SUSTAINABLE LUNAR EXPLORATION THROUGH SELF-REPLICATING ROBOTS

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ABSTRACT

Self-replicating robots on the Moon require a lunar industrial ecology which by virtue of its recycling loops represents a sustainable approach to in-situ resource utilisation (ISRU). However, the industrial ecology has only been implemented piecemeal on Earth yet it is required to function as an integrated entity on the Moon. To that end, we explore some approaches to manufacturing architectures anticipating their application through the processing chain from raw material mining through to chemical processing to 3D printing of the self-replicating machine's constituent parts such as electric motors and electronics.

1 INTRODUCTION

Current plans to explore the Moon are destined to be unsustainable because sustainability is regarded as an addendum rather than a central plank in lunar in-situ resource utilisation (ISRU). Sustainability is premised on ensuring that future generations are not faced with a barren wasteland through the reckless abandon of current generations. Implicit in this definition is the need to plan our ISRU practices over the long-term to ensure [1]: (a) we do not consume and waste scarce resources; (b) we employ renewable technologies as far as is feasible; (c) we adopt processes that do not yield toxic material; (d) we minimise waste through recycling loops. To observe this, we need to design a long-term approach to lunar ISRU that adopts the philosophy of indigenous peoples – exploit that which is abundant and waste nothing. We must live off the land as much as possible to minimise our reliance on an Earth-based supply chain. Rather than focusing on building specific products from lunar material, we have adopted to build the *means of production*; in the case of a self-replicating robot [2], this constitutes a universal constructor that can build all its own components – and all such components will serve general utility. The self-replicating robot imposes severe sustainability constraints including a lunar industrial ecology supported by high energy return-on-investment (EROI). The first step in defining our self-replicating robot is to determine our lunar resource availability in terms of required resource functionality. Our demandite list incorporates all the basic functional materials derived from lunar materials required to construct mining robots, unit chemical processors, manufacturing robots and assembly robots.

All robotic machines comprise a specific configuration of actuators controlled by a system of electronic logic. Hence, we have selected two key components to be manufactured from lunar material – electric motors for actuation and vacuum tubes for computing machines (specifically, analogue neural network architectures). We have adopted 3D printing as our universal manufacturing technique inspired by the RepRap 3D printer [3]. We have demonstrated 3D printing of a suite of electric motor parts. Vacuum tubes also provide the basis for electrical energy generation (thermionic conversion of Fresnel lens-based thermal energy) and while motors provide the basis for energy storage (motorized flywheels). The former can potentially yield high conversion efficiencies exceeding 30% sourced from lunar materials [4]. These fundamental components define the composition of the demandite list. From the demandite list, the industrial ecology adopts a small number of chemical processing procedures with recycling loops in conjunction with 3D printing to minimise material wastage. This is a perquisite for minimising energy consumption both contributing to sustainability. In conjunction with high energy conversion efficiency, this suggests that energy return on investment (EROI) can be attained, a condition of self-replication - the self-replicating robot approach is essential if ISRU is to be sustainable.

2 LUNAR INDUSTRIAL ECOLOGY

The basic unit of the lunar industrial ecology is the unit chemical processor. A chemical plant comprises a set of large vessels for using chemical reactions to produce chemical products. Chemical processes are divided into steps (unit operations) defined by a process that occurs within a single reactor vessel. Unit operation is a basic analytical approach in chemical processing – it involves a physical or chemical transformation of a set of reagents into a set of products, e.g. mixing, separation or distillation, cooling, redox reactions, de(hydrogenation), (de)hydration reactions, (de)alkylation reactions, halogenation, ammoniation, alkaline fusion, polymerization, etc. It typically involves fluid flow, heat transfer and mass transfer resulting in thermodynamic and mechanical processes. The vessels are typically cylindrical with rounded ends suitable for high pressures or vacuums. Each reactor comprises a unit operation defined with a quantified input feed and a quantified output product. Within a single reactor, a unit operation constitutes the chemical process which converts one compound (the input reagents) into another compound (the output products). The chemical processes may be run in continuous or batch mode – in either case, catalysts and packed beds that have been poisoned by deposits may have to be regenerated periodically. Mass transfer rate of fluids through a reactor is defined through dimensionless numbers: $Sh = C.Re^nSc^m$ where $Sh = \frac{kL}{D}$=Sherwood number, $Re = \frac{v\rho L}{\mu}$=Reynolds number, $Sc = \frac{\mu}{\rho D}$=Schmidt number, C=empirical constant, k=mass transfer coefficient (dimensions of velocity), A=cross sectional area, L=characteristic length, D=mass diffusivity, v=fluid flow velocity, μ=fluid dynamic viscosity and ρ=fluid density. The obvious way to increase mass flow rate is to increase the pressure difference between the input and output ports of the reactor. Material and energy balances must be analysed based on chemical analysis. This forms the basis of the design of the controllers to regulate flows and monitor temperatures, pressures, fluid flows, etc by controlling the motorised pumps and valves. Note the centrality of motors. Material composition management (MCM) is the core problem in chemical and manufacturing processes [5]. Conservation of mass requires that all material entering the chemical process either accumulates or exits the process as product or waste (material balance). The reactants are injected into the reaction chamber within which the operating conditions (temperature and pressure) determine the reaction progress. Furthermore, the reaction itself influences those operating conditions which must be measured continuously. The reaction is also determined by the composition of the reagents and their physical properties. The controller must optimize the conditions and reagent flows to maximize the product yield whilst minimizing waste. Complexity is introduced by chemical instabilities, uncertain and incomplete measurement data, limited predictive and diagnostic models, and time delays in chemical dynamics which requires intelligent control with process monitoring based on noisy data to deal with event-driven situations. An example of a single unit chemical processor is the Metalysis FFC process reactor [6] that is central to the lunar industrial ecology. Our lunar industrial ecology processes lunar minerals and volatiles into our demandite list. The most important lunar minerals for metal extraction include ilmenite (Fe and Ti), anorthite (Al, Si and Ca) and orthoclase (K and Si). The only material required from Earth is NaCl as a recycled reagent of the ecosystem (it is not consumed). We require Ni-Fe-Co meteoritic material available in lunar craters from which these and other elements may be extracted through the carbonyl process. Lunar volatiles of interest include hydrogen (from water), carbon compounds and small amounts of nitrogen which can be extracted thermally and fractionally condensed. The carbon provides the basis for silicone plastic manufacture. The adoption of mineral preprocessing with HCl acid permits the Metalysis FFC process to reduce pure metal oxides into metal powder with >99% purity. The $CaCl_2$ electrolyte may be resupplied as a byproduct of metal extraction.

The lunar industrial ecology (Appendix 1) is an approach to in-situ resource utilisation that is sustainable by linking many different chemical processes together into an ecological system in which the waste of one process becomes the feedstock for another. The lunar industrial ecology constitutes multiple unit chemical processors – this is unique to the lunar environment as most terrestrial chemical processing systems involve only a small number of single throughput processors. The lunar industrial ecology essentially constitutes a fan-in to a suite of 3D printing facilities forming the core of a bow-tie configuration from which manufactured products fan out [7,8]. We must now address how our lunar ecology might be architected to operate in a coordinated fashion to honour recycling loops between processes with maximum efficiency. Lessons may be applied from the manufacturing factory into which the lunar industrial ecology must be integrated. For example, a traditional functional factory layout arranges machines into functional sections – milling, grinding, drilling, etc. Unfortunately, in such layouts, around 95% of total throughput time is spent in transport or queuing for processing. A material flow network connecting modules of machines represents the most efficient production layout [9]. It combines the adaptability of the distributed layout with high efficiency transport of compact layouts. Physical transport networks must adapt to local conditions. The Zipf inverse distance law quantifies the volume of material N as inversely proportional to the distance D travelled: $N = \frac{k}{D}$. A more sophisticated gravitational model that declares that distance travelled is dependent on the strength of attraction imposed by additional factors such a relief, obstacles, etc: $N = k\frac{(w_i p_i - w_j p_j)}{d_{ij}^a}$ where p_i=demand at location i p_j=demand at location j, d_{ij}=distance between locations i and j, a=exponent of distance that determines the sharpness of attraction, $w_{i,j}$=weighting factors that quantify other factors such as relief, obstacles, etc. This can be modelled readily by a potential field representation to minimise distance for the transport of material.

An automated factory requires several functions: (i) product specification of complete product; (ii) production planner to schedule and coordinate manufacturing; (iii) parts production – in this case through 3D printing technologies; (iv) material handling and transport by mobile robots and conveyors; (v) parts assembly by manipulators including jigs; (vi) parts inspection by sensors through self-diagnosis; (vii) computer coordination of the production process. An example of an automated lights-out factory is the Fanuc system of two-armed industrial robots equipped with vision and force/torque sensors that assemble robots. The Fanuc has not yet expanded throughout the manufacturing industry. Most industrial processes can be operated without human intervention, the human aspect being reserved primarily for setup, reprogramming and servicing. These can similarly be automated. Setup and servicing require sophisticated manual dexterity which is the preserve of manipulator robotics which has applications to space debris mitigation and on-orbit servicing [10,11]. The axiomatic approach to manufacturing factory design flows down from its top-level functional requirements to the design parameters. There are two axioms of manufacturing [12-14]: (i) Maintain independence of a minimum number of functional requirements of a product (independence axiom); (ii) Minimise information content (cost) of a product consistent with (i) (information axiom). This may be formalised as: {FR}=[A]{DP} where FR=functional requirements vector, DP=design parameters, A=design matrix=diagonal matrix when axiom (i) is observed. A critical aspect is the decomposition of higher level system requirements (what) into lower level components of that system to achieve the requirements (how) [15]. Effective design for manufacturing can reduce manufacturing costs by 80% [16]. The methodology has subsequently been widened to design for manufacturing and assembly including logistics to minimise production costs [17]. 3D printing is an approach that effectively minimises costs consistent with these principles and indeed offers a more versatile mode of manufacture than subtractive modes. It can also be legitimately be widened to incorporate the (electro)chemical processing of raw materials and the mining chain, i.e. from raw material mining through to final product – in the case of the self-replicating system, this forms a closed loop. As a conjecture, it is conceivable that self-replication may introduce problems for the axiomatic approach in a similar manner that Godel's theorems on self-reference introduced incompleteness and/or inconsistency to axiomatic mathematics.

3 FLEXIBLE MANUFACTURING SYSTEMS (FMS)

If a self-replicating machine serves only to replicate itself, a relatively fixed throughput system would suffice for its manufacture. A self-replicating system *per se* is of little utility. Its power lies in its universal construction capabilities which require the ability to reconfigure itself with high flexibility to adapt to manufacturing any other product – this requires a flexible manufacturing systems (FMS) approach. FMS has been enabled by integration of computer aided design (CAD), computer aided manufacturing (CAM), computerised numerically controlled (CNC) machining and robots to collectively form computer integrated manufacturing (CIM) systems [18,19]. CIM is the key element in FMS in which distributed workstations are linked by computer-controlled material handling systems. Material handling processes are an essential part of designing the material flow structure in any distributed manufacturing system. Automation implies a reduction (towards elimination) of human labour with higher throughput at higher quality at lower cost. CIM includes CNC machines and robots, production control through just-in-time manufacture, and transport vehicle control that are part of FMS. The manufacturing cell with a highly automated compact footprint is the basic unit of FMS [20]. FMS comprise multiple cells of robots, CNC machines and material handling linked by a computer network to maximise its autonomous capabilities [21]. It is a multicell system interconnected by self-driving transport vehicles on guide rails between cells. A cellular manufacturing system is a type of FMS based around groups of machines (cell) that are specialised for a specific function [22,23]. Cellular manufacturing groups all related activities together into a CNC machining centre tended by a central robot to minimise human intervention. A robot can select a workpiece and emplace it onto a conveyor to transport it to a CNC machine. Another robot picks up the workpiece and emplaces it into the CNC machine. Finished parts are removed, emplaced onto another conveyor and picked up by another robot for assembly with other parts. A typical manufacturing cell includes five functions overseen by a centralised cell supervisor – manufacturing operations, machining planning, workpiece preparation, supplementary operations and inventory stocking [24]. The cell supervisor controls and co-ordinates machine tools, robots, sequencing tasks, production processes, parts and instigate quality control. In the automated lights-out manufacturing system, the intelligent cell provides automated manufacturing, planning and stocking functions with zero manual preparation and supplementary functions. Only manufacturing operations add value to the workpiece through the input of energy, information and material so all other aspects of manufacture must be minimised. Traditionally, the cost of raw material is only a small fraction of total product cost but for a self-replicating machine, the capital costs of machinery are derived directly from the constituent material costs. An FMS specification may be transformed automatically into a coloured Petri net model [25]. An FMS may be defined as a 7-tuple FMS={M, B, H, Op, C, Mob, T} where M=set of machines, B=set of buffers, H=set of material handling systems, Op=set of operations for each machine, C=storage capacity for each buffer, Mob=mobility of position range of handling system; T=transportation capacity of handling system. This may be transformed into a manufacturing model P={G,P} where G=set of manufacturing processes, P=set of finished products. Cellular manufacturing reduces work-in-progress allowing a just-in-time approach [26]. Deadlocks can occur when two or more parts require the same resources at the same time. This can invoke a freezing behaviour unless the deadlock is resolved through detection and recovery methods.

The manufacturing cell concept provides a balance between flexibility and efficiency. Mass production maximises efficiency at the expense of flexibility while small lot production of complex systems requires high flexibility at a cost of decreased efficiency. The need is to provide a balance between these two factors which allows frequent redesign. In the self-replicating machine, economies of scale are not enabled through mass production but through exponential production [27]. Universal construction requires the ability to rapidly develop and manufacture new products with quality, reliability and diversity in response to rapidly changing market demands. FMS offer the advantages of mass production with the flexibility of customisation. Product variants can be accommodated readily from raw materials to parts to assemblies. This flexibility has several components – organisational flexibility to adapt to changes, machine flexibility to implement different machining operations, material handling flexibility to move different part types efficiently, operational flexibility to produce different parts in different ways, process flexibility to maximise parts types without major setup, product flexibility to create new parts, routing flexibility to produce parts through alternate routes through the production process, volume flexibility to adjust output levels, expansion flexibility to adjust capacity and capability as needed, program flexibility to run autonomously for long periods, production flexibility to manufacture a multitude of parts without new capital equipment, and market flexibility to adapt to market changes [28]. Maximum flexibility implies the ability for rearrangement, change in materials and machining, machining more complex geometries to increase the product range and variation, and the ability to integrate new machining technologies – 3D printing offers these capabilities if it can be proven that it can manufacture complex systems such as robotic machines. These requirements are exactly those required of a universal constructor which is a logical extension of the FMS which must be extended through the manufacturing chain from raw material mining through the industrial ecology to the final product systems. Recently, lean production has emphasised a reduction in inventory stock (production to demand rather than stock for supply), rational sequencing of operations and the elimination of waste – indeed, the lunar industrial ecology implements this through recycling. Lean manufacturing combines the high-quality customisation of craft production with the high quantity cheapness of mass production, a task to which 3D printing is eminently suited. Examples of this include just-in-time manufacturing (minimise excess inventory by matching production rate to demand) and total quality management (minimise product waste through continuous quality control). Just-in-time manufacturing bears similarities to generalised assembly line balancing along a conveyor to consecutively distribute the total manufacturing workload along the flow line. A variation of total quality management is 6 sigma quality which aims to reduce tolerance deviance beyond the traditional 3 sigma levels at every stage of the production process. All are effectively concerned with the minimisation of waste.

4 MANUFACTURING ARCHITECTURES

Control architectures in manufacturing have evolved from centralised hierarchies into distributed heterarchies [29]. Centralised architectures offer complete global control effort but are slow to respond to perturbations due to high overheads. This may be modified into a top-down hierarchy which overcomes the overhead problem through task decomposition but the response problem remains. The hierarchy is the most traditional organisational form with its tree-like structure where fewer higher agents have more global views than more numerous lower agents in the hierarchy. Complex systems often form hierarchies of interrelated subsystems in which the interactions between subsystems are suppressed with respect to those within subsystems – they are nearly decomposable such that subsystems can be treated as if they are almost independent of each other. This is the principle of decomposition of increasing precision with decreasing intelligence [30]. An example applied to FMS is a three-layer hierarchy of an organisation level for scheduling integrated sets of machines (factory level), coordination level for coordinating machines (cell or job shop level) and execution level for controlling each machine task (machine level) [31]. The hierarchy may or may not have same level interactions through internal links. Hierarchies implement a divide-and-conquer strategy but are brittle.

Hierarchies may be modified by allowing some same level interactions in a more distributed approach. The heterarchical architecture is a flexible distributed multi-agent approach to problem solving in which no single agent has a global view of the problem, only a partial view. Blackboards such as the NASREM architecture are of this nature [32]. The heterarchical structure is flat characterised by entirely same level interactions in a distributed fashion without any central or global control. Decentralised control with localised intelligence linked with adaptive communications will be essential. In biological systems, distributed control of modules operating on the basis of local information only without centralized arbitration is ubiquitous. As long as communications exist between these subunits, coordination through a higher level self-organised centralised controller is possible [33]. Fully autonomous mining and manufacturing will require self-learning and self-optimisation to adapt flexibly and rapidly to a variable demand environment, i.e. reconfigurability is essential [34]. There are certain design principles required for reconfigurability that goes beyond traditional flexible manufacturing systems (FMS) [35]. They are based on flexibility, convertibility, scalability and modularity and the key element is the implementation of actuators for multiple degrees of freedom. The distributed heterarchy is highly fault tolerant to perturbations but is difficult to predict. Decentralised approaches may be combined with supervisory control.

Complex multi-agent manufacturing systems may be configured several different ways. The object-oriented paradigm has given way to agent-based design. Agent-based systems are ideally suited to distributed architectures. Agents are a development of this concept involving autonomous well-defined entities with well-defined boundaries and interfaces [36]. Agents are objects in the object-oriented paradigm – it comprises a set of tasks which interact through message passing. However, whereas object-oriented approaches are built around passive objects, agent-based approaches place emphasis on active agent interactions. Swarm-based approaches using multiple agents with simple local behaviours to generate complex behaviours is the most robust approach to multi-robot coordination. Agent-based distributed architectures comprise a set of agents – cooperating autonomous entities that can self-organise into a population without any global controller. Each agent has knowledge for its task; each agent has an interface to interact with other agents and/or the environment; each agent is hierarchically constructed. There are many applications of agent-based computing [37]. CORBA (common object request broker architecture) is an industrial middleware agent-based protocol applied to an intelligent machine cell to coordinate its subsystems [38]. An open systems architecture can partition the FMS into autonomous entities (modules) that communicate and coordinate with each other [39]. Agents must learn from their environments to adapt - with multiple agents, this is complex requiring mechanisms of coordination. There are several market-based approaches to multi-agent mechanisms [40]. The bucket brigade algorithm optimises work allocation between resources to maintain load balance without supervision. The contract net protocol is a market-based technique that involves agents competing for subtasks through the submission of bids [41]. However, optimisation-based allocation of tasks among agents is superior to market-based approaches in multi-robot task allocation [42,43]. Optimisation generally implies linear programming with respect to utility, fitness value or resource cost of a task [44]. The evolutionary algorithm is an optimisation procedure that is suited to manufacturing schedules [47]. Similarly, it has been proposed that an information-theoretic measure – generalised correlation entropy - of spatiotemporal coordination of multiple modules of a distributed robotic system be employed as the fitness function of a genetic algorithm to evolve the system [46]. Self-organisation can be applied to multi-agent manufacturing in which multiple agents form a society of agents to solve problems beyond any individual agent's capacity [47]. Agents have only local interactions and interact with each other through a coordination model. Local interactions between components result in emergent global properties without any central control or supervision. For self-organisation, a critical threshold must be exceeded for the emergence of global order to occur. It is the multiplicity of short-range interactions that yield complex "emergent" global behaviours that are not reducible to the behaviour of its parts. The commonest example is the collective behaviours of insect colonies of ants, termites, bees and wasps. The ant colony is a self-organising system in which stigmergy provides the mechanism for implicit rather than explicit coordination [48]. Each ant observes cues from its environment independently to invoke simple behaviours individually. By depositing pheromones, some fluctuations grow while others fade. These accumulating pheromones drive individual agents that appear coordinated. Communication between insects is indirect and mediated through the environment – stigmergy. Individual insects mark their environment using volatile chemicals – pheromones – which collectively coordinate them. Ants modify their environment by depositing pheromones locally and the pheromones propagate spatially as a global dissipation field. It is these local modifications that communication to other foraging ants. A specific sign in the environment triggers specific actions by the agents. This can be directly applicable to ant agents in a mine, processing and manufacturing environment. Life is a complex system in that it is characterised by multiply interacting agents which themselves may be simple with nonlinear interactions subject to simple short-range laws. Biological complex systems operate far-from-equilibrium and open to external energy and information with a self-organised hierarchical internal structure with internal feedback loops. Emergent global properties have their own causal rules irreducible to component causal effects.

Reconfigurability reduces the complexity and cost of FMS by adaptively matching capacity to need [49,50]. Reconfigurable manufacturing systems are designed to accommodate rapid changes in manufacturing architecture in response to new demands in productive function. They minimise unused capacity but can adjust rapidly to new demands [51]. This rapid response to changing demands is the hallmark of agile manufacturing (itself similar to lean manufacturing except that agile manufacturing is proactive while lean manufacturing is reactive) [52,53]. Reconfigurable systems are distinct from FMS in that they are rapid but limited in flexibility to part diversity whereas FMS has maximum flexibility in part range. We need both. There are six principles of reconfigurability: (i) modularity; (ii) integrability of interfaces; (iii) customised flexibility; (iv) scalability of factory; (v) convertibility of factory to different production requirements; (vi) diagnosability of abnormal behaviour [54,55]. Modules can be reconfigured rapidly into an integrated system which can be readily modified with new modules to adjust both product and capacity. Modular design of products permits agile manufacturing by configuring modules into different products, the configurations of which can be searched using tabu search [56]. Tabu search is suitable for solving NP-hard problems by starting from an initially feasible solution to search for better solutions subject to minimum cost. Genetic programming also may be employed to evolve the self-organisation of parts into a final self-assembly [57]. The genetic program has a hierarchical structure with components for assembly that can be randomly selected subject to assembly constraints defined by fitness. Reconfigurable manufacturing allows ready flexibility to perturbations that can affect throughput without re-design of the manufacturing plant. Many reconfigurable systems employ material transport systems such as gantries and conveyors that form the backbone of the system with an emphasis on CNC machining. The flows of service or goods in such a transport network are controlled by demand and supply in a market economy system forming a network topology. The volume of service or goods through the transport network may be quantified by Kirchoff's circuit laws. Petri nets may also be used to model concurrent manufacturing activities as noted earlier. There are several types of reconfigurable manufacturing architecture in providing dynamic flexibility of distributed cells – fractal, holonic and bionic [58]. The units in each case are slightly different. The fractal manufacturing architecture is a reconfigurable system whose chief characteristic is that its autonomous agents are self-similar and reconfigurable and these agents cooperate through message passing to solve problems [59,60]. They are self-similar at all levels of their hierarchy, the configuration of which is controlled by a system agent. It can autonomously self-organise its organisational structure (but not its physical structure) in response to a dynamic environment through reinforcement learning [61]. Reinforcement learning lies between the exact feedback of supervised learning and the lack of feedback of unsupervised learning. It is unclear how the fractal architecture might be implemented practically.

The holonic architecture is the most popular agent-based approach to manufacturing systems control as it combines hierarchical and heterarchical architectures [62]. The holonic system has been adopted in automotive factories based on Arthur Koestler's concepts on the material basis of mind-brain duality in his "Ghost in the Machine" (1967) [63]. Biological cells are comprised of organelles while also being part of tissues (holonic architecture). Inspired by organelles of the biological cell, the holonic factory model comprises a hierarchy of tissue holons comprised of multiple cell holons. Each cell holon comprises a nucleus holon (for decision-making), a golgi complex holon (for inventory), a lysosome holon (for reprocessing and recycling), an endoplasmic reticulum holon (for transport) and ribosome holons (for production) in which mRNA act as a messaging system and tRNA as a negotiation system. The holarchy is a system of holons that permits a heterarchical system implement a nested hierarchical structure to provide conflict resolution with the holon representing a hybrid character of both whole and part [64]. A holon is simultaneously both a subordinate agent comprised of parts from a lower level and part of a larger superordinate agent. The holonic architecture self-regulates in response to perturbations from the environment modelled as a social system [65]. It is based on cooperating holons forming an integrative holarchy based on functional decomposition. The holarchy combines the static stability of the hierarchy with the dynamic flexibility of the heterarchy through the dual nature of the holon [66]. The holon is an autonomous, self-contained, self-regulating module yet it is part of higher order holons and itself is comprised of lower order holons, smearing the difference between part and whole, i.e. holons may be aggregated (exhibiting emergent complex behaviours from interactive simple behaviours) or specialised (exhibiting the inheritance of agents). The holarchy comprises different sets of alliances – short-lived coalitions, task-oriented teams, long-lived congregations, long-lived societies governed by social laws, loosely bound federations. Holons interact through broadcast messaging and contract net protocol. Metamorphic control of holonic systems is an approach for real time operation [67]. The holarchy can be augmented with stigmergy to enhance clustering through self-organisation [68]. Stigmergy is a bio-inspired approach that implements communication between components through modification of the local environment.

PROSA (product-resource-order-staff architecture) is an agent-based holonic manufacturing reference architecture based on four types of holonic agents [69,70]: (i) order holons (agents for workpiece tasking, logistics and its control and timing); (ii) product holons (agents for product functionality such as process planning and quality assurance); (iii) resource holons (agents for physical and information resource handling such as machine or factory); and (iv) staff holons (agents for global centralised supervision). Software agents acting as virtual ants coordinate between physical agents so they can aggregate multiple agents to form holonic systems. PROSA has a self-similarity aspect incorporating a fractal architecture. An example of an holonic system is the plug-and-produce software reconfiguration facility of an holonic robot assembly system comprising three manipulators, one belt conveyor and two warehouses [71,72]. Stigmergy has been demonstrated within the context of PROSA as an indirect mechanism of coordination in multi-agent holonic manufacturing system [73,74] in which PROSA agents were coordinated for adaptability to changes in the environment. Termite-inspired robots using only very simple behavioural rules could build structures from magnetically-connected bricks through emergence. PROSA may be extended ontologically into the bionic architecture based on a hierarchy of biological cell analogues (modelons) including the possibility of biological morphogenesis. A cell may be differentiated into different functions but all are based on the same underlying architecture.

The Biological Manufacturing Systems is a bio-inspired approach to manufacturing for coping with internal and external environmental perturbations during the product lifecycle. In this paradigm, manufacturing machines breed products in which potential fields attract dynamically jobs to machines [75]. A classifier system with if-then production rules with bucket brigade credit assignment was adopted to implement genetic learning [76]. Genetic algorithms have also been applied to finding a minimum cost machine layout for a factory floor based on interaction forces between different manufacturing activities [77]. A neuroendocrine-inspired manufacturing system (NEIMS) emulates the biological neurocontrol-hormonal regulation system and its characteristic adaptability [78]. The endocrine system releases hormone signalling molecules through the hypothalamus-pituitary-adrenal axis to the bloodstream in response to neural stimulus – hypothalamic neurons stimulate pituitary CRH (ACTH-releasing hormone) to stimulate adrenal ACTH (adrenocorticotropic hormone) synthesis which in turn stimulates biosynthesis of cortisol which inhibits CRH/ACTH production. The nervous system implements adaptive control while the endocrine system implements biochemical homeostasis. NEIMS implements hierarchical neural control under nominal conditions but switches to hormone regulation for agile adaptation under off-nominal conditions with a reorganisation of resources. Hormonal secretion quantity is given by [79] $\rho_{ij} = \frac{a}{c_{ij}}(1+\lambda)^{t-1}$ where a=constant, c_{ij}=position-dependent cost for task, t=duration of job, λ=control parameter. This latter is particularly analogous to the lunar industrial ecology of chemical processors.

5 CONCLUSIONS

Our lunar industrial ecology represents a sustainable approach to ISRU which feeds into a manufacturing system based on 3D printing to constitute a self-replicating machine. Although multiple machines that must be coordinated are characteristic of manufacturing, this is not so in chemical processing plants. The lunar industrial ecology however involves multiple chemical processors that must be coordinated with extensive recycling loops. The design and architecture of manufacturing factories may be applied to the lunar industrial ecology and these approaches have been reviewed. Although these approaches are appropriate throughout the processing chain from mining to final product, a central facet of any ISRU system will involve exploration of the planetary environment and acquire physical resources [80]. This will require complex strategies involving coordination of multiple roving robots.

Appendix. Near closed loop lunar industrial ecology (emboldened materials are pure metal oxides for direct reduction using the FFC Cambridge process)

Lunar Ilmenite

$Fe^0 + H_2O \rightarrow$ ferrofluidic sealing

$FeTiO_3 + H_2 \rightarrow \mathbf{TiO_2} + H_2O + Fe$

$2H_2O \rightarrow 2H_2 + O_2$

$2Fe + 1.5O_2 \rightarrow Fe_2O_3/Fe_2O_3.CoO$ - ferrite magnets

$3Fe_2O_3 + H_2 \leftrightarrow Fe_3O_4 + H_2O)$ – formation of magnetite at 350-750°C/1-2 kbar

$4Fe_2O_3 + Fe \leftrightarrow 3Fe_3O_4$)

Nickel-Iron Meteorites

W inclusions – high density of 19.3 → Thermionic cathodic material

Mond process:

$W(CO)_6 \leftrightarrow 6CO + W$

$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175°C/100 bar) → Tool steel

$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55°C/1 bar) → Electrical steel

$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150°C/35 bar) → Permalloy

S catalyst

Alloy	Ni	Co	Si	C	W
Tool steel				2%	9-18%
Electrical steel			3%		
Permalloy	80%				
Kovar	29%	17%	0.2%	0.01%	

$4FeS + 7O_2 \rightarrow \mathbf{2Fe_2O_3} + 4SO_2$

(Troilite) $SO_2 + H_2S \rightarrow 3S + H_2O$

$FeSe + Na_2CO_3 + 1.5O_2 \rightarrow \mathbf{FeO} + Na_2SeO_3 + CO_2$

KNO_3 catalyst $Na_2SeO_3 + H_2SO_4 \rightarrow Na_2O + H_2SO_4 + Se \rightarrow$ photosensitive Se

$Na_2O + H_2O \rightarrow 2NaOH$

$NaOH + HCl \rightarrow NaCl + H_2O$

Lunar Orthoclase

$3KAlSi_3O_8 + 2HCl + 12H_2O \rightarrow KAl_3Si_3O_{10}(OH)_2 + 6H_4SiO_4 + 2KCl$

orthoclase illite silicic acid (soluble silica)

$2KAl_3Si_3O_{10}(OH)_2 + 2HCl + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2KCl$

kaolinite
[$2KAlSi_3O_8 + 2HCl + 2H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2KCl + \mathbf{SiO_2} + H_2O$]
$KCl + NaNO_3 \rightarrow NaCl + KNO_3$
$2KCl + Na_2SO_4 \rightarrow 2NaCl + K_2SO_4$

<u>Lunar Olivine</u>
$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3\mathbf{SiO_2} + 2H_2O$
fayalite magnetite
$Mg_2SiO_4 + 4H_2O \rightarrow \mathbf{2MgO} + \mathbf{SiO_2} + 4H_2O$ → 3D Shaping binder
forsterite $MgO + HCl \rightarrow MgCl_2 + H_2O$ → 3D Shaping binder

<u>Lunar Anorthite</u>
$CaAl_2SiO_8 + 4C \rightarrow CO + \mathbf{CaO} + \mathbf{Al_2O_3} + 2Si$ at 1650ºC → CaO cathode coatings
$CaO + H_2O \rightarrow Ca(OH)_2$
$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
$CaAl_2SiO_8 + 5HCl + H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + \mathbf{SiO_2}$ → fused silica glass + FFC electrolyte
$AlCl_3.6H_2O \rightarrow Al(OH)_3 + 3HCl + H_2O$ at 100ºC
$Al(OH)_3 \rightarrow \mathbf{Al_2O_3} + 3H_2O$ at 400ºC → $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$ (thermite)
AlNiCo hard magnets
Al solar sail

<u>Lunar Pyroxene</u>
$Ca(Fe,Al)Si_2O_6 + HCl + H_2O \rightarrow Ca_{0.33}(Al)_2(Si_4O_{10})(OH)_2.nH_2O + H_4SiO_4 + CaCl_2 + Fe(OH)_3$
Augite montmorillonite silicic acid iron hydroxide

<u>Lunar Volatiles</u>
$CO + 0.5\ O_2 \rightarrow CO_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300ºC (Sabatier reaction) → $CH_4 \rightarrow C + 2H_2$ at 1400ºC for steel/anode regeneration
Ni catalyst
850ºC 250ºC
$CH_4 + H_2O \rightarrow CO + 3H_2 \rightarrow CH_3OH$ 350ºC
Ni catalyst Al_2O_3 $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ 370ºC $+nH_2O$
Al_2O_3 $CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2 \rightarrow ((CH_3)_2SiO)_n + 2nHCl$ → silicone plastics/oils

$N_2 + 3H_2 \rightarrow 2NH_3$ (Haber-Bosch process)
Fe on $CaO+SiO_2+Al_2O_3$
$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$
WC on Ni
$3NO + H_2O \rightarrow 2HNO_3 + NO$ (Ostwald process)
$2SO_2 + O_2 \leftrightarrow 2SO_3$ (low temp)
$SO_3 + H_2O \rightarrow H_2SO_4$

<u>Salt of the Earth</u>
$2NaCl + CaCO_3 \leftrightarrow Na_2CO_3 + CaCl_2$ (Solvay process) → FFC electrolyte
350ºC/150 MPa
$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2$ → piezoelectric quartz crystal growth (40-80 days)
1000-1100ºC
$CaCO_3 \rightarrow \mathbf{CaO} + CO_2$ (calcination)
$NaCl(s) + HNO_3(g) \rightarrow HCl(g) + NaNO_3(s)$
$2NaCl(s) + H_2SO_4(g) \rightarrow 2HCl(g) + Na_2SO_4(s)$

<u>Metalysis FFC Process ($CaCl_2$ electrolyte)</u>
$MO_x + xCa \rightarrow M + xCaO \rightarrow M + xCa + ½xO_2$ where M=Fe, Ti, Al, Mg, Si, etc
$CO + 0.5\ O_2 \rightarrow CO_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300ºC (Sabatier reaction) → $CH_4 \rightarrow C + 2H_2$ at 1400ºC
Ni catalyst → steel/cathode regeneration

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