Engineering Artificial Extraterrestrial Life?

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Abstract

We present an outline of steps to engineer the physical embodiment of a universal constructor-based self-replicating machine. Given the centrality of self-replication to life, we offer some insights learned in our design of our universal constructor. Nevertheless, our self-replicating machine serves a practical purpose – to generate high productive capacity on the Moon at low-cost by exploiting its exponential population growth. The core of this machine is 3D printing technology that bears more than a passing resemblance to the universal Turing machine concept and the biological ribosome device. Our focus is on a fully functional end-to-end system capable of full self-replication. We present prototype components of our self-replicator concept.

The universal constructor concept conceived by John von Neumann (Burkes 1966) has only recently been simulated (Pesavento 1995). We have selected the Moon as our target environment due to its tectonic inertness, lack of environmental fluctuations and homogeneous geological properties. Furthermore, self-replication of productive capacity represents the only cost-effective approach for developing extraterrestrial resources (Freitas et al 1980; Chirikjian et al 2002). Our approach is to develop the basic components of a universal constructing self-replicator from the ground up rather than top-down to emulate (after a fashion) the process of the origin of life. The main problem has been to create sufficient functionality with a minimum of physical resources. Every component has a back-catalogue of processes and tools required for its manufacture. It is essential therefore to exploit simplicity, use multifunctional components, and use minimal materials to ensure material and parts closure. We present electric motors and vacuum tubes as multifunctional structures that enable a wide array of functions with a modest materials inventory.

The core of our self-replicating machine concept is the artificial ribosome – in this case, one or more 3D printers for layered manufacturing of metal, ceramic and plastic products from powdered feedstock material. There are several 3D printing technologies available that are differentiated by their printing heads – they offer general physical construction capabilities beyond that possible with subtractive manufacturing methods such as turning or milling. Our inspiration for the self-replicator is the RepRap, a fused deposition modelling 3D printer, that can print its own plastic parts (Jones et al 2001). To enable a RepRap-like 3D printer print a copy of itself, it would have to print in multiple materials – in principle, selective laser sintering can print most materials while electron beam freeform fabrication can print metals. A laser would be challenging to incorporate into the self-replication process; an electron freeform fabricator however is essentially a high voltage electron gun in a vacuum tube. The self-replicator must be able to print its sensors, its motors, and its electronics. It was this sensorimotor aspect that was stressed in von Neumann's universal constructor through the constructing "robot" arm. The 3D printer is in fact merely a specific kinematic configuration of motors – a Cartesian robot. A reconfigurable robot can of course assume any specific kinematic configuration of motors according to its task (Yim et al 2007). It is these sensorimotor aspects that are our main concern but the control systems we are exploring are simple – we are avoiding any consideration of complex adaptive systems to explore the capabilities of simplicity.

The motor system is fundamental to any actuation capability as well as the 3D printer platform and printing head. Investigations into different motor concepts yielded our selection of traditional electromagnetic approaches but emphasizing simplicity of construction. Our universal electric motor design has been designed to be 3D printable. The motor core comprises alternating layers of silicon steel and plastic insulation which may be 3D printed and assembled in a hopper. Copper wire may be wound longitudinally using a spindle. The DC motor prototype functioned excellently and the core design is in the process of being 3D printed in both metal and plastic. Eventually, the stator magnets will be replaced by electromagnetic cores with a similar configuration as the rotor. A fully 3D-printable electric motor will demonstrate the viability of the self-replicator as the motor provides the basis for all other machines required (such as for surface finishing) – mechanisms, assembly grippers, grinders, lathes, mills, punches, conveyors, vehicles, drills, etc.

Our next consideration concerns the medium of control for our self-replicator – in our case, this is mediated through electronics. To eliminate reliance on solid-state electronics whose manufacture is complex, we propose vacuum tubes which possess relatively simple construction – heated cathode of tungsten with nickel conductors, metal control grid and metal anode plate encased in a glass tube. We have selected analogue neural networks as the fundamental unit of our control architecture given that it is Turing-complete (Siegelmann & Sontag 1995) and indeed may offer super-Turing capacities (Siegelmann 1995). We have built a modified Yamashida-Nakaruma analogue neuron constructed from an op-amp configuration (Yamashita & Nakaruma 2007). A two-neuron version has been demonstrated controlling a desktop rover successfully implementing obstacle avoidance. We are currently investigating a means to implement online backpropagation learning in hardware. Task-specific neural networks offer a more compact physical footprint in vacuum tubes than attempting to construct a room-sized general purpose architecture. A 3D printer implementation thus constitutes a Turing machine that prints a specific neural network circuit for the task required according to its input program (be it punch cards or other storage medium).

Given that most sensory modalities (velocity, force, pressure, etc) are derivative from position sensors, potentiometers in conjunction with RCL circuitry offer feedback and general measurement capability. We have demonstrated that simple sensors in the wheels of a rover vehicle, in conjunction with neural net models, can provide online estimates of soil parameters as the rover traverses the soil (Cross et al 2013) – a useful capability for geotechnical surveying. Further sensors that may be readily manufactured include piezoelectric sensors (of quartz manufactured from lunar silica) and light sensors (of selenium mined in association with FeS deposits from iron meteorites).

Material feedstock for 3D printers must be mined from raw material, concentrated, and chemically processed – this goes beyond the von Neumann kinematic and cellular automata models. Such in-situ resource utilization is scheduled to be demonstrated with the Resource Prospector Mission (RPM) scheduled for launch to the Moon in 2018. The principle here is to minimize the elements that we extract. Lunar regolith is an unconsolidated inorganic soil representing a mixture of minerals and adsorbed volatiles. Lunar regolith may be readily scooped by rover such as a bucket wheel. One of the minerals in lunar regolith is ilmenite ($FeTiO_3$) that may be readily extracted magnetically. Ilmenite also concentrates volatiles hydrogen, helium and a number of carbon gases that may be extracted by heating ilmenite to ~700°C and then fractionally distilled. Further heating with hydrogen to ~1000°C decomposes ilmenite into evolved water, iron metal and titania ceramic. The water may be electrolyzed with the hydrogen recycled and oxygen stored. Titania is a useful ceramic that together with natural or manufactured lunar glass offers thermal and electrical insulation. Titania (and/or tungsten) may also be used for casting crucibles. Iron is a highly versatile metal that offers a range of alloys – wrought iron for tensile and compressive structures; tool steel (using tungsten) for cutting tools; electrical steel (using silicon) for high electrical resistance in motor cores; and kovar (using nickel and cobalt) for high conductivity electrical wiring and electrodes. Similarly, hydrogen and carbon compounds may be chemically processed with silica to yield silicone plastics that are both temperature and radiation resistant while minimizing consumption of scarce carbon sources. This provides flexible electrical insulation and oils for lubrication. The requirement for alloying materials – nickel, cobalt and tungsten (latter also for vacuum tubes) – requires iron meteorite sources (in near pure metal form). Mass concentrations detectable gravitationally mark the location of subsurface iron meteorite ores that will require drilling. We have explored the possibility of deploying bio-inspired drilling technology based on the wood-wasp ovipositor to minimize drilling infrastructure (Gao et al 2007). All the chemical processes proposed involve only indigenous material with the exception of Na and Cl required as recyclable reagents. These must be imported from Earth but this provides a salt contingency to mitigate against replication proliferation.

All metabolic activity requires a source of energy – on the Moon, the self-replicator may exploit the most prodigious supply of energy, the Sun. Given that the majority of energy required will be thermal for material processing, Fresnel lenses can concentrate solar energy from 1360 W/m^2 to sufficient temperatures. Electrical energy may be generated through thermionic emission, commonly used in space nuclear reactors. It offers a practical conversion efficiency of ~10% superior to photovoltaic conversion in amorphous silicon. Thermionic emission is implemented through vacuum tubes. Electric motors provide the means for energy storage during the lunar night through flywheels.

We envisage our self-replicator to be self-contained within a regulated environment to minimize perturbations. This involves the use of automated manufacturing methods, site preparation and extensive jigging but will still require some adaptability within limits. Nevertheless, the self-replicator will require effectors to acquire resources in an unstructured environment. This will involve rover vehicles for surface material acquisition and drills for subsurface material acquisition.

We have presented an overall architecture for a practical self-replicating machine. In addition, we have provided more detailed assessment of several component aspects – (i) 3D printable electric motor; (ii) hardware neural networks; (iii) geotechnic measurements; and (iv) biomimetic drilling. We suggest that this self-replicating machine does not constitute artificial life though it possesses most of its attributes. The traditional measurable properties of life (as defined for astrobiology missions) - self-replication, metabolic activity and self-encapsulation - are necessary but insufficient conditions for life. The key property of life is a history of information extraction from the environment and transmitting it onto subsequent generations, ie. a demonstrable evolutionary history (rather than the mere capacity to evolve which is implied by self-replication subject to the second law of thermodynamics). It is through the process of evolving a non-Markovian, non-commutative history that it demonstrates its autonomy as a living entity, ie. all living entities must be Darwin machines.

References

Burkes A (1966) *Theory of Self-Reproducing Automata*, University of Illinois Press, Illinois

Pesavento U (1995) Implementation of von Neumann self-reproducing machine. *Artif Life* 2 (4): 3370-354

Freitas R and Gilbreath W (1980) Advanced Automation for Space Missions, NASA Conference Publication 2255, University of Santa Clara

Chirikjian G, Zhou Y and Suthakorn J (2002) Self-replicating robots for lunar development. *IEEE/ASME Trans Mechatronics* 7 (4): 462-472

Jones R, Haufe P, Sells E, Iravani P, Olliver V, Palmer C, Bowyer A (2001) RepRap – the replicating rapid prototype. *Robotica* 29 (1): 177-191

Yim M et al (2007) Modular self-reconfigurable robot systems: challenges and opportunities for the future. *IEEE Rob & Autom Mag* (Mar): 43-52

Siegelmann H & Sontag E (1995) On the computational power of neural nets. *J Comp & Sys Sci* 50: 132-150

Siegelmann H (1995) "Computation beyond the Turing limit" *Sci* 268: 545-458

Yamashita Y & Nakamura Y (2007) Neuron circuit model with smooth nonlinear output function. *Proc Int Symp Nonlinear Theor & App*, Vancouver, pages 11-14

Cross M, Ellery A and Qadi A (2013) Estimating terrain parameters for a rigid wheeled rover using neural networks. *J Terramech* 50 (3): 165-174

Gao Y, Ellery A, Vincent J, Eckersley S, Jaddou M (2007) Planetary micro-penetrator concept study with biomimetic drill and sampler design. *IEEE Trans Aero & Elect Sys* 43 (3): 875-88