My Dastardly Plan to Colonise the Universe

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Extraterrestrial In-Situ Resource Utilisation

- In-situ resource utilisation (**ISRU) is foundational** to sustainable space infrastructure development
- Extraterrestrial mining and manufacturing imposes **several challenges**:
  - (i) Energy generation is local
  - (ii) No manual labour – autonomous robotics is essential
  - (iii) Built-in robotic maintenance required
  - (iv) High-weight equipment unviable
  - (v) Limited geotechnical data for siting infrastructure
  - (vi) Environmental constraints – vacuum, dust, wide temperature fluctuations, radiation, micrometeoroid bombardment
  - (vii) Partial (moon) or negligible (asteroids) gravity
- LUNAR WATER: There is an estimated average ~5.6% water ice by mass of regolith at cold traps (40 K) – permanently shadowed craters at poles
- **Total inventory ~10^{11}-10^{12} kg** ≡ ~ 10^{-4}-10^{-5} x water vapour in Earth's atmosphere

Extraction of Water

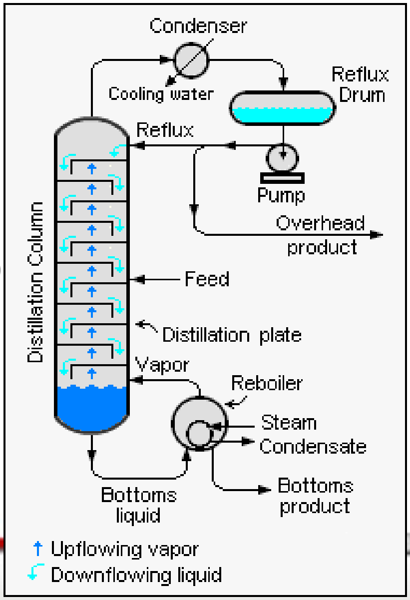
- Water requires minimum processing (shallow ISRU) BUT it requires extensive infrastructure
- **Solar Power Generation**
  - permanently shadowed craters by definition lack access to solar energy
  - solar farms to be emplaced at adjacent peaks of eternal light to beam solar energy
  - beaming distance ~km (horizontally and vertically)
- **Mining Operations at 40 K**
  - dome-like tent to capture water vapour re-condensed at passively-cooled cold traps
  - solar concentrators to sublime ice of surface regolith thermally
  - PV-derived electrical energy for subsurface heaters in pre-drilled boreholes
- **Launch Operations**
  - electrolytic propellant production plant to electrolyse liquid water
  - LOX/LH2 cryogenically stored (LH2 requires active cooling to 20 K with 3%/d boil-off)
  - propellant production co-located with launch pad

Lunar Volatiles

- Volatiles mining by heating regolith to 700ºC releases 90% of volatiles esp from smaller ilmenite particles (extracted magnetically): 96% H_2, <4% He, **CO**, **CO_2**, **CH_4**, **N_2**, **N**H_3, H_2**S**, **S**O_2, Ar, etc
- **Carbon compounds** ~80-120 ppm

Volatile	Average Concentration ppm (µg/g)	Mass/m³ regolith (1.8 tonnes)
H	46 ± 16	76
^3He	0.0042 ± 0.0034	0.007
^4He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	133
F	68 ± 45	116
Cl	44 ± 67	50
Ar	0.5 ± 0.19	
S	715 ± 216 (primarily troilite)	
H_2O	$5.6 \times 10^4 \pm 2.9 \times 10^4$	

- **Fractional distillation** for well-separated fractions (assuming STP):
  He (4.2 K), H_2 (20 K), **N_2 (77 K)**, **CO** (81 K), **CH_4** (109 K), **N_2O** (185 K), **CO_2** (194 K), **H_2S** (213 K), **NH_3** (240 K), **SO_2** (263 K) **NO_2** (294 K) and H_2O (373 K)
- **VERY VALUABLE STUFF!!!!**
- We should husband this stuff as we extract water ice……



Water as Propellant/Oxidiser

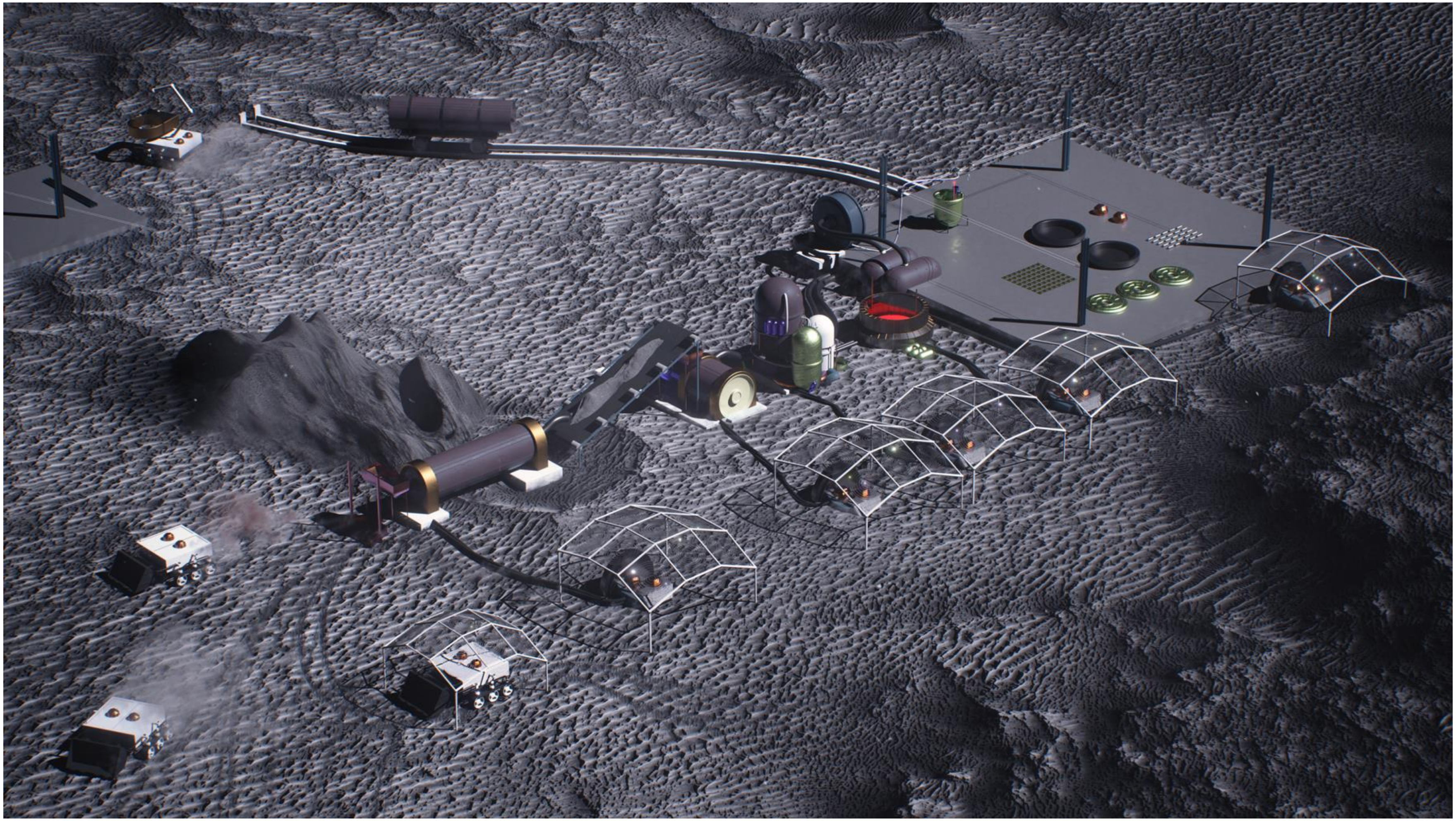
- Water is electrolysed into **rocket propellant – cryogenic LOX/LH2** (highest I_{sp}=450 s)
- Propellant/oxidiser constitutes the highest mass fraction (**cost**) of all space missions
- Primary goal for lunar LOX/LH2 is to fuel **human missions to Mars** staged from Lunar Gateway in 1,500 x 70,000 km polar orbit
- **Mars Design Reference Architecture 5.0** baseline imposes a Δv of 3.0 km/s in 3 legs (excl landing):
  - (i) 534 tonne Mars Cruiser to Mars orbit of which 260 tonnes LOX/LH2
  - (ii) 359 tonne Cargo Vehicle to Mars orbit of which 175 tonnes LOX/LH2
  - (iii) 274 tonne Earth Return Vehicle to Earth orbit of which 133 tonnes LOX/LH2
- Total LOX/LH2 inventory of **568 tonnes required at the Gateway**
- Lunar surface to Gateway imposes Δv of 3.7 km/s requiring mass ratio of 2.28, i.e. **1,295 tonnes** LOX/LH2
- Total requirement is **1,863 tonnes LOX/LH2 per Mars mission**
- Burning of <u>irreplaceable</u> finite resources – this is NOT sustainable – as lunar activities grow, so will water demand
- Use renewable energy sources for launch – electromagnetic launchers (saves 1295 tonnes)
- LOX/LH2 mass ratio is 6:1 - for Mars mission, this is 487 tonnes O_2 but only 81 tonnes H_2

Utility of Water

- **Water must be husbanded** carefully - future lunar facilities require water but with recycling:
- Human consumption/day – 4.4 kg water incl 2.5 kg for imbibing
  + 0.9 kg O_2 derived from water
  + 0.7 kg dehydrated food

  - 6 kg/astronaut/day → ~2 tonnes/astronaut/y → 40 tonnes Earth launch propellant/y
- Current CELSS offer high recyclability of water and oxygen to support humans ~80-90% recycling efficiencies
- Regenerative fuel cells – H_2/O_2 recycled
- Lunar agriculture (esp. hydroponics) – H_2O recycled
- Industrial fluids – lubrication, froth flotation, machining coolant, drilling mud – partially recycled
- How do we resolve this problem with more sustainable - renewable - approaches?
- To build a **sustainable lunar infrastructure**, we must leverage and utilise in-situ resources that are **abundant and/or recyclable**
- **CRADLE-TO-CRADLE LIFECYCLE ANALYSIS**

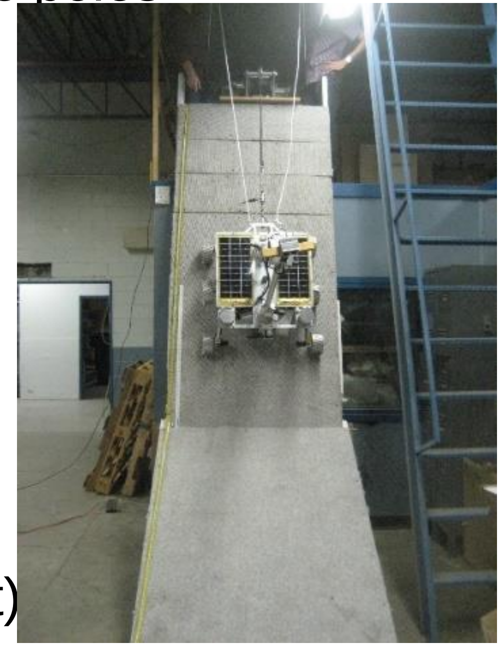
Lunar Industrial Architecture



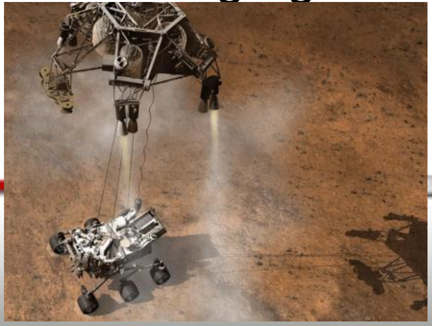
Lunar Prospecting & Mining

Natural Mines on the Moon

- There are natural subsurface mines with potential water **ice deposits more readily accessible** than shadowed craters at the poles
- **Skylights** are partially collapsed roofs to subsurface **lava tubes**
- Examples include three skylights at Mare Igenii, Mare Tranquillatis and Marius Hills with diameters ~50-100 m and depths ~40-100 m
- Kapvik microrover can abseil down steep crater cliffs using tethers - it adopted a freewheeling descent with descent controlled by tether deployment (unlike cliffbot)



- **Winching from a skylight into a lava tube** would be more challenging due to stability vulnerabilities – winching from **skycrane** already demonstrated on Mars



Rover Prospecting

- Prospecting for lunar in-situ resources is required to determine **stripping ratios (of waste to ore)** to determine how to recover metals, glasses and ceramics from lunar minerals

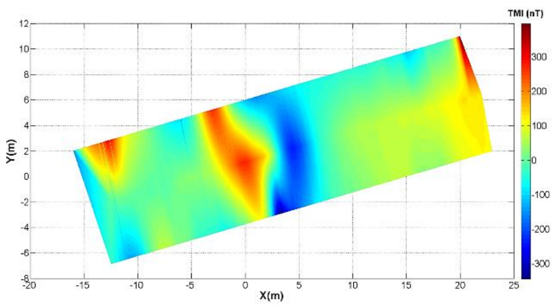
- We have conducted rover-based trials using a Pioneer robot at the open quarry asbestos **Jeffrey Mine, Quebec to search for serpentine deposits** (Mars methane sources)
- This mainly to test CSA ExDOC software control system
- Our **Kapvik micro-rover** has been a testbed for exploring several issues relevant to advanced ISRU activities on the Moon especially mining
- We are interested in sourcing **subsurface NiFe asteroidal orebodies** in the Moon
- There may be indications of such deposits through **local magnetic anomalies** on the surface detectable by rover

Lunar Mining Strategy

- It is expected that low angle asteroid impacts may result in **asteroidal material survival on or beneath the lunar surface**, i.e. ~600 crater candidates
- Non-indigenous **Ni-Fe-Co-W-Se** may be sourced from these regions
- Subsurface incidence, size and distribution of meteoritic **orebodies is unknown**
- There are several constraints we can impose on lunar mines for asteroid ores:
  - lunar mines will be **smaller in scale** than terrestrial mines
  - large-scale highwall mining machines are discarded due to prohibitive costs
  - **spiral strip mining** is more efficient than rectilinear parallel strip mines
  - open-pit mining wastes effort in removal of large amounts of **overburden**
- **Underground mining** is characterised by their wall and roof supports – room-and-pillar, stope-and-pillar, cut-and-fill stoping, sublevel caving, etc
  - mechanised **cut-and-fill mining** may be most suitable
- Automated **load-haul-dumper vehicles** are essential in all mine types

Geomagnetic Survey

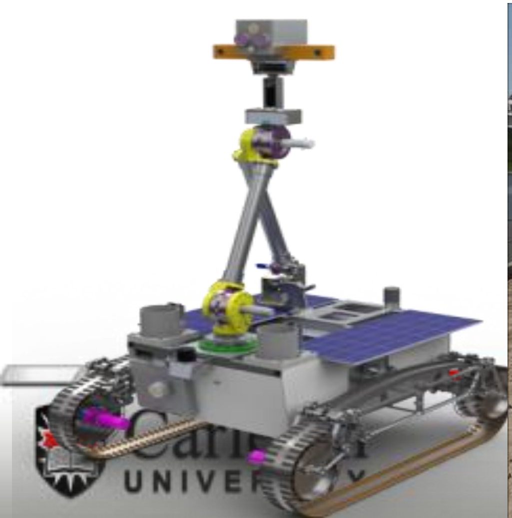
- Rover surveying is essential to find specific in-situ resources
- We wish to detect local surface magnetic indications of **near-surface NiFe asteriodal ores**
- Kapvik microrover was fitted with a **boom-mounted magnetometer** instrument to field test ground magnetic survey at the Carleton University campus

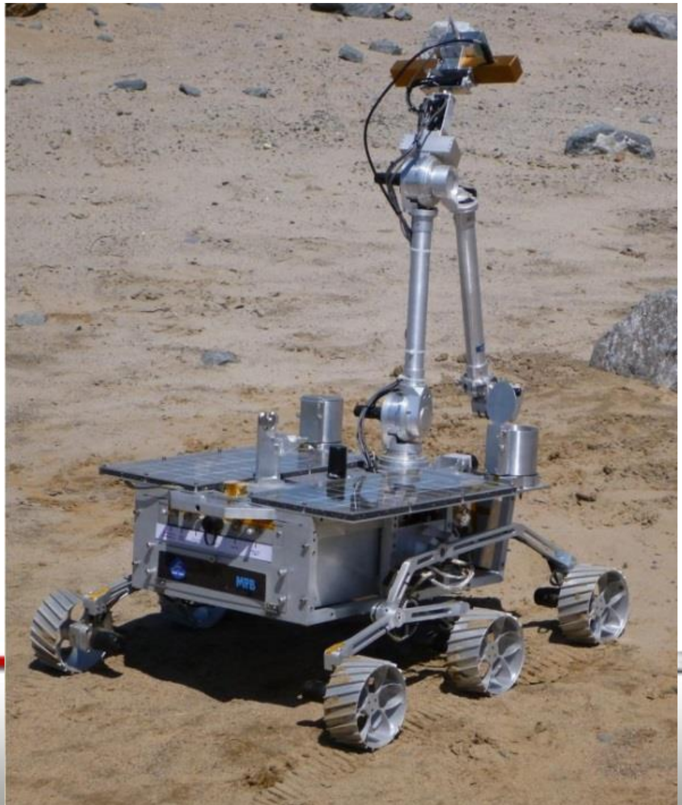


- It detected an underground storm sewer and a local fault, successfully demonstrating the **principle of rover-mounted magnetometry**
- Similar surveying methods may be applied to ilmenite deposit detection

Kapvik Microrover

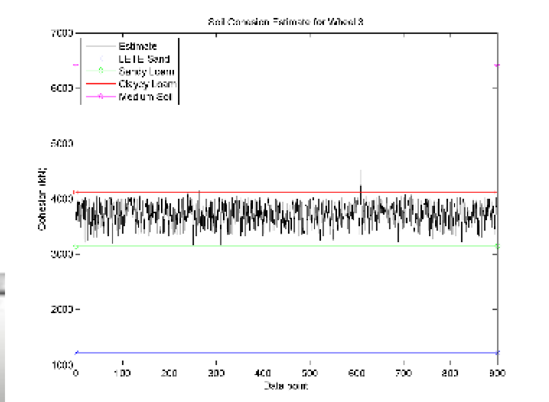
- Kapvik (Inuit for wolverine) is a 32 kg end-to-end microrover prototype for lunar mining
- (i) JCB prototype with **regolith scoop** – it could be fitted with loader/bulldozing blade
- (ii) autonomous navigation capability using UKF implemented on two FPGAs
- (iii) reconfigurable/exchangeable modular chassis, e.g. **elastic loop mobility system** for
- high traction on rugged terrain
- (iv) **sensorised chassis** for online regolith characterisation
- (v) hybrid 4 DOF **camera mast/manipulator** arm
- (vi) pan/tilt camera at elbow with full observability of scoop
- (vii) abseiling capability for crater/skylight surveying

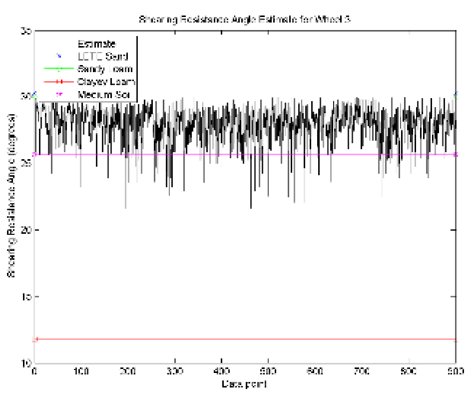


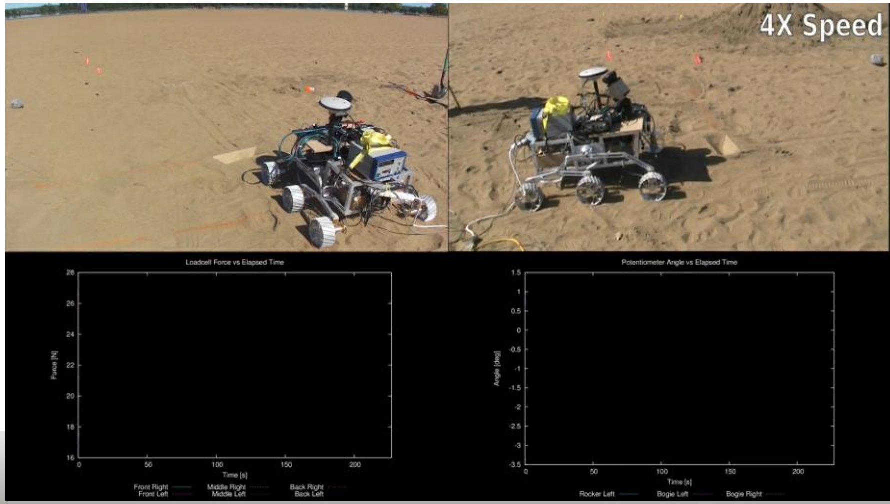


Geotechnic Survey by Rover

- Terramechanics metric, drawbar pull DP=H-R where H=soil thrust derived from Mohr-Coulomb relation $\tau = c + \sigma tan\phi$, τ=soil shear, c=soil cohesion, φ=soil friction angle, σ=soil stress, R=soil resistance dominated by compaction resistance due to sinkage $z = (\sigma/k)^{1/n}$, k=pressure-sinkage coefficient, n=soil exponent
- Sinkage may be estimated from wheel pressure σ from wheel loads measured by load sensors integrated above each wheel station of Kapvik
- Neural network model yields soil cohesion and friction angle estimates – tactile sensing of geotechnic data for lunar bases as the rover traverses terrain

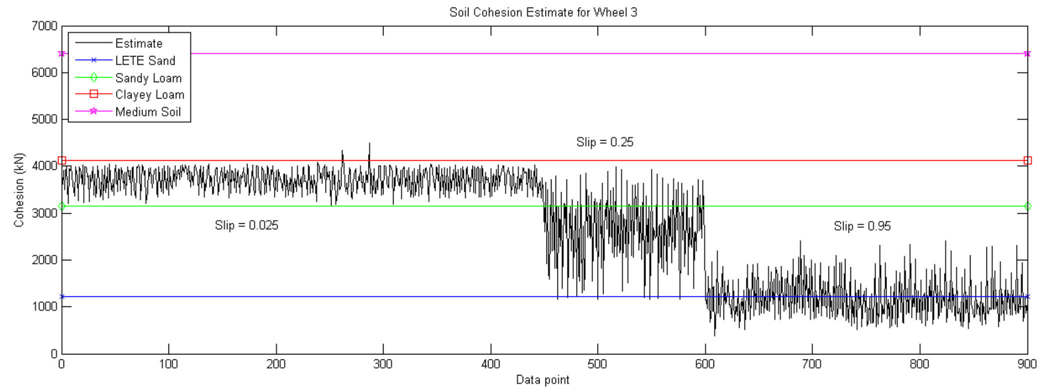




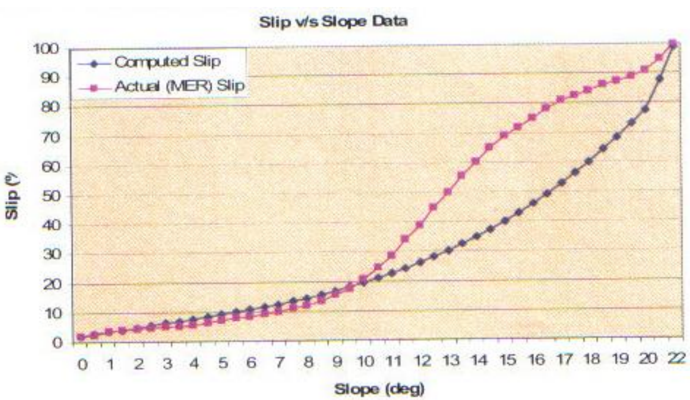


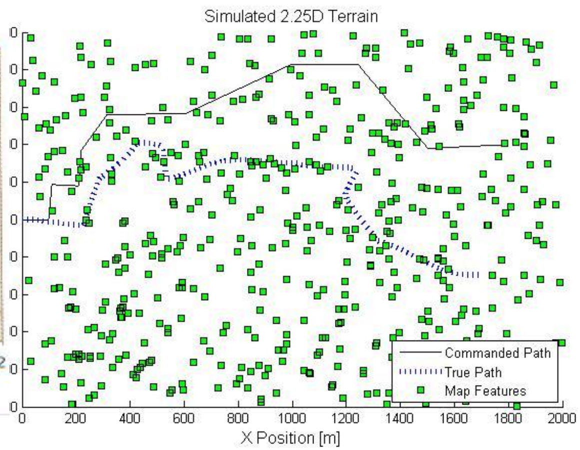
Rover Slip Compensation

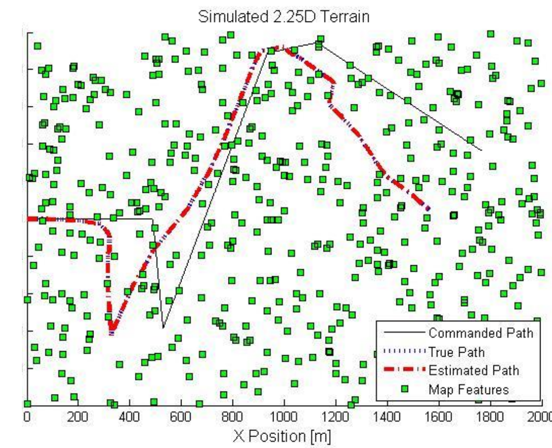
- Slip can also be estimated while traversing terrain as a sharp shift in soil cohesion
- We simulated slip over Martian terrain using the Lindmann-Voorhees polynomial slip model



- We trained a neural network model using EKF learning rule to predict slip based on mine descent angle and compensate for it

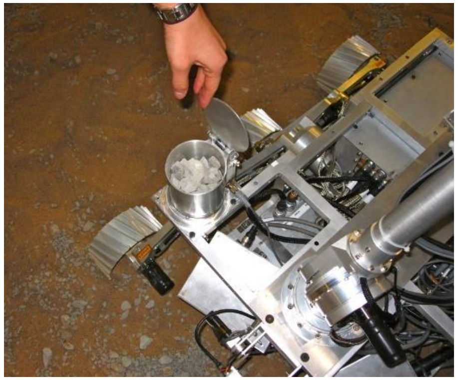






Kapvik Ho!

- Kapvik is configured similarly to a JCB with a 4 degree-of-freedom articulated arm at the end of which is a soil scoop

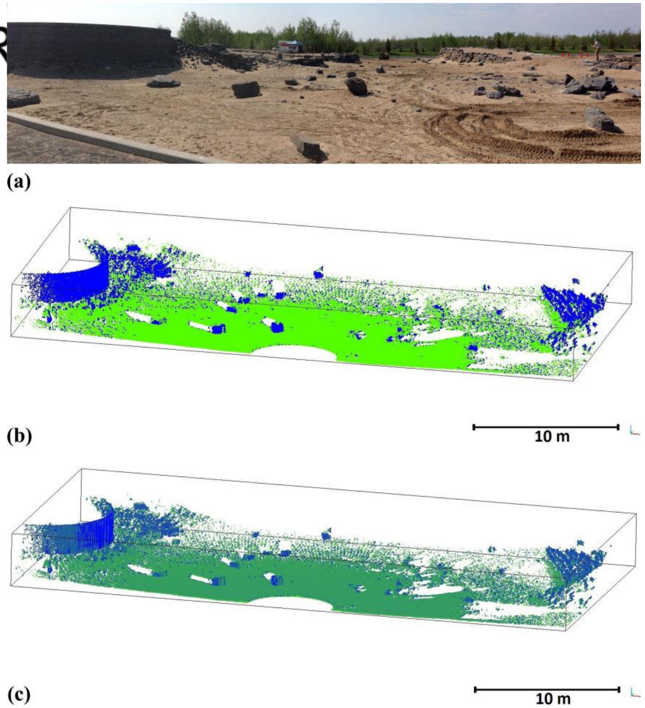


- From Reece earth-moving equation, maximum total tool digging force applied by Kapvik's weight on the Moon limits digging depth to 17 cm

Parameter	Symbol	Value
Soil density	ρ	1520 kg/m^3
Soil cohesion	C	170 Pa
Soil friction angle	Φ	35^o
Tool width	b	0.20 m
Tool cut height	h	
Tool rake angle of approach	α	80^o
Soil shear plane angle	β	45+φ/2
Soil-blade friction angle	δ	φ/3

We can iteratively re-compute digging stroke with cut depth

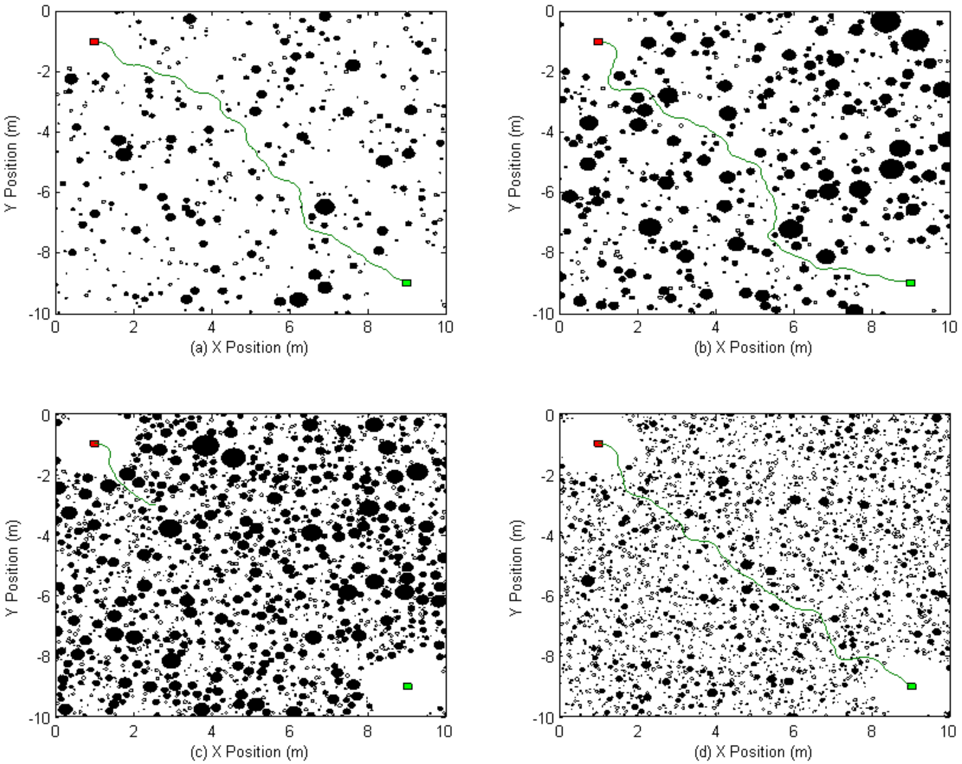
Simultaneous Localisation & Mapping



- Kapvik's primary navigation instrument is a LIDAR scanner for 3D mapping of the local environment
- AutoNav is based on SLAM in which a rover locates itself within a map of its environment characterised by landmarks represented as 3D point clouds
- Map is occupancy grid of cells labelled with probabilistic classifications of traversibility
- We used neural network classifier of terrain trained by EKF learning rule of the form $w_{t+1} = w_t + K_t\left(y_t^d - h(x_t)\right)$ where $K_t = P_t H_t\left(1/\eta + H_t^T P_t H_t\right)^{-1}$=Kalman gain, $\eta = \left(H_t P_t H_t^T + R_t\right)^{-1}$ P_t=learning rate – EKF exploits more info than BP
- Kapvik implemented several SLAM algorithms on two Xiphos Q5 FPGA platforms

Path Planning

- We investigated potential fields for path planning and execution
- Potential fields implement sum of attractive (goal) and repulsive forces (obstacles) to generate traverse gradient along potential minimum path while avoiding obstacles: $F=F_{gl} + \Sigma F_{obs}$
- We simulated the Fajen-Warren polar potential field through Mars rock distributions but it failed through highly cluttered MPF rock field



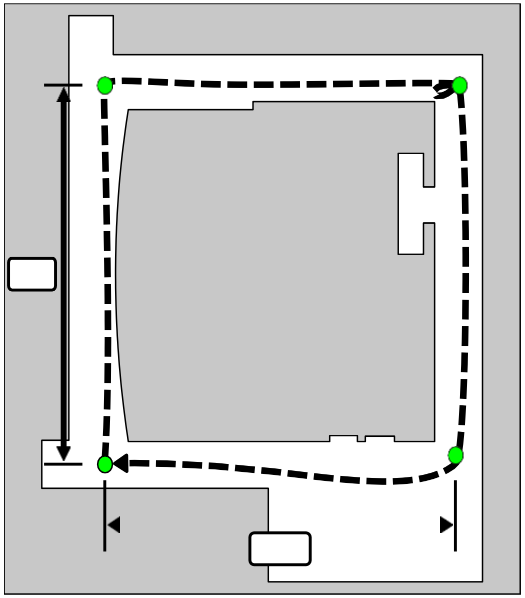
Path Planning 2

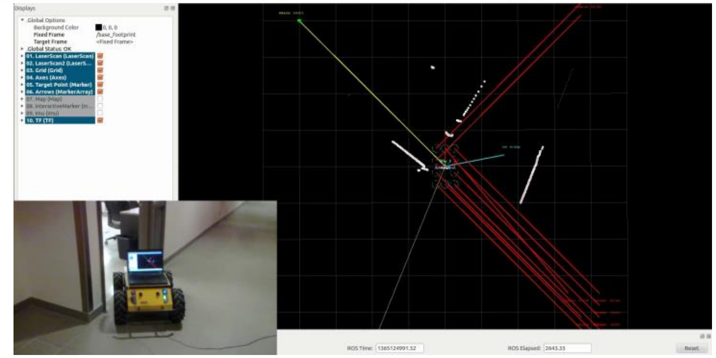
- We require a more robust strategy for dealing with cluttered environments, especially narrow passageways (characteristic of underground mines)
- We added risk and tangential forces to shape the potential field
- Risk force applies an exponential velocity factor to obstacle force to slow down close approaches

  $F_{rsk} = -\varepsilon k_{rsk} F_{obs}$ and $\tau_{rsk} = -\varepsilon k_{rsk} \tau_{obs}$ where $\varepsilon = exp(-k_{dcy} v_x)$, k_{dcy}=const
- Tangential force applies an exponential velocity factor that generates a bias force when rover slows to eject from local minima

  $F_{tgl} = \varepsilon \gamma k_{tgl} R(\pi/2) F_{obs}$ and $\tau_{tgl} = r_f \times F_{tgl}$ where k_{tgt}=const
- These tailoring forces are effective in coping with cluttered environments
- Potential field is suitable for multi-rover coordination

“Field” tests of Tailored Potential Field





Lunar Resources & Chemical Processing

Material Constraints Imposed by Lunar Geology

- Moon exhibits a range of resources – volatiles, regolith and minerals from which ceramics and metals may be extracted
- There are several <u>material constraints</u> on the Moon
- Moon is **deficient in specific elements**, most notably Cu, Na, halogens
- Zn, Sn and Pb are deficient so most **solders and brazing alloys are not viable** (but Al-Si may be used for brazing Al joints)
- Organic or organic-derived material is depleted so **most plastics are not viable**
- The constraints define gaps for which **substitutions are necessary**, e.g. Al for Cu
- **Material multifunctionality** (e.g. Al) of specific lunar-derived materials is key
- **NaCl must be imported** to the Moon as reagents that are not consumed but recycled
- Extracting **Cr and Mn** from lunar minerals as alloying elements is too challenging for first generation ISRU - **Cr** is for oxidative corrosion-resistance so this can be eliminated - **Mn** (to fix O and S for malleability) vs **C** (for hardening) - **both may be dispensed with**
- In general, terrestrial alloys **fine-tune material additives** to optimise physical properties, minimise oxidative/aqueous corrosion and reduce processing temperatures
- On the Moon, material constraints require **satisficing** physical properties with <u>no requirement for corrosion-resistance</u> and <u>relatively abundant energy sources</u>

Minimalist Demandite

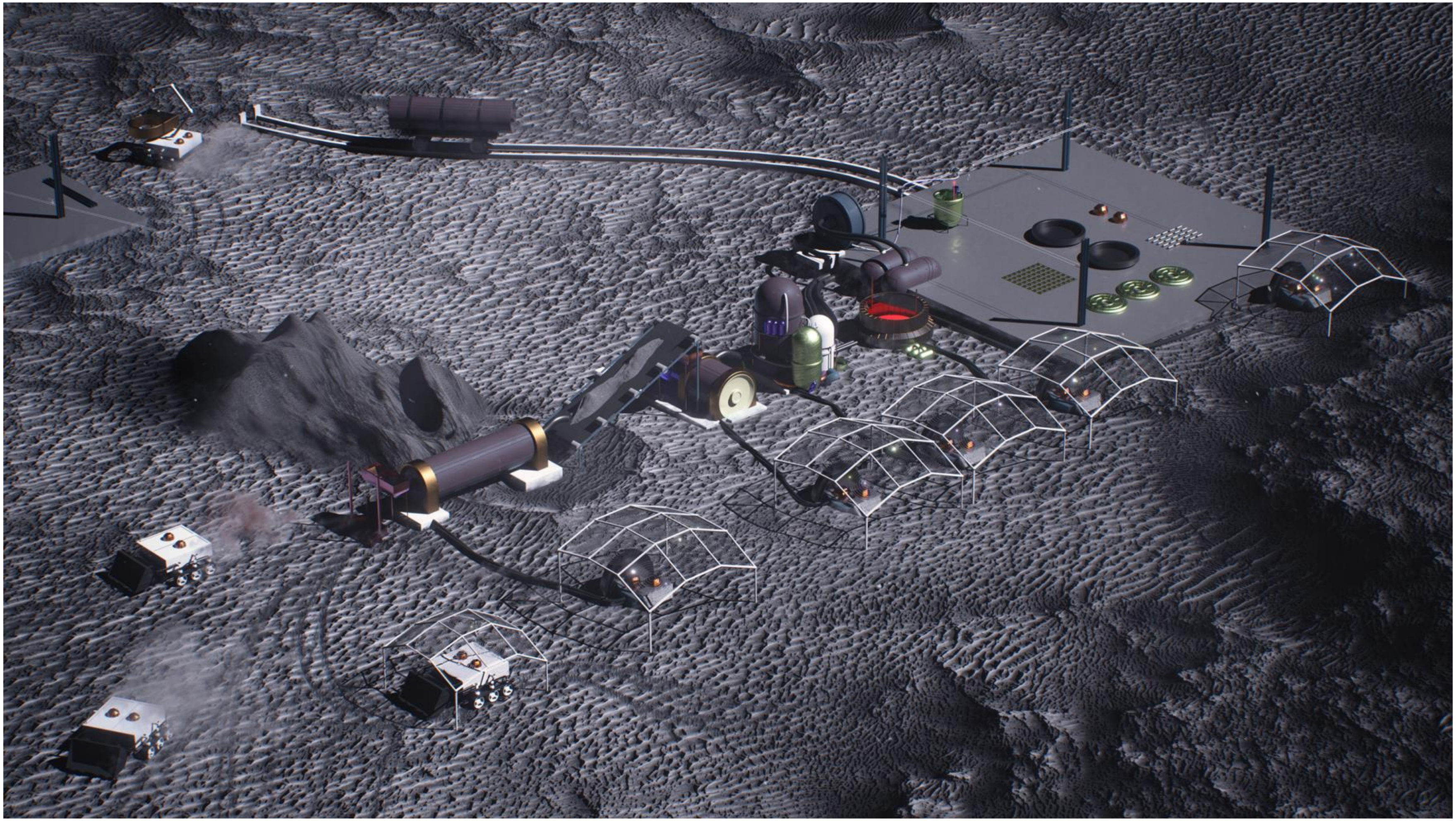
- Moon has not experienced aqueous processes of weathering and erosion that yield geographical concentrations of orebodies
- Moon has a relatively simple geology comprising a few common rock-forming minerals, e.g. **plagioclase feldspars** (esp anorthite) – **pyroxene** - **olivine** – **ilmenite**
- Our **DEMANDITE** concept maps functional material requirements with available resources
- **10 basic materials** can supply full functionality for all the subsystems of a generic robotic spacecraft
- We require only a minimal set of reagents including (a) scarce volatiles for recycling; (b) NaCl imported from Earth (salt contingency)
- {Nanophase iron introduces the possibility of **microwave melting** techniques by rapidly melting of internal bulk regolith at 1200-2000^{o}C at 1000^{o}C/minute
- **Nanophase iron** in regolith may be used for **ferrofluidic seals** for rotating parts if it can be extracted (TBD)}

Demandite Proportions

- To determine the **proportions that constitute the demandite**, we use a variation on a standard spacecraft model with a dry mass allocation of 100%
- We expect avionics to be constant at 12% across different lunar platforms for power electronics – communications – onboard computing
- Wiring harness is allocated 8%
- We have allocated 25% to tensile structure
- Mechanical actuators and sensors are allocated 5% each for deployables
- Thermal insulation (night) and thermal radiators (day) are allocated 3% each plus 1% for thermal distribution
- Ceramic materials are required for hard structures (3%) and high thermal tolerance (4%) for ISRU applications
- ISRU thermal subsystem is allocated 11%
- Most payloads are dominated by imagers for which we allocate 11% to mirrors and lenses (for thermal applications)
- Electric power system is allocated 20%

Functionality (mass fraction)	Lunar-Derived Material
Tensile structures (25%)	Wrought iron Aluminium
Compressive structures (+50%)	Cast iron Regolith + binder
Elastic structures (trace)	Steel springs/flexures Silicone elastomers
Hard structures (3%)	Alumina
Thermal conductor straps (1%)	Fernico (e.g. kovar) Nickel Aluminum
Thermal radiators (3%)	Aluminium
Thermal insulation (3%)	Glass (SiO_2 fibre) Ceramics such as SiO_2
High thermal tolerance (4%)	Tungsten Alumina
Electrical conduction wire (7%)	Aluminium Fernico (e.g. kovar) Nickel
Electrical insulation (1%)	Glass fibre Ceramics (SiO_2, $Al_2O_3$and TiO_2) Silicone plastics Silicon steel for motors
Active electronics devices (vacuum tubes) (12%)	Kovar Nickel Tungsten Fused silica glass
Magnetic materials for actuators (5%)	Ferrite Silicon steel Permalloy
Sensory transducers (5%)	Resistance wire Quartz Selenium
Optical structures (11%)	Polished nickel/aluminium Fused silica glass lenses
Lubricants (trace)	Silicone oils Water
Power system (20%)	Fresnel lens + thermionic conversion Flywheels
Combustible fuels (+250%)	Oxygen Hydrogen

Lunar Industrial Architecture

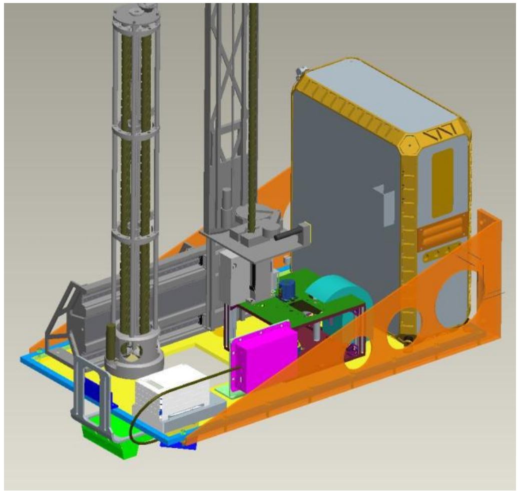


ISRU Technology Demonstrator

- **Resource Prospector** mission (formerly RESOLVE) was a NASA-led mission to demonstrate ISRU on the Moon
- A **72 kg payload** package included scientific instruments to measure a set of experiments based on **stepped heating of regolith**:

  (i) Water ice extraction

  (ii) Oxygen generation through hydrogen reduction of ilmenite-bearing regolith



- **Canada's contribution** was to comprise:

  (i) rover platform

  (ii) coring drill system

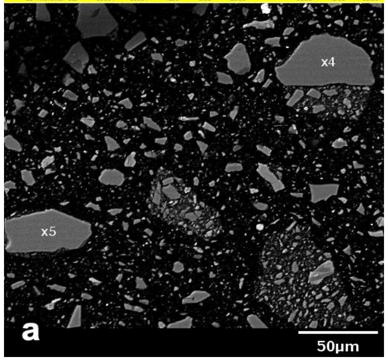
  (iii) a science team
- **Canada pulled out scuppering the entire project** – congratulations, CSA!
- Instruments (but not experiments) are slated to fly on the American-only VIPER…
- Canadian 100 kg **Hephaestus payload** concept as proof-of-concept for lunar manufacturing (RESOLVE on steroids) – Anorthite + HCl leach + FFC electrolysis + 3D Al printer - Raman/LIBS measurements of throughput
- CSA uninterested - Hephaestus slated to the aether….

Physical Pre-Processing - Comminution

- Early stages of physical pre-processing of lunar regolith are **crucial to yield high quality functional materials downstream**

- **Comminution** reduces raw material into single mineral fragments
- **Ball-milling** grinds all regolith into fine particles using grinding balls
- Our ball mill uses steel balls but a lunar-leveraged facility would use either alumina or silumin balls
- Our preliminary ball milling of LHS-1 simulants suggest that 4 h is sufficient to yield single anorthite particles

Pt.	Descrip.	X	Y	Z	Na2O	CaO	K2O	Al2O3	SiO2	Total
10	180-Anorthite-4	4936	13775	4150	2.23	16.55	0.06	32.95	48.12	99.91
11	180-Anorthite-5	4718	13643	4150	2.51	16.21	0.07	32.68	47.83	99.29
12	Anorthite - std	39004	33064	4150	0.01	20.55	-	36.38	43.00	99.93



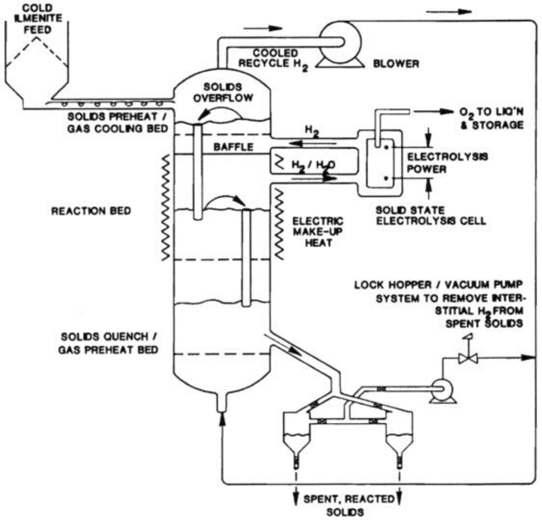
- **Ball milling is essential for the preparation of sintered material** for subsequent processing stages, e.g. sintered metal oxide cathodes for FFC electrolysis

Physical Pre-Processing - Beneficiation

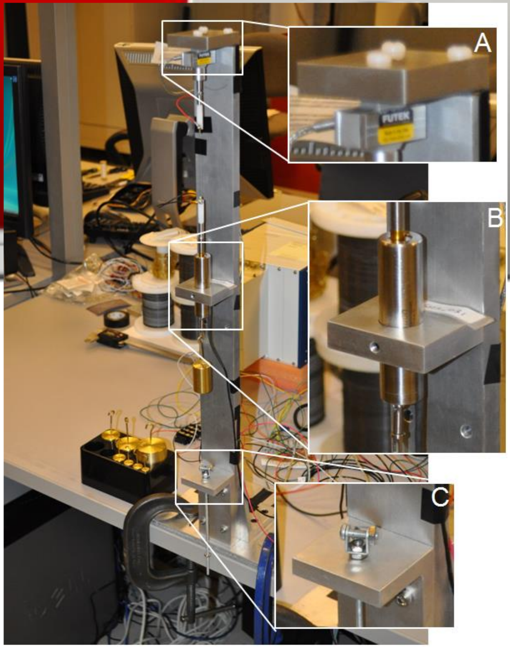
- Beneficiation separates different mineral fragments to ensure recovery of desired phases
- Beneficiation generates the most tailings and so minimises downstream energy consumption on processing waste
- There are several methods of beneficiation but many are not suited to lunar application, e.g. froth flotation
- **Two types of beneficiation** are necessary:
- **Magnetic beneficiation** involves separating out magnetic iron fraction – we used simple magnetic separation of a magnetic fraction from LHS-1 simulant
- More sophisticated magnetic separation would be superior to yield purer anorthite with <0.1% contaminants for high quality materials
- We have yet to investigate **electrostatic separation methods** which may be applied to non-magnetic phases, e.g. pyroxene from anorthite
- Comminution and beneficiation will be crucial to ensure downstream processing quality

Iron Metallurgy on the Moon

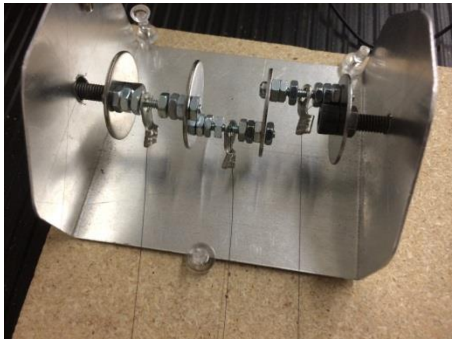
- **Hydrogen reduction of ilmenite** at ~1000°C creates oxygen, iron and rutile
  $FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$ and $2H_2O \rightarrow 2H_2 + O_2$
- Fe separated from TiO_2 by liquation at 1600°C
- **Wrought iron** is tough & malleable for tensile structures
- **Cast iron** (~2-4% **C** + 1-2% **Si**) is more brittle for compressive structures (e.g. Iron Bridge for 200+y)
- **Tool steel** (<2% **C** + 9-18% **W**) for cutting tools, e.g. milling head (substitutable with **silumin**)
- **Invar** (64% Fe, 36% Ni) and **inovco** (62.5% Fe,33% Ni,4.5% Co) for high precision mechanisms with low CTE
- **Silicon (electrical) steel/ferrite** (up to 3% **Si** and 97% Fe) for electromagnets and motor cores - 3% Si increases electrical resistivity by 4 x
- **Kovar** (53.5% Fe, 29% **Ni**, 17% **Co**, 0.3% Mn, 0.2% **Si** and <0.01% **C -** Mn reduces brittleness) – fernico alloy for high temperature electrical/thermal conductors
- **Cryogenic** fernico (to -180°C) trades more (31%) Ni for less (15%) Co
- **Permalloy** (20% Fe + 80% **Ni**) provides magnetic shielding with μ_r~10^5 H/m (replace 5% Ni with Mo gives supermalloy with μ_r~10^6 H/m) for electron guns

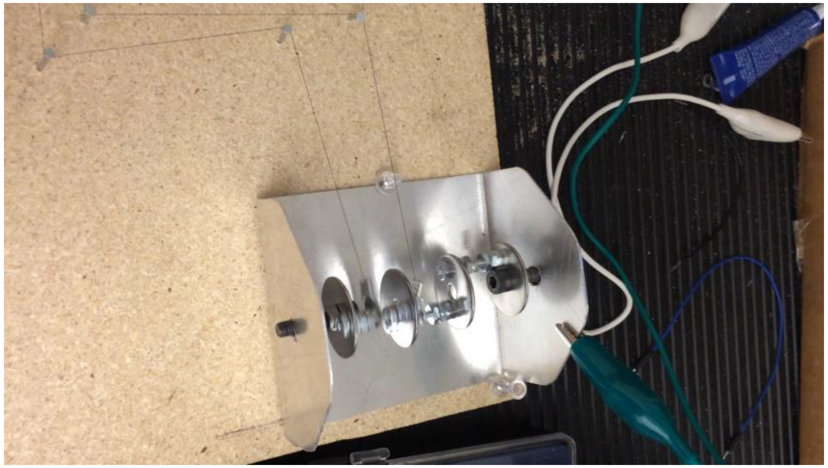


Shape Memory Alloys



- **Rutile** (TiO_2) may be reduced to >99% Ti metal using FFC electrochemistry - Ti has superior strength-to-weight ratios
- **Ti6Al4V** alloy - V is omitted in medical applications
- **NiTi** (50:50) alloy is shape memory alloy for solar sails
- We performed experiments in continuous PID control of NiTi wires for solar solar applications
- The use of NiTi wires as linear actuators (artificial muscles)





- It worked with good torque output but:
  - (i) thermal inertia limits cycling to ~1 Hz
  - (ii) 5% strain yields short stroke and compaction problems

Tunicose Ores from Meteoritic Sources

- We need to source Tungsten, Nickel and Cobalt for our alloy range
- **Asteroidal NiFe** resources are expected to be located at shallow-angle impact craters
- Some 25% lunar impactor material survives impact at or near surface of crater (670 crater >10 km diameter)
- **Mascons may** indicate location of **NiFe** meteorite ore concentrations, e.g. northern rim of SPA crater
- M-type asteroid-derived meteoritic NiFe dominated by kamacite/taenite (**88% Fe/10%** Ni alloys) - typically **contaminated with 0.5% Co**
- Ni and Co have similar electrical conductivities
- Ni and Co are common catalysts and alloying material – Ni for heat tolerance and Co for corrosion-resistance in steels
- Special alloys, e.g. **AlNiCo** permanent magnets
- NiFe alloys **enriched in W microparticle inclusions** which can be crushed and separated out through several processes (W has high density of 19.3 and high melting temperature of 3422^{o}C)

Extraction of NiCo

- This is applicable to all M-type asteroid resources
- Carbonyl (Mond) volatilises powdered NiFeCo alloy into transition metal carbonyls $M_x(CO)_y$
- This yields 99.99% purity elemental metal with Fe, Ni and Co separated by **fractional distillation**

Physical Conditions (LHS)	Carbonyl Process	Physical Conditions (RHS)
175-230°C and 60 bar	$Ni + 4CO \leftrightarrow Ni(CO)_4$	50-60°C
200°C	$Fe + 5CO \leftrightarrow Fe(CO)_5$	105°C and 100-300 bar
80-120°C and 95-110 bar	$2Co + 8CO \leftrightarrow Co_2(CO)_8$	55°C and 35 bar

- Carbonyls decompose thermally into high purity metals using S catalyst
- **S** catalyst recovered at 750-1100°C from troilite (**FeS**) in <u>meteoritic inclusions</u>, lunar regolith (~1%), or lunar volatiles (SO_2 and H_2S gases)

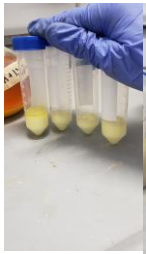
$4FeS + 7O_2 \rightarrow 2Fe_2O_3 + 4SO_2$ and $SO_2 + H_2S \rightarrow 3S + H_2O$

- Carbonyl process is suited to low-temperature **CVD** of Fe, Ni and Co coatings

Lunar Anorthite

- Plagioclase feldspar **anorthite** ($CaAl_2Si_2O_8$) comprises >80% of lunar anorthosite in the highlands – aluminium enrichment is around 33% by mass
- **HCl leaching** is a two-part process (artificial weathering):

(i) HCl gas erosion of anorthite at 160°C is followed by **precipitation of silica** from silicic acid: $CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2SiO_2$




$AlCl_3.6H_2O$ is precipitated and crystallised

Cl and H_2O are removed by heating at 400°C to **recycle HCl**

(iii) Roasting $AlCl_3$ at 900°C maximum for 90 minutes yields **Al_2O_3**

$$2AlCl_3.6H_2O \rightarrow Al_2O_3 + 6HCl + 9H_2O$$


- **Lunar orthoclase** may be similarly treated with HCl to yield silica and kaolinite clay – <u>kaolinite is the basis of porcelain</u>:

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

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

Lunar Ceramics

- **Refractoriness** and chemical inertness of ceramics are ideal for reactor crucibles for melting metals, e.g. Al_2O_3
- **Hardness** of ceramics offer tooling applications (including drilling)
- Both alumina and silica are refractory ceramics used in thermal applications
- Al_2O_3 physical properties are second only to diamond
- **Cermet** may comprise Al_2O_3 or MgO in a Ni binder for high strength with high temperature tolerance
- High melting points and brittleness of ceramics render casting, machining and sintering difficult
- **Ceramic particles** may be SiO_2, Al_2O_3, $CaSiO_3$, MgO, kaolin, etc
- Ceramics are typically processed as ceramic particles in a polymer binder – 30-50% ceramic particles in liquid polymer to be deposited and thermally sintered at 900-1300^{o}C – **not viable**
- **Direct thermal sintering** of ceramic particles such as Al_2O_3 may be achieved through Fresnel lens solar concentrators for high compressive strength and high temperature tolerance to 1800^{o}C
- Glass fibres incorporated into ceramic matrices compensate for brittleness - **unclear**

Lunar Glasses

- Regolith – basalt – aluminosilicate – formed into glass at 1300°C
- Lunar glass is contaminated with Fe so suitable only for non-optical applications, e.g. glass fibre/cloth for thermal/electrical insulation of electrical wiring
- Porcelain from fired kaolinite may be adopted for electrical insulation of junctions
- This is **knob-and-tube** technology for electrical distribution
- Na is scarce on the Moon so soda glass is not feasible
- **Fused silica glass** (derived from anorthite) formed at 1600°C is transparent material – resistant to chemicals, mechanical stresses and temperatures up to 1000°C – suitable for **Fresnel lenses**
- **Optical fibres require internal reflection**

  - internal gradation of refractive index between core/cladding of glass/plastic

  - metal cladding of Ni or Co around silica core offers high temperature tolerance
- **Embedded active optics** - not feasible for 1st generation ISRU

  - chalcogenide glasses containing S allows fibre to act as resonating cavity

  - doping of silica with rare earth element erbium provides light amplification

The Plastics Question

- Carbon is relatively scarce on the Moon so should be husbanded
- We may adopt **silicone plastics/oils** with multiple advantages over hydrocarbon plastics
  - (i) Si-O backbone **minimises C resource consumption**
  - (ii) UV radiation resistant
  - (iii) high operational temperature tolerance (350ºC c.f. 120ºC)
  - (iv) it is used only sparingly for flexible **wire sheathing**
- From syngas to polydimethylsiloxane **(PDMS) – simplest siloxane** (Rochow process)
- Silicones (and other plastics) should be avoided:
  - Rigid plastics may be substituted with ceramics
  - Plastic elastomers may be substituted with metal springs (except where electrical insulation is required)
  - Glass cloth and porcelain may be used as flexible/rigid electrical insulation (as in knob-and-tube technology)
  - Wire coil insulation in motors is typically enamel (fused powdered glass)
  - Silicone oils may potentially be substituted with dry lubricant such as talc, a clay derived from the pyroxene enstatite

Lunar Industrial Ecology

Industrial Ecology

- We have the backbone of a complete **<u>industrial ecology</u>**
- We have two objectives - near-100% supply from in-situ resources
  - near-100% closed cycle industrial ecology
- **IPAT equation** quantifies environmental **impact to be minimised**: I=PAT where P=population of industrial products produced, A=material consumed per product, T=waste per resource unit consumed
- **Sustainable manufacture** is built on two pillars:
  - (i) <u>dematerialisation</u> through minimisation of material consumption A
  - (ii) <u>detoxification</u> of waste T through waste recycling
- **Industrial ecology**
  - (i) material multifunctionality through reuse
  - (ii) minimises waste by converting it into resource through recycling loops – <u>recycling is fundamental to sustainability</u>
- Industrial ecology has a **bowtie architecture** similar to biological metabolism
- This is a pathway to lunar industrialisation….

Lunar Industrial Ecology

Lunar Ilmenite

$Fe^0 + H_2O \rightarrow$ ferrofluidic sealing
$FeTiO_3 + H_2 \rightarrow \mathbf{TiO_2} + H_2O + \mathbf{Fe}$
$2H_2O \rightarrow 2H_2 + O_2$
$2Fe + 1.5O_2 \rightarrow Fe_2O_3/Fe_2O_3.CoO$ - ferrite magnets

Nickel-iron meteorites

$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175°C/100 bar) $\rightarrow$
$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55°C/1 bar) $\rightarrow$
$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150°C/35 bar) $\rightarrow$

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

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

W inclusions – high density of 19.3 $\rightarrow$ cathodic material

Olivine

$Mg_2SiO_4 + 2CH_4 \rightarrow 2CO + H_2 + \mathbf{2MgO} + Si$ at 2000°C $\rightarrow$ 3D Shaping binder
$MgO + HCl \rightarrow MgCl_2 + H_2O$ $\rightarrow$ 3D Shaping binder
$CO + 0.5\ O_2 \rightarrow CO_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300°C (Sabatier reaction) $\rightarrow CH_4 \rightarrow C + 2H_2$ at 1400°C for steel
Ni catalyst

Lunar Anorthite

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

Lunar Volatiles

$CH_4 + H_2 \xrightarrow{850°C} CO + 3H_2 \xrightarrow{250°C} CH_3OH$
Ni catalyst Al_2O_3
$CH_3OH + HCl \xrightarrow{350°C} CH_3Cl + H_2O$
Al_2O_3
$CH_3Cl + Si \xrightarrow{370°C} (CH_3)_2SiCl_2 \xrightarrow{+nH_2O} ((CH_3)_2SiO)_n + 2nHCl \rightarrow$ silicone plastics/oils

$3NO + H_2O \rightarrow 2HNO_3 + NO$
$2SO_2 + O_2 \leftrightarrow 2SO_3$ (low temp)
$SO_3 + H_2O \rightarrow H_2SO_4$

Salt of the Earth

$NaCl + CaCO_3 \rightarrow Na_2CO_3 + CaCl_2$ $\rightarrow$ metalysis electrolyte
350°C/150 bar
$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2 \rightarrow$ piezoelectric quartz
$NaCl + HNO_3 \rightarrow HCl + NaNO_3$

Lunar Orthoclase

$2KAlSi_3O_8 + HCl + 9H_2O \rightarrow H_4Al_2Si_2O_9 + 2KCl + SiO_2 + H_2O$
Kaolinite $KCl + NaNO_3 \rightarrow NaCl + KNO_3$

Lunar Industrial Ecology - 1

Ilmenite

$Fe^0 + H_2O$ → ferrofluidic sealing

$FeTiO_3 + H_2 \rightarrow \mathbf{TiO_2} + H_2O + Fe$ and $2H_2O \rightarrow 2H_2 + O_2$

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

$3Fe_2O_3 + H_2 \leftrightarrow Fe_3O_4 + H_2O$) → magnetite at 350-750ºC/1-2 kbar

M-type Asteroids

$4Fe_2O_3 + Fe \leftrightarrow 3Fe_3O_4$)

W inclusions → thermionic cathodic material

Carbonyl process:

$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175ºC/100 bar)

$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55ºC/1 bar)

$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150ºC/35 bar)

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

S catalyst

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

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 $Na_2SeO_3 + H_2SO_4 \rightarrow Na_2O + H_2SO_4 + Se$ → photosensitive Se

$Na_2O + H_2O \rightarrow 2NaOH$

$NaOH + HCl \rightarrow NaCl + H_2O$ (recycle)

Orthoclase

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

orthoclase illite silicic acid (soluble silica → $\mathbf{SiO_2} + H_2O$)

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

kaolinite $KCl + NaNO_3 \rightarrow NaCl + KNO_3$ (recycled)

Anorthite

$CaAl_2SiO_8 + 4C \rightarrow CO + \mathbf{CaO} + \mathbf{Al_2O_3} + 2Si$ 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 → $2Al + Fe_2O_3$ → $2Fe + Al_2O_3$ (thermite)

→ AlNiCo hard magnets

Olivine

$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3\mathbf{SiO_2} + 2H_2O$

fayalite magnetite

$Mg_2SiO_4 + 4H_2O \rightarrow \mathbf{2MgO} + \mathbf{SiO_2} + 4H_2O$ → 3D Shaping binder (Sorel cement)

forsterite $MgO + HCl \rightarrow MgCl_2 + H_2O$ → 3D Shaping binder (Sorel cement)

Lunar Industrial Ecology - 2

Pyroxene

$Ca(Fe,Al)Si_2O_6 + HCl + H_2O \rightarrow Ca_{0.33}(Al)_2(Si_4O_{10})(OH)_2.nH_2O + H_4SiO_4 + CaCl_2 + Fe(OH)_3$

augite — montmorillonite — silicic acid — iron hydroxide

$6MgSiO_3 + H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + Mg_3Si_4O_{10}(OH)_2$ → dry lubricant talc

enstatite — serpentine — talc

C-type Volatiles

$CO + 0.5\ O_2 \rightarrow CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300ºC (Sabatier reaction) $\rightarrow CH_4 \rightarrow C + 2H_2$ at 1400ºC → steel additive/anode regeneration

Ni catalyst

850ºC 250ºC

$CH_4 + H_2 \rightarrow CO + 3H_2 \rightarrow CH_3OH$ 350ºC

Ni catalyst Al$_2$O$_3$ catalyst $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ 370ºC +nH$_2$O (Rochow process)

Al$_2$O$_3$ catalyst $CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2 \rightarrow ((CH_3)_2SiO)_n + 2nHCl$ → silicone plastics/oils

$N_2 + 3H_2 \rightarrow 2NH_3$ (Haber-Bosch process) ↑_______________________________________|

Fe on CaO+SiO$_2$+Al$_2$O$_3$ catalyst

$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

WC on Ni catalyst

$3NO + H_2O \rightarrow 2HNO_3 + NO$ (Ostwald process)

↑_______________|

$2SO_2 + O_2 \leftrightarrow 2SO_3$ (low temp)

$SO_3 + H_2O \rightarrow H_2SO_4$

C-type Salts

$2NaCl + CaCO_3 \leftrightarrow Na_2CO_3 + CaCl_2$ (Solvay process) → FFC electrolyte

350ºC/150 MPa

$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2$ → piezoelectric quartz (40-80 day growth)

1000-1100ºC

$CaCO_3 \rightarrow$ **CaO** $+ CO_2$ (calcination)

$NaCl(s) + HNO_3(g) \rightarrow HCl(g) + NaNO_3(s)$ → recycled acid leach

Flexible Chemical Systems

- Flexible manufacturing systems balances flexibility with efficiency of throughput with reconfigurability for adaptation to demand
- **FMS principle may be applied to the lunar industrial ecology** to adapt to different products
- There are several **biomimetic approaches** we can adopt to provide adaptability
- **Simplest is a bistable control of metabolic reactions**:
- Monod-Jacob operon model of gene regulation involves **two operators** – <u>inducer</u> and <u>repressor</u>, (e.g. lac operon of *E coli*) with **two states (bistable)**
- (i) <u>inducer</u> binds to repressor → repression prevented → <u>protein produced</u>
- (ii) <u>no inducer</u> binding to repressor → repressor activated → <u>no protein produced</u>
- A **more sophisticated model** is the Hill extension of Michaelis-Menton reaction kinetics determined by balance of anabolism and catabolism:

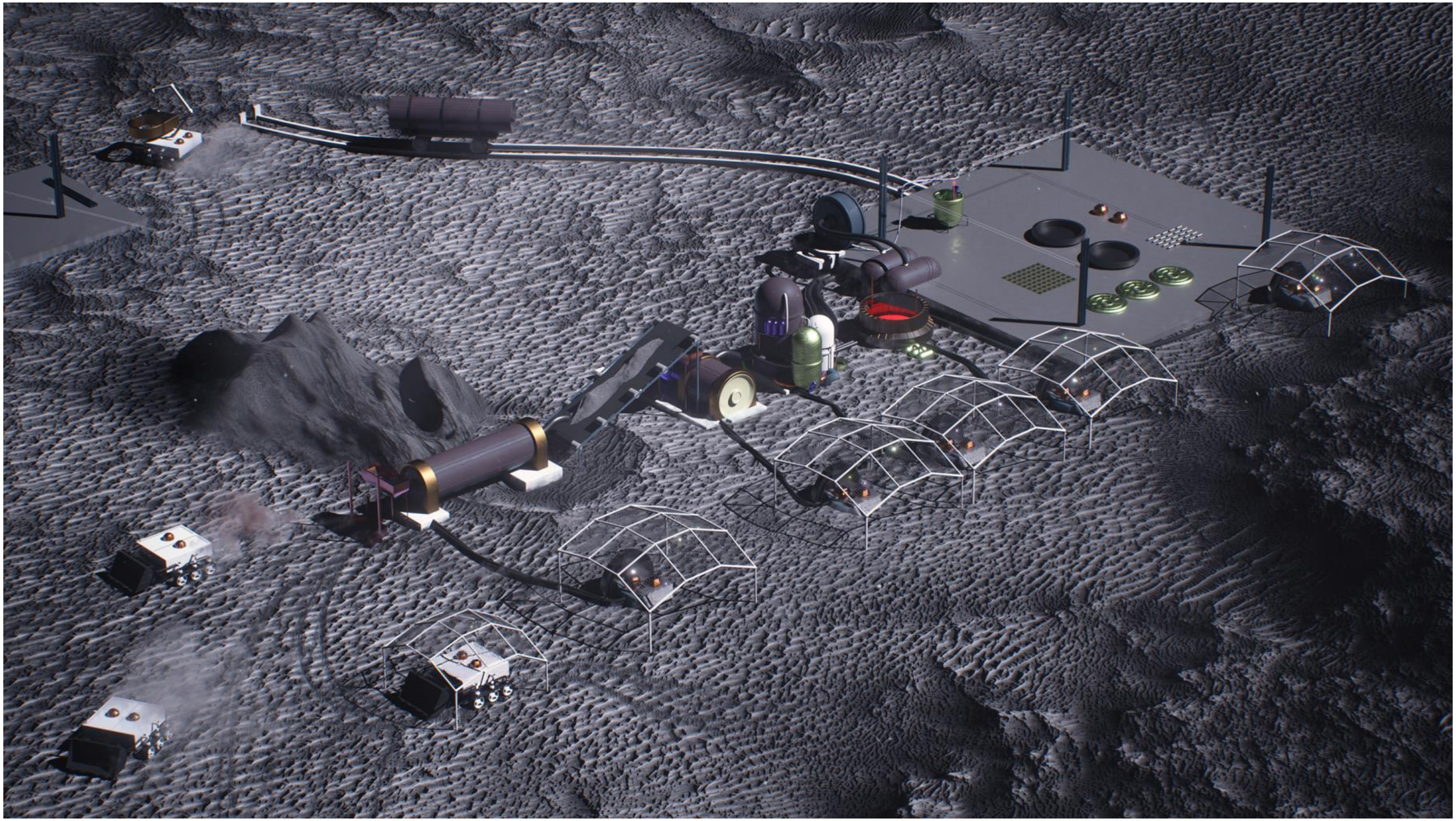
$$\frac{d[a]}{dt} = [a]_{max}\left(k_0 + \frac{[a]^n}{K+[a]^n}\right) - k[a]$$

- This sigmoidal function (shape determined by K and n) implements bistability through a threshold of inducer concentration [a]
- This implements logical rule "If ~INDUCER and REPRESSOR then OPERON"

Genetic Regulatory Networks

- We can increase complexity of metabolic responses through additional states, e.g. zinc fingers act as molecular switches for **graded regulation with four states**:
- gene switched <u>ON at basal rate</u> only (default)
- repressor binding switches gene <u>OFF</u>
- activator binding switches gene <u>ON at higher rate</u>
- enhancer binding to activator switches gene <u>ON at highest rate</u>
- GRN constitute **networks of interacting regulatory proteins** that control gene expression **in response to complex metabolic conditions**
- GRN logic of **bacteriophage λ lysis-lysogeny circuit** is given by complex metabolic conditions yielding two states:
- IF [C1]>θ OR (X AND Y) → lysogeny
- IF Y NAND [C2] → lysis
- GRN form **complex circuits with feedback/feedforward signals**
- We can apply simplified network models to the **lunar industrial ecology**

Lunar Industrial Architecture

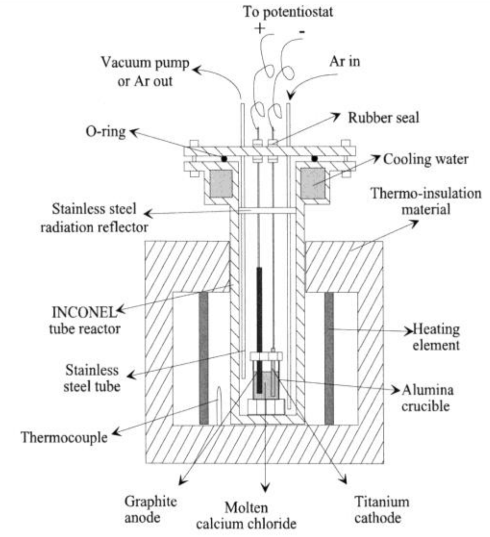


FFC (Molten Salt Electrolysis) Process

- Our lunar industrial ecology yields a set of **metal oxides**
- **FFC (molten salt electrolysis) process** is a generic **solid state technique** that can reduce **any metal oxide to >99% pure metal** – it does not require melting (only the electrolyte is molten) so it is energy efficient
- Electrolytic reduction vs thermochemical reduction
  - (i) higher product yields
  - (ii) reduced impurities
- **Sintered solid metal oxide cathode** in **$CaCl_2$ electrolyte** at 900-1100^{o}C undergoes **solid state reaction**

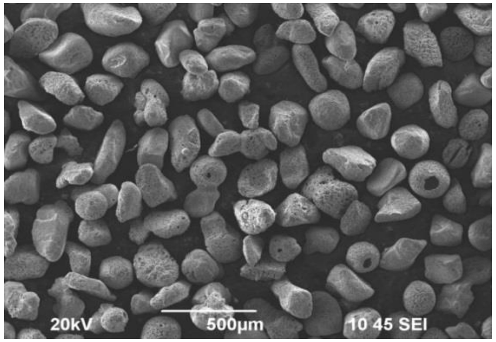
  $MO_x + xCa \rightarrow M + xCaO \rightarrow M + xCa + \frac{1}{2}xO_2$
- O_2 evolved at inert anode (assumed non-eroding)
- **O_2 stored** for human consumption or propellant oxidiser
- Anorthite processing with HCl yields **$CaCl_2$ electrolyte** replenishment:

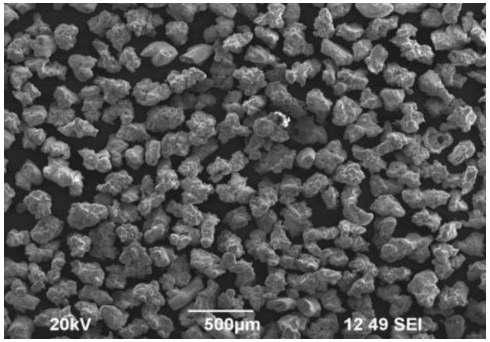
$CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2SiO_2$

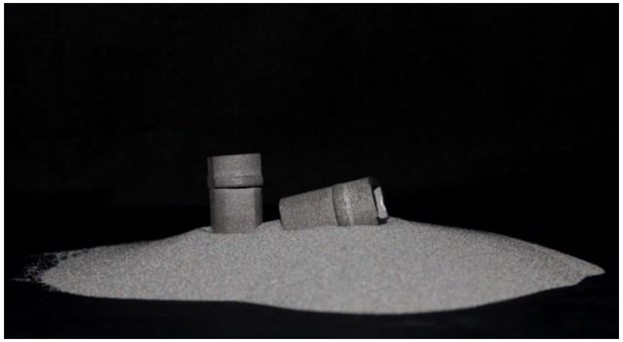


FFC Process = Universal Chemical Processor

- There are several options for inert anodes but graphite anode is usually adopted – this yields **CO/CO_2** which must be recycled through the **Sabatier process** followed by thermal cracking to reconstitute graphite
- Product is >**99% metal alloy sponge** that can be crushed into powder for powder metallurgy or 3D printing – **SLS printing has been demonstrated** with Ti test parts







TiO_2 powder → Ti powder → 3D printed Ti parts

- FFC process requires **97% thermal heating and 3% electrolytic energy**
- Thermal heating may be implemented directly by solar concentrators <100% (though there exists the problem of diffusing solar energy into electrolyte)
- Electrical energy may be supplied by thermionic conversion with ~30% efficiency

Direct Reduction of Raw Minerals into Mongrel Alloys

- (A) Reduce lunar **ilmenite ($FeTiO_3$)** from maria regions to **FeTi alloy**:
  - (i) General purpose structure
  - (ii) ~~Ferrotitanium (45-75% Ti) alloy for oxidant mop-up purification~~
  - (iii) **Solid rocket fuel** powder with O_2
- (B) Reduce lunar **anorthite ($CaAl2Si_2O_3$)** from highland regions to **AlCaSi alloy**:
  - (i) General purpose structure
  - (ii) ~~**Silumin (3-25% Si**) alloy for high durability (Ca removal required)~~
- (C) Reduce lunar **olivine (Mg_2SiO_4)** from crater regions to **Mg_2Si alloy**
  - (i) General purpose structure
  - (ii) Small amounts of **Mg_2Si** additive to Al produces high strength Al alloy (e.g. Al 6061)
- Properties and applications of mongrel alloys require investigation
- Versatility of FFC process in the reduction of pure metal oxides suggests pre-processing through lunar industrial ecology to provide alloy controllability

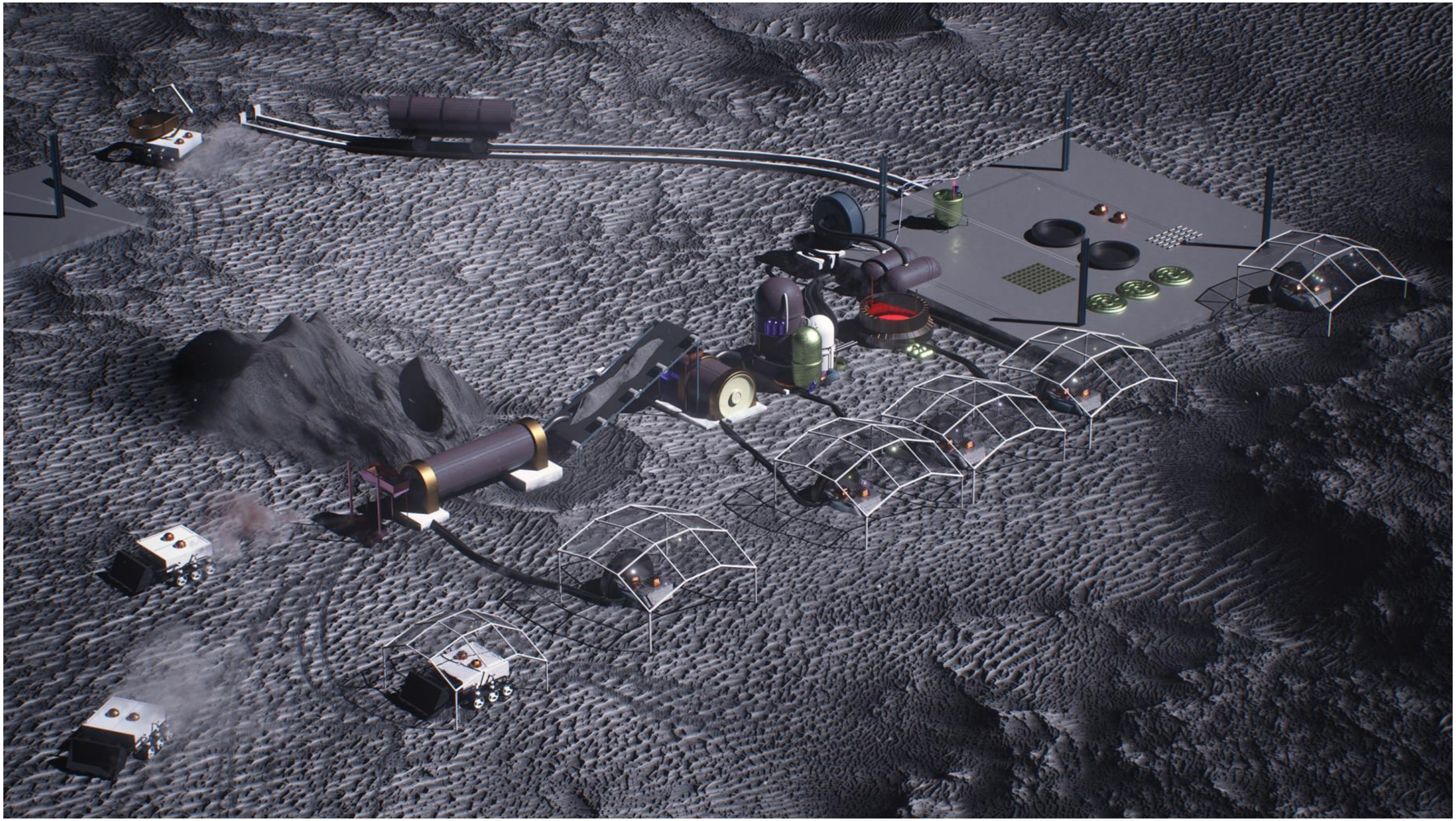
Multifunctional Aluminium

- Alumina may be reduced directly to >99% Al metal through **FFC process**
- **Aluminium is a multifunctional metal** – its versatility suggests that it should be a **high priority target**:
  - - good thermal conductor at low temperature below 520°C
  - - good thermal radiator for thermal louvres/radiators
  - - good electrical conductor (pylon-mounted electrical cables)
  - - lightweight structural metal ideal for spacecraft structures
  - - Al powder combusted with Fe_2O_3 acts as thermite weld
- Al 1000 series is essentially pure Al for universal applications
- Al 6061 comprises 97.9% Al – **1% Si – 0.7% Mg** – ~~0.25% Cu – 0.2% Cr~~
- ~~Al 7075 reliance on 5.6% Zn eliminates it as a candidate Al alloy including foil~~
- Al 8176 comprises 99.3% Al – 0.6% Fe – 0.1% Si for electrical wire
- AlNiCo permanent magnets constitutes 8-12% Al – 14-25% Ni – 5-38% Co – ~~3-4% Cu~~ – 0-8% Ti, rest is Fe)
- Silumin 87Al13Si (e.g. Al 4006 - 98.3% Al – 1% Si – 0.65% Fe) for hardened high wear applications)

Carleton UNIVERSITY

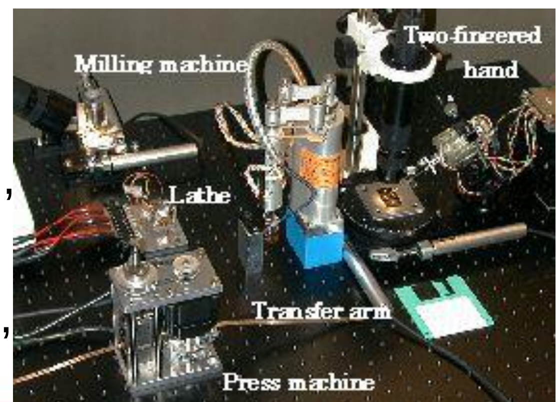
Manufacturing & Assembly

Lunar Industrial Architecture



Manufacturing & Assembly

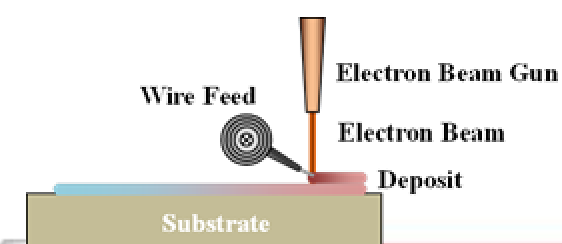
- Manufacturing converts **feedstock into parts and components**
- There are many manufacturing machines for fashioning objects – casting, moulding, lathe, milling station, drill press, bending press, laser cutter, electric discharge machining, etc (e.g. FabLab)
- There are many joining operations including parts assembly, friction stir welding, wire winder, etc
- Almost all such processes may be integrated into a cartesian robot configuration – the 3 or 5 DOF **CNC machine**
- **Subtractive manufacturing methods waste ~90% materia**
- Additive manufacturing (3D printing) builds parts and components layer-by-layer without wastage
- There are many 3D printing technologies – FDM, SLA, LOM, SLS/M, EBAM, BJ, etc
- Almost anything can be 3D – engineering materials, cement, organs, food, etc

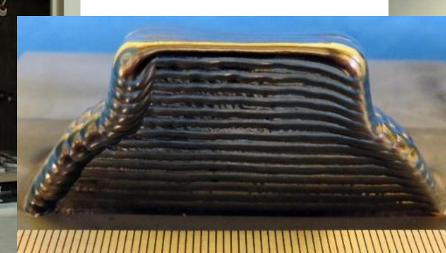


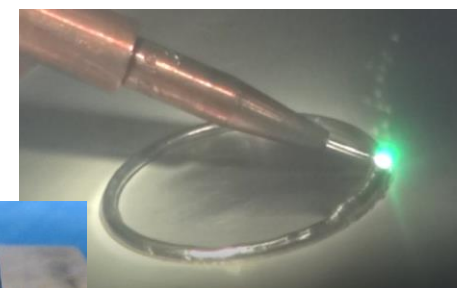
Generalised 3D Printing Suite

- 3D printing is a versatile manufacturing method for constructing 3D structures
- All 3D printers = XY printing head on Z deposition table = **cartesian robots**
- We focus on two technologies – **selective solar sintering** and **EBAM**
- **Selective solar sintering** uses solar concentrators for generating thermal energy
- We have a 2m x 2m diameter Fresnel lens capable of generating up to ~1500^{o}C spot temperature

- Quartz rod → fibre-optic cabling → **selective solar sinterer**
- **EBAM** is **electron gun** (high voltage **vacuum tube**) but restricted to metals
- Wire-fed EBAM (NRC) can print Al alloy amongst other metals





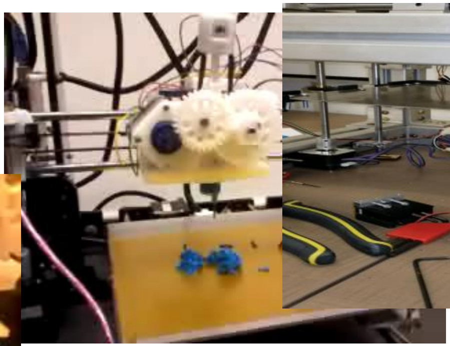


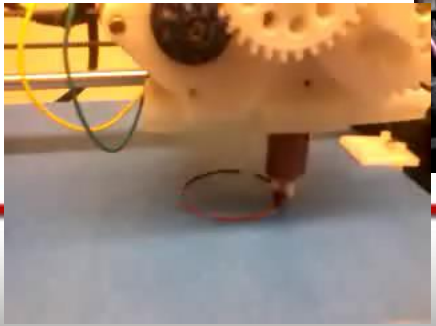
Multi-Material 3D Printer

- We are building rigid multi-material 3D printer to print in metals and plastics
- Solar furnace based on 1.2 m x 0.9 m **Fresnel lens** for melting Al alloy in ceramic crucible → 3D printing by **Fresnel lenses**
- We have deposited molten Al wire tracks onto silicone plastic insulation: **Al alloy (440ºC m. p.) ↔ silicone (350ºC op temp)**
- We have demonstrated metal deposition on plastic!

- Two heads being added – fibre optic and silicone plastic extrusion head
- Phase 2 - 3rd milling head for integrated surface finishing
- Phase 3 – 4th wrist assembly head for component assembly
- Phase 4 – Migrate to steels/silicone-derived ceramics

  $SiO_xC_y + (1\text{-}x+2y)O_2 \rightarrow SiO_2 + yCO_2$
- Initially, we shall **3D print passive electronic circuitry**





Self-Replication Technology

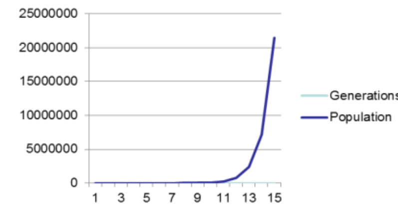
Self-Replication on the Moon

- In 1979, NASA commissioned a study "Advanced Automation for Space Missions" to analyse the concept of a self-replicating lunar factory using in-situ resources
- It concluded that a self-replicating factory on the Moon was feasible but required significant new technology to be developed - it was ignored
- **Johns Hopkins** University focussed on architectures on the Moon based on prefabricated parts
- **Columbia University** focussed on modular self-assembly
- **NASA Kennedy** advocated retroactive partial self-replication after lunar infrastructure established
- My interest is in exploiting self-replication on the Moon exploiting in-situ resources with <u>full self-replication at t_0</u> to leverage low cost
- We need to <u>build from the ground up</u> <u>an engineered version of the origin life</u> (**lunar photolithoautotroph**)

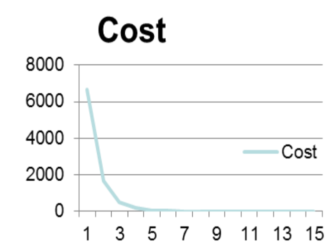
Power of Self-Replication

- **Self-replication** is the ONLY robust approach to space exploration
- **Self-replication** offers **exponential** growth in productive capacity

  P= $(1 + r)^i$ where r>1
- This is a cellular approach in which each cell is an identical factory
- Consider launch of a single 10 tonne self-replicating factory to the Moon at a cost of $7.5 B



Number of offspring per generation	Number of generations	Population	Specific Cost ($/kg)
1	10	1024	$732/kg
2	7	2187	$343/kg
2	13	1,594,323	$0.47/kg



- Cumulative population is >**1.5 x 10^6 within 13 generations**
- Initial capital cost of $7.5 B is amortised over an exponentially increasing productive capacity
- For r=2 over 13 generations, specific cost to the Moon has dropped from $750,000/kg to **<50 cent/kg** of productive capacity
- If each 10-tonne factory takes 6 months to build, we have >1.5 million factories in 6.5 years
- We have exponentially constructed mass parallel production facilities
- If each of the10^6 factories produces 10^3 products, we have10^9 production units
- **SELF-REPLICATION EFFECTIVELY SIDESTEPS LAUNCH COSTS**

Self-Replication imposes Closure Constraints

- SR must be supplied with the appropriate resources to self-replicate: matter+energy+information
- The most important constraints are closure conditions:

(a) Material and parts closure – each component has a portfolio of materials, processes and machines required for its manufacture – to close the matter loop by:

(i) Restricting raw material inventory to minimise mining and chemical processing cost, e.g. demandite list, industrial ecology, FFC process

(ii) Restricting parts inventory to minimise manufacturing and assembly cost, e.g. 3D printing

(b) Energy closure – energy generation must exceed energy cost (energy return on investment (EROI)) – to close the energy loop by:

(i) Maximise use of direct environmental energy, e.g. thermal energy for chemical processing

(ii) Maximising electrical energy conversion efficiency, e.g. PETE >30%

(iii) Minimise energy wasted in processing waste by eliminating waste, e.g. industrial ecology

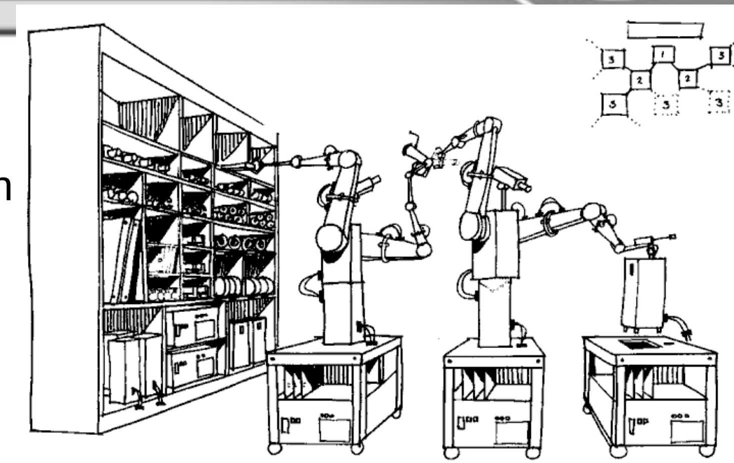
(iv) Restrict all physical processes to minimise energy consumption, e.g. FFC process, 3D printing

- **(c) Information closure** – information required for specification does not exceed capacity to store/process specification - to close the information loop by:

(i) Maximise parts re-use (exaptation) to minimise information specification, e.g. electric motors co-opted for energy storage as flywheels and vacuum tubes co-opted for energy conversion

(ii) Maximise information compression substituting CAD coordinates with growth algorithms

Universal Constructor ⊃ Self Replicator

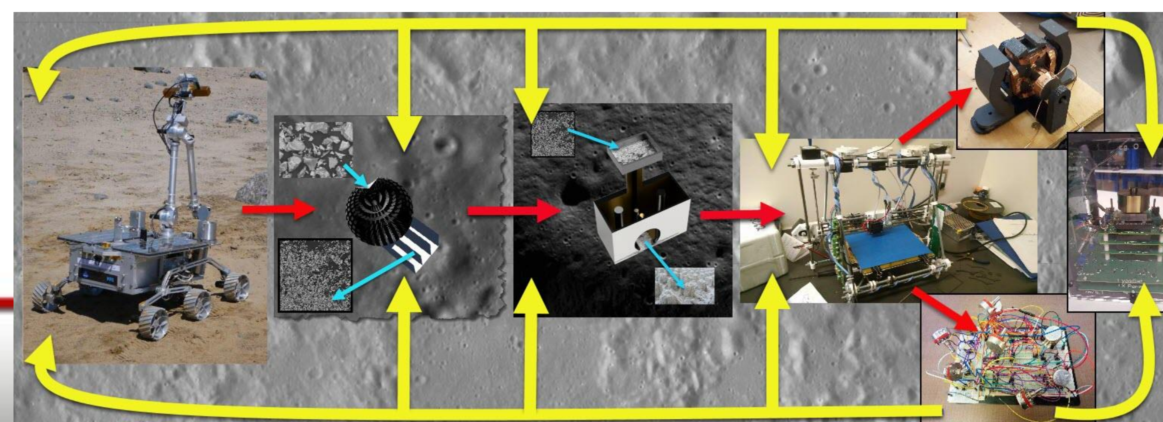


- John von Neumann – a sufficient (but not necessary) condition for self-replication is universal construction
- **Universal constructor is a kinematic machine** that can manufacture any other machine *including a copy of itself*
- UC is generalisation of the universal Turing machine
- UC is idealised as a programmable "generalised" kinematic arm in a sea of parts (structured environment)
- We adapt UC to unstructured environments through a suite of **kinematic machines**: (i) load-haul-dumpers and drills as mining robots; (ii) programmable pumps for driving unit chemical processors; (iii) mills, lathes and 3D printers for autonomous manufacture; (iv) manipulators for robotic assembly
- **Kinematic machines** are specific kinematic configurations of **electric motors**
- **Sensorimotor control** system:

  - motors

  - computational electronics

  - sensors



Kinematic Machines = Robots

- **Hypothesis**: 3D printer suite constitutes a **Universal Constructor** as a generalized kinematic machine that can construct any other kinematic machine
- **Corollary**: Motor system – <u>actuators, control electronics and sensors</u> - is **core of all kinematic machines**:
  - (i) replace 3D printer head with **3 DOF wrist** for parts assembly
  - (ii) construction of **FabLab** manufacturing tools (CNC machines)
  - (iii) actuators for **pumps and stirrers** for driving unit chemical processes
  - (iv) **comminution** with crusher jaws, grinders and centrifugal ball mills
  - (v) ball milling and hot isostatic presses for **surface finishing**
  - (vi) reconfigurable serial **manipulators** with end-effectors for general purpose manipulation and assembly
  - (vii) rover **mobility** systems for surveying, excavating, trenching, paving, bulldozing, etc
- <u>**All machines of production are kinematic machines**</u>

<u>**Any kinematic machine is a specific configuration of motors**</u>

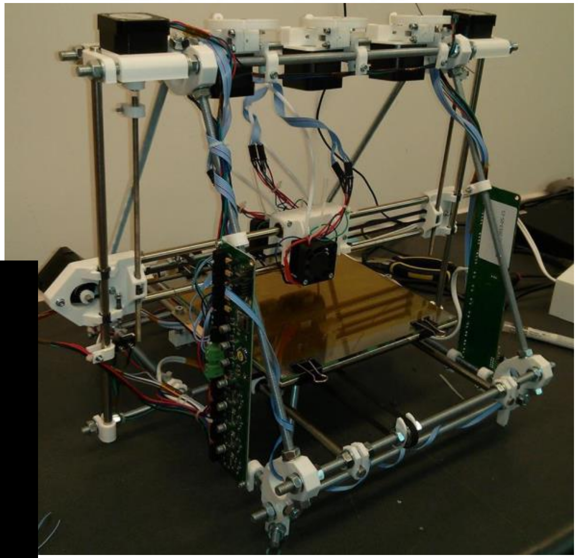
3D Printing = Universal Construction Mechanism

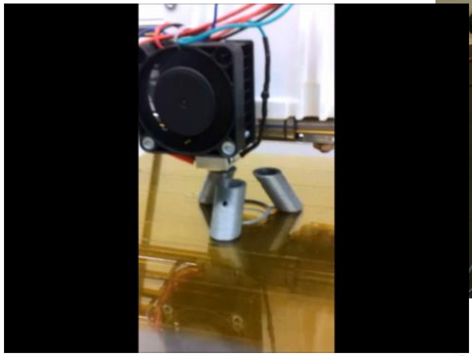
- **RepRap** FDM 3D printer can print many of its own **plastic parts**

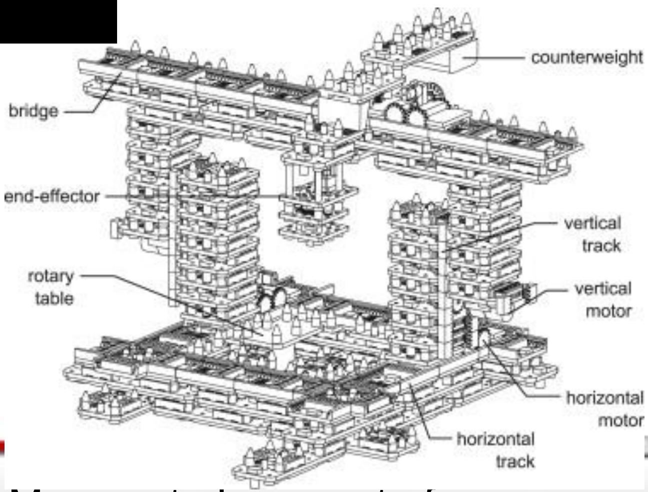
- Full self-replication requires 3D printing:
  (i) structural metal bars and components (SLS/M or EBAM)
  (ii) joinery (replaced with cement/adhesive)
  (iii) **<u>electric motor drives</u>**
  (iv) **<u>electronics</u>** boards
  (v) **<u>computer hardware/software</u>**

- Full self-replication also requires:
  (i) <u>self-assembly</u> (proxy for manipulator motors)
  (ii) <u>self-power</u> (solar-thermionic/flywheel)
  (iii) material processing into feedstock - <u>ISRU</u>

<u>From 3D printed electric motors and electronics,</u>
<u>omnia sequitur…</u>





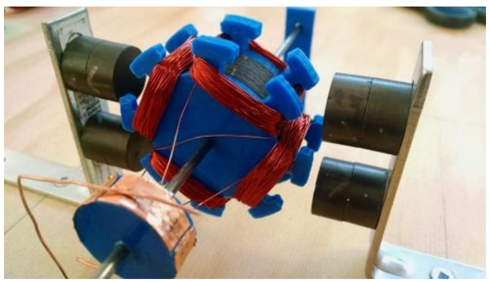


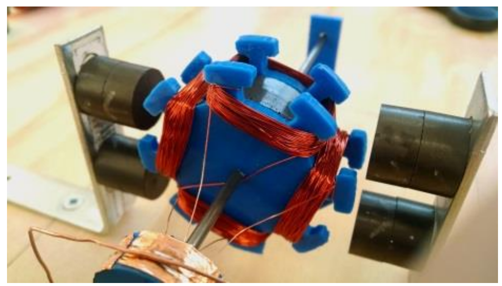
Moses et al concept of universal constructor

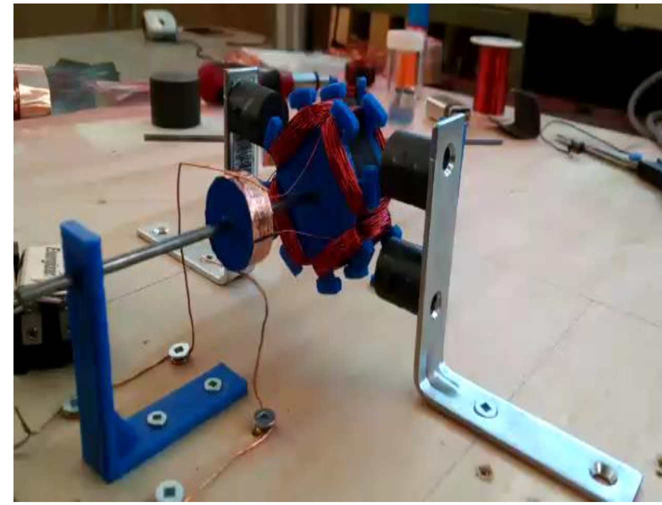
1st of the Mechatronics Triad - Actuators

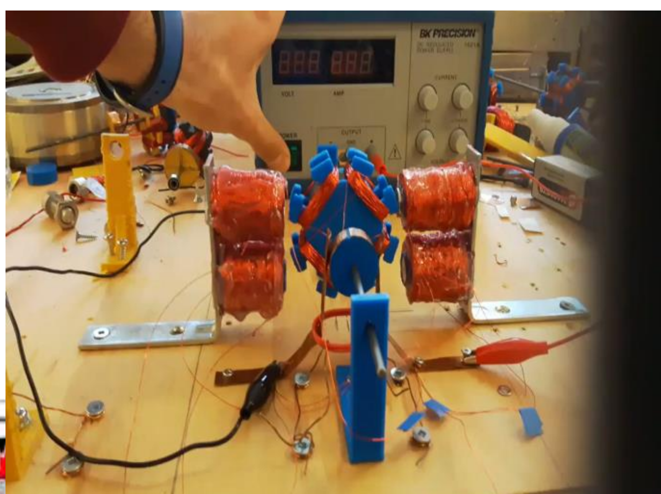
3D Printed DC Motor for Flywheel

- DC electric motor partly 3D printed by FDM using Prusa i3
- Rotor - 50% Fe powder in 50% PLA matrix (ProtoPasta)
- Stator – same
- Copper wire/brush/commutator



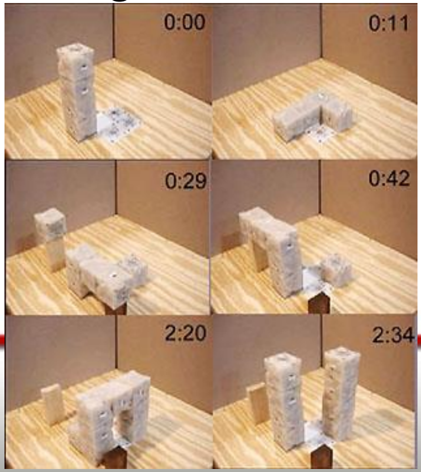


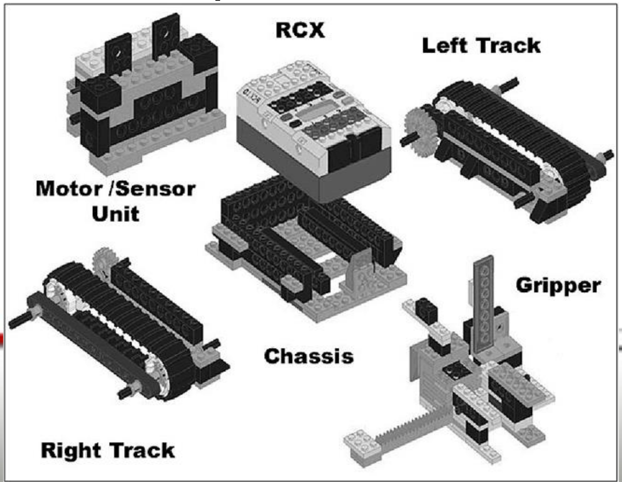




Self-Assembling Systems

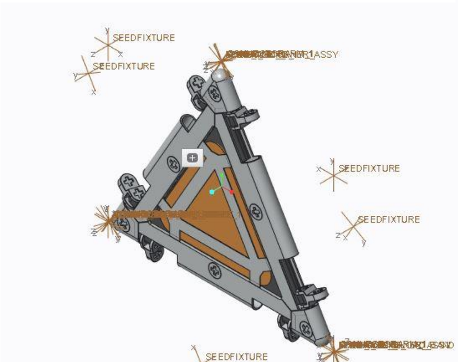
- Self-assembly is a step towards self-replicating systems
- 3D printing reduces assembly but does not eliminate it
- 3D printing with self-assembly offers powerful combination of capabilities
- Most 3D printing efforts to date have focussed on printing structures
- Efforts to 3D print robots have 3D printed structures with cavities and joint structures for insertion of prefabricated (not 3D printed) mechatronics - actuators, sensors and electronics
- Our interest is in 3D printing complex electromechanical robotic systems
- We have focussed on 3D printing DC electric motors as part of self-assembling system

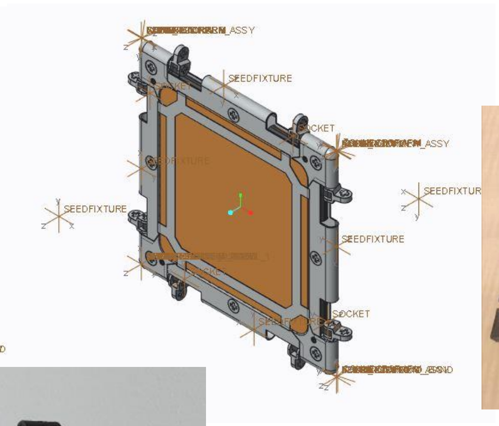


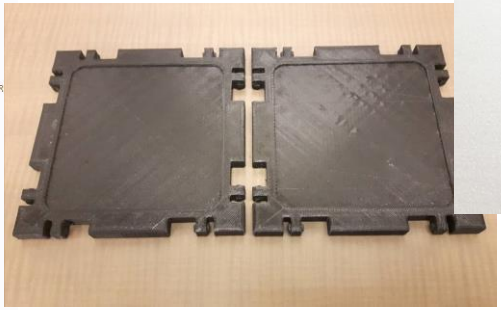


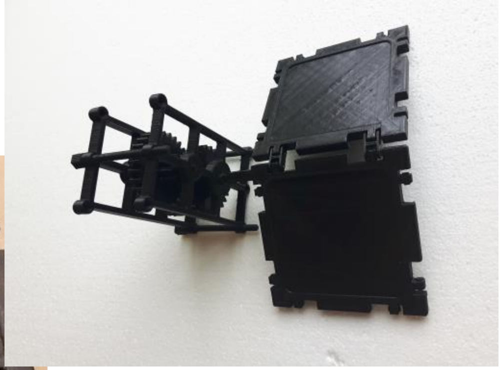
3D Printed Self-Assembly

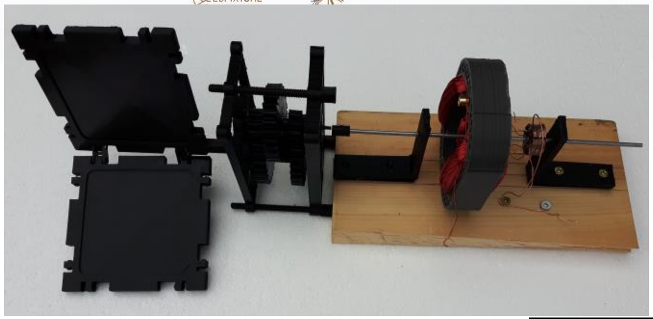
- 3D printed motor (less wiring) married to 3D printed JPL TRIGON panels to demonstrate basic flat-pack self-assembly

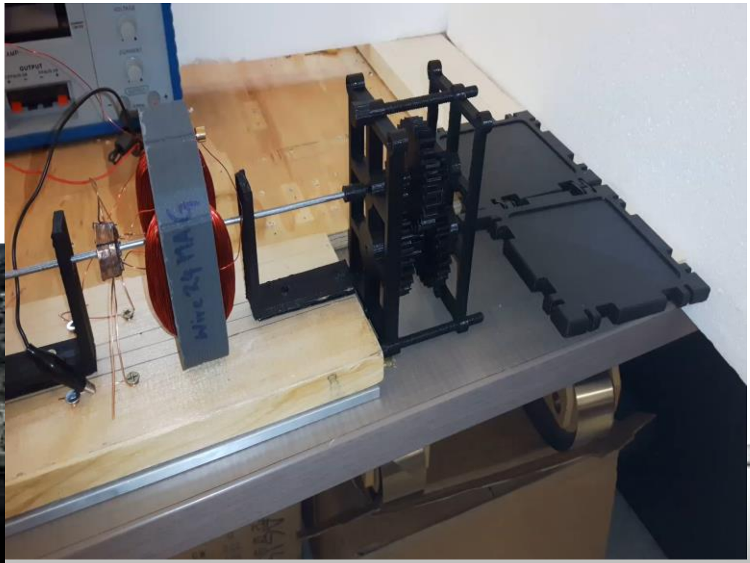






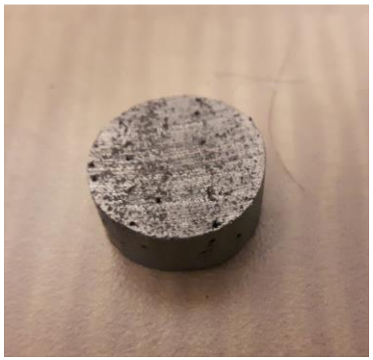
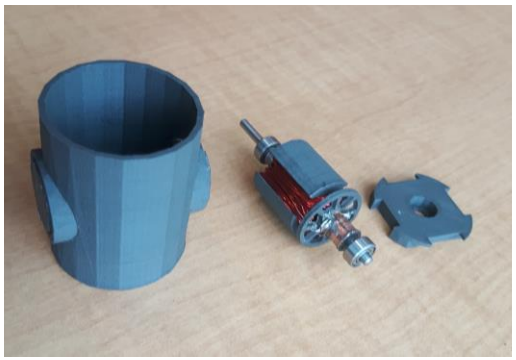


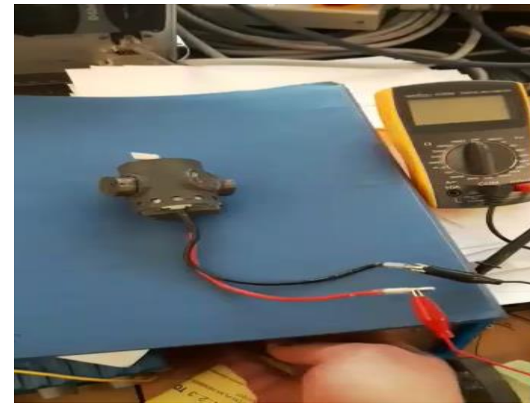




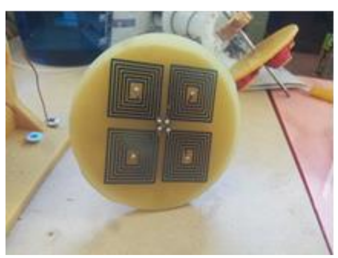
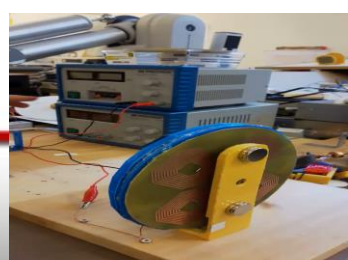
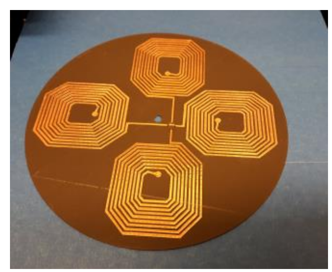
Evolution of 3D Printed Motor

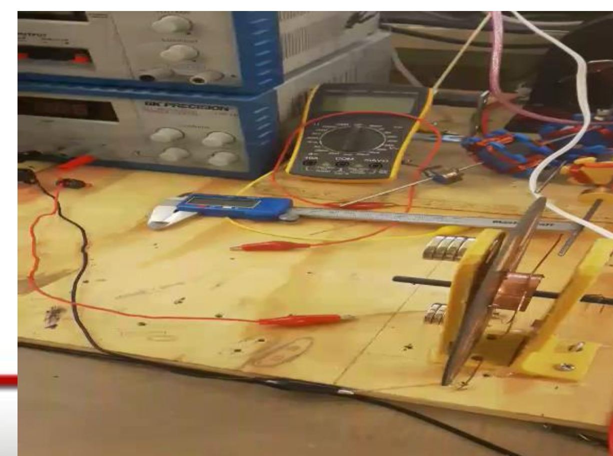
- 3D printed permanent stator NdFeB magnet (Oak Ridge National Laboratory)
- Minitiaturising DC motor (for panel integration)



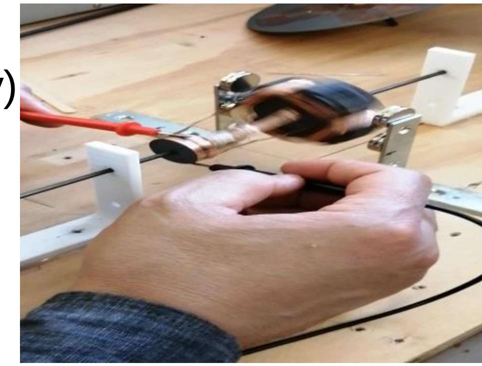
- Motor wiring has been particularly challenging- pancake motor test assemblies

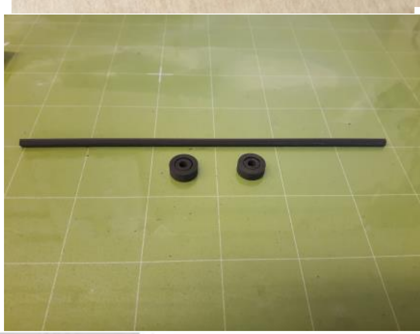





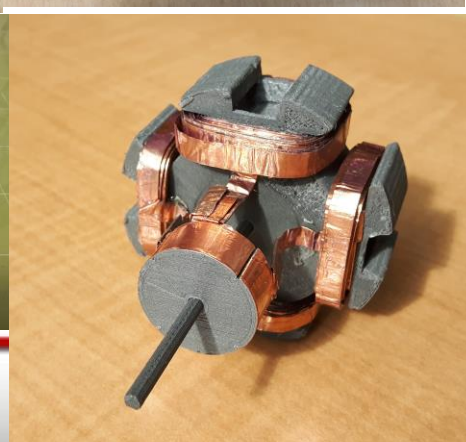



Fully 3D Printed Motor

- 3D printed rotor (ProtoPasta)
- 3D printed permanent stator magnet (Oak Ridge National Laboratory)
- LOM-style copper tape wiring/commutator wound around rotor
- 3D printed shaft + bearings







Lunar Motors 1

- Copper may be substituted with Al wiring
- Plastic electrical insulation may be substituted with glass cloth, enamel (sintered glass powder) or porcelain
- **Magnetic materials** are fundamental to electric motors
- <u>Permanent magnetic stators</u> require high magnetic capacity and high magnetic coercivity
- <u>Soft magnetic armature core</u> require high magnetic capacity and low magnetic coercivity
- **Fe** has significant magnetic capacity of 1.3 T - permalloy 45 (55% Fe + 45% Ni) offers soft magnetic properties but Fe is electrical conductor → eddy currents
- Addition of 3-3.5% Si forms **silicon steel** (magnetic capacity of 1.6 T) of high electrical resistance
- Addition of 4.5% Cr forms FeSiCr further improves soft magnet performance – Cr excluded from first gen ISRU
- **Ferrite ceramic** (MFe_2O_4 where M=divalent metal cation) is electrically resistive but ferrimagnetic

Lunar Motors 2

- Soft ferrites have low coercivity for ferrite cores, e.g. **$NiFe_2O_4$**
- Hard ferrites have high coercivity such as **$CoFe_2O_4$** (also magnetostrictive)
- Ceramic ferrites can be manufacture under lunar conditions:
  - (i) Mixed metal oxide powders suspended in water with organic binder, plasticiser and dispersant to form ceramic paste
  - (ii) Binder/placticiser may be substituted with clay (byproduct of HCl processing)
  - (iii) Ceramic paste extruded through nozzle and deposited layer-by-layer
  - (iv) Heating beyond 350^{o}C drives off water and organics
  - (v) Sintering >1300^{o}C for 60 h yields fully dense ferrite
- Powerful ferromagnetic materials include iron-cobalt alloys (magnetic capacity of 2.2 T up to 940^{o}C), AlNiCo, SmCo and rare earth magnets
- **AlNiCo** (**35% Fe, 35% Co, 15% Ni, 7% Al,** ~~4% Cu~~ **and 4% Ti**) alloy magnets double the magnetic energy density from iron and ferrites up to 540^{o}C – Cu imparts ductility so it is not essential
- **AlNiCo** permanent magnets are favoured for lunar application

Carleton UNIVERSITY

2^{nd} Gen ISRU - Rare Earth Magnets

- Rare earth magnets offer high magnetic energy density
- Addition of 0.15% Nd increases magnetic capacity of electrical steel
- High power hard magnets $Nd_2Fe_{14}B$ with B=1.4 T but only at <200°C
  - B recovered from solar wind impregnation of regolith?
  - addition of prasaeodymium for corrosion resistance is unnecessary
  - addition of dysprosium and terbium increases T<300°C but B=1.0 T only
  - SmCo alloys $Sm_2(Co,Fe,Cu,Zr)_{17}$ offer B=1.1 T at 300-550°C
- Magnetic coercivity is dependent on grain size – it reaches a maximum of 1000 kA/m at 250 nm
- 3D printing offers tailorable magnetic properties including graded magnetism
- KREEP basalts on the Moon are 10-100 x abundance of REE than asteroids (<0.6 ppm in chondrites) but similar to Earth ~10-20 ppm

2nd Gen ISRU – KREEP Resources

Element	KREEP	C1 Carbonaceous Chondrite	KREEP/C1 Multiplier
La (µg/g)	110	0.23	478
Ce (µg/g)	270	0.61	443
Nd (µg/g)	180	0.41	439
Sm (µg/g)	49	0.13	377
Gd (µg/g)	57	0.173	329
Tb (µg/g)	10	0.031	323
Dy (µg/g)	65	0.20	325
Ho (µg/g)	14	0.052	269
Er (µg/g)	39	0.133	293
Yb (µg/g)	36	0.147	245
Lu (µg/g)	5.0	0.023	217
Y (µg/g)	300	1.27	236
Zr (µg/g)	1700	3.6	472
Nb (µg/g)	80	0.36	222
Ba (µg/g)	1800	2.4	500
Hf (µg/g)	37	0.125	296
Ta (µg/g)	4.0	0.0134	299
Th (µg/g)	18	0.37	486
U (µg/g)	5	0.01	500
Li (µg/g)	506	1.3	43
Na (µg/g)	6.4	5.5	1.2
K (mg/g)	6.9	0.56	12.3
Rb (µg/g)	22	2.0	11.0
Cs (µg/g)	2.0	0.19	10.5
P (mg/g)	3.4	0.84	4.1
Sr (mg/g)	200	8.4	23.8
Eu (mg/g)	3.0	0.049	61
W (mg/g)	2.0	0.088	22.7

2nd Gen ISRU - Rare Earth Element Extraction 1

- There are 3 rare earth minerals on Earth which may be traced by U and Th gamma ray spectra on the Moon:
  (i) Bastnaesite is a carbonate associated with iron
  (ii) Monazite and xenotime are phosphates associated with sand
  (iii) Apatite has low rare earth concentrations (but can be up to 19% by weight)
- Only the last is plausible for the Moon but is not mined commercially on Earth
- REE have similar physical and chemical properties so separation is challenging
- To reduce grinding energy, REE carbonates and phosphates are roasted at 400-1000^{o}C into friable oxides
- Grind material into mono-mineral grains using jaws/rollers/ball mills
- Multiple stages of beneficiation:
  - (i) Low intensity followed by high intensity magnetic separation to separate ferromagnetic, paramagnetic and diamagnetic minerals
  - (ii) Electrostatic separation separates by electrical conductivity
  - (iii) Gravity separation using high-speed centrifugal concentrators

2^{nd} Gen ISRU - Rare Earth Element Extraction 2

- REE extraction involves multiple modes of dissolution of REE minerals:
  - (i) Dissolution in a hot conc NaOH solution at 140-150°C yields REE hydroxides - hydroxides are reacted with HCl to form rare earth chloride solution for ppt
  - (ii) HCl leaching of apatitie out the REE oxides - oxides converted into soluble sulphates with hot H_2SO_4 up to 300°C (acid roasting) for ppt
  - (iii) HF leaching yields REE fluoride which is reacted with Ca at high temperature to generated reduced REE and CaF_2 – metal is melted *in vacuo* to purify it
  - (iv) Solvent extraction by serially adding specific organic compounds to form aq solution of REE salts that extract one REE at a time - poor REE selectivity
  - (v) Flush ion exchange resin with $CuSO_4$ solution displaces lanthanide cation - this generates significant chemical waste
  - (vi) Solid-state silica gel support with metal-selective chelating agent that binds to REE metal ion followed by flushing column with H_2SO_4 – this has been used for PGM extraction
- All involve complex deployment of fluids

2nd of the Mechatronics Triad - Sensors

Physical Dimensions

- **What sensors can we construct from lunar resources?**
- We begin with **fundamental dimensions**: Amount [N] – mass [M] – length [L] – time [T] – temperature [θ] – electric current [I] – luminosity [J]
- All sensory measurements are **derived from these**
- Although **temperature** is crucial (for signal processing), we do **not address** it here except to observe that electrical resistance is dependent on temperature (basis of thermistor and bolometer)
- We focus on **two basic parameters** - displacement measurement and luminosity measurement as these are the most pertinent **for robotic machines**
- **Displacement measurement** is the most fundamental measurement as other measurements of **internal state** are derivative (velocity, acceleration, force, pressure, stress, etc)
- **Light intensity measurement** is fundamental to measurement-at-a-distance for **external state** determination (vision)
- By exploiting **biomimetics**, we can explore innovative means of measurement using a narrow suite of sensors

Displacement Sensing

- **Displacement measurement is fundamental**
- Simplest displacement sensor is the **potentiometer** (rheostat)

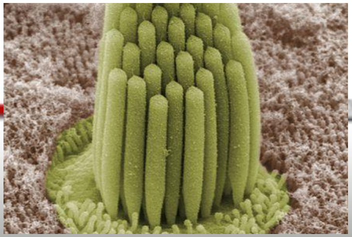
  - a tapped resistance wire (e.g. Al or Ni) in a voltage divider configuration (rotary pot in robotics)
- Resistance change with temperature offers **temperature measurements** (bridge ccts for compensation)
- Resistance change in “W” configuration connected to a wheatstone bridge offers **strain measurement**
- Strain gauges are fundamental to **biological sensing by universal hair-cells** by instrumenting elastomeric membranes (e.g. silicone):

  (i) Tactile sensing using whiskers mounted onto membrane in mammals

  (ii) Gyroscopic sensing of Coriolis forces using halteres mounted onto membrane in blowflies

  (iii) Acoustic measurement of hair cell deflection in the cochlear

  (iv) Gyroscopic sensing of hair cell deflection on labyrinth



Pressure/Tactile Sensing

- Force/**pressure** (force/area) is the **primary modality of tactility**
- **Piezoelectricity** provides an ideal transduction mechanism between applied stress (force/area) and electrical voltage
- Simplest piezoelectric material is **quartz** (SiO_2) – manufacturable from silica derived from lunar silicates such as anorthite
- Silica is melted with Na_2CO_3 at 800^{o}C under high pressure of 150 bar to form Na_2SiO_3
- **Quartz is crystallised** below 570^{o}C hydrothermally from aqueous solution of molten silica
- Quartz is the active transduction mechanism of the **quartz microbalance** for accurate **mass measurements**
- Tactility comprises arrays of pressure sensors protected by thin silicone sheet
- **Tactility** is exploratory – it is fundamentally an **actuator-driven capability**
- Quartz is also a short-stroke high frequency oscillator
- Basis of radiofrequency signal processing

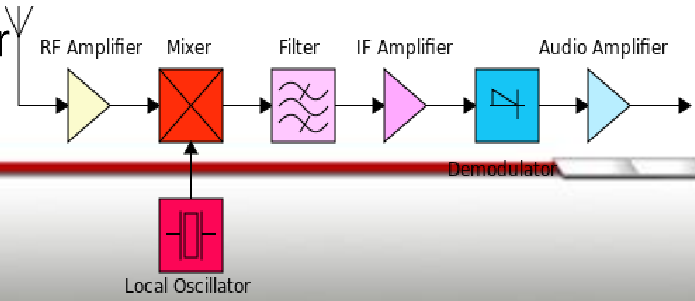
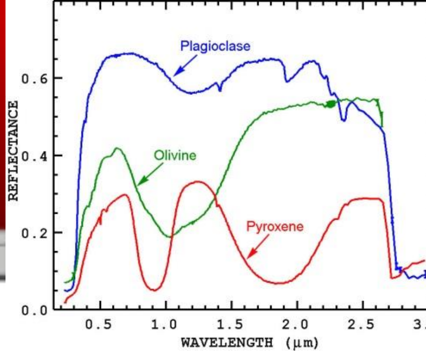


Photo-Sensitive Materials



- Imaging camera array is fundamental as a remote distance sensor
- P-type semiconductor **selenium** was used in Victorian photophone (1880)
- **Se is found in association with metal sulphides** but, although rare on the Moon, chalcopyrite (Cu-Fe-S) deposits exist
- **S/Se ratio** in carbonaceous meteorites is **~2450** with **S~5%** content of same
- Se may be sourced as **FeS (troilite)-substituted FeSe ~1/2500** as grains in NiFe asteroid alloy
- Iron selenide may be smelted with soda $\mathbf{Na_2}CO_3$ and saltpetre $\mathbf{KNO_3}$ catalyst:

  $FeSe + Na_2CO_3 + 1.5O_2 \rightarrow FeO + Na_2SeO_3 + CO_2$
- Selenite Na_2SeO_3 is acidified with H_2SO_4 (recycled) to yield selenous acid (H_2SeO_3) from which **Se may be precipitated**:

  $H_2SeO_3 + 2SO_2 + H_2O \rightarrow Se + 2H_2SO_4$
- Se is recovered with sulphuric acid recycled
- **Imported reagent Na** is necessary for Se extraction as part of the \`salt\` contingency (Na_2O product is recycled by water into $NaOH + HCl \rightarrow NaCl + H_2O$)

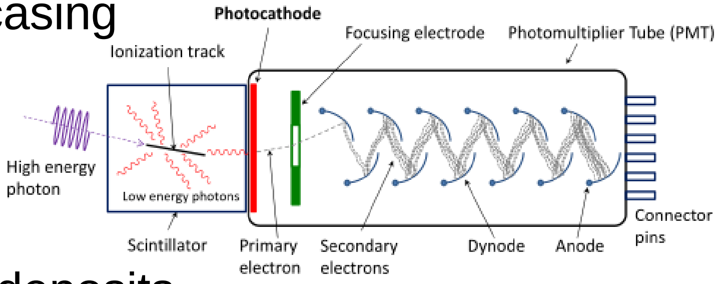
Vision – Photomultiplier Tube (PMT)

- Solid-state detectors are not feasible due to manufacturing complexity
- Photomultiplier tube (PMT) is a vacuum tube with electrodes coated with Se (primary emitter) and Al_2O_3/MgO (secondary emitters)
- Vision involves an array of light-sensitive pixels forming an image
- PMTs may be arrayed into **small microchannel plates** in which each PMT is a pixel
- **PMTs are vacuum tubes** – (silica) glass tube encasing

  Ni electrodes – cathode – dynodes - anode:

  (i) **Photoemissive cathode** of Se-coated Ni

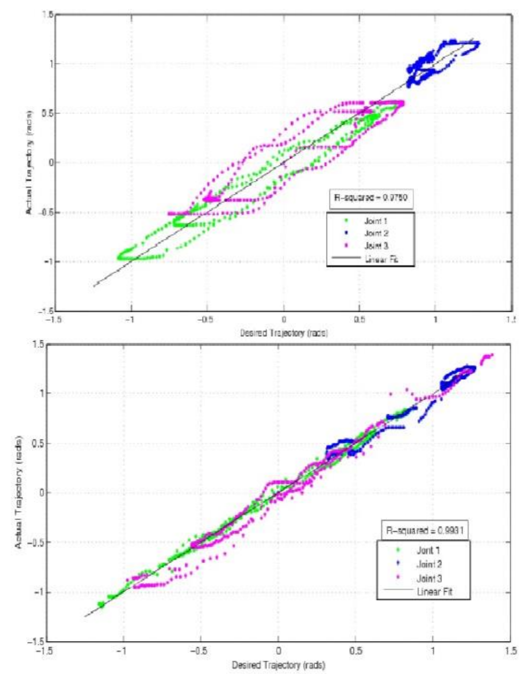
  (ii) **Secondary electron-multiplying dynodes**



- Ni electrodes may be sourced from NiFe asteroid deposits
- Electron-emitter **coatings for dynodes** include lunar-derivable **Al_2O_3/MgO**
- Resolution of PMT array will be small and limited in FOV

Vision – Imaging Arrays for Active Vision

- Following a biomimetic approach, image processing may be separated into a **“where” pathway** to locate objects **based on optic flow** and a **“what” pathway** to identify objects **based on active vision**
- Active vision motorises the imaging camera to **scan its limited FOV** over the visual field **through gaze shifting**
- Pulse-coupled neural network (PCNN) can select visual targets for auto-foveation
- There are two options for motor feedback – optokinetic response (OKR) and vestibular-ocular reflex (VOR)
- **VOR requires gyroscopic feedback** but we can compensate using **pan-tilt motor feedback with feedforward neural net** model of joints
- **Microstepping between pixels** by exploiting higher resolution of motor potentiometers to overcome limits in pixel resolution



3^{rd} of the Mechatronics Triad – Electronic Control Systems

Raison D’Etre for In-Situ Electronics

- Import “bag of chips” from Earth vs In-situ production of electronics on the Moon

(i) Service **availability** to online failure requires **warehousing** of spares with controlled environments due to limited response times of the 3-day trip plus launch preparations (**no on-demand responsivity**);

(ii) Related to (i) is that **integrated avionics** is ubiquitous in systems today and requires hardware-expensive plug-in modules whereas in-situ production offers greater flexibility of **integrated manufacture**;

(iii) Opportunity for change – terrestrial computational electronics has reached the point of diminishing performance gains and the death of Moore’s law;

(iv) Related to (iii) is that terrestrial microelectronics is highly sensitive to space environment conditions such as **radiation** to which vacuum tubes are immune favouring more compact approaches with reduced reliance on error detection and correction coding which consumes memory resources;

(v) Related to (iii), **neural networks** are the favourite AI mode today that are better suited to neural network hardware architectures than von Neumann CPU bottlenecks

Passive Circuitry

- Cu has higher electrical conductivity of 5.96×10^7 S/m than Al of 3.5×10^7 S/m so Al wiring requires **re-gauging by 1.61**
- Al metal ribbon may be printed directly onto insulating sheets and PCB milling/drilling removes excess metal to form circuit patterns
- **Resistors** may be printed as clay thick-film paste with powdered fernico alloy onto ceramic surfaces – following heat-curing at 150-170^{o}C, they may be trimmed to precisely required resistance
- **Capacitor** comprises Al metal foil electrodes sandwiching 25 μm thick powdered ceramic dielectric - ε_r~9 for Al_2O_3 and ε_r~117 for TiO_2
- **Inductors** (and transformers) may be formed by printing conductive tape of high magnetic permeability onto multiple layers of ferrite ceramic tape
- Following deposition, resistors, capacitors, inductors and transformers may be co-fired at <1000^{o}C

Feasibility of Solid-State Electronics

- Around **30 different processes** are required to manufacture computer chips
- **Solar grade Si has purity ~10^{-6} while electronics grade has purity ~10^{-9}**
- Siemens process to increase metallurgical grade of Si appears feasible on the Moon – lunar industrial ecology supplies recycled HCl reagent and 1150°C for CVD of trichlorosilane is similar to FFC temperatures
- Higher purity through zone refining is feasible for in-space manufacturing
- Czochralski process at 1500°C in a vacuum for high purity single crystal Si in quartz crucible is similar to quartz crystal growth
- Doping implants dopant ions at 3 keV to create pn junctions - Si may be p-doped with Al and n-doped with P but **P requires extraction from KREEP minerals (2nd Gen ISRU)**
- Thin film deposition introduces several different options:
  - CVD deposits evaporated material onto substrate at 1000°C
  - Electron beam physical vapour deposition involves electron beam deposition of metals only
  - Molecular beam epitaxial growth has been demonstrated in space (Wake Shield Facility) but Si_3N_4 cannot be sourced on the Moon limiting insulation to SiO_2

Feasibility of Solid State Electronics 2

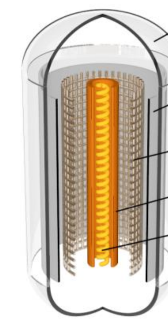
- It is the **lithographical processes that are infeasible on the Moon** due to their reliance on complex processing materials – photolithographic masks, PMMA photoresists, adhesives, UV/X-ray lasers, HF acid, suite of etchants such as HNO_3, CH_3COOH, $NaOH_{(aq)}$, $KOH_{(aq)}$, EDP (Al is difficult to etch)
- It is not feasible to construct solid state electronics on the Moon given the required **manufacturing sophistication:**
  - (i) paucity of common reagents used in solid-state manufacture
  - (ii) stringently controlled environmental conditions required in solid-state
  - manufacture
  - (iii) extreme temperatures required for solid-state manufacture (vapour-phases)
  - (iv) unsuitability of solid-state electronics to severe thermal and radiation
  - environments extant on the Moon;
  - (iv) extreme cost of electronics foundries
- Surface micromachining using micro-milling or electron beam micro-machining may be a viable option for 2nd gen ISRU

Alternatives to Solid State Electronics

- Bletchley Park (1943) Heath Robinson code-breaking computers used electromagnetic relays - mechanical computers have pedigree in space, e.g. Globus IMP navigation instrument on Soyuz (until 2002)
- Electromagnetic relay were derived from telegraphy and limited to ON-OFF switching so it does not perform signal amplification
- Vacuum tubes
  - - **far superior** performance to mechanical relays
  - - **less susceptible** to radiation than solid-state electronics
  - - **highly reliable** if operated in power-on state for thermal stability
- Operational amplifiers were based on vacuum tubes through 1941-61
- Bletchley Park (1943) Colossus programmable code-breaking computer comprised 2400 vacuum tubes designed by the great and unsung **Tommy Flowers**
- Vacuum tubes are still used for TWTAs on spacecraft

Vacuum Tube Electronics

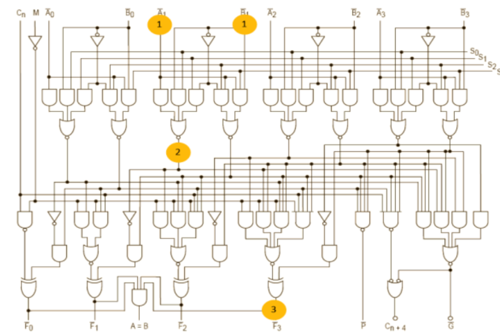
- Vacuum tube is a **thermionic** device with a relatively simple construction that is potentially 3D printable (TBD)
  - - sintered **tungsten** hot cathode at ~1000^{o}C that emits electrons
  - - **CaO-Al$_2$O$_3$** coating to reduce cathode work function
  - - **Ni** anode and control grid
  - - high temperature **kovar** wiring
  - - evacuated **silica** glass tube



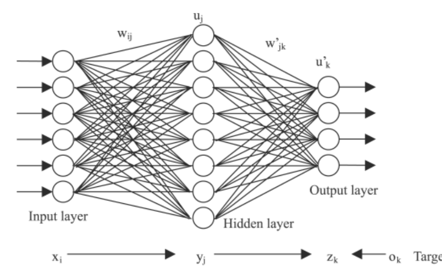
- It uses the kovar resistance wire to heat the oxide-coated tungsten cathode to 1000-2000^{o}C to evaporate electrons accelerated by the control grid to the anode in the glass envelope
- **W is scarce** – lunar highlands have average of 0.3 μg/g W
- NiFe asteroids are enriched in W microparticles inclusions
- W may be extracted and purified through **carbonyl processing** into W(CO)$_6$
- W cathodes are manufactured using powder **sintering with Co, Ni or Fe binder**
- **Scarcity of W** prevents its use for crucible linings, for high temperature (up to 1800^{o}C) ceramic WSi$_2$ heaters or for high temperature dry lubricant WS$_2$

Steam-Punk Electronics

- Vacuum tubes are bulky - circuit complexity growth with task program size, e.g. ENIAC with 17,000 vacuum tubes occupied a large room

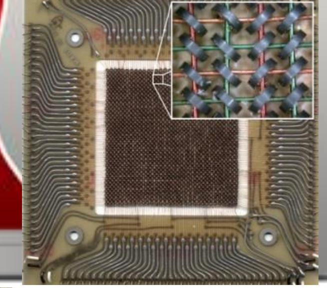


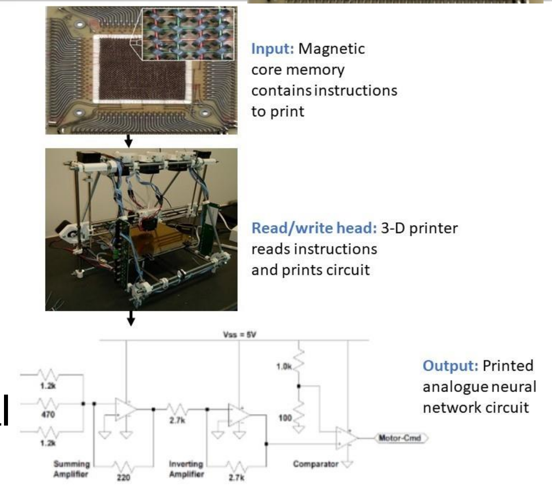
- **CPU-based architectures grow exponentially**, e.g. 8086 CPU architecture is an early simple von Neumann architecture
- **Modern CPUs are highly complex** and cannot be implemented practically using vacuum tubes
- **Recurrent neural networks** with rational weights are **Turing-complete** (indeed, analogue neural nets with real weights offer super-Turing capabilities) so offer an alternative computational architecture



- Artificial neural networks may be deployed to exploit two properties:
  - (i) their physical footprint grows only **logarithmically** with task size according to Parberry analysis
  - (ii) General purpose computer architecture can be replaced with **distributed architecture** of specialised analogue neural network circuits
- Neural networks implement a weighted switching function $y_i(x(t)) = f\left(\sum_{j=1}^{n} w_{ij} x_j(t) + w_i\right)$
- ….implemented in hardware $V_{out} = f\left(\sum_{i=0}^{N} V_{w(i)} V_{in(i)}\right)$

Implementation of a Turing Machine

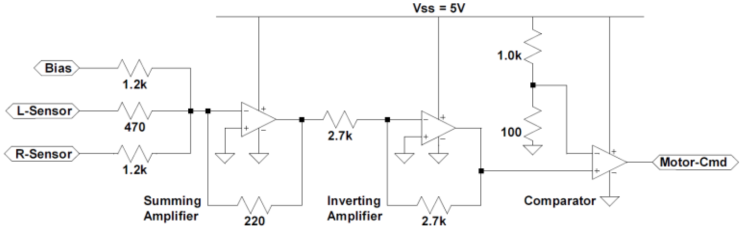




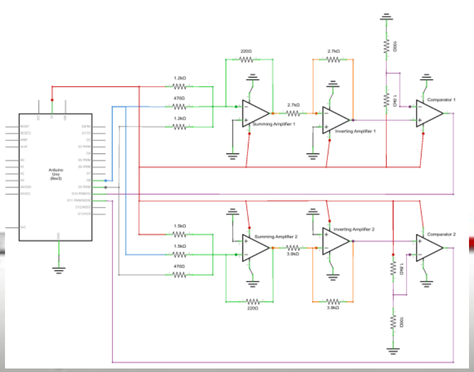
- We implement a direct model of the original Turing machine
  Input tape = **magnetic core memory** (comprising the same components as an electric motor)
  Output tape = analogue neural net circuits
  Read/write head = 3D printer
- There are numerous **hardware implementations of neurons**
  - - spiking neurons such the Hodgkin-Huxley model exhibit temporal neurons but are highly complex
  - - simpler Izhikevich spiking integrate-and-fire neurons are too complex for analogue realisation
  - - in spiking neurons, learning is difficult due to non-differentiability of discrete spikes
- We have adopted a standard neural network model
- **Analogue neural network circuits** offer advantages of reduced energy consumption during computation over digital forms

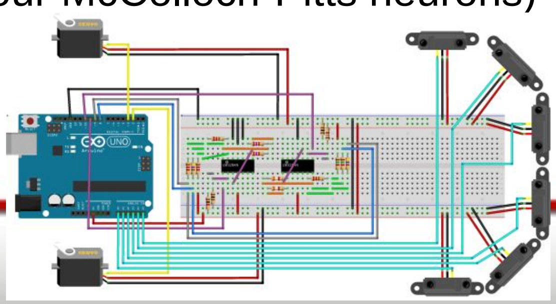
Analogue Neural Nets for Rover Obstacle Avoidance

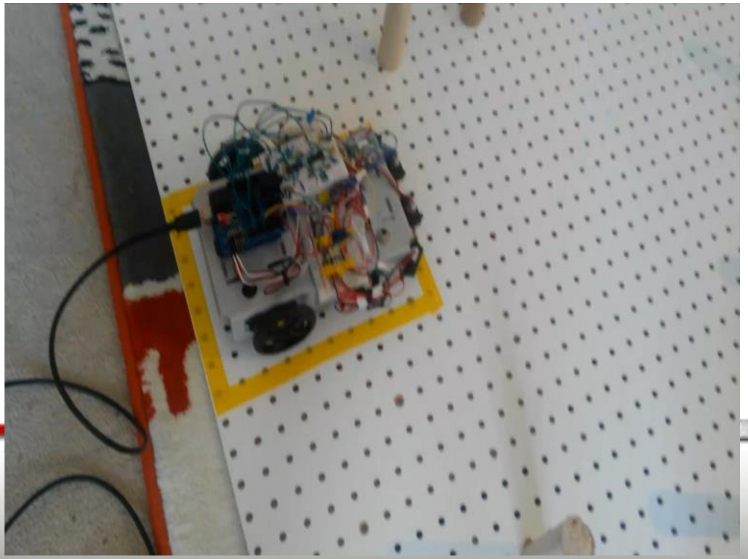
- We adopted a modified **Yamashita-Nakamura analogue neuron model** (we replaced the sigmoid with McCulloch-Pitts signum function) with fixed synaptic weights based on 3 stages – weighted input summer amp + time delay + nonlinear feedback amp – using 4 op-amps, 2 diodes, 7 resistors and 1 capacitor



- We implemented a **Braitenburg control architecture** in directly connecting motors with sensors
  - BV1 → wandering behaviour
  - BV2 → attractive/repulsive behaviour
  - BV3 → attractive and repulsive behaviour
- Pre-weighted **two YN-neuron hardware circuit** has implemented reactive **BV2/BV3** class behaviour on a desktop rover (obstacle avoidance)
- BV3c and BV4 offers throttling at repulsion/attraction
- BV5 implement logic gates (which can be realised with our McColloch-Pitts neurons)







On-Line Learning through Backpropagation Circuitry

- BV6 implements learning....online learning is a necessary capability to update weights to compensate for hardware irregularities
- Earliest hardware learning rule was Madaline Rule II/III based on weight perturbations
- Simple Hebbian learning rule has been implemented as voltage activations on a series of circuits
- Synaptic weight w_{ij} may be represented as a voltage V_{ij} on a capacitor:

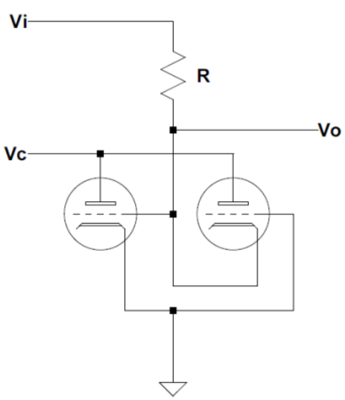
$$V_{ij} = \frac{I_c}{C} \propto V_i V_j$$

- Back propagation of MLP is given by: $w_{ij}(t+1) = w_{ij}(t) - \eta \frac{\partial e}{\partial w_{ij}}$

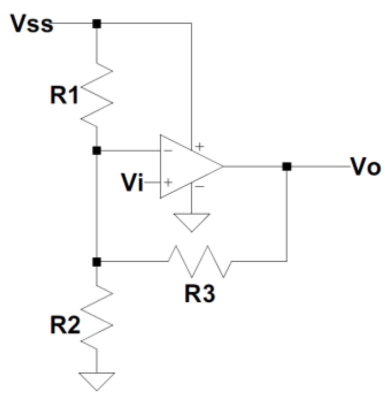
  where η=RC=settling time constant
- Back propagation may be approximated by finite differences

Neural Learning Simulation

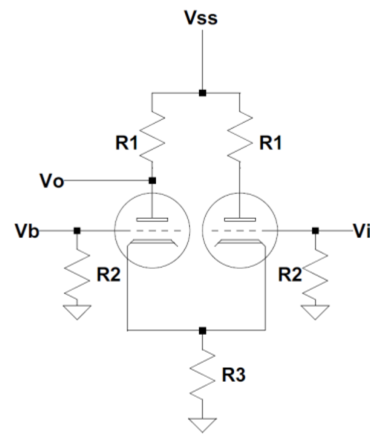
- We simulated a 2-3-1 neural network configuration
- Forward network – op-amp based weighted summer – squashing activation function cct - op-amp based multiplier – voltage-controlled resistor for weights



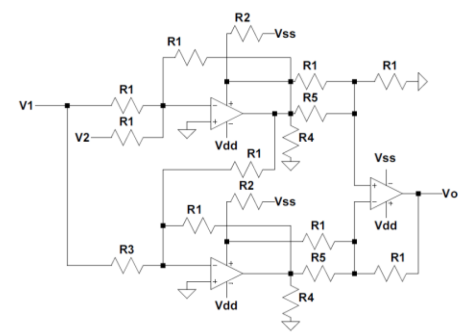
VCR



Activation fn



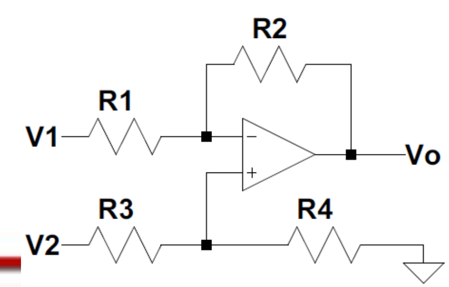
Vacuum tube diff amp



Op-amp multiplier

- Backpropagation – subtraction cct (error) – VCRs – multiplication block

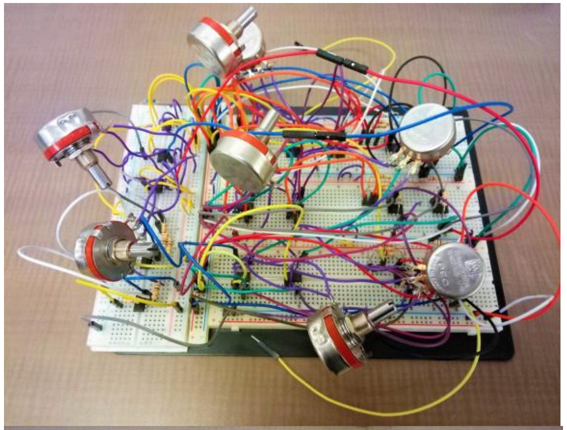
- Simulations failed to update neural weights…..VCRs?

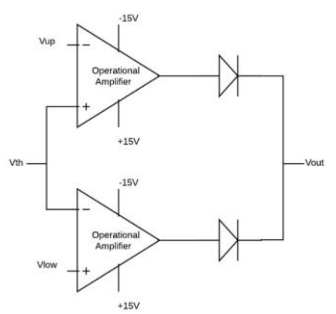


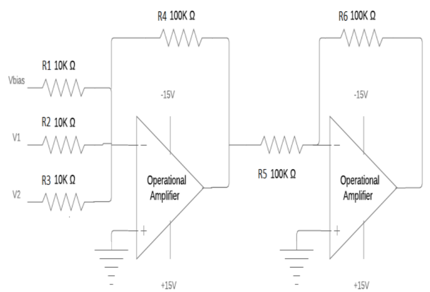
Subtraction cct

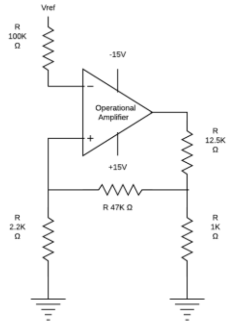
Neural Learning Electronics

- We constructed a trainable analogue neural network with 2(+1)-2(+1)-2 with input and hidden bias neurons
- We replaced VCRs with variable potentiometers
- BP circuit – window comparator – summer – voltage comparator



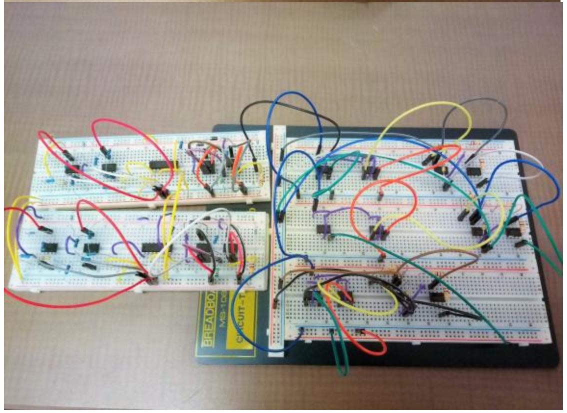






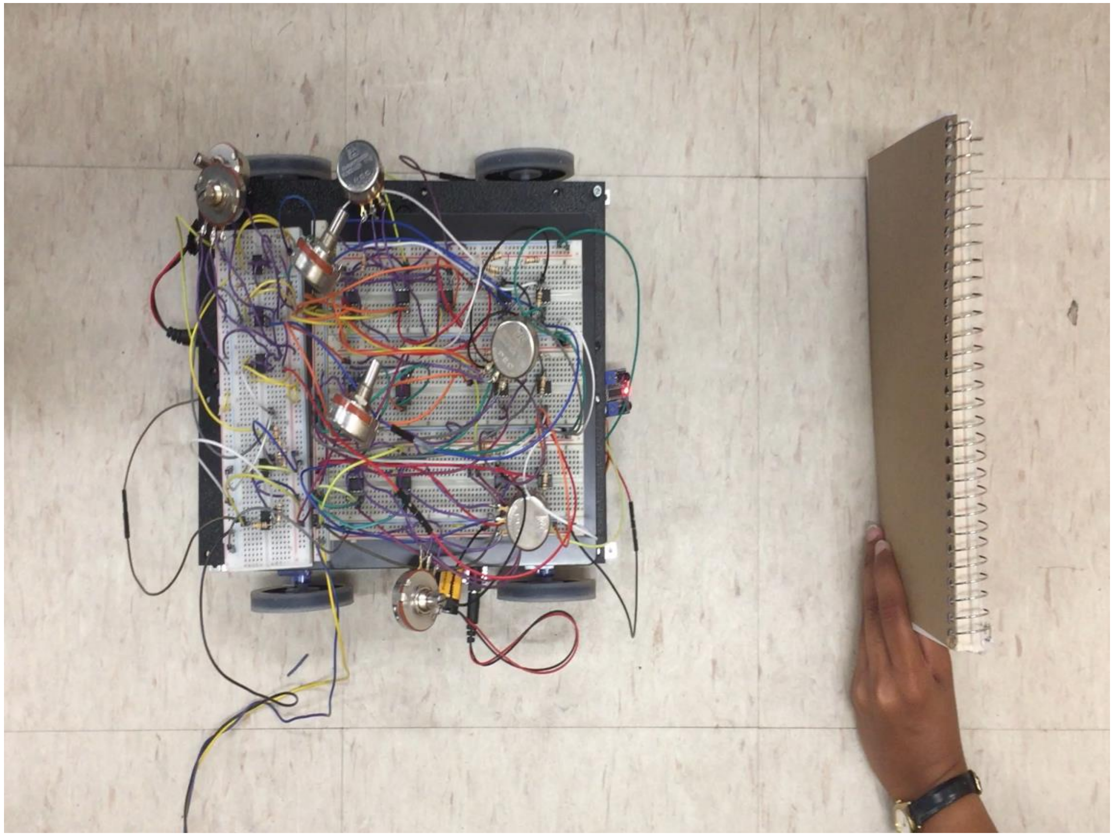
Window comparator Summing amp Voltage comparator

- Potentiometers were updated according to voltage outputs from BP circuit during training
- Voltage Vx to update weight is determined by the potentiometer



Analogue Neural Nets = Turing Complete

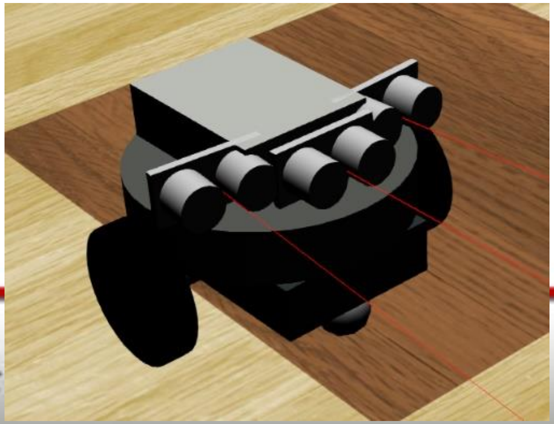
- MLP neural net circuit with BP circuit for obstacle avoidance:

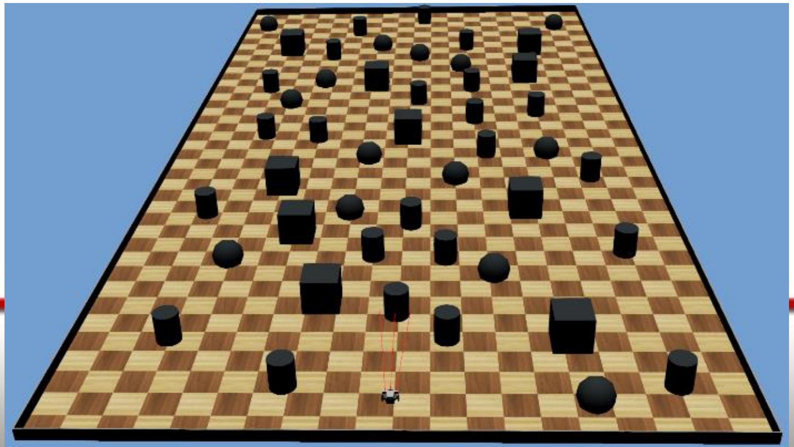


- Weights can be updated but not topology – limits on learning

Cognitive Mapping

- BV 7-14 implement associative neural learning of cognitive maps with predictive capabilities
- We modelled a software simulation of **MLP using BP to control a rover** in Webots
- Simulated 5 x 10 m environment comprised a **randomly-generated rockfield** which presented to the rover with different goals
- **MLP has a 5-4-4-4 topology** – 5 inputs from range sensors to obstacles and goal and 4 motor output states (on/off for two wheels)
- A single MLP configuration successfully learned its traverses
- A more sophisticated ALVINN neural network controlling a vehicle implemented a 30 x 32 visual input layer feeding into a 5-neuron hidden layer and a 30-neuron steering output layer
- C elegans nematode worm comprises 380 neurons for simple but adaptive behaviour
- **Modest-sized ANN can control an autonomous vehicle in a non-dynamic, cluttered planetary environment**





Neural Network Applications

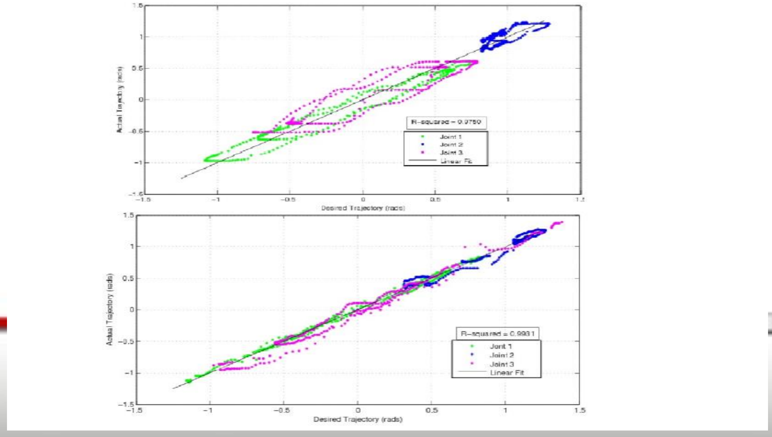
- **Neural networks** are suitable for multiple ISRU tasks
- Kalman filtering – KF is a Bayesian algorithm that can implement sophisticated learning rule

  $\hat{w}(t+1) = \hat{w}(t) + K(t)[y^d(t) - h(\hat{x}(t))]$

  $[y^d(t) - h(\hat{x}(t))]$ = error between desired and estimated measurements

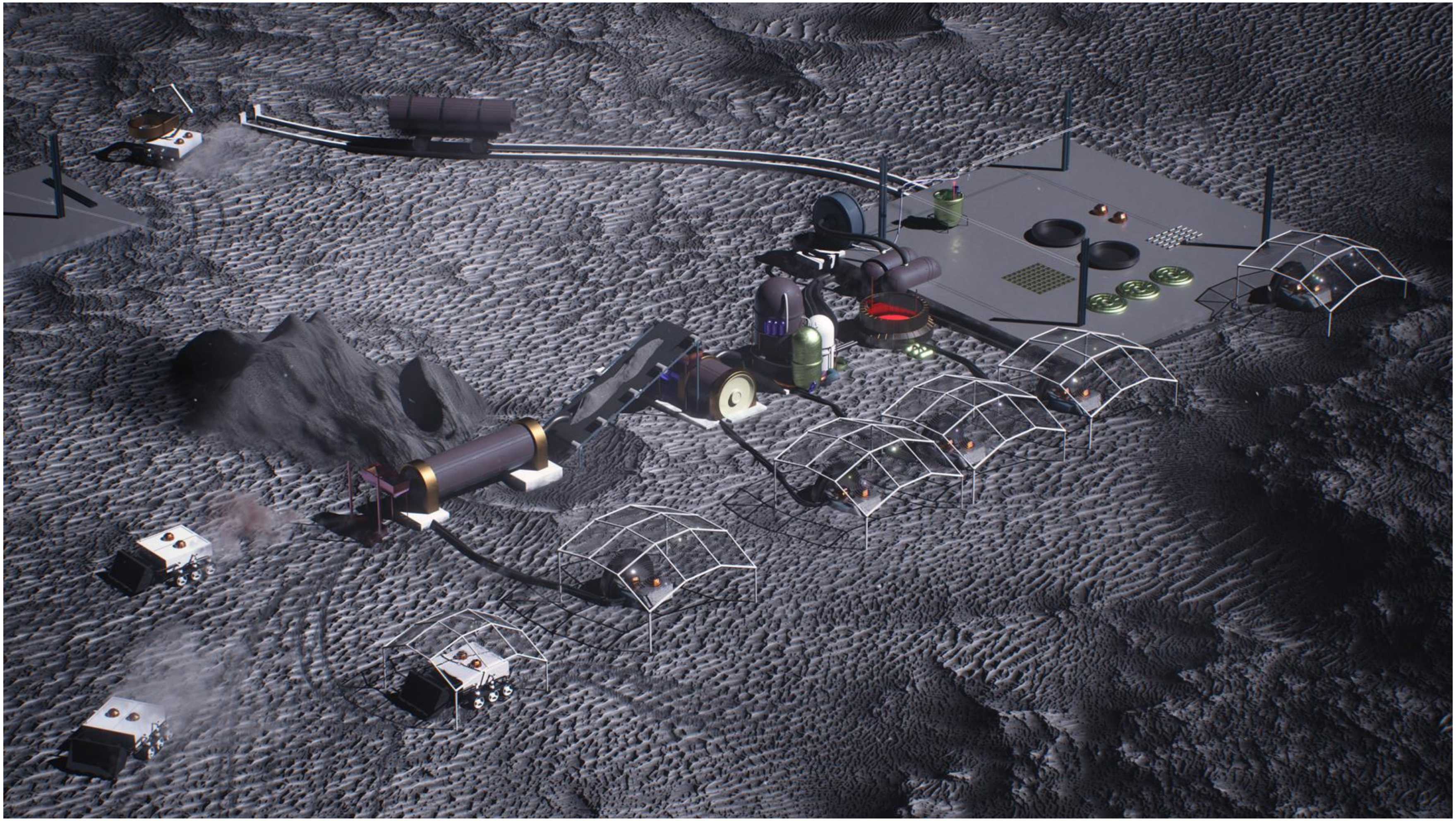
  $K(t) = P(t)H(t)[(1/\eta)I + H(t)^T P(t)H(t)]^{-1}$ = Kalman gain

  $\eta = [H(t)P(t)H(t)^T + R(t)]^{-1}P(t)$ = learning parameter
- RatSLAM model of hippocampus – bio-inspired SLAM based on topological map of place cells connected by synaptic links representing associations between sensed and stored landmarks
- Neural fields are polar potential fields that implement dynamic path planning and for oculomotor gaze shifting
- Robotic manipulator control in space – in particular, we developed neural **feedforward models** to robustify manipulator control
- Control of chemical and manufacturing processes including stirred tank reactor models and additive manufacturing – **feedforward models will be crucial for predictive plant control**



In-Situ Power Systems

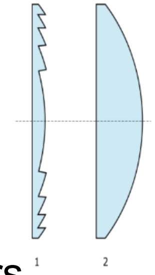
Lunar Industrial Architecture



Profanity of Solar Photovoltaics

- **Basic structure of in-situ solar cell**: Rutile antireflector - glass substrate – Al electrodes – Al-doped Si base with P-doped Si emitter (pn junction) – glass cover
- Solar cells are typically manufactured by **epitaxial growth via vacuum deposition**
- On the Moon, rover-mounted solar concentrators focus light onto a fibre optic bundle to direct melt regolith
- Silicon purity? **Solar grade ~10 ppm >> metallurgical grade <1 ppt**
- Metallurgical grade Si can be yielded from SiO_2 by FFC process
- Solar grade Si requires formation of trichlorosilane at 1150^{o}C
- Czochralski process grows single crystal Si in vacuum
- Dopants (n-type such as P from KREEP and p-type such as Al from anorthite) require **highly controlled thermal diffusion at 1000^{o}C**
- **Microwave drill applicator** may be an option but its precision is unclear (TBD)
- Secondary impurities rapidly decrease efficiency (under 10 ppm or more stringent depending on impurity)
- **In-situ amorphous Si solar cell efficiency ~5%**

Sanctity of Solar Concentrators

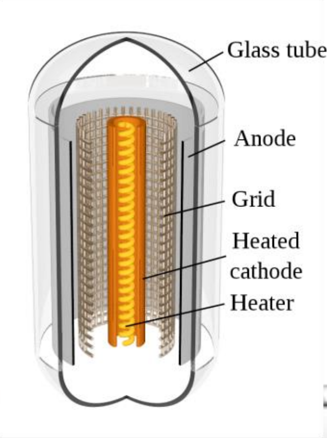


- Solar concentrators are often used to increase photovoltaic efficiency
- They may be employed for generating thermal energy – the dominant requirement for ISRU processing
- Parabolic mirrors of polished Al or glass/silicone Fresnel lenses concentrate light with ratios ~10^4
- Absorber temperature, $T_{ab} = T_s((1-R)\tau(\alpha/\varepsilon)(C/C_{ideal})^{1/4}$

- Optical concentrators → solar furnace is based on parabolic mirrors (R_{Ni}~90% or R_{Steel}~75%) or **Fresnel lens** to create 1600ºC and 2700ºC respectively
- Layered solar sintering of sand into glass has been demonstrated (Markus Kayser of RSA)
- **Fused silica glass requires melting temperature of 1710ºC** (160ºC higher than anorthite)
- **3 m Fresnel lens focused on s 5 cm diameter spot yields T_{ab}>2000 K**
- Ceramic (Al_2O_3) crucible is required depending on temperature
- Our solar furnace based on 1.2 m x 0.9 m **Fresnel lens** for melting Al alloy in ceramic crucible

Solar-Electric Conversion

- Thermal-to-electric conversion is common in high temperature **nuclear thermal sources**
- RTG thermoelectric (Seebeck) conversion , e.g. GPHS uses SiGe alloy with η~5-7%
- Thermoelectric silicides may be sourced in-situ but optimal at lower temp ~330-580°C – $FeSi_2$, CoSi and **Mg_2Si** offer ZT_{max} of 0.2, 0.2 and **1.2** respectively
- **Mg_2Si optimal at 700 K** manufactured by heating SiO_2 (from silicate) with Mg powder (from olivine)
- Poor efficiency alleviated somewhat with 0.2% embedded soft magnetic nanoparticles (e.g. nanophase iron?)
- Closed cycle turbines <30% efficiency at cost of complexity
- **Russian TOPAZ reactor used 5 kW thermionic conversion with efficiency 10-15%**
- Thermionic vacuum tube has a simple construction:
  - CaO coated cathode (from anorthite)
  - Tungsten cathode (from NiFe meteorites)
  - Nickel anode and control grid (from NiFe meteorites)
  - Kovar wiring (from ilmenite/NiFe meteorites)
  - Fused silica glass tube (from lunar silicates)



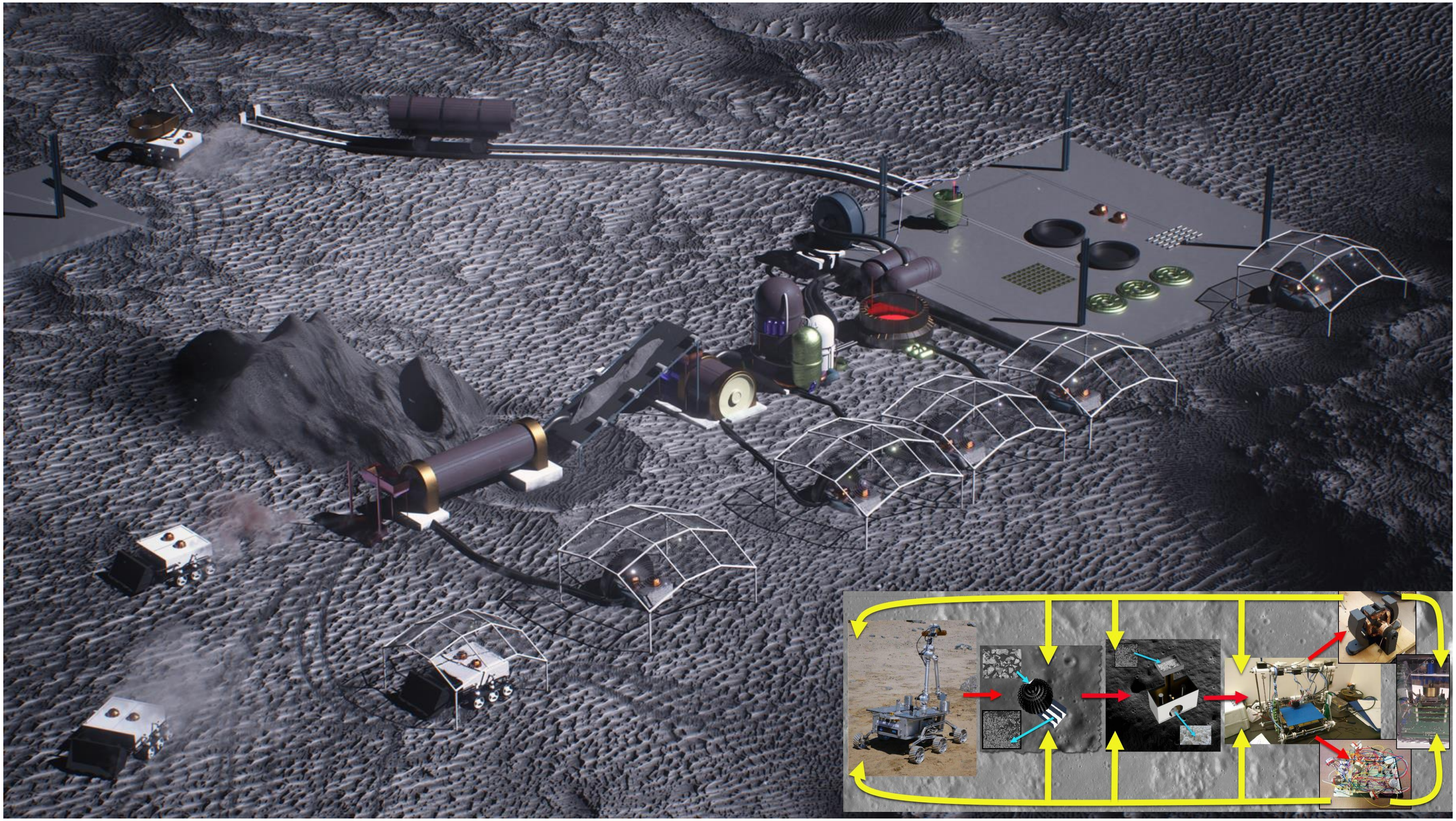
Thermionics

- Work function = min energy required to liberate electrons φ~2-6 eV (dependent on material)
- For most materials, φ>3 eV so T >1000°C required, e.g. 4.52 eV for refractory **tungsten** requires T>1400°C
- Alkaline earth oxide mixture BaO-CaO-Al_2O_3 in 4:1:1 ratio yields φ=2.87 eV – **only CaO and Al_2O_3 available in-situ from anorthite**
- Al-doped haematite photocathodic coating?
- **To reduce space charge effect**:
  - (i) K vapour at > 760°C (similar low ionization potential as Cs – K recovered from orthoclase)
  - (ii) minimize inter-electrode distance ~1-10 μm
  - (iii) **electrostatic field by control grid electrode to shape electron transmission – η~40%**
- **Photon-enhanced thermionic emission (PETE) with η=30-50% -** solar photons liberate valence electrons into conduction band which are energized thermionically
- P-type semiconductor with ideal bandgap ΔE=1.4 eV, e.g. GaAs
- **Undoped Si has ΔE=1.1 eV offers good response**
- PETE may be supplemented by second stage thermoelectric conversion at anode, e.g. Mg_2Si
- Conservative estimate **η=30%** (subject to detailed analysis/experiment)

Flywheel Energy Storage

- Electromechanical batteries **(flywheels) offer zero DoD** and insensitivity to charge/discharge cycling
- High energy density ~100 kJ/kg and good power density ~50 Wh/kg
- Energy stored, $E = \frac{1}{4}mr^2w^2 = \frac{1}{2}Iw^2$ where w~20,000-50,000 rpm
- Tangential velocity is determined by wheel material $v = \sqrt{\frac{\sigma}{\rho}}$
- **Specific energy ~30 Wh/kg for steel – 40 Wh/kg for titanium – 100 Wh/kg for glass**
- To minimize radial stresses, rim constructed from concentric hoops separated by elastic material (e.g. silicone elastomer)
- Halbach motor configuration – permanent magnet array in rotor - no iron laminations in rotor - stationary coils in stator – magnetic bearings for frictionless operation
- **Brittleness of magnetic material to hoop stresses suggests use of magnetic composites comprising magnetic powder in a plastic matrix**
- Lunar-sourced material – **AlNiCo** permanent magnets, **silicon steel/silica** soft magnets, **aluminium** wiring and **Ti/glass** wheel structure

Self-Replicating Machine



Some Issues in Self-Replicating Machines

Prevention of Uncontrolled Replication

- Uncontrolled replication → **grey goo scenario** (Bill Joy)
- Solution: (i) Population control by imposition of **Hayflick limit**
  (ii) **Prevention of evolution**ary change
- Methods:
  - (i) **salt contingency** - denial of salt import from Earth (Earth-controlled kill switch)
  - (ii) **tunicose contingency** - denial of asteroid-sourced tunicose (Moon-controlled kill switch)
  - (iii) **denial of evolution** - error detection and correction coding (EDAC)
  - (iv) denial of excess offspring production – invocation of **cancer beyond Hayflick limit**
- It should be feasible to implement **multi-tiered defence** against grey goo scenarios

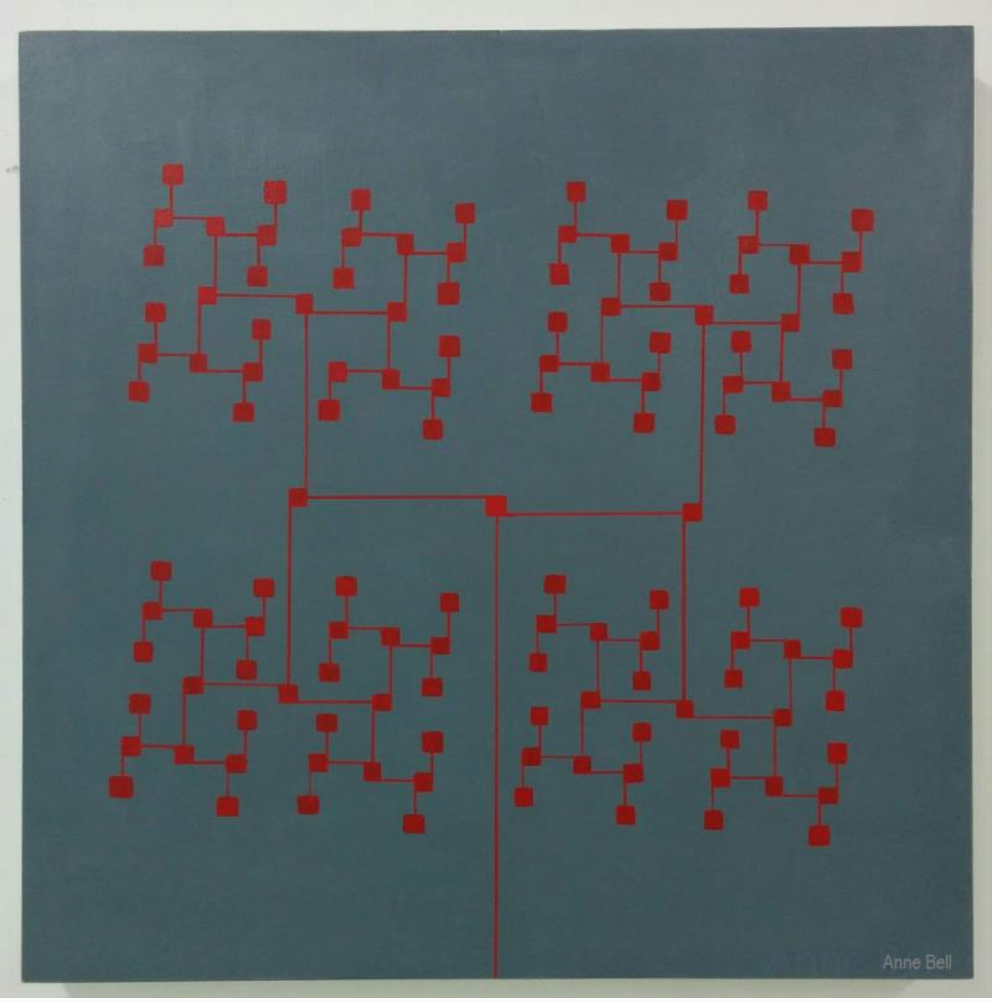
Life But Not As We Know It

- **Darwinian evolution** is a consequence of 2nd law of thermodynamics introducing **copying errors** in self-replication
- This introduces **uncontrollability**
- **Repetitive coding** may be employed for critical functions such as a **Hayflick limit** (telomerase shortening = copy counter), i.e. **coding redundancy**
- Redundancy is inefficient - **channel coding** adds parity bits is more efficient for general codes
- We assume a self-replicating machine with a BER ~10^{-9} for a max population of 10^6 yielding BER requirement of 10^{-15}
- There are two types of code – block codes and convolutional codes
- **Block codes** can be implemented with simple EX-OR gate circuits
- **Convolutional coding** can be implemented using simple shift registers
- Decoding may be implemented using neural network models, e.g. Viterbi algorithm
- EDAC prevents evolutionary change to retain control over self-replication
- There are philosophical arguments that suggest that lack of evolutionary capacity imparts **inanimation properties** (according to Joycean definition of life)

Information Closure

- **EDAC expands information** required for specification rather than compresses it
- Information closure requires that we **minimise the information content** of the self-replicator, i.e. compression
- Specification of 3D printed structures in **STL files** is information-heavy because it specifies slices, each represented as an **array of cartesian points**
- **Nature achieves information-compression** through embryonic development – half of your 3×10^9 bit genetic code describes the structure of your brain with its 10^{11} neurons and 10^{14} synaptic interconnections
- This problem was studied by Alan Turing as **morphogenic fields that control growth**
- We can emulate this through **Lindenmayer systems** that implement grammatical rules for the growth of structures
- This rule-based approach should offer a far more **compact approach to encoding geometry**
- Another interesting option is more direct – using **potential (neural) fields for emulating morphogenic fields** (also applicable to self-assembly)

Anne Bell's Artist Impression of a Self-Replicating Lunar Infrastructure

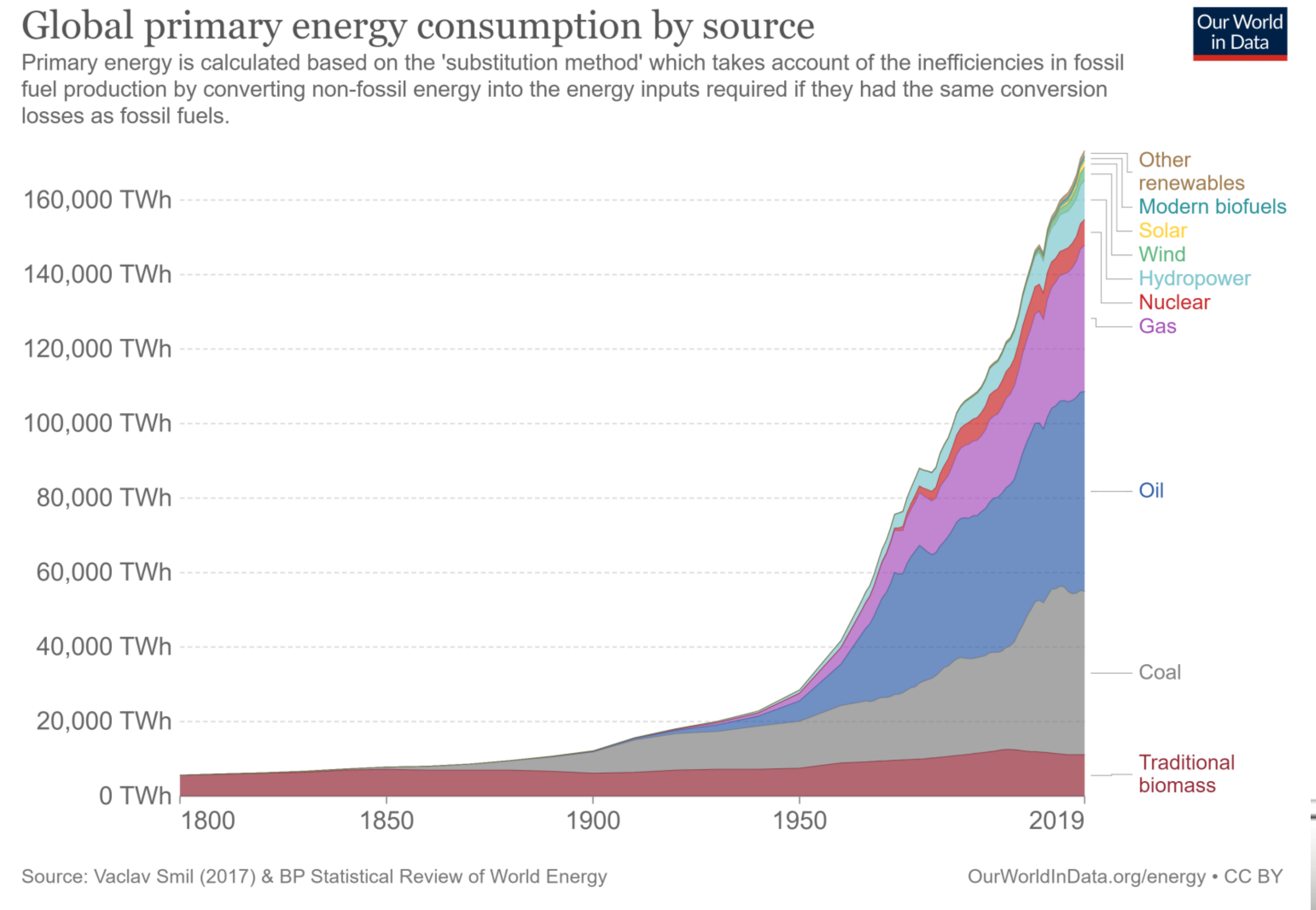


Lunar Solar Power Satellite Production

Preamble

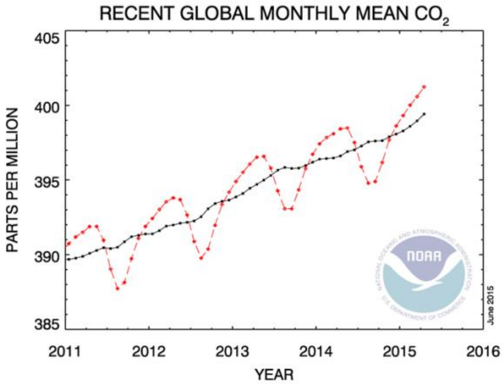
Global problem: Climate change due to increasing GHG emissions

Solutions?



Status of Climate

- **Paris Agreement** (2015) of UN Framework Convention on Climate Change - global warming **limited to ≤1.5ºC**
    - + 1.5ºC ↔ 50% probability of sea level rise of 1.5 m by 2100
    - + 2.0ºC ↔ 50% probability of sea level rise of 2.7m by 2100
- Global CO_2 concentration passed 400 ppm in 2015
- Current global warming has reached **0.6-0.9ºC** above pre-industrial levels
- Thermal inertia → + **0.8-1.25ºC** over 40-60 years **with no further GHG emissions**
- This excludes other factors
    - + CH_4 and NO_x emissions…..
    - + Reduced coal burning → reduced aerosols → reduced cooling
- There is **no sign of abatement of GHG growth**
- Paris Agreement limits already surpassed!



Growth in Energy

- Herman Daly – if everyone in the world had North American living standards, we would require the **resources of 4 Earths** (*Beyond Growth* 1996)
- Energy efficiency savings are being dwarfed by growth in energy demands
- Most projections of **growth assume BAU** but technological shifts are part of economic growth

(i) <u>Growth of internet</u> – 40,000 satellites to be launched to expand internet coverage – information costs energy (incl launch)

(ii) <u>Cloud computing</u> consumes a growing fraction of energy because data demands are cumulative - if 10 billion people snap lunch and dinner 3 times per week, we will need incremental growth in data storage of 5 x 10^{18} bits/year (at 0.2 mJ/bit gives ~1 x 10^{15} J/y)

(iii) <u>Internet-of-things</u> – *everything* will RFID-tagged and trackable – data to be stored and processed through cloud computing resources

(iv) as aquifers are drained, <u>freshwater demands</u> for agriculture (99% water consumption) will require energy-intensive <u>water desalination</u> at ~3 kWh/m^3 (fresh beef requires 15 m^3 water/kg compared with 1.5 m^3 water/kg cereal crops)

(v) as land use are pressured, <u>vertical farming</u> (incl <u>hydroponics</u>) will require more water to increase agricultural productivity (potato) by 280% from 5.4 x 10^6 kcal/km^2/day to 1.5 x 10^7 kcal/km^2/day

Current Solutions

- Projected energy mix in 2030 (with 40-50% energy increase from 2010):
  - 25-30% oil - 20-30% coal - 20-30% gas (**70-80% fossil fuel**)
  - 5-10% nuclear
  - 20% renewables (encouraging growth)
- Natural gas → 50% GHG emission with respect to coal – it is NOT a transition fuel!
- GHG emissions will still increase (**curbing rate of increase does not "solve" problem**)
- Renewables - **problem of power load matching** (high daytime load during summer and winter) due to intermittency of supply
- Renewables requires **extensive power storage** – Li ion batteries pressure on Li resources
- Renewable energy offers **poor areal efficiencies ~ 2 (wind) - 20 (solar) W/m^2** (David MacKay – *Sustainable Energy without the Hot Air* + Vaclav Smil – *Power Density*)
- Nuclear power imposes a number of political issues incl waste disposal
- There is no terrestrial renewable energy scheme suitable for baseload power supply
- <u>Most countries are off-track to their net-zero commitments</u>
- **FACT A – we have exceeded the capacity of Earth to support our growing population in an evolving lifestyle to which we are accustoming ourselves**
- Energy lies at the foundation of the industrial/economic world that has emancipated humanity from the vagaries of the natural world (Hobbes' *Leviathan* – man's natural state of life was solitary, poor, nasty, brutish and short)
- There is however a suitable non-terrestrial solution **which can grow with demand**

Case for Solar Power Satellites

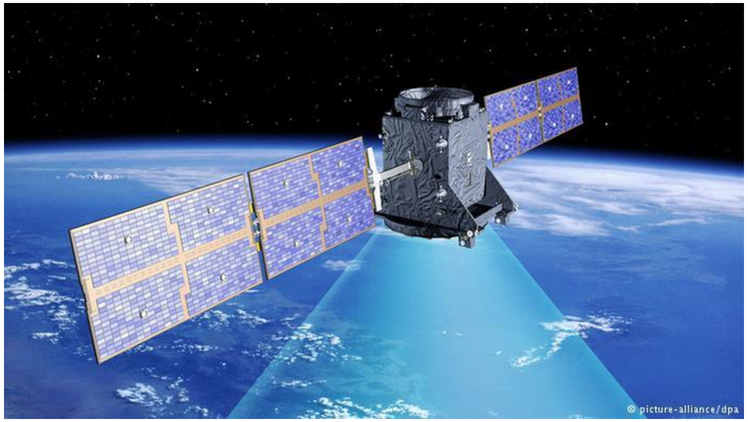
Primary Energy Technology	Terrestrial Renewables (CLEAN)	Fossil Fuels (DIRTY)	Solar Power Satellites (CLEAN)
Source of supply	Intermittent supply	Continuous supply	Near-continuous supply
Demand (load matching)	Energy storage/fossil fuel supplement	No energy storage required	No energy storage required
Areal power density (scalable growth capacity)	2-30 W/m^2	~1000 W/m^2	~230 W/m^2

Climate Change as Disease

- **Solar power satellites (SPS) offer ~200 W/m^2** delivery to rectenna arrays
- SPS is the **ONLY SUSTAINABLE** solution for baseload power with zero GHG emissions
- SPS removes energy generation industry off-Earth to relieve Earth's biosphere of industrial stresses
- **Earth is a geophysiological system** (a la James Lovelock's "Gaia" concept)
- Climate change is a geophysiological disease
- Medical diseases are treated by **symptoms** and the underlying **aetiology**
- **Analgesic** treats symptoms – short term pain-relief through **geoengineering (solar shield constellation at Sun-Earth L1)**
- **Antibiotic** treats causative agents – long term health through **clean energy** sources **(SPS)**
- **Integrated approach** to climate change mitigation - solar shield + SPS are based on same underlying technology
- Lessons of Montreal Protocol on CFC ban - this requires only a single (space) industry to implement a global solution to world's energy and climate problems
- Geopolitical lesson – global energy capacity is a **hardened version of soft power**

Solar Power Satellites

- NASA SPS Reference Model involves 60 x 1 GW 250 tonne SPS satellites at GEO (36,000 km altitude)



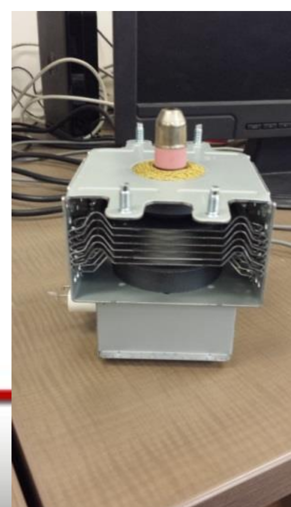
- **Four major components** to SPS:
  - (i) 1.5 km x 1.5 km PV array
  - (ii) klystron/magnetron converters*
  - (iii) microwave transmit antenna beam to Earth (2.45 GHz)
  - (iv) ground-based passive rectenna waveguide array
- Alternative architectures are possible
- Current global energy consumption is 15 TW (of which 2 TW is electrical energy)
- Assume that electric cars, etc will shift towards increased electrical energy share
  - (a) constellation of **$2 \times 10^9 \times 1m^2$ satellites generating 15 TW forming a GEO ring ~1 km wide** for 24/7/365 days/year (no energy storage required)
  - (b) highly redundant with graceful degradation
  - (c) Fresnel lens concentrators for thermionic conversion
  - (d) solar sail propulsion

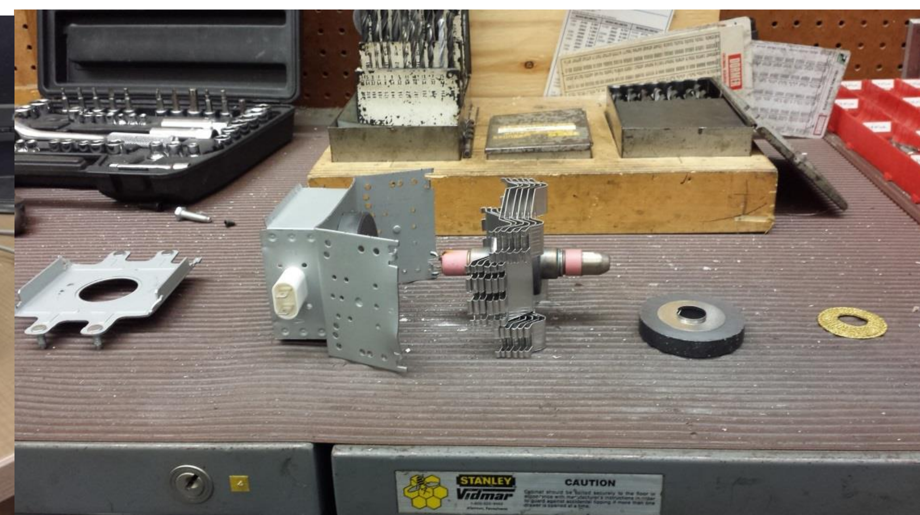
Problem – launch cost of \$75T (@\$20,000/kg)
– cf. US DoD is \$700 B/y

Magnetron

- We intend to 3D print a magnetron – it is a macroscopic vacuum tube with "motor" elements + cooling fins
- We wish to explore direct thermal heating of the cathode using solar concentrators to eliminate electrical conversion stage
- Magnetron is the centrepiece of the SPS
- Magnetron introduces further capabilities for self-replication:

  (i) regolith processing; (ii) pn junction doping; (iii) scientific analysis instruments (MIBS)
- We have experimented with metal powder (copper) impregnated clay with microwave melting



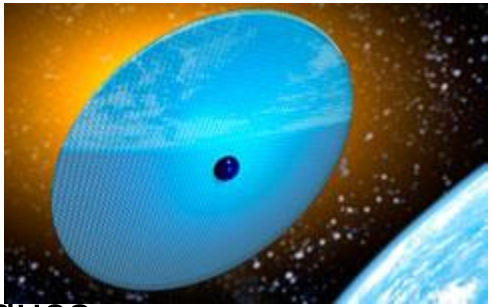


Space-Based Geoengineering – Solar Shield

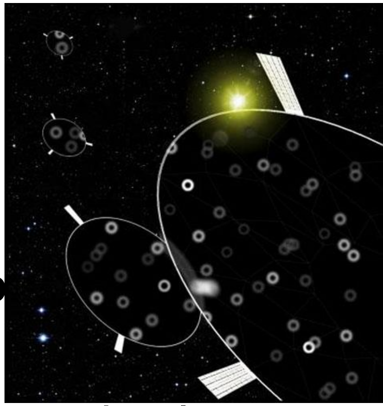
- Space-based geoengineering (solar shield) - is commonly ignored for its enormous cost and technological immaturity
- It deserves re-consideration as it offers advantages:

(a) no direct chemical interaction with the Earth's atmosphere

(b) controllable, modulatable and fully reversible



- **Fresnel lens** (monolithic or distributed) at **Sun-Earth L1** to reduce solar flux by 1.8% (1000 km diameter)

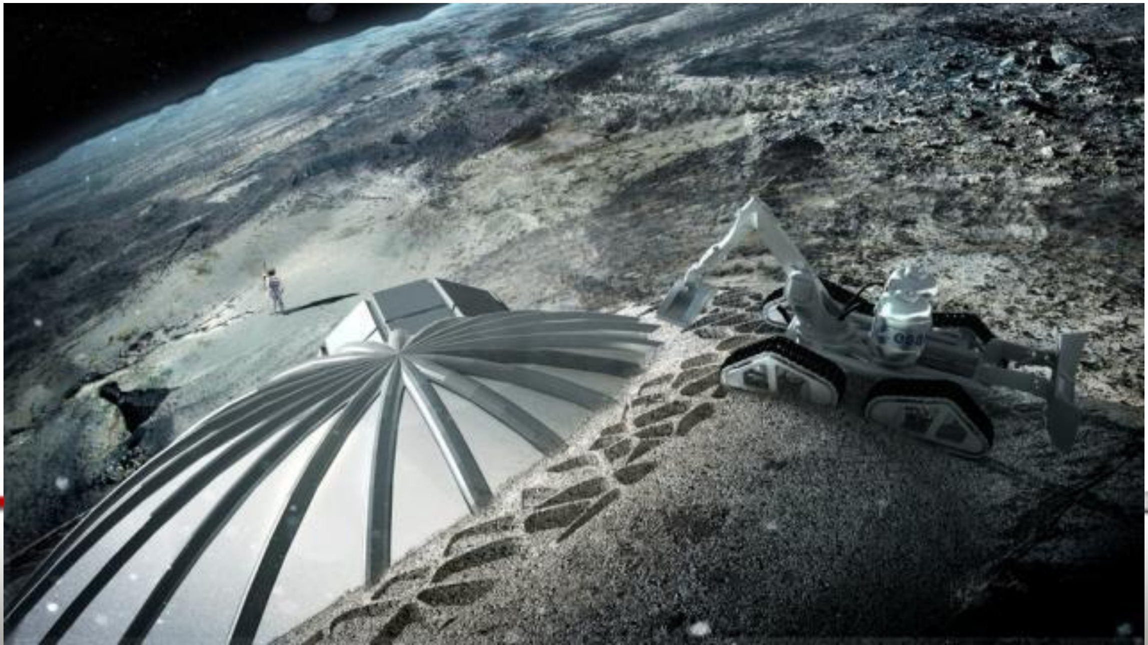


- Angel approach proposes diffuse cloud of 1.6 x **10^{13} refracting glass discs** of 60 cm diameter each embedded in a solar sail
- Requirement: **1 tonne sticks of 800,000 discs every 5 minutes for 10 years by 20 x 2 km railgun launchers from Earth**
- Cubesat technology offers greater sophistication for controllability, e.g. circular constellation rather than diffuse cloud
- Problem - launch cost
- SOLUTION: **Universal construction of SPS fleet/solar shield modules on the Moon**

In-Situ Construction of Lunar Bases

Lunar Base Concepts

- Lunar base is constructed robotically from in-situ resources prior to human arrival and occupancy
- Moon Village is an open concept to build a complete infrastructure comprising several lunar bases devoted different tasks operated by different institutions
- Planetary habitat assumes 120 m^2 per person
- **Thin metal (nominally aluminium ~10-12 cm thick) enclosures are simple and expandable in modular design with tubular connecting corridors – aluminium extractable from anorthite**
- Mobile habitats are of this type but limited to ~10 tonnes
- *Inflatables, tensegrity structures and trusses require internal layers typically flexible organic fabrics –* **organic material is scarce → unsustainable**
- 2.5 m thick regolith covering provides both radiation protection and thermal insulation



Lunar Base Infrastructure

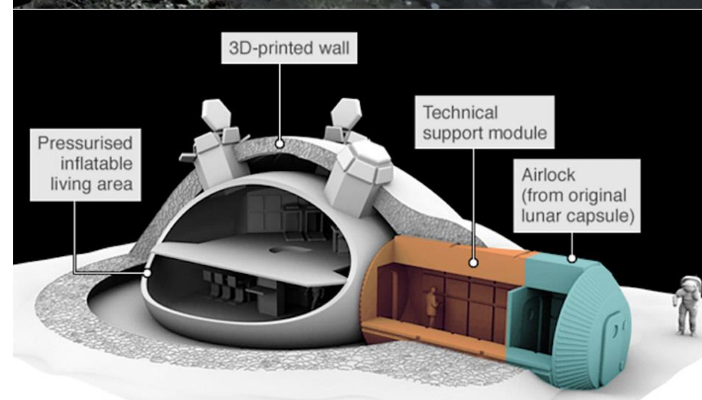
- Several possible modular configurations typically involving the arrangement of private quarters in relation to bridge, wardroom/galley and labs
- Vitruvius' *Ten Books on Architecture* comprised 8 books on buildings, one book on mathematical astronomy and **one book on machines**
- **Robotic systems** for transport, surveying, exploration, mining, processing manufacturing, assembly, recycling and repair are crucial
- Construction machines – kinematic machines - are the key to leveraging in-situ resources
- <u>We concentrate on module construction</u>:
  - **Compressive load material for civil construction** using **cranes, 3D printers, etc**
  - **Internal décor** esp private quarters
  - Paved or rail roads or subway tunnels using **drills, borers, etc**
  - Cargo-handling using **LHD rovers, cranes, etc**
  - Bridge (control and communications)
  - Galley and wardroom
  - Medical lab/sickbay + science laboratories
  - Life support systems + airlocks/suitports + EVA suits + personal hygiene
  - Agricultural hydroponics/aquaculture (greenhouse facilities)
  - Launch pads/electromagnetic launchers

Civil Engineering Materials

- Various cements may be considered:
- (i) Traditional Portland cement is not feasible on the Moon due to material restrictions
- (ii) Sulphur concrete is not suitable because: (a) it requires large amounts of scarce sulphur; (b) its melting point at 120^{o}C is incompatible with lunar day temperatures
- (iii) Lunarcrete – 60-69% CaO (from anorthite), 20-24% SiO_2 (from silicates), 3-4% alumina (from anorthite) and 2-4% haematite (from ilmenite) melted at **3000 K**, quenched and mixed with water (reduced to 15-25% by pressurized steam injection)?
- Regolith can be exploited in several ways:
- (i) 90% regolith + 10% thermoplastic binder heated to 230^{o}C require binder import from Earth (1 tonne per 10 tonne regolith)
- (ii) 98% regolith + 2% aluminosilica geopolymer activated by (Na_2SiO_3+NaOH) solution requires bulk NaCl from Earth (200 kg per 10 tonne module)
- (iii) *60-70% regolith + 30-40% aluminium or steel powder binder (from anorthite or ilmenite)*
- (iv) *100% regolith sintered thermally at 1800^{o}C using solar concentrators (trading sustainable solar energy for unsustainable imports from Earth)*
- *Basalt – powdered and melted at 1200-1300^{o}C then cooled slowly*

3D Printing Civil Engineering Structures

- **Compressive structures** include columns, shells, bricks and beams under compression may be 3D printed
- Bricks and joints **welded together using thermite reaction**: $Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3$
- Each of these materials is amenable to casting in moulds and **3D printing** through automated construction cranes – **cement, regolith (with binder or sintered) and basalt**
- 3D printing on the Moon has become *haute couture* amongst architects, e.g. 3D shaping
- In **contour crafting and D-shaping**, lunar regolith is mixed with a binder and extruded in layers to form **outer shells** of lunar bases
- <u>**Contour crafting**</u> **extrudes paste** through nozzles and smoothed with robotic trowels layer-by-layer
- <u>**D-shaping**</u> **extrudes regolith premixed with binding fluid** from nozzles and deposited in layers using a gantry-mounted extrusion head
- Binder is saturated $MgCl_2.6H_2O$ solution (derivable from olivine with bulk NaCl import) which reacts with regolith MgO in ratio 1:3 to form **Sorel cement $Mg_4Cl_2(OH)_6(H_2O)_8$**
- Thermal regolith sintering is compatible with 3D printing technology



Source: ESA, Foster+Partners

Versatility of 3D Printed Lunar Base

- 3D printing lunar bases introduces **decorative architecture at minimal material cost**:
- Arches and accolades
- Balconies and balustrades
- Columns and cornices, e.g. **classical orders**
- Facades and fanlights
- Eaves and gables
- Pediments and oriels
- Vaults and domes, etc

- **Shermerhorn symphony centre Nashville** (opened 2006) indicates the **versatility of neoclassical architecture within the constraints of functional form**
- ***Kaolinite is a waste product of lunar industrial ecosystem - heating to 1200-1400^{o}C yields porcelain***
- Electrical cabling, water pipes and air ducts require construction of cavities for (i) prefabricated cables, pipes and ducts OR (ii) ability to **3D print cabling, piping and ducting** in-situ in different materials during build
- **Electric cables** – metal (aluminium) conductors integrated within electrically insulating ceramic (porcelain) or glass enamel, fibre or cloth
- **Air ducts** are typically aluminium with airflow controlled with **motorised fans**
- **Water/sewage pipes** are commonly iron (requiring internal lining of cement in lieu of galvanisation) or ceramic (such as **basalt**) with fluid flow controlled by **motorised pumps**

Internal Decor

- **Human psychology is an important facet of lunar bases** and is influenced by light intensity, colour, texture, acoustics, etc
- Hydrated gypsum ($CaSO_4.2H_2O$) plaster mixed with glass fibre can be sandwiched between fiberglass mats to form **plasterboard for internal walls and ceilings**
- Evolutionary psychology is premised on the evolution of **human cognition in the natural environment** – we enjoy **natural landscapes** as vistas, paintings and photographs (e.g. John Constable)

- Visual cues that <u>emulate the natural</u> terrestrial environment <u>enhance human harmony</u>
  - Faux wood-like wall paneling
  - Faux wood-like painted furniture
  - Walnut dash effect on instrument panels
  - Porcelain tile flooring (with stone or wood-like effect)
- **Greenhouse** for psychological and physiological value introduces further possibilities such as (i) <u>interior plants</u> and wall-climbing vines; (ii); PLA (from corn starch) for faux wood; (iii) wall soft-furnishing <u>fabrics from silkworms and hemp</u> to dampen acoustic noise from rotating machinery

Internal Décor II

- **Coloured paints leveraged from lunar resources**:
- (i) Ochre is a mixture of clay and haematite giving colours from mustard yellow to earthy red
- (ii) Addition of small amounts of manganese oxide provides sienna, a browner hue – manganese is rarified on the Moon
- (iii) White (TiO_2) and black (Ti_2O_3) pigments are derivable from lunar ilmenite
- (iv) Egyptian blue $CaCuSi_4O_{10}$ is manufactured by heating copper carbonate, quartz sand, calcium carbonate and small amounts of natron (mixture of hydrated soda ash and baking soda):

  $Cu_2CO_3(OH)_2 + 8SiO_2 + 2CaCO_3 \rightarrow 2CaCuSi_4O_{10} + 3CO_2 + H_2O$

  This requires sourcing copper and carbon which are rarified on the Moon but cobalt blue may be possible
- (v) Cr_2O_3 is a green pigment – chromite relatively abundant on the Moon
- **Interior of communal areas** may be painted warm earthy brick-red/burnt orange using ochre
- **Interior of work areas** may be painted earthy green using chromite
- **Interior of laboratories**, sickbay and galley may be painted sterile off-white to reduce glare such as battleship (haematitite-tinged) grey
- **TiO_2 nanoparticles** (derived from ilmenite) decompose organic contaminants in the presence of solar UV light → self-cleaning interior surfaces, disinfecting indoor air and contaminated water:

  $TiO_2 + C_2H_4 + 3O_2 + hv \rightarrow TiO + 2CO_2 + 2H_2O$

  $TiO + ½ O_2 \rightarrow TiO_2$

Environment Control & Life Support Systems (ECLSS)

- Human consumes 38.5 kg **consumables/person/day**
- This is dominated by **25-30 kg water** (which reduces to 13.7 kg with grey water recycling) including 3.2 kg for imbibing
- In addition, we require 0.8 kg oxygen + 0.64 kg dry food
- We excrete 0.94 kg faeces + 1.63 kg urine + 0.95 kg CO_2
- Early space missions were open loop in which all consumables were supplied and stored onboard and waste dumped
- **To optimise launch cost savings with minimum technological effort,** water recycling or in-situ resupply is prioritorised
- Subsequent missions began physicochemical recycling of bulk consumables – water and oxygen

  e.g. ISS Oxygen Generation System and Water Recycling System provides 70-80% water/oxygen recycling
- On the Moon, there are significant **resources of water ice** but these are earmarked for burning as propellant/oxidiser – a competing resource user

Closed Ecological Life Support Systems (CELSS)

- If the goal is to **maximise independence from Earth**, this requires elimination of Earth supply by CELSS and/or in-situ resupply
- Bulk nutrients, macronutrients and micronutrients are supplied in growth medium (soil or hydroponic solution) – **extensive recycling will be required**
- Bulk needs are ***C***HO***N***PKS
- C and N are rarified in lunar volatile form so cannot be supplied from lunar resources
- **Macronutrients**/person/day – 3.5g **K**, 2.5g Na, 1g **Ca**, 0.26g **Mg**, 0.14g **Fe**, 0.07g Zn
- **Micronutrients** – Mn, Cu, Sn, Mo, Pb, **Al**, **Ti**, B, **Ni**, **Cr**, V and **Co**
- K, P and S could be sourced from KREEP minerals, orthoclase and NiFe asteroid material (as troilite FeS) respectively but KREEP processing is a 2^{nd} Gen ISRU technology
- **Ca, Mg, Fe, Al, Ti, Ni, Co** may be sourced through the **closed lunar industrial ecology system**
- This favours **bioregenerative (closed ecological) life support** with 100% waste recycling
- If food production is included, inedible plant waste increases waste generated by a further **10 kg/person/day**
- This requires much greater technological effort

Waste Recycling in CELSS

- Key to CELSS is **waste recycling of nutrients**:

  (i) Simplest waste recycling is **water recovery from urine/faeces**

  (ii) **Wet oxidative combustion of waste** in $H_2O_2 \rightarrow CO_2$ gas and mineralized waste (source of N, etc) + Knopf's solution → manure

  (iii) Haber-Bosch process $N_2 \rightarrow NH_3$ with catalyst (Fe_3O_4 core + FeO shell + Al_2O_3 + CaO - all derivable from lunar ilmenite and anorthite respectively)

- Fritz Haber – hero or villain?

  - Haber-Bosch process increased crop production by 25-30% by eliminating crop rotation by nitrogen fixation by rhizobium-infected legumes

  - As a German, Haber also pioneered Cl_2 gas as a chemical weapon during WW1

  - As a former Jew, Haber left Nazi Germany in 1933 but died en-route to Palestine

- Biofilm fouling reduced by **NO** that interrupts quorum sensing in pathogenic bacteria
- **MELISSA** is CELSS based on 5 bioreactor compartments based on microbial activity **–** (i) anaerobic composter; (ii) fatty acid-food converter; (iii) urea-nitrate converter; (iv) hydroponic photosynthesiser; (v) human consumer

Food Production

- 10 m^2/person cultivated land area provides:
  (i) 100% O_2 recycling through photosynthesis
  (ii) 200% water recycling through evapotranspiration
  (iii) 50% food requirement
- Hydroponics/aeroponics eliminates reliance on lunar regolith and its minerals
- Hydroponics permits vertical farming with reduced areal footprint
- Rockwool growth medium may be constructed from in-situ manufacture basalt fibres
- **Reliable manufacture of nutrient-laden Knopf's solution from lunar/recycled resources will be crucial**
- Algae offer 10-15% photosynthetic efficiency compared with 1-3% in higher plants
  (i) Spirulina is cyanobacteria – yummy, yummy?!
  (ii) Seaweed is algae, e.g. laverbread (Welsh dish)
  (iii) Agar agar is red algae used in molecular gastronomy
- Range of **20 vegetables** provides a robust diet

Animal Husbandry

- **Insects such as silkworms** (e.g. China) – ground into protein-laden flour
- Seafood (such as prawn aquaculture) including fish (e.g. tilapia) have neutrally buoyant lifestyle requiring 5-20 times less specific energy to rear
- e.g. armoured catfish Hassa – bottom-feeding fish feeds on algae, benthic invertebrates and detritus in mudpools of Guyana – easily cultured
- Curry paste – high in antioxidants (incl garlic – turmeric – ginger – coriander - chili)
- Guyanese bhaji (spinach – chilli – onion – garlic – tomato)

- From Alica's pepperpot
- Rice is not viable

Self-Replication on Mars

Mars Exploration

- SpaceX proposes delivering **“naked” astronauts** to the Martian surface
- The ability to “**live off (of?) the land**” is implied
- **Differences from Moon**:

  (a) Haematite (low Ti) not ilmenite for Fe

  (b) Abundant volatiles and salts – C, S, Cl, etc

  (c) Abundant CO_2 as a carbon resource
- ISRU is a leverage technology for human Mars exploration first proposed by Robert Zubrin
- In particular, the **Sabatier reaction with water electrolysis** has been adopted as the default ISRU technology:

  $CO_2 + H_2O \rightarrow CH_4 + 2H_2O$ and $H_2O \rightarrow H_2 + 0.5O_2$
- This involves minimum complexity processing for the provision of consumables (thereby reducing costs)
- **Lunar industrial ecology may be adapted to exploit Martian resources**
- Self-replication is the most efficient means to exploit in-situ resources – it guarantees independence from Earth supply

Extraction of Iron/Alumina/Silica

- **Carbothermal reduction of haematite** at ~1000^{o}C creates iron and CO_2

  $Fe_2O_3 + 3CO_2 \rightarrow 2Fe + 3CO_2$
- Carbothermic reduction can be applied to other oxides
- **Extraction of silica/silicon** may occur through several different mechanisms:

  (i) Carbothermal reduction of plagioclase ($CaAl_2Si_2O_8$)

  $4CH_4 \rightarrow 4C + 8H_2$ (T=1400^{o}C)

  $CaAl_2Si_2O_8 + 4C \rightarrow CaO + \mathbf{Al_2O_3} + 2\mathbf{Si} + 4CO$ (T=1650^{o}C)
- **Alumina ceramic has engineering properties tending towards diamond**

  (ii) Carbothermal reduction of lunar olivine (Mg_2SiO_4):

  $Mg_2SiO_4 + 2CH_4 \rightarrow 2CO + 4H_2 + 2MgO + \mathbf{Si}$ (T= 2000^{o}C)

  (iii) Artificial weathering of plagioclase with HCl (derived from salts):

  $CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2\mathbf{SiO_2}$
- This produces **$CaCl_2$ electrolyte** for FFC process
- **Martian ISRU proceeds in the same way as lunar ISRU with minor differences**

Silicone Oils/Plastics Manufacture

- **Syngas ($CO + H_2$) is the starting point** for the manufacture of both plastics and siloxanes.
- Formation of syngas at 850^{o}C and 4 MPa over **Ni** catalyst: $CH_4 + H_2O \rightarrow CO + 3H_2$
- Formation of methanol (or higher alcohol) at 250^{o}C and 5-10 MPa over **Al_2O_3** catalyst: $CO + H_2 \rightarrow CH_3OH$
- Formation of chloromethane by **HCl** action at 350^{o}C over **Al_2O_3** catalyst: $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$
- Formation of dialkyl dichlorosilane from **Si** at 370^{o}C in presence of catalyst (**Ni or clay mineral**): $2CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2$
- Formation of polydimethylsiloxane **(PDMS) – simplest siloxane – by hydrolysis**: $n(CH_3)_2SiCl_2 + nH_2O \rightarrow ((CH_3)_2SiO)_n + 2nHCl$
- This is the **Rochow process** and HCl is recycled
- **Plastic elastomers** are used for flexible insulation, transmission belts, fluid hoses, sealant and gaskets, adhesive and expansion joint, and sock/vibration mounting
- **Silicone rubbers** are elastomers stable at high temp ~300^{o}C (cf polyurethane cap at 120^{o}C) and UV-resistant
- **Silicone oils** for mechanical lubrication and cooling fluid
- **High utility plastics** – BoPET (mylar), PEEK (high temperature), PVDF (piezoelectric), PMMA (multi-use) – require complex manufacturing processes – **do we want to transport our terrestrial mistakes to new environments?**

Asteroid Mining

Strawman Asteroid

- S-type constitute 17% asteroids dominantly in the inner belt (50% NEA)
- SM-type constitute 15% asteroid population primarily in the inner belt
- M-type asteroids constitute only 8% asteroid population
- C-type asteroids constitute 75% asteroids dominating the mid and outer belts (20% NEA)

Asteroid Mining Targets

- There are 4 main types of NEA – **C-type, S-type, SM-type and M-type**
- **Some of each is ideal** for their different compositions but they reside in widely varying orbits, often with high inclination differences.
- We have highlighted a **relatively "localised" group**:

NEA	Population	Type	Eccentricity	Semi-Major Axis (AU)	Perihelion (AU)
4660 Nereus (1982 DB)	Apollo	M	0.36	1.49	0.95
162173 (1999 JU3)	Apollo	C	0.19	1.19	0.96
25143 Itokawa (1998 SF36)	Apollo	S	0.28	1.32	0.95

- This still requires **significant manoeuvring capability between asteroid** while the Moon requires only land traverse vehicles powered by solar energy.

Moon versus Asteroids!

Material	C-type	S-type	M-type	Moon
Fe	10%	6-19%	88%	0.1%
Ni	1.4%	1-2%	10%	0
Co	0.1%	0.1%	0.5%	0
C	1-3%	3%	0	0.014%
H_2O	5-12%	0.15%	0	0.045%
S	1-2%	1.5%	0	0.12%
FeO	15-22%	10%	0	15.8%
SiO_2	28-33%	38%	0	42.5%
MgO	20-24%	24%	0	8.2%
Al_2O_3	2-3%	2%	0	13.8%
Na_2O	0.3-0.6%	0.9%	0	0.44%
K_2O	0.04%	0.1%	0	0.15%
P_2O_5	0.25%	0.28%	0	0.12%
CaO	0	0	0	12.1%
TiO_2	0	0	0	7.7%

C-type Volatiles

- C-type asteroids are host to a diverse assemblage of 30% organic material:

Organic Compound	Abundance (μg/g or ppm)
Carbon dioxide	106
Carbon monoxide	0.06
Methane	0.14
Aliphatic hydrocarbons	12-35
Aromatic hydrocarbons	15-28
Carboxylic acids	332
Amino acids	60
Aldehydes	11
Amines	8
Urea	25
Pyramidines	0.06
Purines	1.2
Sulphonic acid	67
Phosphonic acid	1.5

$CO + 0.5\ O_2 \rightarrow CO_2$ and $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300°C (Sabatier)

$CH_4 \rightarrow C + 2H_2$ at 1400°C Ni

- C-type asteroids constitute 75% of NEAs with up to 20% water of hydration - this requires heating to 600-700°C to extract water from hydrated minerals
- Some 10% NEA are spent comet nuclei offer ready source of volatiles – water, organics and silicates
- **As for the Moon, we assume that these resources are unavailable**

M and S type Asteroids

- **M-type asteroids** are dominated by NiFe metals:

Material	Composition					Function
	Fe	Ni	Co	Si	C	
Electrical steel	97%			3%		Soft magnetism
Permalloy	20%	80%				Magnetic shielding
Kovar		29%	17%	0.2%	0.01%	Conductive wiring

- **S-type asteroids** are dominated by silicates (e.g. olivine):

  $Mg_2SiO_4 + 2CH_4 \rightarrow 2CO + H_2 + 2MgO + Si$ at 2000°C

  $MgO + HCl \rightarrow MgCl_2 + H_2O$
- **E-type asteroids** are dominated by the pyroxene enstatite
- We assume that **SM-type asteroids offer variable proportions of S and M-type asteroids** e.g. A-type asteroid comprises (**50% M/50% S**)

Milli-g Operations

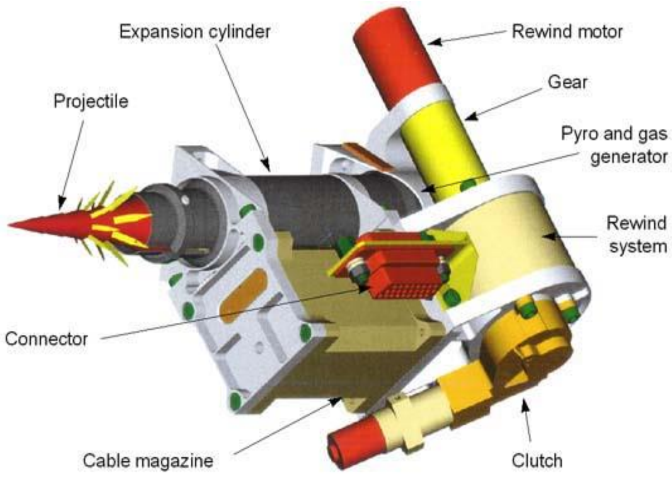
- **Milli-g gravity field of asteroids requires anchorage**
- Terrestrial infrastructure machinery exploits gravity to generate reaction weight
- **Reliable anchorage will be essential** for (i) traverse; (ii) digging/trenching; (iii) drilling; (iv) comminution; beneficiation; (v) fractionation; (vi) 3D printing
- **Trenching** is determined by excavation force:

$$F = N\sin\delta + \mu N\cos\delta + Rb$$

- Partial solution - percussive vibration/preraking reduces applied forces by 20-30%
- **Beneficiation**, e.g. Mond process requires fractionating columns $\frac{A_M}{A_E} = \sqrt{\frac{g_E}{g_M}}$
- Partial Solution: centrifugation
- Drilling performance is based on **weight-on-bit**:

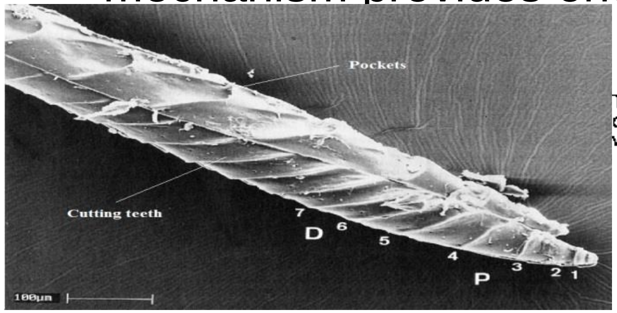
$$PR = \frac{kwW^2}{D^2\sigma_c^2}$$

- Lessons of the Philae lander harpoon loom forebodingly

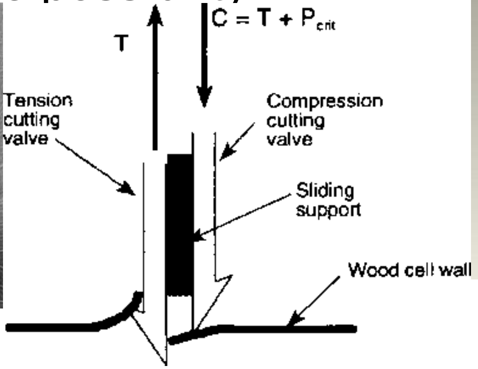


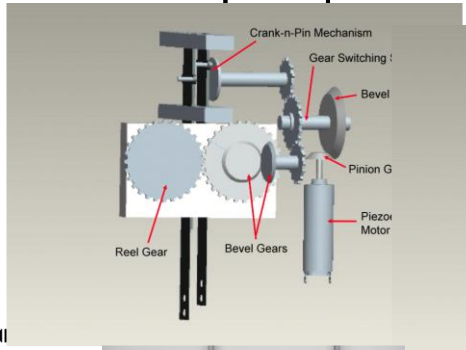
Tunnelling into Asteroids

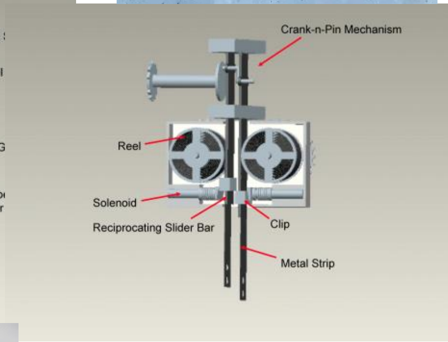
- Extraction of asteroid material may require more sophisticated mining techniques than surface scooping – deep drilling into compactified regolith ~100 m+ depth
- **Bio-inspired drilling** based on the percussive woodwasp ovipositor mechanism provides one possibility



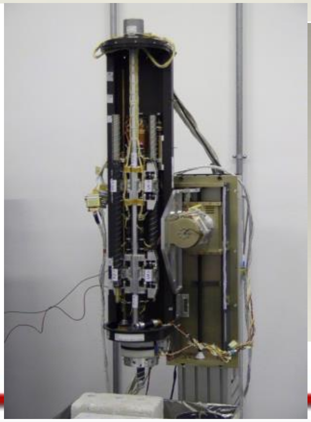
Wood wasp ovipositor

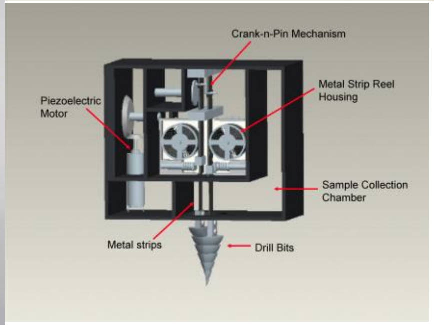






- Minimises structural load on drill string
- **Eliminates weight-on-bit infrastructure**
- **Coiled** for compact storage – this eliminates drill string assembly





This concept requires further development

Milli-g Manufacturing

- 3D printing requires gravity field to settle layers and minimise delamination

Gravity Regime	Layer Thickness
Zero-gravity	1.43
Lunar gravity	1.13
Mars gravity	1.0
Earth gravity	1.0
2g gravity	0.78

- Partial solution: Made In Space claim to have solved the problem with plastic extrusion on ISS (by viscosity control?)
- Applicability to high temperature metal 3D printing?
- Welding – friction stir welding requires no gases, etc but requires applied forces ~10 kN
- Partial solution: Thermite welding - Electron beam welding
- These issues are similar to those imposed by a Space Manufacturing Facility

Consumption of Asteroid Threats through Self-Replication

Introduction

- Traditional impact threat from asteroids was the Earth orbit crossing Aten and Apollo NEO population.
- There are **170 impact craters on Earth**:

  (i) 250 km diameter Sudbury crater (1.8 Gy old)

  (ii) 180 km diameter Chicxulub crater (65 My old) otherwise we would all be velociraptors

  (iii) 1.3 km diameter Barringer crater Arizona (50,000 y old)

  (iv) **No crater but Tunguska** (1908) was caused by a 30-40 m diameter stony asteroid airbursting at 8 km altitude – it destroyed 2000 km^2 forest

  (v) **No crater but Chelyabinsk (2013)** was caused by a 18m diameter stony asteroid airbursting at 20 km altitude blast-injuring 1500 people
- Global-killer NEO **threat has diminished** thanks to Spaceguard-type observation surveys
- **Threat of regional devastation remains** + comet threat is still unknown

Asteroid Mitigation Problem

- Prior to encounter, there are certain physical parameters that can be estimated remotely from magnitude – diameter, mass, Jacobi constant and rotation period
- A series of reconnaissance manoeuvres will be required for more detailed analysis
- Many mitigation techniques require despinning – this may be accomplished by yo-yos or implanted thrusters
- The required Δv to deflect an asteroid from impacting Earth by $2.5R_E$ is given by:

$$\Delta v = \frac{d_{min}\sqrt{\mu r}}{3t\gamma v_E}\frac{1}{\sqrt{a(2a-R_E)}} = 3.5\times 10^{-2}/t \text{ m/s where t=warning time (y)}$$

- Earth has a diameter of 12,759 km travelling at 30 km/s (one Earth diameter in 425s, i.e. just over 7 minutes)

Asteroid Mitigation Solutions

- There **8 main approaches to NEO impact mitigation**:

  (i) Kinetic impactor

  (ii) Nuclear detonation

  (iii) Gravity tractor

  (iv) Surface ablation by solar concentrator or laser

  (v) Rocket engine emplacement

  (vi) Ion beam deflection

  (vii) Albedo manipulation

  (viii) Tethered ballast
- These may be grouped into **3 categories** – (a) destructive approaches, (b) remote deflection approaches, (c) landed asset deflection approaches
- Most asteroid impact mitigation techniques require **1-20 years warning time** (warning time depends on size of the impactor)

Basic Principle of Asteroid Mitigation Approach

- We propose a self-replication process to minimise the cost and warning time and maximise adaptability
- A single **10 tonne self-replicating machine** is delivered by a 15 tonne spacecraft (launched to GTO by a Falcon 9 launcher) to the surface of 0.5 km diam Bennu (target of ARM)
- We assume C-type asteroid offers diverse assemblage of sufficient raw materials
- It constructs as many **copies of itself** as necessary from local asteroidal resources until required productive capacity is attained
- Whence, it constructs in parallel required number of **electromagnetic launchers from local resources**

Material Percentage	C2 Carbonaceous Chondrite	NiFe Meteorite
Fe	10.7	91.4
Ni	1.4	7.6
Co	0.11	0.49
C	1.4	0.3
H_2O	5.7	
S	1.3	<0.005
FeO	15.4	
SiO_2	33.8	
MgO	23.8	
Al_2O_3	2.4	
Na_2O	0.55	
K_2O	0.04	
P_2O_5	0.28	
P	-	0.19

Electromagnetic Launcher

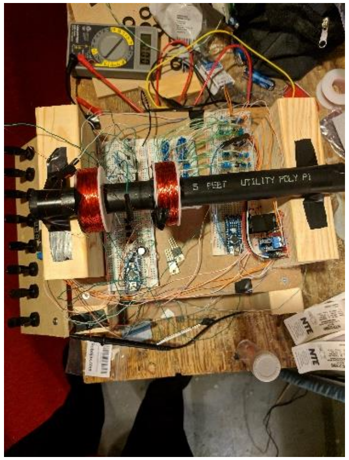
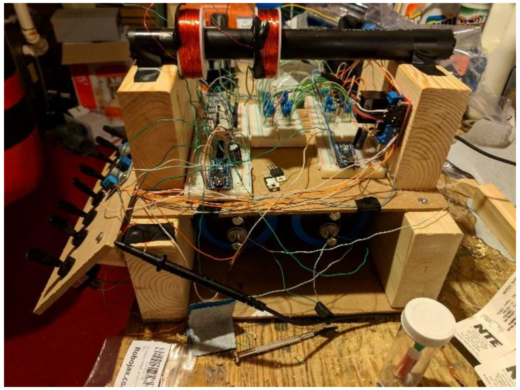
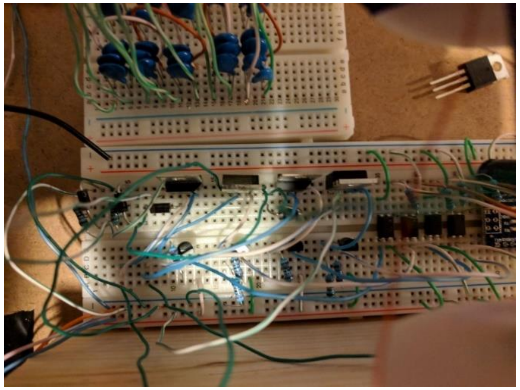
- **Electromagnetic launcher extracts raw material and ejects it as propellant to impart thrust**
- Two options:

  (i) railgun requires sliding contact between rails

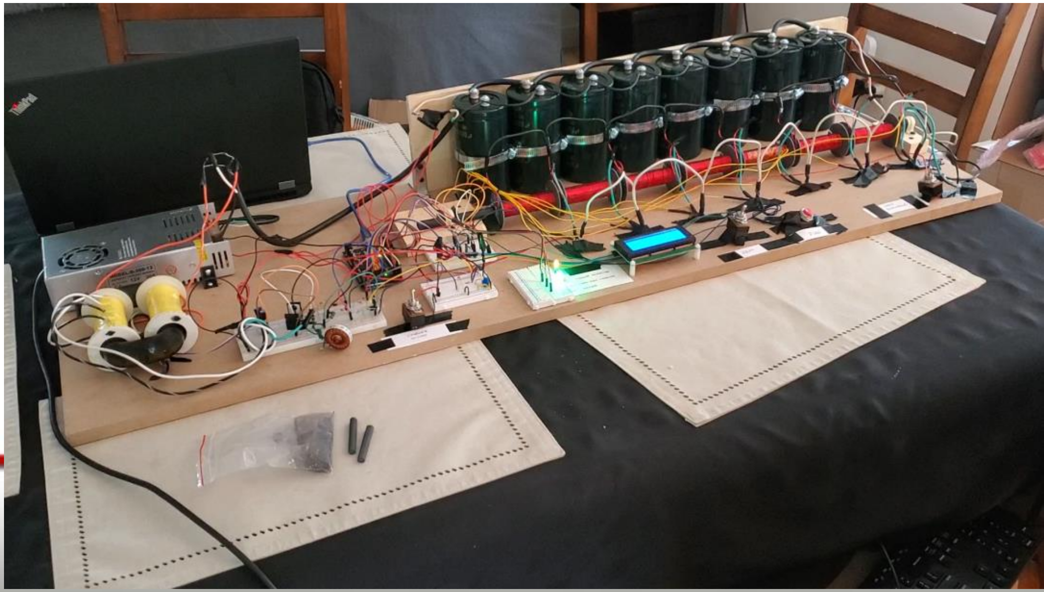
  (ii) coilgun requires no contact
- <u>Coilgun</u> uses electromagnetic Lorenz interaction (F=JxB) to accelerate a conducting armature
- Built from modular sections to form a barrel
- Each stator coil current pulse must be synchronised sequentially to create a travelling magnetic pulse to accelerate the armature

Electromagnetic Launcher

- Electromagnetic launcher consumes only solar-derived energy
- Electromagnetic launcher – **coilgun is a rolled out linear DC motor**

- Carleton desktop e/m launcher built by Alex Craig-Sheldon



Carleton UNIVERSITY

Coilgun Operation

- The coilgun generates a Δv given by:

$$\Delta v = \frac{n.m_{pellet}}{m_{ast}(t)} v_{ex}$$

$m_{ast}(t)$=asteroid mass, n=number of pellets, $m_{pellet} = \frac{2P\Delta t}{v_{ex}^2}$, Δt=time between pellets

$$P = IV = \frac{\pi}{2}\frac{mv^2 l_c v}{\eta l_s l_a}$$ =20 GW

- This is due to 200 MJ over 0.012s accelerating a 20 kg payload at 200 km/s^2 along a 15m long gun to eject at 2.5 km/s

$$\frac{V}{n} = \frac{\pi v}{l_a}\sqrt{\frac{1}{2}\frac{\mu_0 r_c^2 k_L(1-k_a^2)(1+k_c)mv^2}{2\eta l_s}}$$ =21 kV with n=2

$$I = \frac{1}{2}\frac{\pi m v^2 l_c v}{\eta l_s l_a (1+k_c)V}$$ =490 kA

- The 9 tonne mass of coilgun (specific mass of 400 kg/m) is dominated by its power supply

Power Supply

- Each **1 tonne power supply module** comprises 1 km^2 mirror reflectors (specific mass ~0.1 kg/m^2) generating 1.2 GW (assuming solar constant of 1360 W/m^2 and reflectivity of 0.9)
- Thermionic conversion to electrical energy yields η~15% with **0.18 GW electrical power/1 tonne module**
- Each electromagnetic launcher requires 110 mirror modules **for 20 GW**, i.e. **100 tonnes**
- Electromagnetic launcher **throughput is 20 kg at 80 Hz** (1600 kg/s) supplied by a bucket-wheel excavator
- **One electromagnetic launcher imparts $\Delta v = 5.7 \times 10^{-5}$ m/s** – this imposes a required warning time of 560 years

Asteroid Exocytosis

- Asteroid Bennu of 0.5 km diameter ($7x10^{10}$ kg) to be **consumed by two phases of operation**:
- **Phase 1**: **Replication of 10 tonne** self-replicating machines that build a population of self-replicating machines
- Effective construction rate of 0.2 kg/s yields a generation time of 14 days to construct 2 x 100 tonne power supply for 20 GW and 2 x 10 tonne electromagnetic launcher coilguns
- **Phase 2**: Consumption of asteroid using population of electromagnetic launchers to eject (consume) 200 kg/s each
- Total warning time $t=t_{prep}+t_{cons}$ where $t_{prep}=pt_{gen}$=preparation time

$t_{cons} = \frac{m_{ast}}{\dot{m}n}$, $n = \frac{3.2x10^{-2}}{t(y)\Delta v}$=consumption time, $\Delta v = \frac{\dot{m}_{prop}}{m_{ast}} v_{ex}$

- Population, $N = (1+r)^p$ so $p = \frac{\ln(n)}{\ln(1+r)}$ generations, i.e. $t_{prep} = \frac{\ln(n)}{\ln(r+1)} t_{gen}$
- For optimal performance, $t_{prep}=t_{cons}$: $\frac{\ln(n)}{\ln(r+1)} t_{gen} = \frac{m_{ast}}{\dot{m}n}$
- Hence, $nln(n) = \frac{m_{ast}\ln(r+1)}{\dot{m}t_{gen}} = 40$
- This yields n=no. electromagnetic launchers=no. universal constructors (minimum time assumption), n=15 (<3 generations of self-replication)
- Total time for both self-replication and consumption of asteroid is **76 days** – this is much faster than any other proposed method of asteroid mitigation
- **Total time scales logarithmically with asteroid mass**

Debris Mitigation & On-Orbit Manufacture

Space Debris Mitigation

- Since 1957, around 6000 satellites have been launched of which around 860 are operational – **non-operational satellites include 30 nuclear reactors from defunct RORSATs**
- There are **22,000 debris pieces larger than 10 cm** increasing to 580,000 pieces larger than 1 cm – spent stages, adaptors, shrouds, etc
- Known **debris events** include Cerise (1996) and **Iridium 33** (2009)
- Deliberate **destruction of Fengyung-1C** (2007) increased debris population by 25% - this highlights the **impotence of the UN Convention** on Liability for Damage by Space Objects (1972)
- **Polar LEO up to 2000 km altitude is close to Kessler limit**
- In GEO, slots over India and Pacific are most heavily populated due to drift
- **UN guidelines** on graveyard orbits at EOL are **ineffective** (observed systematically only by Europe)
- **Refuelling of comsats** will dramatically reduce rate of obsolence, eg. SLES
- **Retrieval of 5-10 largest objects per year** will mitigate against debris growth, e.g. SSC's RemoveDEBRIS tech demo used tethered net and harpoon grappling

Robot Control Systems

- We propose manipulator-based grappling of large debris
- Manipulator control is crucial – biomimetic approach
- Our neural circuitry – sensory cortices, motor cortex, cerebellum and basal ganglia – evolved to solve three computational problems:

  (i) all tasks are defined as movement trajectories of the hand in cartesian world coordinate (all sensors must be cast in the same reference frames)

  (ii) Movement of the hand must be converted into equivalent motion of the arm joints $\theta = f^{-1}(q)$

  (iii) Sequence of joint configurations must be converted into coordinated muscle torques at the joints (inverse dynamics)

  $$\tau_i = D(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta)$$

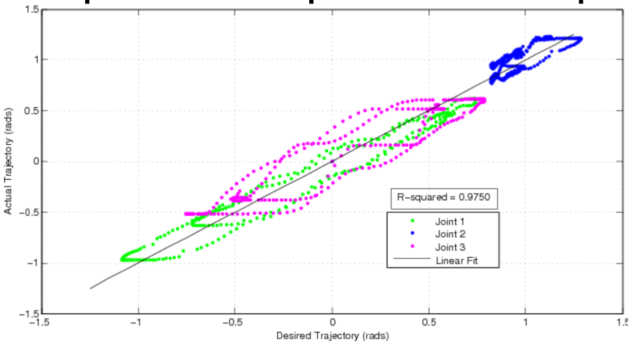
  with a PD control law: $\ddot{\theta}^d = \ddot{\theta} + K_v(\dot{\theta}^d - \dot{\theta}) + K_p(\theta^d - \theta)$

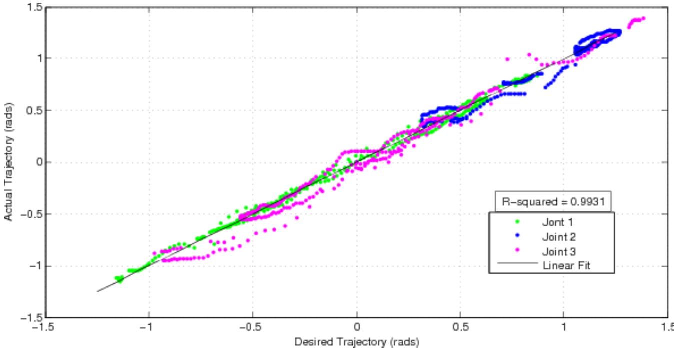
Robust Manipulation

- **Forward model** of manipulator control to emulate human cerebellum:

$$\ddot{\theta} = D(\theta)^{-1}[\tau - C(\theta,\dot{\theta}) + G(\theta)]$$

- **Neural network forward model** was trained from inverse model datasets to implement a predictive capability



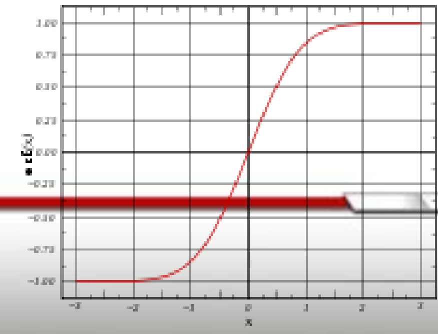


Feedback only　　　　Feedback with feedforward prediction

- We are exploring emulation of **viscoelastic behaviour of muscle-tendon** in electric motors as a zero-order reflex using a sigmoid spring behaviour stabilized with damping in software:

$$\tau = J\ddot{\theta} + b(\theta_{mid} - \theta)\dot{\theta} + k\left(\frac{1}{1+e^{-(\theta_{mid}-\theta)}}\right)$$

- This will enable robust force control (TBD)



Spacecraft Salvage

(A) **Recovery of large separable and refurbishable equipment items** using powered tools for storage:

- Monolithic Al tankage, plates, radiators and frames
- Outer thermal blankets with standard folds
- Wiring harnesses around internal cavity restrained by secondary brackets and cable ties
- Deployment motors/gearing drives for deployment mechanisms for re-lubricating
- Solar array panels for laser annealing
- Internal reaction/momentum wheels and gimbals
- External payload instruments/attitude sensors may be rebuffed using abrasives
- Antennae/travelling wave tubes/transponders/radiofrequency electronics

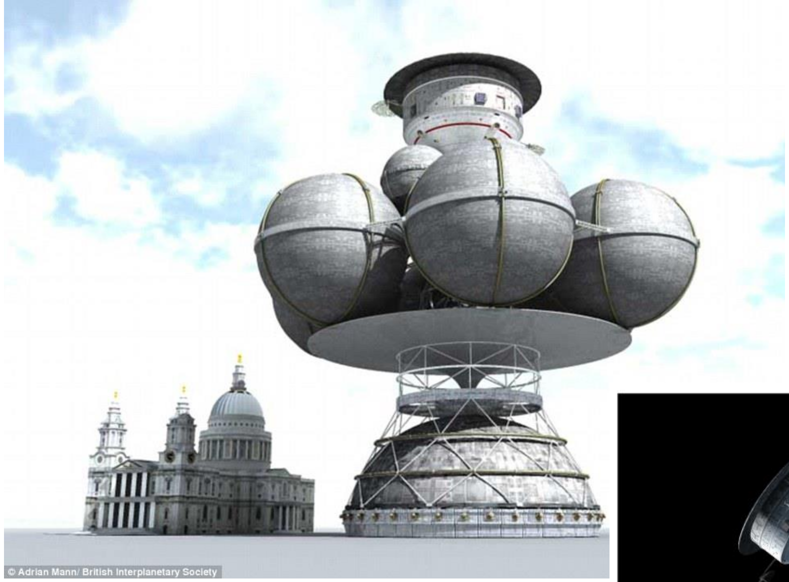
(B) **Process non-recoverable hardware**:

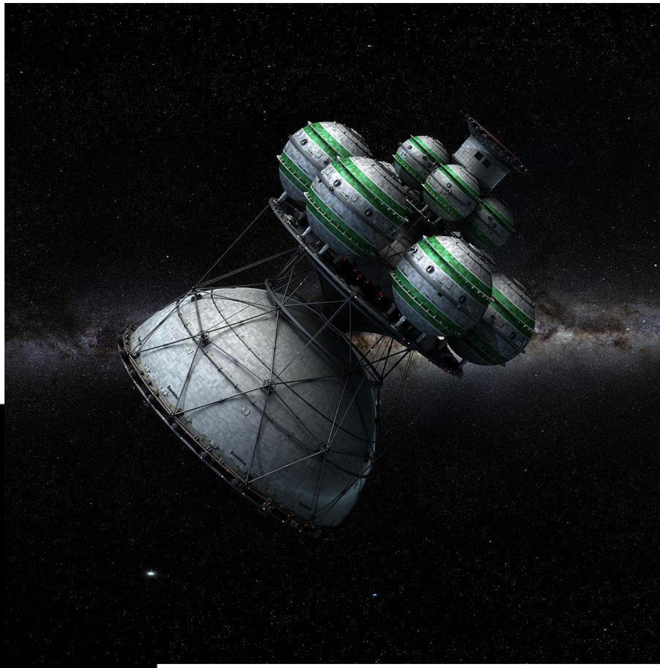
- Grind OBC, batteries, heat pipes into secondary alloy additive powder
- Melt excess Al from primary and secondary structure
- Mix to form space structural alloys as feedstock for EBAM 3D printer for on-demand space structures/solar sail modules

Self-Replication Technology for Starships

Starship Concept

- BIS Daedalus starship (1970s) – two-stage flyby of Barnard's star at 0.12c (50 yr) – D/He^3 nuclear fusion pulse propulsion





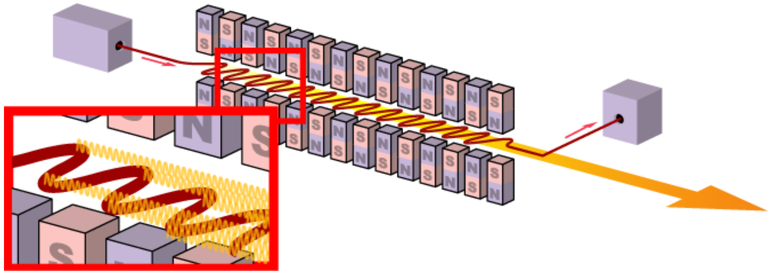
Beamed Interstellar Sail Propulsion

- We may avoid exotic materials and speculative technologies
- **Beamed laser/microwave energy propulsion**

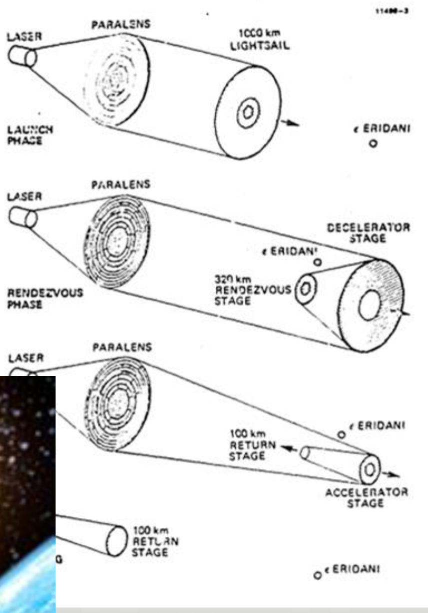
- Lightsail with Mylar/Kapton core (replaceable with **silicone) with aluminium reflector film**
- Tensioning wires of **NiTi shape memory alloy to control sails**
- Deceleration is feasible with magnetic/electric sails – **electromagnetic component manufacture have been demonstrated**

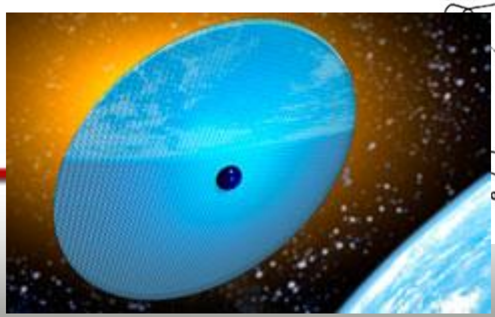
Interstellar Beam Transmission

- Phased laser array options
- **Free electron laser** (FEL) is based on electron gun (vacuum tube) + magnets (motor components) within a Fabry-Perot resonator



- Relativistic electrons are accelerated through **wiggler magnet** (alternating poles) – **coherent e/m radiation** is emitted
- Laser emission is **tunable** from X-rays to microwaves
- Forward lightsail concept requires a **1000 km diameter Fresnel lens** in the outer solar system - fused silica glass
- Solar Shield for space-based geoengineering is similar - - **1000 km diam Fresnel lens** at Sun-Earth L1 to reduce solar flux by 1.8%





System Availability Problem

- Random failures – long-duration components exhibit bathtub failure rate distribution over time
- Infant mortality and senility flank a constant finite orobability of failyre
- Spacecraft fail – software workarounds often yield sub-optimal performance (Exosat 1983)

  - hardware failures require redundant systems, e.g. Galileo Jupiter probe (1989)
- Modern fault diagnosis methods include EKF, PCA, ANFIS, etc
- 50-100 year interstellar flight introduces the problem of system **availability**
- Approaches for the **100-year starship** study was multiple redundancy, high reliability components and computational reconfigurability (e.g. FPGA/GA)
- There are diminishing returns to redundancy

$$A = \frac{MTBF}{MTBF+MTTR+MTFS}$$

- MTBF→∞ is a measure of reliability (traditional approach)
- *MTTR→0 is a measure of maintainability* (<u>onboard servicing</u>)
- *MTFS→0 is a measure of logistic supply* (<u>onboard manufacture</u>)
- A=1 represents perfect availability

Freeflyer Servicing Robots

- Daedalus was supported by several **Wardens** – freeflying servicing “fixit” robots similar to robotic freeflying servicer concepts

ATLAS dual-arm servicer concept to perform simple repairs on satellites

Crucial Starship Design Lessons

- **Solar Maximum Repair Mission** (1984) lost attitude control and required servicing
- Astronauts performed <u>two types of repair</u>:

(i) AOCS ORU replacement with simple bolt-exchanges (7-16 hex bolts) using a single power tool (35 min)

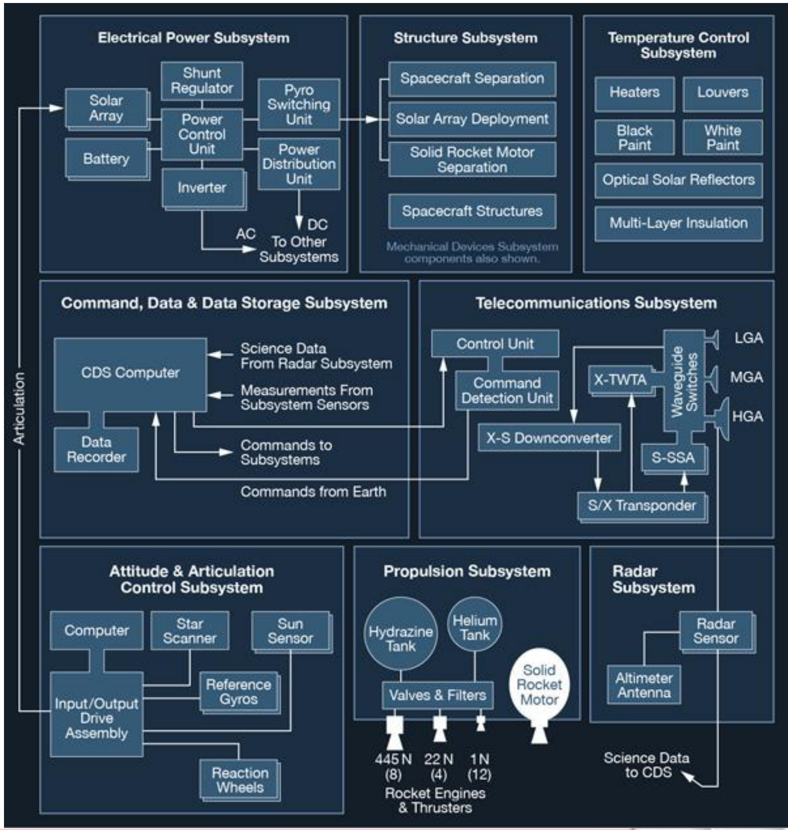
(ii) Non-ORU electronics box replacement required handling, cutting, taping and folding thermal blankets; it required bolt changes of 14 x 10-32 non-capture screws, 4 x 10-32 captive screws and 22 x 4-40 slotted connector screws (2 hrs)

- <u>Lesson 1</u>: standard interfacing of modules – mechanical/electrical/optical/thermal
- <u>Lesson 2</u>: Robotic handling of extended flexible objects requires viscoelastic adaptability
- Modularity simplifies robotic handling
- It assumes that ∃ stockroom of pre-manufactured modules for replacement
- This is not realistic for a starship
- <u>General Lesson</u>: **Full availability requires that starship is designed for self-repair**
- We need full **self-manufacturing facility onboard** to replace ANY component on-demand from a limited set of feedstock

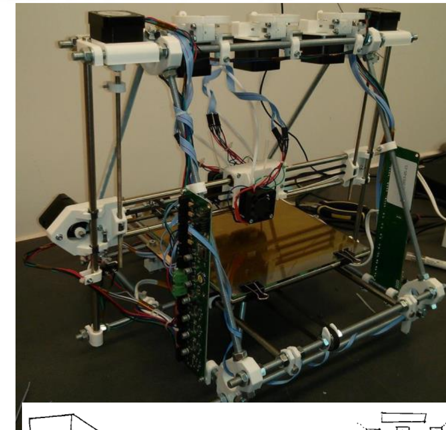
Feedstock Supplies

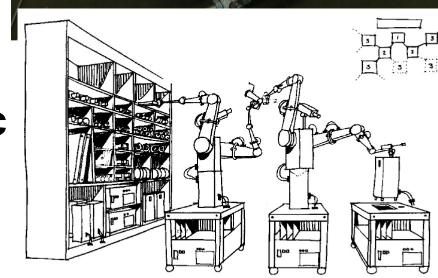
- It is **CRUCIAL** to minimise the range and amount of feedstock required to maintain and repair the starship
- Our **DEMANDITE** concept maps functional material requirements with a fixed set of feedstock resources
- There 7 basic subsystems onboard a spacecraft:
  - Propulsion system
  - Attitude/orbit control including sensors/actuators
  - Structure & mechanisms
  - Thermal control
  - Power
  - Onboard computing including sensor nets
  - Communications (microwave or optical)

- **~10 basic materials** can supply full functionality for all the subsystems of a generic robotic spacecraft
- **Onboard FabLab** must manufacture feedstock into replacement components **including itself**



3D Printing = Universal Construction Mechanism





- **RepRap** FDM 3D printer can print many of its own **plastic parts**
- Full self-replication requires 3D printing:

  (i) structural metal bars and components (SLS/M or EBAM)

  (ii) **<u>electric motor drives</u>**

  (ii) **<u>electronics</u>** boards

  (iv) **<u>computer hardware/software</u>**
- **Universal constructor is a kinematic machine** that can manufacture any other machine *including a copy of itself*
- We adapt UC to unstructured environments through a suite of **kinematic machines**
- **<u>All machines of production are kinematic machines</u>**
- 3D printer suite constitutes a **Universal Constructor** as a generalized kinematic machine that can construct any other kinematic machine
- **Kinematic machines** are specific kinematic configurations of **electric motor systems**
- **<u>From 3D printed electric motors, sensors and control electronics, *omnia sequitur*…</u>**
- If we can 3D print motor systems, we can build any manufacturing machine onboard on-demand

Power of von Neumann Probes for SETI

- **It is but a small step from a self-repairing starship to a self-replicating starship**
- Self-replicating starships are an inevitable consequence of self-repair
- If our interstellar spacecraft carries a self-replicating payload, it constitutes a **von Neumann probe** (self-replicating probe)
- **Premise 1** (**Copernican principle)**: we are developing self-replication technology, ergo so will other technological civilisations if they exist
- **Premise 2 (Tipler premise)**: Self-replicating probes are the most economical means (minimum capital investment amortised over subsequent generations) for interstellar exploration
- Population of self-replicating probes grows as $N = (1 + r)^i$
- **Conclusion:** Entire Galaxy is colonized within 24 generations
- Time to colonise Galaxy is determined by transit time at 0.1c, T~1 My
- **Implication:** This offers rapid transition from Kardashev Type I civilization to Type III civilization
- **Observation**: There are no large-scale technosignatures of industrial activity on our asteroids (**large-scale clay deposits** as indicated by industrial ecology)
- Occam's razor from Kolmogoroc-Chaitin complexity theory: "absence of evidence IS evidence of absence"
- **Corollary**: **ETI do not exist**

Lunar Industrial Architecture