absorption and thus a low Q-factor). It was also feared that the sintering operation would interfere with the cylinder formation. However, we note that there is a wide separation in frequencies between those appropriate for the force field, and those for heating, for realistic material that might be found and used in construction in space. Obviously, there will be interesting combinations of material and wavelengths that offer other possibilities.

Thus, today, our status is that no "show-stoppers" have been identified in the development of TFF technology. This is certainly an exciting realization, in view of the potential to break through the fundamental barriers today hindering human development and exploration of space.

COST / COMPLEXITY METRICS

Mission cost is certainly a critical issue. Below in Table 1 we list points of reference against which to compare the cost elements of the TFF architecture. Again, these do not lead to frightening conclusions: the ISS is certainly large and expensive, but that cost is not prohibitive for a construction system which could build a number of very massive and large stations.

Table 1: Comparison of cost elements of the TFF architecture with current or future projects

Item	Comparison
Total launch cost: 20 launches of 25,000 kg each to LEO by unmanned heavy-lift boosters	Present ISS is 187,000 kg, much of it launched on STS
Development: TFF craft	No space-based references
TFF system engineering	Large GEO telecom satellite
TFF concept validation flight program	Tether validation flights

High-power Radio Resonator Elements	Terrestrial radio equipment development
High-power Oscillators	Terrestrial radio equipment development
Thermal Management	Large GEO telecom satellite
Direct Conversion Technology	Nanofabrication and superconductivity work
Development: Rockbreaker	Robotic space missions/ planetary surface rovers
Robotic Assembly Technology	ISS Robotic Arm
Microwave Power Beaming	Smart Antenna development
Sintering technology	Laser material processing
NEO Rendezvous	NEAP mission
NEO Attachment and Detachment	NEAP mission
NEO Cutting technology in micro-g	Mars drilling equipment development
NEO Cutting and material management	Mars drilling equipment development
Station: Robotic Assembly	ISS Assembly + robotics

CONCLUDING REMARKS

The concept of Tailored Force Field technology has steadily advanced to the validation level for single-particle behavior in both acoustic and electromagnetic fields, and to wall formation in acoustic fields. The extension of observations found in optical fields to microwave fields has been validated experimentally for a single particle, where theoretical predictions compared favorably with experimental measurements.

Mission design has advanced to where it appears that a set of ten 25000 – 50,000kg payloads launched to LEO will suffice to develop a reusable Space Construction system for the large construction projects of the future.

An initial design has been developed for missions to construct a radiation-shielded habitat module at Earth-Sun L-4 using solar primary propulsion and solar power for the entire construction operation. The design appears to close with a 1.2sq.km solar sail/collector size for each of TFF craft and Rock breaker resource extraction craft.

ACKNOWLEDGMENT

The authors acknowledge the support from the NASA Institute of Advanced Concepts and USRA through Phase 1 and Phase 2 projects, and the support of author Wanis' dissertation research through a NASA Graduate Student Reseacher grant. Discussions with, and calculations by, Mike Read, William Agassounon and John Magill of PSI Corporation, Massachussetts on the design of radio-wave resonators for TFF, are gratefully acknowledged, as is assistance from team members Waqar Zaidi (graphics), Ravi Vanmali, Bryan Li and Brandon Tomlinson (Rockbreaker engineering) and Patrick Satyshur (architecture analysis).

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