Manna from Heaven – Preliminary Efforts for a Self-Replicating 3D Printer for Lunar In-Situ Resource Utilisation

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Abstract

The prospect of self-replication technology is explored in the context of robotic in-situ resource utilization (ISRU). It is proposed that self-replication technology is realizable in the near term enabled by the advent of 3D printing technology. Presented are preliminary efforts in developing self-replication. Our corollary is that a 3D printable motor system represents an existence proof that an appropriately designed robotic 3D printer can self-replicate. Two electric motor designs are presented which represent our partial exploration of the concept. Both are based on the use of shape memory alloy wire as the actuating mechanism. The 3D printer as a universal constructor, given the appropriate programming, could potentially build simple spacecraft. The power of self-replication allows full exploitation of in-situ resources to build a complete extraterrestrial infrastructure robotically and open up space to hitherto unimaginable uses for the benefit of humanity.

1 Introduction

The concept of self-replication technology dates back to John von Neumann who devised the concept of the universal constructor. This universal constructor can construct anything including a copy of itself. In essence, it comprises an idealized robotic arm that picks parts from its environment to build a copy of itself and its control system. Through re-programming, it can construct any machine from those same parts. In fact, it was subsequently discovered that DNA replication follows precisely this same logic. The reader is referred to the remarkable "bunny book" [1] 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) and then artificial life were derived. Von Neumann's original kinematic models were discarded but more recently have been revived. In particular, it worth mentioning the landmark NASA study on self-replication applied to lunar exploration [2]. Rather than review the extensive literature on the theory of self-replication, we present only engineering-based efforts towards practical realization of self-replicating systems.

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

Table 1. Power of self-replication

Number of Offspring per Generation	Number of Generations	Population
1	10	1024
2	7	2187
2	13	1,594,323

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. It comprises three main elements. A 72 kg payload package, RESOLVE (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 the 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.

The potential of self-replication capability to ISRU is also evident: consider a typical launch cost of $20,000/kg to LEO – we may assume that this increases by two orders of magnitude to $2M/kg to the surface of the Moon. A 1 tonne "seed factory" launched to the Moon would thus cost $2B. If it self-replicates 1000 copies of itself, the cost drops to $2000/kg which drops further to only $20/kg for 100,000 copies. This dwarfs launch cost savings (~90%) expected from SSTO launch technology to LEO. Hence, self-replication acts as a matter multiplier, to use an economics term, with the multiplier offering many orders of magnitude increase in productive effort. In this paper, we describe a roadmap to realize this self-replication capability.

2 3D Printer as Universal Constructor

Recently, 3D printing has emerged as a generalized manufacturing capability. It is a layered manufacturing technique with wide versatility for printing organic tissue, food, pharmaceuticals, etc. Its primary limitation however resides in its serial nature that has prevented it from growing beyond prototyping functions. An important inspiration was the development of the open source Rep(licating)Rap(id prototyper) 3D printer by Adrian Bowyer in the UK. The RepRap can construct complex geometries in plastic including its own plastic parts. This represents our starting point. Full self-replication offers not just parallel processing throughput but exponential processing throughput. Currently, RepRap can replicate only its plastic parts that constitute its simplest structural parts. It also includes metal structural members that provide the rigidity that plastic cannot match. To close the self-replication loop, the broad categories of parts that must be replicated by the 3D printer include: (i) metal and other materials for structures; (ii) electric motors; (iii) assembler constructed from motors; (iv) electronics; (v) sensors; (vi) energy generation system; (vii) mobility system constructed from motors and associated rover capabilities to mobilize 3D printing for raw material prospecting and mining.

3 Printable Electric Motor

We have selected an electric motor system as our proof of principle of self-replication using 3D 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. It is our corollary that if we can print a motor system, we can print almost anything to realize any functionality we require including a mobile 3D printer. Printing under reduced gravity has not been addressed specifically but we expect that the motor will be a major component in any pump solution. The motor (and the discharge nozzle) determines the resolution of the layering – for instance, the MakerBot Replicator offers 100 μm resolution. Electric motors are complex in construction making them difficult to construct through 3D printing. We have opted for a shape memory alloy wire "muscle" approach based on Nitinol which can yield practical strains of 4% through self-heating resistance. Our first prototype used Nitinol wires operating in antagonistic pairs through a cam-based system to convert linear contraction into rotary motion (Fig 1).

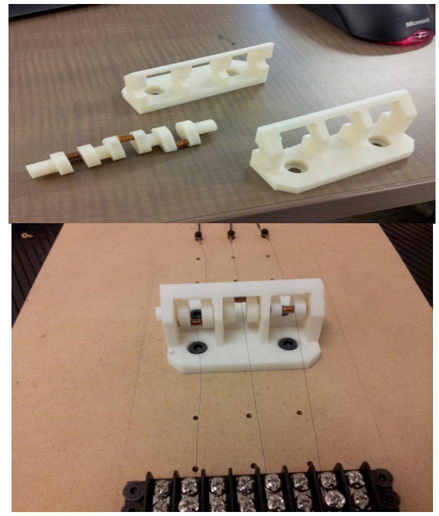

Fig 1. Prototype 3D printable motor

This design worked but was not efficient, the primary problem being excess friction between the working plastic parts. A second design was built from metal to eliminate the problem to demonstrate the design which is still evolving towards more compact designs (Fig 2). Some of the earlier friction issues in plastic have been resolved with finer resolution printing.

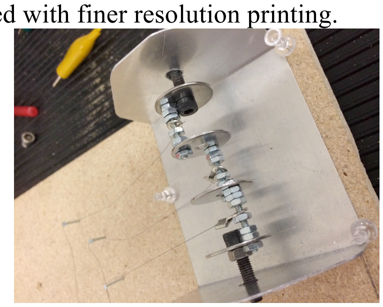

Fig 2. Prototype 2 and fine resolution 3D printing

4 Universal Assembler

The advantage of artificial muscle-type actuators is that they lend themselves to the implementation of preflexes – nonlinear physical viscoelastic behaviour for use in robust manipulation. The lever arm torque is given by:

$$\tau = J_{eff}\ddot{\theta} + b(\theta_{eq} - \theta)\dot{\theta} + k(\theta_{eq} - \theta) \qquad (1)$$

A standard PD control law may be applied normally:

$$\ddot{\theta} = \ddot{\theta}^d + k_v(\dot{\theta}^d - \dot{\theta}) + k_p(\theta^d - \theta) \qquad (2)$$

where J_{eff}=effective inertia of cam system, b=viscous friction for damping as a function of deviation from equilibrium, k=stiffness for compliance, θ_{eq}=joint equilibrium position, θ^d=desired joint position, k_p=proportional gain, k_v=derivative gain. Applied to any motor, this will yield general compliant operation beyond that achievable with the remote centre compliance mechanism for peg-in-hole tasks. The motor provides the basis for a 3 DOF wrist assembly that replaces the printing head of RepRap. This enables RepRap to be adapted to perform 6 DOF assembly operations within its workspace. A variation on his theme might be a Stewart platform as used in atomic force microscopes for precision manipulation. Assembly operations may be supported by printed jigs to hold components in place for assembly. The same approach may be used to print IBM-type punch cards with Hollerith codes to control the assembly process similar to a Jacquard loom. Punch cards may be read using photomultipliers (cf. Turing's "bombes").

5 Printable Electronics

Modern digital electronics requires a foundry costing around ~$10B which employs around 30 different complex physical and chemical processes (such as vapour deposition, molecular beam epitaxy, etc) to create solid-state transistors and other solid state devices. This is not feasible as part of a self-replicating system and this denies us present-day computer technology, software and solar cells within our self-replication scheme. We have focused on RCL circuits that involve simple potentially printable components (though we have yet to demonstrate such printed circuitry) – resistors are wires, capacitors are parallel plates and inductors are coils of wire of relatively simple construction. From RC filters and LC oscillators, a large range of electronic circuits can be constructed.

For computing systems, we considered mechanical systems (such as the Globus IMP 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. Vacuum tubes are thermionic diodes that use resistance wire to heat a cathode to 800-1000^{o}C in an evacuated envelope (which may not be necessary in a vacuum). They are less susceptible to radiation than solid-state electronics. 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. Op-amps are highly versatile – they can be used for bandwidth filters, PID controllers, differential equation modelling, electronic mixers, Braitenburg control architectures for robot behaviour control, shifter circuits for optic flow hardware (Reichardt detectors), Tilden's nervous nets, Reynolds' boids-type swarm control, Buffon's needle algorithm (useful for surveying), etc. The implementation of stigmergy offers potentially sophisticated construction capabilities. Some 2400 vacuum tubes were used in the Colossus computer at Bletchley Park, the first programmable electronic computer. They are reliable if maintained at power-on in a thermally stable environment (such as buried in lunar regolith), being used in the wartime British Post Office telephone exchange – a BBC pentode transmitter operated for 232,592 hours from 1935 to 1961. Travelling wave tube amplifiers (TWTA) are vacuum tube amplifiers with radio-frequency amplification of ~70 dB that are still used in high-power communications satellites. The cavity magnetron is also a microwave amplifier vacuum tube that offers potential for microwave mining – microwave energy is absorbed and causes differential thermal expansion of minerals offering the potential for beneficiation without physical crushing (though not essential for self-replication).

6 Printable Controllers

Rather than opting for a traditional computer architecture, we have chosen to adopt 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 analogue circuitry. Although the artificial neural network has been used for nonlinear mapping, it is far more powerful than that. The neural network represents a powerful computational medium for robotics - it can map complex control decisions that would be difficult through traditional means. Three rover-specific applications illustrating its versatility are: (i) feedforward models to supplement the limitations of feedback systems; (ii) complex signal processing for Gabor-style image processing; (iii) autonomous navigation through RatSLAM (self-localisation and mapping). The electronic neuron models the nonlinear input-output relation where the output is given by:

$$y_i = f\left(\sum_{j=0}^{n} w_{ij} x_i\right) \quad (3)$$

where x_i=input, w_{ij}=weighting factor, f(.)=nonlinear squashing function.

A suitable analogue neuron comprising a summing integrator, sigmoid output and a comparator has been described that is constructable from simple op-amp based circuits [3].

Most of the complexity of the neural network resides in the learning algorithms that implement some form of gradient descent on the error surface:

$$w(t+1) = w(t) - \eta \tfrac{\partial e}{\partial w} \tag{4}$$

where η=learning parameter, e=output error.

This is typically realized in software although hardware approaches have been demonstrated using FPGAs which are not feasible for our purposes. We have used extended Kalman filter-based learning rules for learning forward models of manipulator dynamics but this would challenging to implement in hardware. Learning also requires variable resistors and capacitors that suffer from drift making their use undesirable in circuitry (though potentiometers can used as noisy sensors). Initially, we are adopting an off-line learning approach using genetic algorithms. We have been exploring the evolution of robust obstacle avoidance capabilities through the presentation of multiple training environments comprising variable rock fields for a rover. Initially, we shall be implementing our analogue neural networks using off-the-shelf electronic components to demonstrate the viability of our approach. Beyond this, Adaline-type learning systems that employ memristors may offer a viable approach for implementing online learning in hardware though we have yet to investigate this possibility.

7 Printable Sensors

To create a full motor system, we need sensors. Although this has yet to be addressed, there are two fundamental types of sensor, both of which are required in a motor control system: displacement and incident light. Indeed, displacement may be measured through potentiometers or optical encoders. Displacement may be measured using piezoelectric quartz – unfortunately, it does not occur naturally on the Moon but may be grown from silicon dioxide through hydrothermal synthesis below 573^{o}C and seeding in sodium silicate at 350^{o}C and 150 bar. 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. For radio frequency applications, a forge-synthesised chalcopyrite-zinc oxide junction was commonly employed as Perikon diodes prior to solid-state electronics. For optical sensitivity, rather than using pn junction materials, we have chosen the simplest light-sensitive material – selenium that was used in the Victorian photophone. It occurs in metal sulphide ores but these are rare on the Moon but there do exist chalcopyrite (CuFeS) deposits. Similarly, PbS (galena) and PbSe offer infrared sensitivity. Photocathodes and photomultipliers are derived from vacuum tubes. We have yet to identify a suitable potential ultraviolet-sensitive material that would be useful in detecting ilmenite which exhibits characteristic spectral responses in this waveband [4].

8 Simple Rover Surveying

For the RPM mission, we are developing a novel 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 to "feel" the terrain over the rover traverses. Changes in cohesion and friction caused by icy soil for instance can be readily detected. Such sensors were implemented on the Kapvik micro-rover prototype and field-tested to demonstrate the proof of principle [5]. 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^{o} friction angle over the traverse indicative of sandy-loam as expected – details are presented in [5]. Hence, we have preliminarily demonstrated that simple sensors may be deployed for basic surveying in support of surface mining of regolith. We are currently developing this technique to detect surface water ice and fluffy soil indicating evaporated ice for application with RPM.

9 Mining & Materials Processing

ISRU is typically regarded as an adjunct to support human missions rather than as an enabling critical technology. ISRU has concentrated on the extraction of consumables – oxygen, hydrogen, water – as these are viewed as the major logistics commodities in human spaceflight. Indeed, the RPM will acquire lunar regolith to extract water ice and to demonstrate oxygen production by hydrogen reduction of ilmenite:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2 + \tfrac{1}{2}O_2$$

Rather than premising ISRU on human missions, we envisage developing a complete lunar (and asteroidal) infrastructure robotically through a combination of telerobotics and automation. Our interest is also in the Fe and Ti metal waste from hydrogen reduction. We do not consider certain practical issues such as dust mitigation at this stage which is a generic problem rather than specific to self-replication [6]. We assume that mining would be conducted from a roving 3D printer by scooping regolith as it traverses. There are several possibilities for beneficiation and selection. Ilmenite exhibits preferential concentration of volatiles as well as being a source of metal and oxygen. Beneficiation may be implemented through physical crushing or more speculatively through microwave heating followed by magnetic separation. Note that this procedure is not implemented on the RPM demonstrator which will process unsorted soil samples.

Although we are using plastic for our self-replication system currently, this is not available on the Moon though there have been experiments in mixing combinations of regolith, or metal particles with plastic or clay binder, eg. Mini-Metal Maker. Metal printing (although using much more sophisticated 3D printers) is well established and uses selective laser sintering. The first Maimon laser was a lamp-pumped synthetic ruby (chromium-doped corundum) laser. Rubies can be synthesized from a mixture of Al_2O_3 and Cr_2O_3 heated to 2000°C in a hydrogen-oxygen torch and seeding in sodium carbonate at 445°C and 380 MPa. The chief challenge will be accurate mirror grinding and the alignment of the mirrors (which may be calibrated using a Stewart platform). We have not addressed 3D metal printing as yet but obviously this will be critical.

To address this, we shall be constructing a Gingery-like foundry to smelt material to illustrate bottom-up design from the simplest of components. The Gingery foundry is a charcoal-fired metal bucket lined with sand and clay holding a steel crucible [7]. It can melt pure metals with low melting point such as Al (660°C) and Zn (420°C) which can then be cast or powdered. Demonstration of metal powdering method would be a critical capability for handling metal with a 3D printer. We expect to demonstrate the extrusion of Niinol wire initially. In the Gingery scheme, the components for a simple lathe can also be cast from such metals and then assembled. The lunar analogue would be a lunar solar furnace-based foundry based on a printed or cast Fresnel lens concentrator to create temperatures of ~3500-4000°C. This enables the layered sintering of regolith into ceramic structures built layer-by-layer – this will be essential for casting [8] (though the layering resolution would need to be addressed). In addition, it enables the smelting of lunar anorthite $CaAl_2Si_2O_8$ (similar to bauxite) for Al metal, fibreglass and oxygen. The foundry provides the key to power generation without using solar cells. A bank of thermocouples provide thermoelectric energy conversion as used in RTGs. The motor becomes a critical component for energy storage using motorised flywheels over long periods.

10 Applications of Self-Replicating ISRU

Last year (2013), CO_2 levels passed 400 ppm compared to 280 ppm pre-industrial levels – it is projected to reach 450 ppm around 2020 generating a 2°C rise in average temperature globally. Canada's contribution with Albertan oil sands yields three times more CO_2 than traditional oil combustion. Global climate models do not account for catastrophic systems such the effects on the ocean conveyor or methane clathrate evaporation. Storms are increasing in frequency and ferocity. Yet over the last few years, we speak of tolerance and accommodation of climate change rather than combatting it.

Geoengineering involves intervention in climate to reduce global temperatures - it includes sulphate aerosol injection into the stratosphere and the seedng of oceans with Fe particles to create algal blooms (like El Nino). These methods are not reversible though they dissipate over time – for this reason, they require annual application. Space-based geoengineeriing involves the construction of a solar shield at L1 with an equivalent radius of 1824 km to reduce incident radiatiom by 1.6% corresponding to a temperature drop of 1.75°C. Alternatively, 10^{12} 60-cm diameter discs may be delivered by 20 railguns on Earth launching 10^6 silicon disks every 5 minutes for 10 years. 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 3D printed spacecraft using solar sails to maintain their mean location at Sun-Earth L1. These solar shield units may implement swarm control behaviours such as neural fields, potential fields or equilibrium control approaches. These approaches are fully controllable, reversible and modulable unlike most geoengineering solutions.

This same approach may be evolved into the more challenging problem of generating clean energy for Earth. In the long-term, fossil fuel use must be curtailed – natural gas is still a fossil fuel which enits greenhouse gases when burned. Renewable energy sources – solar, wind, tidal, biomass, etc – will yield only around 10-20% of current energy demand in the west. This energy and land use demand is growing as wealth spreads. Nuclear energy is viable as a large scale energy source but there are political, terrorism-related and waste hurdles. We need a clean global energy source – one possibility is solar power satellites which beam microwave energy to rectenna arrays on Earth, the principle of which has been demonstrated. A solar power satellite system could be constructed as a swarm of small units created through self-replication technology.

11 Conclusions

We have outlined the core capabilities necessary for our self-replication demonstration proof. Although there are many problems with which to contend, there appear to be no fundamental hurdles. Our focus initially is on a 3D printable motor system which is currently in progress. Demonstration of 3D printing of the electric motor and, at a larger scale, the self-replicating 3D printer requires most of the component technologies required for the construction of spacecraft – optical sensors using arrays of selenium pixels as a generalised payload (or star camera), structure and motorised mechanisms, attitude control through motorised flywheels, data handling electronics, communications electronics, power generation and storage from solar heat sources and flywheels, thermal control through judicious use of materials. These spacecraft systems are derivative: for instance, simple thermal control may be implemented through a combination of resistance heaters, metal thermal straps, metal radiators, bimetallic thermal switches, motorised louvres, and fibre glass insulation. We tacitly assume that propellant and oxidiser may be manufactured more readily than the components that we have addressed. The devil of course is in the details – we have no illusions of the magnitude of the task ahead. The later steps towards full self-replication will be just as challenging – they will focus on organisation, control, throughput and logistics [9] rather than individual components as we have done thus far. Self-replication offers immense potential fot the space sector. In the short term, self-replication can address immediate climate mitigation. In the long-term, self-replication offers the prospect for the Earth's energy production industry and a vibrant space industry to be migrated off-world, relieving the Earth's biosphere from the damaging effects of such industries. Space exploration may yet be the key to solving our most pressing global problems.

12 Acknowledgment

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