Building Physical Self-Replicating Machines

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Abstract

This paper introduces the concept of a physical self-replicating machine for deployment on the Moon utilizing raw material available on the Moon. A detailed but selective review is given in order to highlight clearly the novel aspects of this concept. In particular, it is hypothesized that if electric motors and vacuum tubes can be 3D printed from the limited repertoire of lunar materials, 3D printing constitutes a universal construction mechanism. This follows from the observation that mechatronic components are the constituent parts of all robotic mechanisms. In particular, we examine the use of 3D printing of electronics as a physical instantiation of a Turing machine. Several general implications of such a self-replicator are considered including whether it constitutes artificial life and mitigation against runaway replication.

Introduction

This paper is concerned with the physical implementation of a self-replicating machine (Freitas and Merkle, 2004). We are concerned with a macroscale self-replicating machine rather than nanoscale self-replicators typified by molecular assemblers. Our goal is to develop a self-replicating factory complex that can be programmed to manufacture solar power satellites in large quantities on the Moon to provide a scalable power source for Earth's future energy needs (Ellery 2016a). The lunar self-replicating machine is described but special consideration is given to the manufacture of electric motors and vacuum tubes as essential mechatronic components for self-replication. 3D printing is introduced as a mechanism of universal construction but also of universal computing. The 3D printer, in printing neural electronics represents a physical instantiation of the universal Turing machine. A contextual review then follows concluded with a consideration of more general implications with respect to artificial life and unrestrained replication.

A Lunar Self-Replicating Machine

The key concept in self-replication is the universal constructor generalizing on the universal Turing machine encapsulating the notion of computing (Burks and von Neumann, 1966). Critical to universal construction is parts closure – this has three aspects, namely, matter, energy and information closure, though material closure is our primary concern here – any deviation from material closure invokes the necessity to import material from Earth which should be minimized. Closure requires restriction of both the materials inventory required (and so the number of extractive processes) and the families of components (and so the number of manufacturing processes). To minimize the materials requirement is to base the self-replicating machine on a restricted suite of readily available materials in the lunar regolith. The core of this materials inventory is iron (and a number of its alloys). The forthcoming lunar Resource Prospector (RP) mission will be demonstrating a number of relevant technologies for the extraction of raw material on the Moon (George et al, 2012). The RP mission is a 10 day lunar surface mission to the Cabeus crater near the lunar south-pole where water ice has been detected by the LCROSS satellite. It comprises a lunar rover carrying the 72 kg RESOLVE (regolith and environment science and oxygen and lunar volatile extraction) payload to demonstrate in-situ resource utilization of lunar material. It includes a drill to acquire core samples of lunar regolith to a depth of 1m, a reactor to heat samples to 150^{o}C to evolve water and other gases and then to 900^{o}C to extract oxygen (O_2), pure iron (Fe) and titania (TiO_2) from ilmenite ($FeTiO_3$) via hydrogen reduction. The rest of the RESOLVE payload is instrumentation – neutron spectrometer to detect subsurface hydrogen (water) during the rover traverse and a near infrared spectrometer to detect evolved volatiles from the heated samples. From the carbon-based volatiles and lunar silicate minerals, silicone plastics may be manufactured using traditional techniques. The manufacture of a range of iron alloys – wrought iron, steels (such as tool steel and silicon steel), fernico and permalloy require access to silicon (from silicate minerals), nickel, cobalt and tungsten. Access to tunico (tungsten, nickel and cobalt) elements requires subsurface mining at mascon (mass concentration) locations where subsurface nickel-iron meteorite materials are buried. There are two major mining approaches that may be considered. Room and pillar mining involves excavating subsurface materials

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to form rooms supported by pillars. This leaves large blocks of ore in the pillars. Longwall mining involves tunneling with a shearer to cut the ore face. The tunnel is supported by roof supports. A series of conveyor belts return the ore to the surface. These approaches are highly energy intensive whereas drilling would reduce the amount of overburden removed (Ellery, 2016b).

Once raw materials have been extracted, they must be fashioned into parts and components. The use of 3D printing alleviates the parts closure problem by simultaneously addressing both parts and manufacturing diversity. RepRap uses fused deposition modelling ((FDM) to manufacture many of its own plastic components (Jones et al, 2011). This first step towards a self-replicating machine requires several extensions to become a fully self-replicating machine: (i) 3D printing metal parts; (ii) 3D printing electric motors; (iii) 3D printing electronics including computers; (iv) self-assembly. There are seven major types of 3D printing technologies but we are concerned with only four: (i) fused deposition modelling (FDM) of molten plastic; (ii) selective laser sintering/melting (SLS/SLM) fuses powder of metal, plastic or ceramic using lasers; (iii) electron beam freeform fabrication (EBF3) sinters/melts metal rod only using an electron beam; (iv) binder jetting involves layers of polymeric binder to ceramic, metal or plastic particles. Powder bed methods such as SLS/SLM are generally disallowed in micro-gravity or vacuum environments due to powder dispersion and vacuum welding of the powder respectively. This leaves FDM for plastic, EBF3 for metal and binder jetting for a variety of materials. We have had some successes in developing 3D printing of electric motors using FDM of iron particle-impregnated PLA plastic (Fig 1):

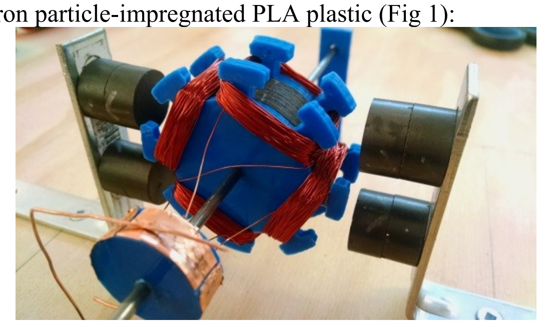

Fig 1. Iron-impregnated PLA-based electric motor

In particular, we have been concentrating on 3D printing the magnetic core of the motor as the most fundamental basis of both rotor (in dc motors) and stator (in ac motors). Magnetic core electromagnets can also substitute for permanent magnets. We are experimenting with photolithographically printed coils in different configurations (currently implemented in a pancake concept for testing – Fig 2) which will be incorporated into the rotor concept.

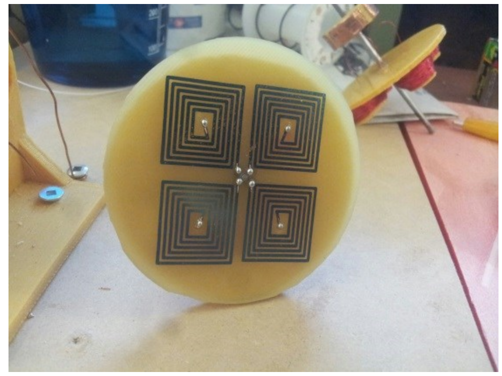

Fig 2. Photolithographically-printed coils

A 3D printed electromagnet-based stator will essentially complete the 3D printed motor. Currently, our 3D printed stator electromagnets constructed from iron-impregnated PLA generate insufficient magnetic field intensity even with 200 windings (Fig 3) – we are redressing this by employing SLS-printed magnetic steel for the stator.

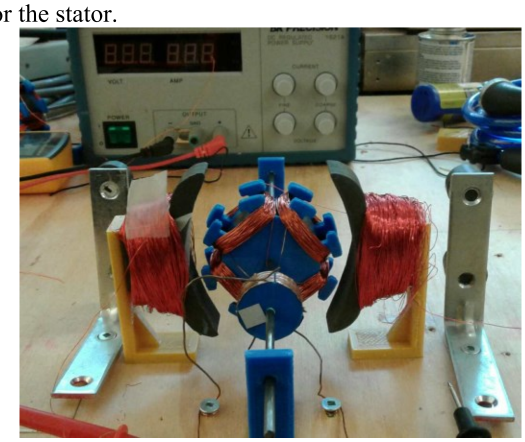

Fig 3. Rotor with proposed stator configuration

We have yet to demonstrate 3D printing of electronics though we have demonstrated the viability of our approach. For computing circuitry, solid state transistors are infeasible for lunar manufacture due to their complex fabrication procedures involving extreme conditions and reagents. Although simple RC filter circuits can be inkjet printed in polymer (Chen et al, 2003), plastic electronics is not well developed. We have been exploring 3D printing multiple materials with regard to melting temperature compatibility. Silicone plastic has operational thermal tolerance up to 300^{o}C but we have found that it can tolerate much higher temperatures for short periods. We have lain molten Zn-Al (ZA8) alloy (melting temperature of 375-404^{o}C) onto a silicone plastic substrate to emulate a metal 3D printing process (Fig 4). We laid an Al alloy wire track onto the silicone substrate as a first step towards 3D printing metal circuitry. In addition, we demonstrated melting of 3004/3105 aluminium alloy using a 1.5 m x 1.5 m Fresnel lens to emulate the use of lunar solar concentrators.

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Fig 4. Aluminium track on silicone plastic substrate

We have adopted vacuum tubes as an alternative to transistors without their inherent fabrication complexity. Vacuum tubes are more efficient and versatile than electromagnetic relays that have in fact been 3D-printed (Malone and Lipson, 2007). Rather than adopting traditional general von Neumann computer architectures which impose large physical footprints, we have adopted an analogue neural net circuit based on a modified Yamashida-Nakaruma design (Yamashida & Nakaruma, 2007) (Fig 4):

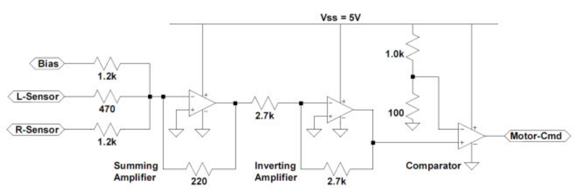

Fig 4. Modified Yamashida-Nakaruma neuron circuit

We have demonstrated that two neurons based on this circuit can control a desktop rover imparting it with BV3 Braitenberg behaviours (Braitenberg, 1984) (Fig 5).

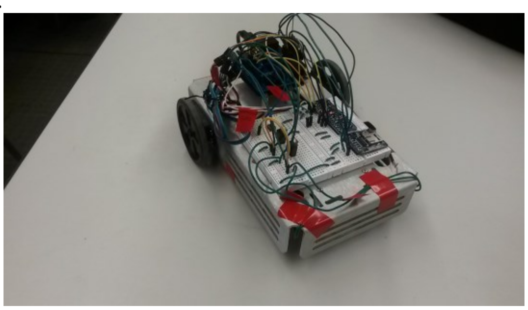

Fig 5.Desktop rover controlled with a two-neuron circuit

Neural network hidden node footprint grows only logarithmically with task complexity (Parberry, 1994) and recurrent neural networks have been proven to be Turing-complete (Siegelmann and Sontag, 1995), perhaps even offering super-Turing capabilities (Cabessa and Seigelmann, 2012). A universal Turing machine comprises an infinitely long tape which stores a program and its input data which after the computation is replaced by the program's output data. The tape is scanned by a reading head which moves backward and forward reading and manipulating each symbol in turn according to the program and then writes the output onto the tape. It is envisaged in our 3D printer setup that programs are stored in magnetic core memory (with a similar material configuration as magnetic cores of electric motors) which constitutes the input tape to a Turing machine represented by a 3D printer-type device. The output is a physically 3D printed neural network circuit for the specific task. Different neural circuit configurations correspond to different programs stored in magnetic core memory. The complete system is a universal Turing machine but the printed output circuits represent specific programs. They may be fine-tuned through an electrical circuit representation of the backpropagation algorithm (Martinelli and Perfetti, 1991; Larson and Ellery, 2015).

If electric motors and vacuum tubes can be 3D printed using materials extractable from lunar resources (Table 1), all these tasks would be achievable, thereby demonstrating that 3D printing would constitute a universal construction mechanism (Ellery, 2016c).

Functionality	**Lunar Material**
Tensile structures	Wrought Fe, cast Fe, steels
Compressive structures	Fused regolith
Elastic structures	Fe alloy springs/flexures, Silicone elastomers
Thermal conductors	Steel, fernico/ Al
Thermal insulation	Glass (fibre), TiO_2 wool
Thermal tolerance	W
Electrical conduction	Fernico, Al, Ni, steel
Electrical insulation	Glass, ceramic, silicone plastic, silicon steel
Active electronics	Vacuum tubes (fernico, Ni/steel, W, glass)
Magnetic materials	Silicon steel/laminate (electromagnets), Permalloy
Sensors and sensory transduction	Quartz, Selenium, Thermionic conversion
Optical structures	Polished Ni/Al Glass
Liquids	Silicone oils

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	Water
Gases	Oxygen – hydrogen

Table 1. Lunar material inventory

There are three major resource repositories on the Moon: (i) the ubiquitous regolith; (ii) adsorbed volatiles in the regolith; (iii) asteroidal material. Initial recovery of raw material from the Moon is simple using bucket wheels followed by electrostatic and magnetic beneficiation. We envisage a number of basic chemical processes to extract 3D printer feedstock:

(i) Extraction of lunar volatiles for the production of fuel/propellant and silicone plastics/oils
(ii) Extraction of iron alloys for structure and electric motors
(iii) Extraction of Al metal for structure and electrical wiring
(iv) Extraction of Si and SiO_2 for alloying, ceramics and silicones

We outline just one or two representative extractive processes here. 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 the noble gas Ar. Heating the regolith to 700°C would release 90% of these adsorbed volatiles. Silicone plastics (siloxanes) can be manufactured from syngas providing superior resistance to radiation and thermal extremes while minimising carbon consumption in comparison with hydrocarbon plastics. Further heating regolith to 900-1050°C permits hydrogen thermo-reduction of ilmenite:

$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$

$H_2O \rightarrow H_2 + ½O_2$

Further heating to 1600°C allows molten iron to be bled off. From asteroidal material, Ni, Co, W and Se are extractable for diverse alloy creation. Ceramics present a challenge for 3D printing due to the high temperatures required for sintering or melting. To 3D print ceramics, plastic pre-ceramic resins can be 3D printed as plastic gel into structures which are then fired into a high temperature ceramic. One possible mechanism that we have yet to explore is to employ silicone plastics as precursors to ceramics. Silicone may be converted to silica by flame combustion in oxygen:

$SiO_xC_y + (1\text{-}x+2y)O_2 \rightarrow SiO_2 + yCO_2$

This provides a mechanism for 3D printing ceramics without involving extreme temperatures of direct sintering while the CO_2 is recovered (thereby conserving carbon resources). From silica, quartz may be crystallised (as a piezoelectric sensor material)

Actuators-controllers-sensors constitute the key components for any robotic mechanisms (including 3D printers which are effectively Cartesian robots) so are central to any self-replicating machine. Furthermore, these two components – electric motors and vacuum tubes - provide the basis for energy generation (through thermionic emission) and energy storage (through motorized flywheels). Assuming 10% efficiency, solar energy provides an electrical energy density of 130 W/m^2 (or equivalently, 1 MW requires under 90 m x 90 m solar concentrator (nominally, Fresnel lenses) area. Vacuum tube technology is also the basis of the klystron and magnetron for high-power microwave generation required for solar power satellites (Ellery, 2016d). Vacuum tubes are highly reliable and durable when maintained at constant temperature at the power-on state. This suggests that significant steps towards parts closure can be achieved by utilizing components for multiple purposes such as magnetic cores and vacuum tubes.

Contextual Review of Self-Replicating Machines

We present a contextual but selective review of self-replication to illustrate that this work goes far beyond the architectural considerations of past work by attempting to physically realise key components of a self-replicator. The first model of a self-replicating machine is the von Neumann kinematic self-replicating machine (Burks and von Neumann, 1966). It comprised a manipulator (constructing) arm controlled by a separate program of step-by-step procedures stored on a memory tape that instructed the arm to pick components from a sea of component parts and assemble a copy of itself. The copying of a separate description of the self-replicator on the tape avoids the problem of self-reference and infinite regress. The self-replicator comprises four major subsystems that have their biological counterparts (Mange and Sipper, 1998): component A comprises a universal constructor including a construction arm (equating to a ribosome); component B (A + C + D) comprises a tape of instructions describing the specifications of the machine (equating to a genetic code); component C comprises a controller that reads the tape B and passes the interpreted information to constructor A (equating to repressor and inducer proteins); component D comprises a tape copier to copy B (equating to RNA and DNA polymerase). The composition of B, C and D constitute a universal Turing machine that holds a set of instructions (B) which is read to generate control signals (C) and copies those instructions (D). Rather than reading information and then writing information, a universal constructor reads information and then moves a robotic arm. In the kinematic model, the universal constructor exists in an environment comprising a sea of prefabricated parts. A part is randomly selected and inspected to identify it. If it is the required part, it is joined to the growing assembly; if not, it is returned back into the environment and another part selected. Once fully assembled, the copy is supplied with a copy of the program of instructions which is then activated. The parts in the environment included both mechanical elements for implementing mechanisms and logic elements for implementing control – in fact, 8 elementary parts: (i) p or q logic gate; (ii) p and q logic

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gate; (iii) p and ~q logic gate; (iv) rigid link; (v) joining element; (vi) cutting element; (vii) sensory element, and (viii) actuator element. Recognition of each of these elements in the environment depends on their properties detected by sensory elements. The self-replicator would then make a copy of its program tape using a program copier. The instructions are thus read twice: once as instructions to be interpreted, then as data to be copied. In biological systems, this is differentiated by transcription and translation of DNA. The universal constructor may construct any machine given the appropriate instructions and raw material. The need for energy was not considered specifically. Artificial life considered here – let us call it engineered life to differentiate it from artificial and synthetic life - is hardware-based which although restrictive with respect to software simulation (especially in exploring its evolutionary properties) introduces its own insights into physical implementation – indeed, we suggest that any useful physical self-replicator must be a universal constructor.

Because the basic units of the von Neumann kinematic model are complex modules to be assembled, this is more properly a form of self-assembly. An example is a physical template-based self-replication process that exploited stochastic perturbations (Penrose and Penrose, 1957). Multiple copies of 2D plywood tiles with two specific shapes that uniquely fit together in a tray are subjected to random shaking. In the correct configuration, the two shapes A and B form a composite configuration AB or BA. More complex self-replication (self-assembly) of modules has been implemented physically as towers of "molecubes" (Zykov et al, 2005). The molecubes are 10 cm sided cubes with a diagonal axis through which the molecube is split into two halves that can swivel with respect to each other. Encapsulated within the molecube is a motor and a microcontroller. Each face of the molecube contains electromagnets that can be energized to attach to other molecubes. On swivelling, attached molecubes may move and further molecubes may be added – self-assembly rather than self-replication though it can replicate any configuration. Molecubes are reminiscent of 3D physical manifestations of 2D cellular automata. This represents one of number of different approaches to self-assembly of modular units - there are three families of reconfigurable robotics (Yim et al, 2007; Patil et al, 2013): (i) lattice-based configurations form a cubic or hexagonal grid of modules, e.g. molecubes; (ii) chain-based configurations forming trees or chains, e.g. Polybot, MTRAN, CONRO, etc; (iii) mobile architectures that can form chains, lattices or functional robots, e.g. CEBOT. Most artificial mechanisms for configuration require controlled movement for assembly of the units while biological self-assembly is stochastic (e.g. through Brownian motion) for which there are few artificial examples beyond the Penrose tiles example. All these self-assemblers are composed of complex modules and cannot be considered self-replicating. True self-replication must emerge from the dust.

A self-replicating factory will need a means to acquire raw materials and the means to convert these raw materials into final products. Moore's artificial plants concept went beyond self-assembly to suggest machines capable of ingesting air, water and soil as raw material powered by solar energy to grow and procreate (Moore, 1956). We have considered 3D printing as a universal construction mechanism in which raw feedstock is lain in 2D layer by 2D layer and built into 3D structures. The biological ribosome encapsulates a similar core process through 3D protein synthesis of 1D polypeptide chains from amino acid constituents. In this case, transfer RNA acts as the constructing arm while messenger RNA acts as the program tape – our engineered analogues are electric motors as the fundamental component of robotic machines (such as mining robots, 3D printers, assembly manipulators, etc) and vacuum tubes as the fundamental component of a computing machine. Conceptually, our macroscale self-replicator envisaged here combines both von Neumann kinematic and Moore concepts. It is a universal constructor comprising an automated factory with *mining robots* to acquire comminuted raw materials for input to *chemical refining units* to extract feedstock for *fabrication and construction machines* to output parts and components for *assembly robots* to construct final products. Its application is similar to that proposed in the 1980 NASA study involving self-replicating factories on the Moon (Freitas and Gilbreath, 1980; Freitas and Zachary, 1981). The self-replicating seed factory was perceived to be 100 tonnes constituting a seed which could expand and grow to its full capacity for one year prior to the self-replication phase. This NASA reference design comprised a range of computer-controlled robotic vehicles – (i) paving robots mounting parabolic mirrors sinter lunar regolith into a hard basalt foundation surface – this may be supplemented with the laying of rails to reduce navigation requirements of non-mining robots; (ii) front end loader and bucket/dozer mining robots for trenching, strip and spiral mining; (iii) electric carts on rails for transporting material and components within the factory and casting robots for tool and mould construction; and (iv) assembly robots for assembling fabricated parts stored in warehouses. Infrastructure included a radio transponder network to implement local navigation/communications for robot coordination. This enables a central computer control system at the hub to coordinate all robots. Power of 1.7 MW was implemented through an overhead canopy of solar cells erected by mining and assembly robots. Chemical refining of lunar regolith was based on electrophoretic separation followed by HF acid leaching. Chlorine for extracting aluminium was considered to be the limiting reagent – we concur with this (and sodium) though for different reasons. Indeed, in our case, this provides a mechanism for mitigation of uncontrolled replication – a salt contingency in which Na and Cl must

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be supplied from Earth for replication to proceed. Fabrication for converting feedstock into parts was through mould casting and machining and welding by CO_2 lasers. Manipulator arms and tooling would perform construction and assembly of components and parts as in the von Neumann kinematic model. Mechatronic components such as motors, sensors and electronics would be supplied from Earth as "vitamins". The Lackner-Wendt concept is similar in comprising a colony of robotic vehicles running on a grid of electrified tracks within a manufacturing facility for extracting raw material from desert regions powered by solar cells (Lackner and Wendt, 1995). The raw materials are the commonest elements in desert sand – Na, Fe, Mg, Si, Ca, Ti, Al, C, O_2 and H_2 – which are extracted through carbothermic reduction.

The Chirikjian-Suthakorn concept is a further development of self-replicating robots for lunar application (Chirikjian et al, 2002). It comprised four major subsystems: (i) mobile robots with manipulators for mining, transport and assembly of material or components; (ii) regolith sintering, chemical refining and metal casting and other parts manufacturing facilities; (iii) solar energy system based on solar collectors, photovoltaic energy conversion and fuel cells, (iv) electromagnetic railguns for long range delivery of offspring. The Chirikjian-Suthakorn concept demonstration was based on Lego Mindstorms kits comprising a system of robots capable of assembling component modules into replicated robots. Lego provides a modular approach in which standard blocks and plates of ABS plastic with standard mechanical interfaces can be configured into different assemblies. A simple robot comprised of several subsystems – left/right motors, left/right wheels and/or tracks, manipulator wrist, passive gripper and robot control system microcontroller – was demonstrated to construct a copy of itself. It was programmed with an assembly sequence to construct a copy of itself in an assembly area of components using a series of assembly jig fixtures – chassis, motor/wheels, and gripper units - for aligning components for each subassembly. The robot controller was required to program and operate the robot between stations for the assembly. The assembly stations were fairly complex involving conveyor belt/pulley/lift units with sensory feedback, docking unit with sensors, electrical connectors for electrical power, and controller units. Lego was also used for a self-replicating three axis Cartesian manipulator capable of constructing a copy of itself from Lego components (Moses et al, 2014). It comprised 45 parts (of 11 different types) assembled through a sequence of 410 steps though it lacked any form of automated controller. The 11 different types were dominated by racks and rails but most significantly included prefabricated electric motors. Although Lego has snap-fit assembly, many parts were tapered or chamfered in order to permit positioning errors during assembly.

A self-replicating electromechanical intelligence system represented a further step by copying both its program and its hardware circuitry (Kim et al, 2004; Hastings et al, 2004). It also utilized Lego Mindstorms kits and comprised five main components – (i) a control circuit comprising motor driver, motor controller, feedback controller, and optical reader decoder based on logic gates constructed from resistors, capacitors, transistors and switches; (ii) a 2 DOF dual set of robotic arms for assembling circuit elements and feeding physical code components onto the conveyor belt respectively; (iii) a conveyor belt for moving coloured code components to the code reader, (iv) an optical reader array to read colour codes defining discrete actuator positions for acquiring electrical components, and (v) a vertical hopper to guide circuit modules into a copied assembly of the control circuit. This represents a physical instantiation of self-replication of basic modules by self-inspection.

One of the most significant problems is that as the number of unique parts increases, the manufacturing complexity increases exponentially, favouring the use of standardized parts – ultimately, the adoption of simple modular blocks converts self-replication into a self-assembly process (Stevens, 2009). However, this and other self-assembling systems do not consider manufacture of the modules. Our approach does indeed consider these aspects. In particular, we utilize 3D printing to tackle the most challenging of products required for robotic machines – electric motors. We also propose 3D printing vacuum tubes for electronics and the adoption of neural network computer architectures. Rather than architectural issues, we are tackling the nuts-and-bolts issues in an attempt to make self-replicating machines an engineering reality. This is a bottom-up approach rather than top-down approach.

Implications

An interesting question concerns whether the self-replicating machine advocated here constitutes artificial life. It has been suggested that a key feature of heritable genetic representation is non-holonomy which introduces alternative trajectories for a dynamic system (Pattee, 2001). The kinetic energy dynamics and momentum cannot be uniquely integrated to specific potential energy trajectories. This non-conservation of force yields energy degeneracy in which there are alternative configuration states with the same energy that cannot be uniquely determined via mathematical integration. The configuration is trajectory-dependent, i.e. it is rate-dependent on the history of previous states. A physical example is the non-holonomy of angular momentum conservation in a general kinematic mechanism that cannot be integrated into a unique conservation of angular moments because of the non-commutativity of sequences of rotations. There is a dependence on the history of angular states. An infinite

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number of historical paths can yield a particular orientation state. This affords unpredictability to the dynamics of such systems. Evolutionary processes are non-holonomic explorations in phase space and this is a hallmark of life. The artificially constructed self-replicating machine presented here (and others similar to it) has no evolutionary history and therefore does not constitute artificial life (Ellery, 2015). If subsequent evolutionary processes are permitted however, this changes. The introduction of an evolutionary exploration to the self-replicating machine implies that it will then constitute an artificial lifeform. The great fear is the grey goo scenario in which self-replication becomes uncontrollable. However, there are practical difficulties to this scenario. For evolutionary processes to operate, certain conditions are required. The first requirement is self-replication in which copies are manufactured with the offspring inheriting properties from the parents – this is true by definition for the self-replicating machine. The second requirement is that the self-replicating system must suffer from variations due to genetic mutation of which there are two types (Ikegami and Hashimoto, 1995): passive mutation resulting from external noise from the environment and active mutation resulting from noise in the self-replication process itself (in Kalman filtering, this is quantified as sensor and model noise respectively (Stengel, 1994)). This mutation must be heritable so it applies only to self-replication errors in genetic copying. This is relatively straight forward to minimize through error detection and correction coding (EDAC) (Shirvani et al, 2000). Indeed, artificial neural networks can implement Viterbi decoding based on analogue neurons (Wang and Wicker, 1996). The third requirement is the there is a selection process in which there is a variation in the phenotypic success between offspring within the constraints of resource limitations. All technologically designed systems are brittle and any non-nominal variation will fail due to lack of robustness. A pertinent example is genetic programs that self-replicate through only through genetic cross-over but cannot exploit mutation (Koza, 1993). Given the difficulty in creating viable self-replication, it is vanishingly unlikely that random mutational variation will yield improved fecundity. Furthermore, such variations will be detected and corrected through EDAC. It is desirable to prevent evolutionary change in order to retain control of the self-replicator. An additional mechanism is the salt contingency mentioned earlier – imported Cl is required for silicone plastics manufacture and Na for quartz manufacture without which self-replication cannot proceed. Multiple layers of safeguards should provide sufficient protection against the grey goo scenario.

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