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Are Self-Replicating Machines Feasible?

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Recent developments in three-dimensional printing technology have introduced the prospect of self-replication in the context of robotic in situ resource utilization on the moon. The value of three-dimensional printing lies in its potential to implement universal construction. A universal constructor is a machine capable of fabricating any physical product given an appropriate program of instructions, suitable raw materials, and a source of energy in an appropriate form. Such physical products include a copy of itself; a universal constructor is by definition a self-replicating machine. A step in this direction is represented by the RepRap three-dimensional printer that can print copies of its own plastic components. The three-dimensional printing of actuators and associated control electronics would represent an existence proof that an appropriately designed robotic three-dimensional printer system would constitute a universal constructor. In this paper, preliminary attempts have been outlined to develop self-replicating machines by addressing the three-dimensional-printable actuator and electronics aspects within the materials limits imposed by the moon. It is concluded that physical self-replicating machines are within reach. This lunar infrastructure offers space-based geoengineering solutions in the short term and solar power satellite solutions in the long term to the global climate crisis.

Nomenclature

a_c = solar-sail acceleration, $\mathrm{mm/s^2}$
$f(\cdot)$ = nonlinear neural squashing function
t = solar-sail thickness
w_{ij} = synaptic weight between neuron i and neuron j
x_i = neural input to neuron i
y_i = neural output of neuron i
β = solar-sail lightness factor
ρ = solar-sail volume density, $\mathrm{g/m^3}$
σ = solar-sail mass/unit area, $\mathrm{g/m^2}$

I. Introduction

SELF-REPLICATION as a concept dates back to von Neumann, who developed the concept of the universal constructor [1]. Such a universal constructor by definition can construct anything, including a copy of itself, given the appropriate programming, energy supplies, and availability of parts. It comprises an idealized robotic arm that picks parts from its environment to build a copy of itself, its control system, and its program of instructions. It was subsequently discovered that DNA replication follows precisely this same logic [2]. The reader is referred to the remarkable "bunny book" [3] for further information of the development of self-replication theory. Most theory was developed from cellular automata models from which self-replicating programs (without universal construction capability) as the basis of artificial life were derived [4,5]. These theoretical models do not concern us here. Von Neumann's original kinematic models were discarded in favor of cellular automata models but more recently have been revived [6]. Rather than review the extensive literature on the theory of self-replication, we present only the few engineering-based efforts toward practical realization of self-replicating systems. It is worth mentioning, in particular, the landmark NASA study on self-replication applied to lunar exploration [7], aspects of which have been developed further more recently [8,9]. Here, we explore this lunar self-replicating machine concept with regard to material closure. We do not consider certain practical issues such as dust mitigation at this stage, which is a generic lunar problem rather than specific to self-replication [10].

The power of a self-replicating machine is obvious. It can construct any number of copies of itself extremely rapidly; its population grows as $\sim(x+1)^n$, where x is the number of offspring per generation, and n is the generation number (Table 1).

Once sufficient numbers of self-replicating machines have been manufactured, they can then be programmed to manufacture the desired products in parallel, demonstrating exponential productive capacity, an economic exponentiator. Consider a typical launch cost of \$20,000 per kilogram to low Earth orbit (LEO); we may assume that this increases by two orders of magnitude to \$2 million per kilogram to the surface of the moon. A 1 t "seed factory" launched to the moon would thus cost \$2 billion. If it self-replicates 1000 copies of itself (in under seven generations), the cost drops to \$2000 per kilogram, which drops further to only \$20 per kilogram for 100,000 copies and \$2 per kilogram for 1 million copies (in under 13 generations). This dwarfs projected launch cost savings (~90%) expected from single-stage-to-orbit launch technology to LEO such as the Skylon spaceplane concept. Full self-replication offers not just parallel processing throughput but exponential processing throughput. Hence, self-replication acts as a matter exponentiator rather than a mere multiplier, offering many orders of magnitude enhancement in productive capacity.

Self-replicating machines are premised on the ability to use raw materials to bootstrap themselves. In situ resource utilization (ISRU), the exploitation of extraterrestrial resources, has become topical with the proposed lunar Resource Prospector Mission (RPM) to demonstrate fundamental ISRU technologies in 2020. It comprises three main elements. A 72 kg payload package RESOLVE (from "regolith and environment science and oxygen and lunar volatiles extraction") is to demonstrate the extraction of water ice from the lunar surface and to generate oxygen through hydrogen reduction of ilmenite in recovered regolith. A lunar rover will carry this package to locations at the lunar South Pole and extract subsurface samples using a drill. This provides us with a starting point from which to explore a self-replicating machine concept later.

The most critical issue for self-replication is the necessity for near 100% matter, energy, and information closure to ensure that the system's functionality exceeds its structure [3,7,11,12]. For 100% closure, the self-replicating factory needs to manufacture every component part of itself and all the tools necessary to manufacture those components. The parts list grows exponentially with the number of unique parts, and so standardization will be essential. Furthermore, each component has associated with it a portfolio of processes involved in its creation. It is desirable to minimize the

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Table 1 Self-replication as a matter amplifier

Number of offspring per generation (x)	Number of generations (n)	Resultant population
1	10	1024
2	7	2187
2	13	1,594,323

amount of imported material (vitamins). The composition of every component imposes a demandite requirement while in situ resources offer only limited satisfaction of those requirements. The only way to achieve closure is to minimize the diversity of material, diversity of parts, and diversity of manufacturing processes. That is what is addressed here.

The self-replicating machine is premised on a high degree of automation and robotics [13,14]. This of course is a critical question that cannot be addressed in detail here, but robotics has advanced enormously over the years. One means to enhance automation is to control the local environment to reduce the incidence of “surprises”; this is how automated factories (lights-out automation) and biological cells implement their complex processes. Another critical issue concerns human–machine interfacing and the division of labor between humans and robotics [15,16]. Although there is no question of astronaut involvement on the moon, telesupervisory control/monitoring from Earth (or the vicinity of the moon) is feasible. Robotic on-orbit servicing involving complex manipulation tasks has been addressing issues regarding teleoperation from Earth by ground controllers [17]. However, human–machine interfaces must cope with time delays inherent in signal transmission [18–20]. Nevertheless, the degree of telesupervisory human intervention must be minimized as the rapid growth of the machine population on the lunar surface makes human intervention impractical.

II. Three-Dimensional Printer as Universal Constructor

Recently, three-dimensional (3-D) printing has emerged as a generalized manufacturing capability. It is a layered/additive manufacturing technique with wide versatility for printing organic tissue, food, pharmaceuticals, etc. The recent delivery of a glovebox thermoplastic extrusion 3-D printer to the International Space Station is testament to the application of 3-D printing to space exploration [21]. 3-D printing manufactures raw material powder into structural products by fusing the powder layer by layer. There are several additive manufacturing methods, the most common being fused deposition modeling (FDM), selective laser sintering (SLS), and stereolithography [22,23]. SLS is particularly versatile in that it can process metals, plastics, and ceramics, but they do require different environmental conditions, making integrated multimaterial structures infeasible currently. Furthermore, for self-replication, the construction of a laser presents certain difficulties. Although metal can be processed through laser sintering [24,25], electron beam freeform fabrication (EBF3) is another option for metal printing [26]. The great advantage of EBF3 is that it works on the principle of the electron gun, a high-powered high-voltage vacuum tube (introduced later for electronic applications). Demonstration of metal powdering would be a critical capability for handling metal with any 3-D metal printer. A thermal lance may be used to process ceramics in casts (using 3-D printed molds), whereas plastic products may be manufactured through FDM; this eliminates the need for complex inefficient lasers. The primary limitation of 3-D printing technology, however, resides in its serial nature, which has prevented it from growing beyond prototyping functions [27].

An important inspiration was the development of the open-source RepRap (from “replicating rapid” prototyper) 3-D printer (Fig. 1) [28].

The RepRap is based on plastic FDM for constructing complex geometries, including its own plastic parts. This a first step toward the development of self-replication capability. Currently, RepRap can replicate only its plastic parts that comprise its simplest structural parts. To close the self-replication loop, the 3-D printer must be able to 3-D print its other parts: 1) threaded metal rods that provide structural rigidity, 2) joining (that may be replaced with cement/adhesive, 3) electric motors, 4) electronics and computer controller, and 5) sensors. To enhance its self-replication capability, RepRap requires additional functions. To include self-assembly of its parts into its repertoire, it must possess an assembling wrist/hand constructed from multiple motors. To search and extract its own raw materials, it must include a mobility system constructed from motors and associated rover capabilities in prospecting to acquire and mine raw materials. To be fully autonomous, it must include an energy generation system. Thus, the motor provides the central linchpin for self-replication capability.

III. Three-Dimensional Printable Electric Motor

3-D printing is currently limited to printing structures, although it can print complex structures that cannot be manufactured through any other means. However, printing only structures significantly limits the repertoire of 3-D printing. In terms of mechanisms, only kinematic joints have been successfully printed but not motors per se [29] (e.g., Fig. 2), though there have been a few attempts to 3-D print plastic components for motors by hobbyists.

All 3-D printers are in essence Cartesian robots comprising a deposition table and a printing head with three degrees of freedom (DOFs) relative movement. Further DOFs may be added by reconfiguring joints as serial manipulators, adding wheels for mobility, etc. All these mechanisms involve motors. Any self-replicating 3-D printer must be able to manufacture not only all its structural members but also its actuators, sensors, and electronics.

We have been developing several electric motor system concepts as our proof of principle of self-replication using 3-D printing as a universal constructor mechanism. A complete motor system comprises the actuator, control electronics, and sensors as well as the structural material in a complex configuration. Electric motors are often performance-limited by thermal limits, and so any viable electric motor must incorporate thermal control considerations. We present the corollary that if it is possible to 3-D print a complete motor system, it is possible to print almost any physical machine (defined as a mechanism) to realize almost any arbitrary function we may wish to impose. Although 3-D printing under reduced gravity has not been addressed specifically here, pumps will be required to address this issue in which the motor will constitute the core component. The motor (and the nature of the printing head) determines the resolution of layering of 3-D printing; for instance, the MakerBot Replicator offers 100 μm resolution.

Following a review of different approaches to actuation to attempt to minimize design complexity, we initially prototyped a shape memory alloy (SMA) actuated motor design based on our previous experience with continuous control of SMA actuators [30]. Another desirable characteristic is the ability to implement zero-delay

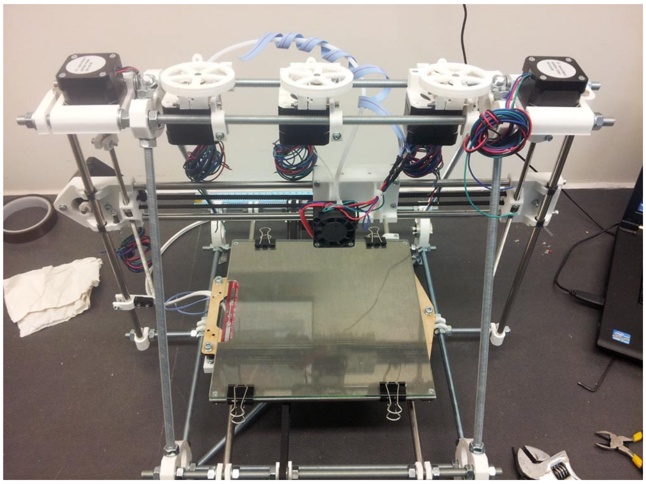

Fig. 1 Fully constructed RepRap 3-D printer.

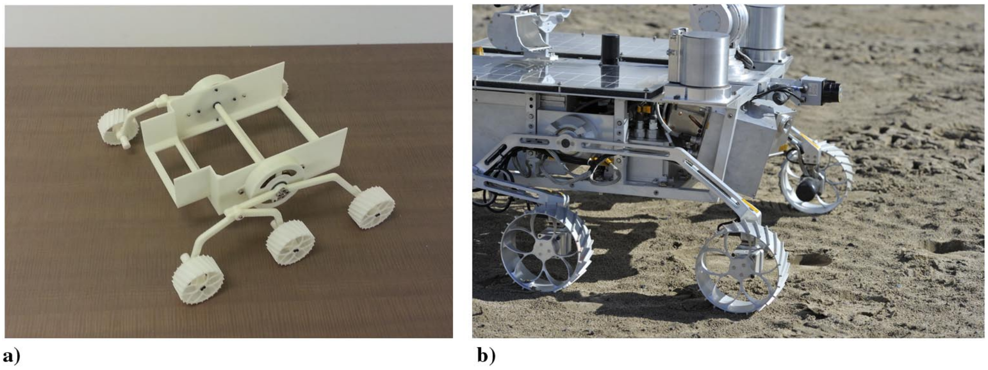

Fig. 2 3-D printed a) one-third size model, and b) actual Kapvik microrover chassis.

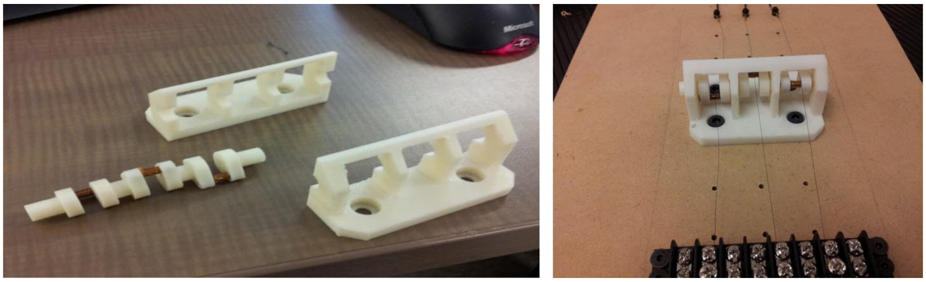

Fig. 3 Prototype 3-D-printable plastic-based electric motor concept.

"preflexes," nonlinear physical viscoelastic behavior for robust compliance useful for assembly manipulation tasks traditionally implemented passively using remote center compliance mechanisms. SMA wire "muscles" of Nitinol yield practical strains of 4% through self-resistance heating. The first prototype used Nitinol wires operating in antagonistic pairs through a cam-based rotor to convert linear contraction into rotary motion (Fig. 3). The plastic parts were 3-D printed in-house.

This design was hampered by the first lesson in the limitations of 3-D printing; the coarse layering yielded excessive friction between the working plastic parts. To circumvent this problem to demonstrate the motor principle, a second design (Fig. 4) was constructed from aluminium/steel to eliminate the friction problem. It successfully demonstrated rotary motion.

Although the torque output was excellent, the heating/cooling cycle limited the angular speed to around 1 Hz. This would be further exacerbated in a vacuum environment where convective heat rejection by air would not be available. Furthermore, the limited 4% stroke of the SMA wire required a significant wire length, making the assembly too complex. A third design based on piezoelectric "fingers" was discarded due to the brittleness of quartz; we are restricted to quartz, which is more readily manufactured from lunar resources than the more elastic polyvinylide fluoride.

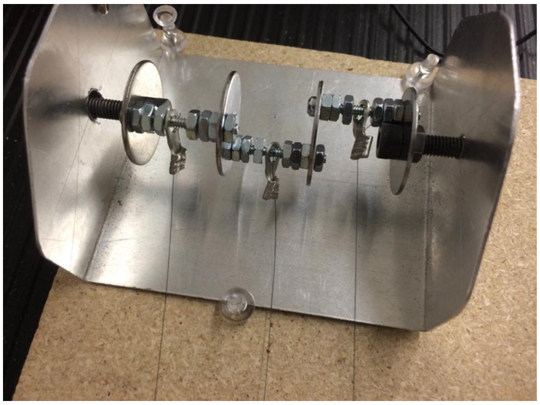

Fig. 4 Prototype 3-D-printable metal-based electric motor concept.

We have adopted a more conventional concept initially with a dc motor configuration to test the motor core construction. A motor core comprises layers of silicon steel laminated with an insulator material: in our case, plastic (Fig. 5). The operation of the motor is far superior to the SMA versions, offering very high rotation frequency (which can be geared for high torque), illustrating the reasons why smart materials have yet to supplant traditional motors in most applications [31].

The alternated layering construction lends itself to 3-D printing; this is in progress. There are, however, considerable hurdles to overcome that highlight many of the limitations of 3-D printing. In particular, the limitation of constructing a complex moving part that comprises several different materials. We have used a Renishaw selective laser sinterer (SLS) to print the steel layers of the motor core with spacing for the plastic insulation (Fig. 6) but printed it as a monolithic unit using interlayer struts (constraint imposed by the high cost of setup).

This is hot off the press, but this configuration will introduce eddy current pathways into the core. This is the first of many prototypes with which we shall be experimenting and testing. We are in the process of experimenting with iron particles dispersed in a plastic matrix, though this approach is expected to yield limited magnetic field threading compared with a traditional laminated core. We are also examining the possibility of printed wiring configurations based on disk-based motor designs. This is an attempt to minimize assembly; each core module currently involves winding of the previously extruded insulated wire around a plastic bobbin, which must be then sheathed over the core. This must be followed by the assembly of each wire-wound core unit into the final central rotor within the surrounding stator configuration. There are many practical considerations that make 3-D printing motors quite the challenge. We expect this to be a lengthy process; nevertheless, we see no fundamental hindrances. A carousel or belt-mounted EBF3–FDM system may manufacture the multiple interleaved metal/plastic layers, thereby demonstrating multimaterial 3-D printing. Once a wire-wound core can be constructed, it opens up the possibility of 3-D printing universal motor designs based entirely on electromagnetics. The universal motor is favored over the use of permanent magnets for versatility and modularity of the motor design. Furthermore, lunar potassium-rare earth element-phosphorus (KREEP) soils are only slightly enhanced over baseline terrestrial

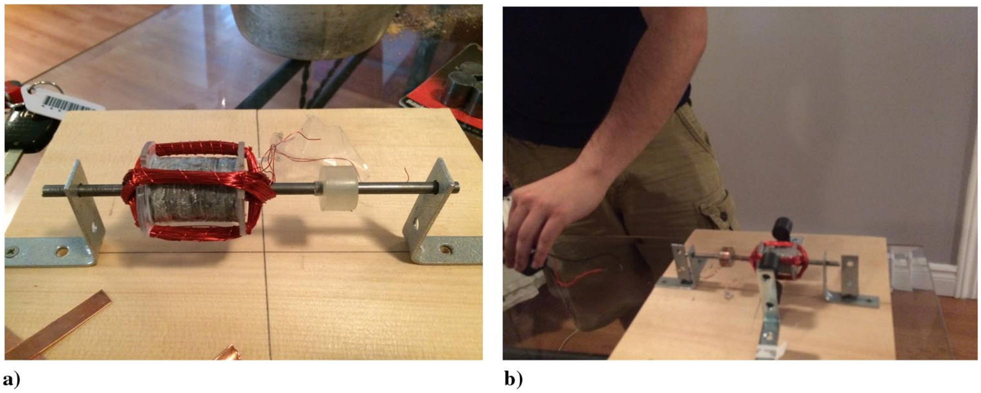

Fig. 5 Photographs of a) wire-wound laminated motor core, and b) in dc motor configuration.

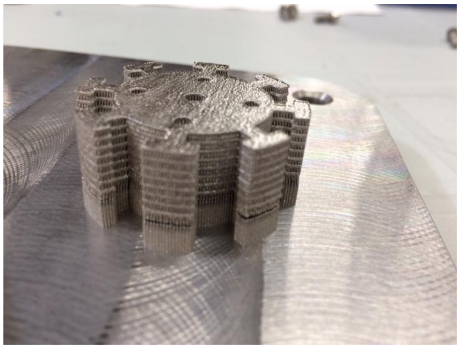

Fig. 6 SLS-printed steel layers for a motor core.

concentrations of Nd (460 ppm) and Sm (127 ppm) required for NdSm permanent magnets, making high-performance magnets unrealistic from lunar material. In the universal motor, coils are used to energize both the rotor and the stator poles; both sets of cores are constructed from plastic laminated layers of silicon electrical steel.

IV. Universal Robots

The electric motor provides the basis for a 3-DOF wrist assembly that could replace the printing head of a 3-D printer. This would enable a 3-D printer such as RepRap to be adapted to perform 6-DOF assembly operations of parts within its workspace. A variation on this theme might be a Stewart platform for precision manipulation. Compliant operation can be achieved with the remote center compliance mechanism for peg-in-hole tasks that is commonly used for assembly tasks. Assembly operations may be supported by printed jigs to hold components in place for assembly; this is part of the "controlled" environment alluded to earlier. A specific complex assembly sequence must be followed for the construction of the 3-D printed electric motor; this currently represents a complex set of assembly tasks, but in principle, assembly is a variation of a 3-D printing head.

Motors are essential for the construction of additional manufacturing tools such as lathes, milling stations, drill presses, bending presses, extruders, and any other motorized tool necessary for a fabrication laboratory. From a 3-D printable electric motor, lathes, milling machines, drill presses, brake presses, and other machines may be constructed because these machines are simply kinematic configurations of motors. There is little doubt that 3-D printers themselves, versatile as they are, do not eliminate the need for further machine tools, though they do minimize their use. The extrusion of metal wire will be a critical capability for the motor coils (if they cannot be printed); an extruder is essentially a motor-driven press. Indeed, plastic extruders are already part of the printing head of FDM-type printers. Furthermore, motors provide the basis for pumps and stirrers for driving throughput in unit chemical processes, beneficiation with jaw crushers, postprocessing through ball milling and shot peening, mobility for surveying, and drilling/trenching/excavation in mining. Without motors, none of these functions can be achieved.

V. Printable Electronics

Modern digital electronics manufacture requires a foundry costing around ~10 billion, which employs around 30 different complex physical and chemical processes (such as vapor deposition, molecular beam epitaxy, etc.) to create solid-state transistors and other solid-state devices. They require extensive reagent inventories for such processing. Even solar cell-grade silicon requires significant processing [32]. Such solid-state electronics foundries would be prohibitively expensive and totally infeasible as part of a self-replicating system. This restriction denies us present-day computer technology, software, and high-efficiency solar cells within our self-replication scheme. Although there has been much progress in developing printed plastic electronics, there are significant hurdles such as stability, especially with organic thin film transistors, and they are generally proposed for limited applications such as radio-frequency identification tags due to their modest performance [33,34]. Furthermore, manufacture of the active organic materials (such as pentacene) and solutions (such as chloroflorm) using lunar materials would be highly complex and difficult effectively ruling this out from consideration here. We have focused on the use of resistor-capacitor-inductor (RCL) circuits that involve simple, potentially printable components (though we have yet to demonstrate such 3-D printed circuitry); resistors are conducting wires of various cross sections, capacitors are conducting parallel plates between a dielectric, and inductors are coils of conducting wire of relatively simple construction. From resistor-capacitor filters and inductor-capacitor oscillators, a large range of electronic circuits can be constructed including filters for signal processing.

For computing systems, we considered mechanical systems (such as the Globus indicator of position navigation instrument in service on Soyuz spacecraft until 2002), electromagnetic relays (such as Turing's "bombes" at Bletchley Park that cracked the Enigma code), and vacuum tubes (first programmable electronic computer, Colossus at Bletchley Park comprised of 2400 vacuum tubes). Traveling-wave tube amplifiers (TWTAs) are vacuum tube amplifiers with radio-frequency amplification of ~70 dB that are still used in high-power communications satellites. The klystron and cavity magnetron are also microwave amplifier vacuum tube derivatives that may be used in high-power radiofrequency applications. Vacuum tubes are thermionic diodes that use a resistance wire to heat a cathode to 800–1200°C in an evacuated glass or ceramic envelope (which may not be necessary in a vacuum but is desirable to mitigate against dust contamination). The cathode comprises a Ni coat within which is a sintered tungsten filament with a high melting point. Tungsten's very high melting point at 3422°C (the highest of all metals) means that it must be sintered rather than melted during manufacture. It may be coated with alkaline earth oxide such as CaO to reduce its work function to operate at lower temperature (~600°C), but this is not essential and would impose a requirement for the extraction of Ca from lunar material, an unnecessary complication. Vacuum tubes offer superior performance to solid-state electronics in being less susceptible to radiation. Furthermore, if vacuum tubes are maintained in the power-on state in a thermally stable environment (such as buried in lunar regolith), they are highly reliable; a British Broadcasting Corporation pentode transmitter operated for 232,592 h from 1935 to 1961. The first differential amplifier was based on a pair of vacuum tubes, and subsequently operational amplifiers were based on vacuum tubes through 1941–1961. The greater instability of vacuum tubes over solid-state devices may be offset through the use of instrumentation amplifier configurations. Furthermore, it is plausible (though yet to be demonstrated) that vacuum tubes' simple construction offers opportunities for miniaturization.

Op-amps as active devices are highly versatile in providing sophisticated capabilities in relatively simple circuitry. Electric motor systems include a motor controller board that incorporates H-bridge and proportional-integral-differential (PID) controller circuits that can be constructed from op-amp circuits and feedback sensors. A simple PID analog controller circuit for a motor would represent a simple implementation of op-amp circuits. Op-amps can be employed for bandwidth filters, PID controllers, differential equation modeling, electronic mixers, Braitenburg control [35] architectures for robot behavior control, shifter circuits for optic flow hardware (Reichardt detectors [36]), Hasslacher and Tilden's nervous nets [37], Reynolds's boids-type swarm control [38], Buffon's needle algorithm (useful for surveying) [39], etc. Hence, simple op-amp circuits can implement highly sophisticated functions without the use of general-purpose computers.

VI. Printable Computers

Beyond the control circuitry that is readily implementable in traditional analog electronics, computing architectures with stored memory are required. Rather than opting for traditional general-pupose computer architectures, we have adopted simple electronic neurons as universal computing elements. A McCulloch–Pitts version of such electronic neurons can implement logic gates, exhibiting its potential for both digital and analog circuitry. Although the artificial neural network has been used for nonlinear mapping of input–output data sets for pattern recognition (by a generalization of the Stone–Weierstrass theorem), it is far more powerful than that. The universal Turing machine has been shown to be implementable on recurrent neural nets of sigmoid neurons [40]. Neural networks can implement logic programs such as expert systems or any type of symbolic artificial intelligence [41]. They offer significantly reduced physical footoprint over general-pupose architectures by virtue of the high information compression in their hidden nodes [42]. The neural network represents a powerful computational medium for robotics; it can map complex control decisions that would be difficult through traditional means. Indeed, the backpropagation algorithm can implement a Bayesian classifier [43] and a degenerate form of the extended Kalman filter [44]. The robotics functions will be critical in providing the adaptability in dealing with complex environments during surveying and mining phases of the self-replication process. Three rover-specific applications illustrating the versatility of neural nets are 1) feedback control systems [45] for manipulators [46], their supplementation with feedforward models [47], and their application to predictive active vision [48]; 2) complex signal processing through Gabor-based processing of visual textures for biomimetic vision [49]; and 3) autonomous navigation of rovers through RatSLAM (from "self-localization and mapping") [50] and neural field path planning [51].

Neural networks of reconfigurable neurons can exploit the hardware-on-demand capability of 3-D printing. In this case, the 3-D printer becomes part of the general computer architecture similar to the original Turing machine concept [52]. In our case, the input tape is represented by a magnetic core memory (broadly similar in construction to a motor core) for storing software programs. The 3-D printer constitutes the read/write head. The output is the specific neural circuit that realizes the selected input program, in this case, a configuration of printed electronic neurons. Rather than building a complex general-pupose computing architecture, the entire assembly constitutes the general-pupose computing architecture, but the output circuits have a relatively small physical footprint.

The electronic neuron models the nonlinear input–output relation with the output y_i given by

$$y_i = f\left(\sum_{j=0}^{n} w_{ij} x_i\right) \tag{1}$$

where x_i is the input, w_{ij} is the weighting factor, and $f(\cdot)$ is the nonlinear squashing function.

A suitable analog neuron (the Yamashida–Nakaruma neuron), comprising a summing integrator, sigmoid output, and a comparator, has been described that is constructable from simple op-amp-based circuits [53]. We modified the design by replacing the sigmoid with a signum function for more stable response. We implemented a two-neuron circuit on a desktop mobile robot platform (Fig. 7). It successfully performed obstacle avoidance tasks in following routes (reactively) through multiple obstacle configurations. This demonstrates the viability of the hardware analog neural network approach in a robotic task.

There is no requirement for online learning in this concept, though inevitably, because of limitations in printed circuit fidelity, tuning may be required.

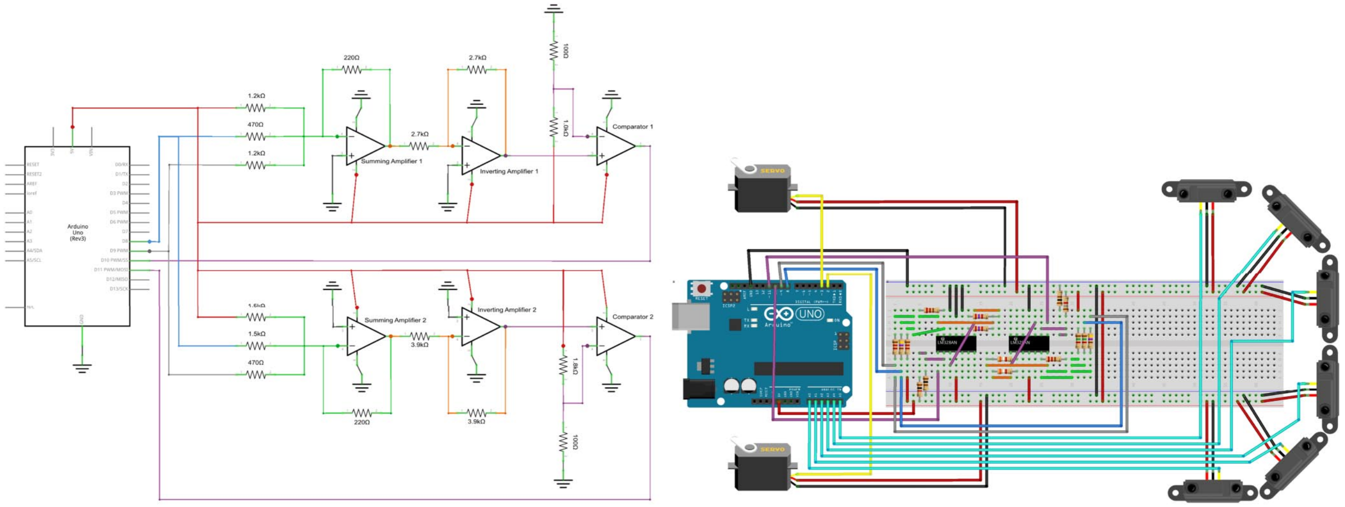

Fig. 7 Circuit representations of a simple hardware two-neuron neural controller.

VII. Printable Sensors

To create a full motor system, we need sensors. There are three fundamental types of sensor, all of which are required in a motor control system: displacement, force/pressure, and light detection. Displacement is the most fundamental of sensing modalities from which most other mechanical properties are derived. Displacement may be measured through rotary potentiometers (variable resistors) or optical encoders. Displacement and force/pressure may be measured using piezoelectric quartz; unfortunately, quartz does not occur naturally on the moon but may be grown from silica. Silica is melted at 2000°C and subjected to hydrothermal synthesis below 573°C followed by seeding in sodium silicate at 350°C and 150 bar. Sodium silicate is a catalyst; Na must be imported from Earth. This is the counterpart to the salt contingency discussed later. If desired, vapor phase pyrolysis may be employed to decompose SiO_2 to Si in a vacuum at 1250°C without the need for catalysts imported from Earth [54].

For optical sensitivity for image sensing and/or Reichardt detectors, rather than using pn junction materials, which require precisely doped silicon, we have chosen the simplest light-sensitive material: p-type semiconductor selenium that was used in the Victorian photophone. Indeed, the first semiconductor junction solar cells were constructed from selenium and gold film, offering 1% efficiency. Photocathodes and photomultipliers coated with Se offer light sensitivity. Both types of devices are derived from vacuum tubes. Other simple photocathode materials include K and Na alkali metals, which are sensitive to visible photons, but these would be complex to extract from KREEP soils. We have yet to identify a suitable potential ultraviolet-sensitive material that would be useful in detecting ilmenite that exhibits characteristic spectral responses in this waveband (see later) [55].

We have developed a novel rover-based surveying technique to measure physical soil properties that are important in geotechnics (cohesion and friction) without using complex spectrometers. We use simple load sensors above each wheel of the rover to "feel" the terrain over which the rover traverses. Changes in cohesion and friction caused by icy soil for instance can be readily detected. Such sensors were implemented on our Kapvik microrover and field-tested to demonstrate the proof of principle. Rover trials were conducted at Petrie Island near Ottawa, a well-known sandy "beach" of reasonably consolidated sand. A multilayer perceptron neural network was trained on sample load-cohesion/friction angle input–output pairs created from a Bekker–Wong terramechanics model. Once trained, this was used to extract soil cohesion and friction angle from the empirical load cell data. As expected, the data gave consistent results of 3.7 kPa cohesion and 28 deg friction angle over the traverse indicative of sandy loam as expected [56]. This technique may be readily applied to detect surface water ice and fluffy soil, indicating evaporated ice in the search for lunar volatiles. This demonstrates that simple sensors in conjunction with neural nets can provide a powerful signal analysis tool for basic surveying in support of surface mining of regolith. More sophisticated instruments for identifying elements may be feasible with neural network signal processing such as microwave-induced breakdown spectroscopy [57]. X-ray reflectance spectroscopy may also be feasible for mineralogy; x-ray tubes are vacuum tubes that generate x rays that evolved from the Crookes tube. The anode in this case is also tungsten like the cathode. The 150 kV electrons from the hot cathode strike the anode releasing x rays through Bremsstrahlung effects.

VIII. Chemical Processing of Raw Materials

ISRU is based on the concept of reducing reliance on transported cargo to support space missions; it is typically regarded as an adjunct to support human missions rather than as an enabling critical technology. It was the linchpin in Mars Direct concept [58]. The most basic lunar resource is regolith, and it is the scooping of surface regolith by the rover that provides the raw materials for ISRU presented here; no trenching or underground mining is necessary (except in the case presented later for drilling). Note that beneficiation of regolith is not implemented on the RPM demonstrator, which will process unsorted soil samples.

Material processing requires a foundry: in its simplest form, a heated crucible [59]. A lunar version would be a solar-furnace-based foundry based either on printed parabolic mirror segments or on cast Fresnel lens concentrators to create temperatures of 1600 and 2700°C respectively, more than required for metal extraction. The reflectivity of polished nickel reflectors is 90%, whereas that of polished steel is 75%. The chief challenge will be accurate mirror grinding and the alignment of the mirrors (which may be calibrated using a Stewart platform). The Fresnel lens is much favored in terms of performance, but precision casting is essential. A tungsten rather than ceramic crucible would be required for the higher temperatures.

A smelting-casting system with 3-D printing demonstrates the principle of bootstrapping machine shop facilities and tooling from raw materials. The solar concentrators enable layered sintering of regolith into ceramic structures built layer by layer; this will be essential for ceramic casting [60]. Lunar glass is abundant in lunar regolith, but its properties are variable, and so the production of lunar glass on demand involves heating basalt in a furnace until it melts as fused silicate/oxide at 1300°C. Glass from the melt requires high cooling rates ($\sim 20\,^{\circ}\mathrm{C/s}$) to prevent its crystallization. Lunar glass will comprise 40–45% SiO_2, 15–25% Al_2O_3, 5–15% FeO, 11–15% CaO, 0.5–8% TiO, and smaller amounts of other metal oxides. It is expected that lunar glass manufactured under vacuum conditions will offer superior mechanical properties to terrestrial glass due to the paucity of water vapor. Glass may be used as electrical and thermal insulation material especially as glass wool.

ISRU has concentrated on the extraction of consumables (oxygen, hydrogen, and water) because these are viewed as the major logistics commodities in human spaceflight. Indeed, RPM will acquire lunar regolith to extract water ice and to demonstrate oxygen production by hydrogen reduction of ilmenite at 900°C:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O \quad 2H_2O \rightarrow H_2 + O_2$$

Hydrogen is recycled. Although oxygen is generally the desired component from the reduction of ilmenite, iron is the main resource material that underlies the entire infrastructure required to support self-replication: an iron-based extraterrestrial industry. Ti is too difficult to extract from titania, but titania may be extruded as fibers for thermal and/or electrical insulation. Iron is an extremely versatile material; before the advent of aluminium in the 1950s, iron had beem the primary structural metal since 1200 B.C.E. Its range of alloys with tailorable properties is vast, but even just a small number of alloys can serve a wide range of functions. Wrought (pure) iron is tough but malleable, suitable for tensile structures. Steel includes low amounts of less than 2% C, which hardens it considerably. The addition of 9–18% tungsten creates tool steel for cutting tools that are resistant to wear. Cast iron with ~2–4 C and 1–2% is more brittle, but it is still suitable as a structural material; the Iron Bridge at Coalbrookdale has withstood the English climate since 1781. Silicon electrical steel comprises up to 3% Si and 97% Fe for high electrical resistivity for use in motors to reduce eddy currents and minimize core losses. Fernico is a family of alloys of Fe, Ni, and Co; of particular note is Kovar, a high electrically and thermally conductive iron alloy (53% Fe, 29% Ni, and 17% Co with minor constituents 0.3% Mn, 0.2% Si, and less than 0.01% C) that provides electrical conducting wires (such as motor coils) and high thermal conduction paths for conducting heat away from hot spots (such as motors). The good electrical properties are imparted by the Ni. This eliminates the requirement for electrolytic extraction of aluminium and/or calcium from anorthite for electrical or structural applications; see later for extraction of Ni, Co, and W.

RPM will demonstrate the extraction of volatile from the lunar regolith, particularly water ice, implanted by solar wind. Solar wind has impregnated regolith with 96% hydrogen (~120 ppm), almost 4% He, and trace amounts of H_2O, CO, CO_2, CH_4, N_2, NH_3, H_2S, SO_2, and noble gas Ar. Apart from water, hydrogen, and oxygen, carbon compounds will be of high value due to their scarcity. Volatiles will comprise an important part of any resource utilization infrastructure [61]. The gases are preferentially absorbed onto small particles of ilmenite favoring beneficiation of ilmenite specifically. Selection of smaller particles with the highest concentrations of volatiles favors sieving, but this would be wasteful of ilmenite. To enhance extraction of purer ilmenite fractions and reduce energy consumption, beneficiation may be implemented through physical crushing [62] or more speculatively through microwave heating. Differences in the magnetic susceptibilities of anorthite, pyroxene, and ilmenite allow the separation of ferromagnetic ilmenite magnetically [63]. Heating the regolith to 700°C would release 90% of the adsorbed volatiles. These can be separated out through fractional distillation: He at 4.2 K, H_2 at 20 K, N_2 at 77 K, CO at 81 K, CH_4 at 109 K, CO_2 at 194 K, and H_2O at 373 K.

Plastic is a highly useful material, too valuable to waste on structural applications. Given the severe limitation in carbon resources on the moon, we restrict plastic purely for flexible wire insulation applications, laminations of electrical steel in motor cores, and bobbins. Motor coils may be insulated or embedded in the bobbin to ensure that short circuits do not occur. Bobbins for wire coils in motors may constructed from cast basalt [64,65] or other ceramics, but its brittleness presents concerns for high-speed rotating machinery. Furthermore, we have selected silicone plastics as manufacturable from lunar resources to minimize carbon use. Silicones are synthetic polymerized organic-silicon compounds (siloxanes) with repeating R_2SiO units, where R is an organic group (typically methyl or ethyl group) linked by Si-O-Si backbones. This also opens the possibility of using plastic binder in mixing combinations of regolith or metal particles with a plastic binder, but this would be wasteful of a scarce resource that may readily substituted by other structural material. Methane and water vapor, both of which may be extracted from lunar volatiles, may be reacted to form syngas at 850°C and 4 MPa with a recyclable Ni catalyst:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Methanol is produced from CO and H_2 (syngas) reacted over an alumina (Al_2O_3) catalyst at 250°C and 5–10 MPa:

$$CO + H_2 \rightarrow CH_3OH$$

Chloromethane is manufactured by reacting the alcohol (methanol in this case) with HCl over an alumina catalyst at 350°C:

$$CH_3OH + HCl \rightarrow CH_3Cl + H_2O$$

CH_3Cl is reacted with Si at 370°C in the presence of a Cu catalyst to form dialkyl dichlorosilanes (R_2SiCl_2):

$$2CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2$$

This is then hydrolyzed:

$$n(CH_3)_2SiCl_2 + nH_2O \rightarrow ((CH_3)_2SiO)_n + 2nHCl$$

This yields the most common siloxane, polydimethylsiloxane, a silicone oil, but other silicone plastics are manufactured in a similar manner. Silicone oil may be employed in motor lubrication as well as hot isostatic pressing of metal powders (in power metallurgy). Silicones are highly versatile plastics; they are radiation tolerant and tolerant to high temperatures up to 350°C (even 500°C for short periods). Silicone elastomers offer superior performance as dielectrics in capacitors for their high dielectric constant with low elastic moduli. RepRap can, in fact, print in silicone plastics. The HCl is recycled. The apparent limitation of requiring Cl (in the form of HCl as a recyclable reagent) that requires importation from Earth can be exploited to advantage: a "salt contingency" that supplies NaCl as recycled reagents. Sodium is more abundant in lunar highland than the mare but is highly depleted by an order of magnitude in comparison to Earth. It appears in bytownite, a minor plagioclase mineral on the moon. Chlorine is depleted almost as much where apatite (calcium phosphate with halogen constituents) is a trace mineral. Hence, the salt contingency imposes a powerful means of control over the self-replication process to eliminate the possibility of uncontrolled replication.

An essential requirement for the self-replicator will be electrical energy. Amorphous silicon extracted from the regolith silicates for photovoltaic power generation is limited to ~1–5% efficiencies unless dopants are used to create pn junction cells. Although it is possible using microwave methods to create *p*-type silicon using Al dopant [66], it is unlikely to be consistently repeatable and requires the extraction of Al, which is not in the current inventory. For ISRU, we require dominantly thermal energy for heating, sintering ceramics, casting basalt, smelting minerals, etc., using solar concentrators. The foundry provides the key to electrical power generation implementing a solar furnace without using solar cells. Radioisotope-thermoelectric-generator-based power conversion involves banks of high-temperature-tolerant SiGe thermoelectric converters, but Ge is rare on the moon. Mg_2Si is a potential thermoelectric converter based on lunar materials, but thermoelectric conversion is less efficient as well as imposing significant chemical processing requirements. Dynamic power conversion as used in nucear reactors requires high-thermal-capacity liquids such as Na(K) (e.g., alkali metal thermal-to-electric converters), high-pressure water (e.g., pressurized water reactor), or gas cooling with He (e.g., advanced gas-cooled reactor). None of these are viable. However, thermionic emission is often used in high-temperature applications such as space-based nuclear reactors to pick off electrical power with 5–20% conversion efficiencies [67] (~10% should be achievable with even a fairly primitive arrangement); it is based on vacuum tube technology, thus offering multiple use of the same product technology. Similarly, for energy storage, motorized flywheels are ideal over long periods during the two-week lunar night. Hence, vacuum tubes and motors are the critical components in both energy generation and energy storage.

IX. Mining of Exotic Materials

Certain materials such as Ni, Co, etc., are scarce on the moon and require access to asteroidal material; the moon has been bombarded for aeons as indicated by its cratering record. Mass concentrations (mascons) on the moon at impact craters induce changes in the local gravity field, indicating massive asteroid impact [68]. They are detectable from their gravity field pattern due to a central gravity excess (due to increased density) surrounded by an inner ring of gravity deficit and another outer ring of gravity excess. Remnants of some of these asteroid strikes are also indicated by magnetic anomalies caused by iron-rich magnetic rock. Metal (NiFe) meteorites constitute around 6% of falls originating from M-type asteroids. Iron asteroids constitute an Ni source from the NiFe alloy. Much of the lunar magnetic anomalies are located around the rim of the South Pole–Aitken basin crater. In any case, there is evidence that there are iron-rich deposits on the moon that originated from asteroid impacts. Ni is a hard ferromagnetic metal primarily found as NiFe alloy (kamacite and taenite) in NiFe meteoritic material as found in the Sudbury astrobleme in Canada. Kamacite is an FeNi (90 : 10 to 95 : 5) alloy often with Co contaminant. Kamacite is found intermixed with taenite in NiFe meteorites; taenite is an FeNi (35-80 : 65-20) alloy. The Mond process may be employed for purifying Ni by reacting with CO at 40–80°C with an S catalyst to form nickel carbonyl. This may be reversed to yield Ni powder at 230°C and 60 bar with the CO recycled: $Ni(CO)_4 \leftrightarrow Ni + 4CO$. Inclusions of troilite are also common as the source of the S catalyst. The Mond process allows separation of Ni from Fe and Co contaminant [69,70]. Cobalt is commonly found in astroblemes on Earth such as the Sudbury crater. Cobalt is a ferromagnetic metal with a high melting point of 1495°C found in natural alloys with iron in NiFi meteoritic material. Both Co and Ni may be extracted magnetically and are used in steel production, in superalloys, and as powdered catalysts in the Fischer–Tropsch process to hydrogenate CO into hydrocarbons. NiFe asteroids are also expected to possess significant amounts of siderophile elements such as Pt (useful as a potential catalyst as well as a precious metal) and rare earth metals. The extraction of pure Ni from the Mond process, a separate source of

Fe from ilmenite, and FeCo alloy offers the opportunity to tailor a range of fernico alloys using simple density measures.

Lunar rock and regolith contain variable amounts of tungsten; Nb, Ta, and W are trace elements less than 1%. High Ta concentrations occur in lunar granites and telsites, and high Nb concentrations occur in ilmenite (2%) in lunar granite [71]. Highland rock is more enriched in tungsten than lunar basalt at an average of 0.3 $\mu g/g$. Tungsten may be recovered from wolframite $(Fe, Mn)WO_4$, scheelite $CaWO_4$, ferberite $FeWO_4$, and hubnerite $MnWO_4$. The ore is converted to oxide WO_3, which is heated and reduced with hydrogen to produce powdered tungsten [72]: $WO_3 + 3H_2 \rightarrow W + 3H_2O$. Hydrogen can be recycled and oxygen recovered. The low incidence of tungsten makes this approach unattractive. However, NiFe asteroids are often enriched in tungsten microparticle inclusions. Tungsten's very high density of 19.3 times that of water, close to uranium and gold, presents a means for its separation from other elements as Fe, Ni, and Co.

Selenide (such as Cu_2Se, PbSe, ZnSe, etc.) and selenite (such as Na_2SeO_3) minerals are rare, and so Se is mostly commonly found in impure form associated with metal sulphide ores, where it partly replaces sulphur. Sulphides of copper, zinc, selenium, etc., are hydrous minerals and so are absent from lunar rock. Lunar regolith, however, is enriched in chalcopyrite (copper iron sulphide) deposits compared with lunar rock due to the existence of volatile compounds resulting from bolide impacts permeating the regolith. Sulphur has a relatively high abundance in lunar soils averaging 700 ppm by mass. Troilite (FeS) is a minor component ∼1% of mare basalt and is typically associated with ilmenite, though it cannot be separated magnetically. Sulphides including FeS are enriched in impact craters, indicating that there are enriched sulphur sources in asteroids. The Se/S ratio tends to be fairly constant in chondrites. Selenium microinclusions in NiFe meteorites makes them the primary ore for Se. Se is manufactured as a byproduct of mining nickel or copper from copper sulphides on Earth. Electrolytic refining of metal sulphide yields Se at the anode. This makes asteroidal material highly desirable as a source of selenium.

It cannot be guaranteed that these materials will occur in adequate form in surface regolith in the locale of mascons. Accessing these resources may be altogether more challenging than surface strip mining of regolith. Fortunately, these materials will be required in only relatively modest amounts. Nevertheless, drilling methods will be required, and perhaps there is scope for some novel approaches [73]. I would anticipate that subsurface asteroid mining may be centrally administered with telesupervisory control as a service to the self-replicating machines, thereby providing a safeguard against uncontrolled replication.

X. Spacecraft Manufacture from Lunar Resources

We have outlined a case that indicates that a complete mechatronic system could be manufactured from lunar resources using 3-D printing technology. If so, it is a short step to show that we have instituted what amounts to a universal constructor (and self-replicator). All the component technologies required for the construction of a spacecraft are present. To be sure, the spacecraft subsystems may be primitive, but parallel manufacture from a vast population of self-replicating factories opens possibilities hitherto regarded as impossible. Once we have manufactured the desired population of self-replicating factories, they may be programmed to manufacture spacecraft en masse.

Electromagnetic launchers may be constructed to launch spacecraft units into lunar orbit. The mass driver comprises a magnetically levitated vehicle accelerated by a linear synchronous electric motor. A coil-based electromagnetic mass driver constitutes the same basic components as an electric motor but in a linear configuration (of larger scale, of course) [74]. The cylindrical armature carries an armature current and resides within a long solenoid (stator) comprising separate coils. The armature is suspended by magnetic induction from the energized coils to eliminate friction. The coils are energized sequentially like a stepper motor so that the armature accelerates along the solenoid axis. Spacecraft-containing buckets are accelerated to launch speeds. From the moon, an electromagnetic launcher must launch into Lagrangian point 1 (L1) transfer orbit at 3 km/s, easily within reach of modest electromagnetic launchers compared with 12 km/s required from Earth. On the moon, a 10 km track can provide 30g continuous acceleration using 2 T electromagnets (within the capacity of soft iron). Large amounts of electrical energy must be stored for release during launches; flywheels are ideal for high power densities and the ability to supply high power over short release times.

A spacecraft onboard propulsion system requires fuel oxidizer or a nonfuel form of propulsion. Compressed propellant H_2 and oxidizer O_2 may be manufactured from lunar volatiles and subjected to passive cooling. Tankage and thrusters of iron and steel, respectively, may be lined with tungsten. Solar sails would be highly desirable for some applications. For a perfectly reflecting solar sail, the performance is determined by the lightness parameter [75]:

$$\beta = \frac{1.53}{\sigma} \tag{2}$$

where σ is the sail mass/unit area (in grams per square meter). Sail acceleration has a lower useful bound of greater than 0.1 mm/s^2 at 1 astronomical unit given by

$$a_c = \frac{\beta}{0.168} = \frac{9.11}{\rho t} \ \mathrm{mm/s^2} \tag{3}$$

Hence, for iron with a density of $\rho = 7.87 \times 106 \ \mathrm{g/m^3}$, the minimum thickness is given by

$$t = \frac{9.11}{a_c \rho} =< 12 \ \mu\mathrm{m} \tag{4}$$

This is a best case scenario; more useful accelerations require thinner sails. It is not currently clear whether solar sails can be manufactured to such tolerances on the moon, and so chemical propulsion will likely be the propulsion system of choice, at least for a first-generation infrastructure.

Wrought iron (and steel where necessary) may be used for the primary and secondary structures. 3-D printing offers greater flexibility in structural design such as isogrid and truss designs. Motorized mechanisms for deployables may employ the electric motors as described. Attitude control may employ reaction wheels, momentum wheels, or control moment gyroscopes driven by the electric motors as described. Thermal control may be based on passive systems such as thermally conductive thermal straps and glass thermal insulation or active methods that rely on resistance heaters and electric motors such as louvres, etc.

Data handling may be implemented through the vacuum-tube-based logic circuits and neural network controllers [76]. The communications subsystem is similar in concept to the data handling subsystem (Fig. 8). Quartz is ideal as a radiofrequency oscillator; the Pierce oscillator may be constructed with a minimum number of components: one inverter, two resistors, two capacitors, and one quartz crystal. The mixer is a transistor/diode circuit, the filter is an RCL circuit, the amplifier is a TWTA, and the demodulator is a diode. Convolutional codes for channel coding may be implemented using Ex-OR gates, whereas Viterbi decoding may be implemented

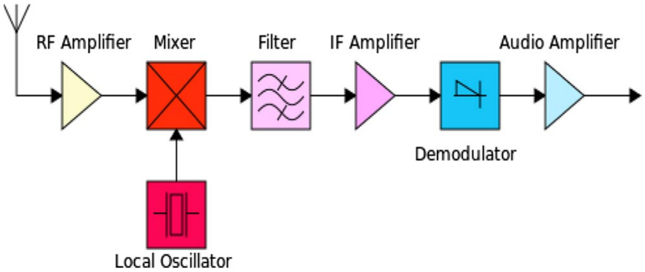

Fig. 8 Communications system hardware chain (RF, radiofrequency; IF, intermediate frequency).

neurally [77]. Hence, a simple communications system may be implemented using vacuum tube technology.

Power generation in space may derive from the lunar approach outlined previously; solar concentrators concentrate light to high heat, which is converted to electrical energy through thermionic emission with a conversion efficiency of ~10%. There is thus no requirement for photovoltaic cells. For short-duration eclipsing, rechargeable NiFe batteries using a KOH electrolyte (extracted from KREEP basalts) are a robust form of energy storage, though with low specific energy of 25 W · h/kg; they were used to power the German V2 rockets. Long-duration power storage may use flywheels if necessary, possibly combining power storage with attitude control [78].

Optical sensors using arrays of selenium pixels may be employed as a generalized camera payload (and/or sun/star cameras).

All the major spacecraft subsystems can be manufactured from lunar resources. To be sure, the spacecraft concept presented will be simple in nature and certainly suboptimal. Given that they will be designed and constructed according to very different constraints from current spacecraft under very different conditions, it is likely that spacecraft design will develop in unforeseen ways. In particular, large constellations will become feasible.

XI. Space-Based Solutions to Global Problems

In 2013, CO_2 levels in the atmosphere passed 400 ppm compared to 280 ppm preindustrial levels for the first time in human history, and there are no signs of abatement (Fig. 9); it is projected to reach 450 ppm around 2020 generating a 2°C rise in average temperature globally.

In reality, little is being achieved to solve the problem for many political, economic, and technical reasons. Indeed, over the last few years, the tone of speech has resignedly shifted from combatting climate change to enduring and accommodating its worst excesses. There is a solution to this human-generated geophysiological disease. The treatment involves treatment of symptoms (painkiller) and treatment of aetiology (antibiotic). For our geophysiological ailment of atmospheric carbon excess, the painkiller involves climate intervention, whereas the antibiotic involves clean energy generation, both from space.

Geoengineering approaches to climate change mitigation are unpopular and regarded with suspicion. It involves intervention in the climate to reduce global temperatures; it includes sulphate aerosol injection into the stratosphere and the seeding of oceans with Fe particles to create algal blooms (like El Niño). These methods are not reversible, though they dissipate over time; for this reason, they require annual application. Until now, space-based approaches have been regarded as unworkable and enormously costly. Space-based geoengineering involves the construction of a solar shield at L1 with an equivalent radius of 1824 km to reduce incident radiation by 1.6% corresponding to a temperature drop of 1.75°C [79]. Alternatively, it has been proposed to deliver 10^{12} 60-cm-diam discs to L1 by 20 railguns on Earth launching 10^6 silicon disks every 5 min for 10 years [80]. Both approaches are impractical. Self-replication technology offers the potential for constructing large numbers of small solar shield units from lunar resources at low cost. Each unit is a small, fully controllable 3-D printed spacecraft using solar petals supplemented by propellant to maintain their mean location at sun–Earth L1. These solar shield units may implement swarm control behaviors such as neural fields, potential fields, or equilibrium control approaches mediated by neural network controllers [81]. These approaches are modest in cost, fully controllable, modulatable, and reversible, unlike most geoengineering solutions. This is the painkiller.

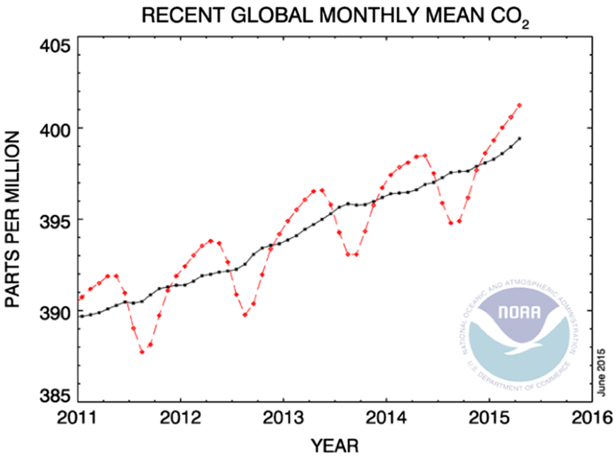

Fig. 9 **Mean CO_2 levels in the Earth's atmosphere (credit National Oceanic and Atmospheric Administration).**

The same approach may be adopted to generate clean energy for Earth. Thus, the argument that geoengineering will discourage weening from fossil fuels is a nonsequitur in this case. Solar power satellites can beam microwave energy to rectenna arrays on Earth [82], the principle of which has been demonstrated. The solar power satellite is a spacecraft with a microwave payload. It is envisaged as a giant structure that uses large photovoltaic arrays to generate electric power, which is then fed into a klystron vacuum tube (i.e., light to electric to heat to electric/microwave energy thence transmitted through a waveguide to Earth). However, it is possible to exploit thermionic emission directly by using solar concentrators to concentrate light to heat the klystron cathode directly to generate microwave radiation for transmission to Earth, bypassing the intermediate electrical energy conversion step. Electrical energy for onboard services can be generated the same way by thermionic conversion to electrical energy independently. This should be of comparable efficiency as photovoltaic conversion, but it is based on pure vacuum tube technology constructed on the moon using a restricted materials inventory. A solar power satellite system could be constructed as a swarm of small units created via self-replication technology. This is the antibiotic.

Such a productive capacity on the moon enabled by self-replicating machines may be exploited by the private sector in ways currently unimagined as the space sector opens to private ingenuity. Much of human exploration on Earth has been driven by such motives. The private space sector has already been demonstrating its vigor in driving progress in space exploration, and I suspect that it would not leave fallow opportunities for the exploitation of extraterrestrial assets. The first step will be the RPM mission.

XII. Conclusions

The core capabilities necessary for this self-replication proof of concept have been outlined. Although there are many problems with which to contend, there appear to be no fundamental hurdles. The present focus initially is on a 3-D printable motor system, which is currently in progress.

The devil, of course, is in the details; there are no illusions of the magnitude of the task in achieving full self-replicaton. The later steps toward full self-replication will be just as challenging; they will focus on organization, control, throughput, and logistics rather than the individual components as discussed thus far. Self-replication offers immense potential for the space sector. In the short term, self-replication can address immediate climate mitigation issues. In the long term, self-replication offers the prospect for migrating the entire energy generation industry off Earth, relieving the Earth's biosphere from the damaging effects of such industries. Space exploration may yet be the key to solving the most pressing global problems.

Application of the techniques for self-replication on the moon to near-Earth asteroids (NEAs) will introduce additional challenges imposed by the microgravity conditions. Nevertheless, the foundations will be laid on the moon. The exploitation of asteroids (and comets in the form of spent comet nuclei) will vastly increase the range of materials available, relaxing some of the constraints imposed by lunar resources. This will introduce a maturity to space infrastructure development. Deimos and Phobos are carbonaceous chondrite asteroids in orbit around Mars. With NEAs and the moon, they provide final stepping stones to the surface of Mars. In conjunction with self-replication technology for exploiting in situ resources, human Mars exploration becomes a more practical and, more importantly, sustainable goal. Indeed, Mars, rather than being an end goal, would represent the major leap in opening the whole of the solar system to human exploration. But this can only be achieved in a sustainable manner through the leverage provided by self-replication technology.

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