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Prospects for a Self-Replication Infrastructure on the Moon using In-Situ Resources & 3D Printing Technology

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Planetary & Terrestrial Mining Sciences Symposium
2015, Montreal

Preamble

- The only viable, low-cost mechanism to exploit our solar system is through self-replication technology – old idea with emerging viability
- Low cost is enabled through exponentially increasing productive capacity as $\sim(x+1)^n$
- Consider launch of a single 1 tonne self-replicating factory to the Moon at a cost of $2B

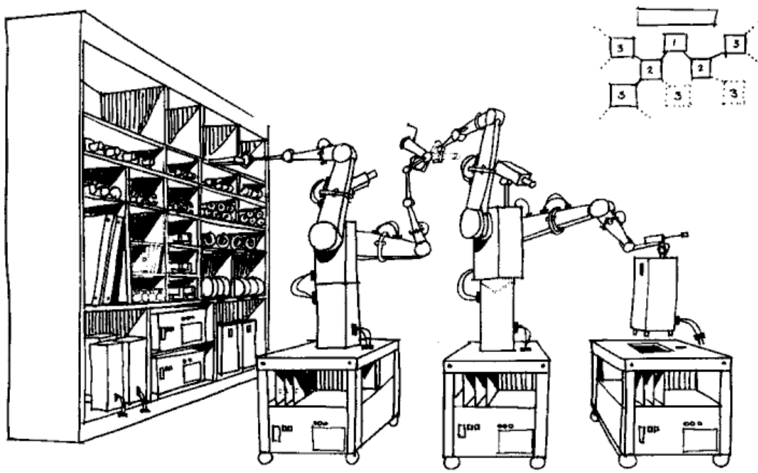
Number of offspring per generation	Number of generations	Population	Specific Cost ($/kg)
1	10	1024	
2	7	2187	<$1000/kg
2	13	1,594,323	<$1.25/kg

- Each of 1 million units produces 1000 units of useful product, we have 1 billion units
- This opens possibilities hitherto prohibitively too expensive to undertake
- We can modulate energy from space - space-based geoengineering (short-term) and solar/lunar power satellites (long-term)
- New engineering philosophy – (i) ground up rather than top down

  (ii) satisficing rather than optimisation

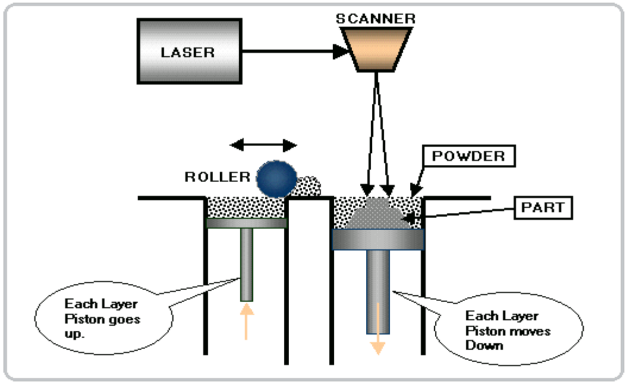
Universal Constructor

- Self-replication *per se* has little utility – we need to create an universal constructor (UC)
- UC is a machine that can manufacture any other machine *including a copy of itself* (generalisation of the universal Turing machine)
- Most important constraint is material and parts closure – each component inherently possesses a back-catalogue of material, processes and control info required
- This means minimising types of raw material and parts to minimise the size of the back-catalogue
- von Neumann idealised UC as a programmable robot arm in a sea of parts
- We need to consider ISRU for feedstock

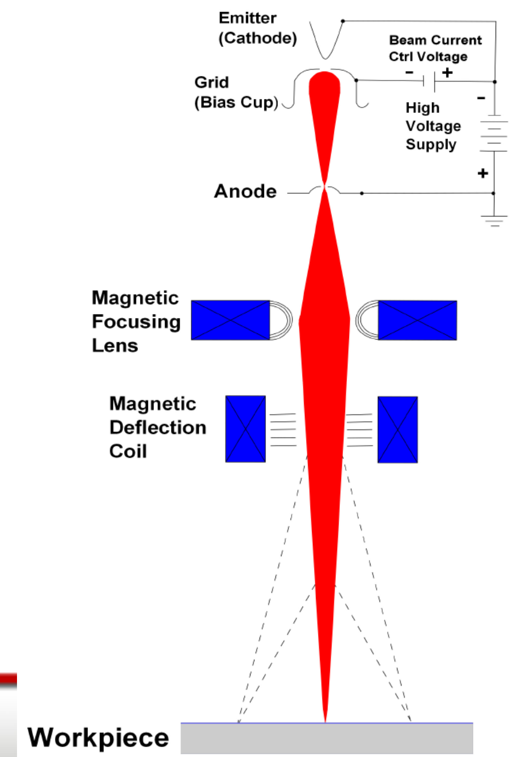


3D Printing for Manufacturing

- We need to manufacture extracted raw material into useful products
- Additive/layered manufacturing (3D printing) involves a suite of technologies but I shall discuss three types (two industrial and one hobbyist)



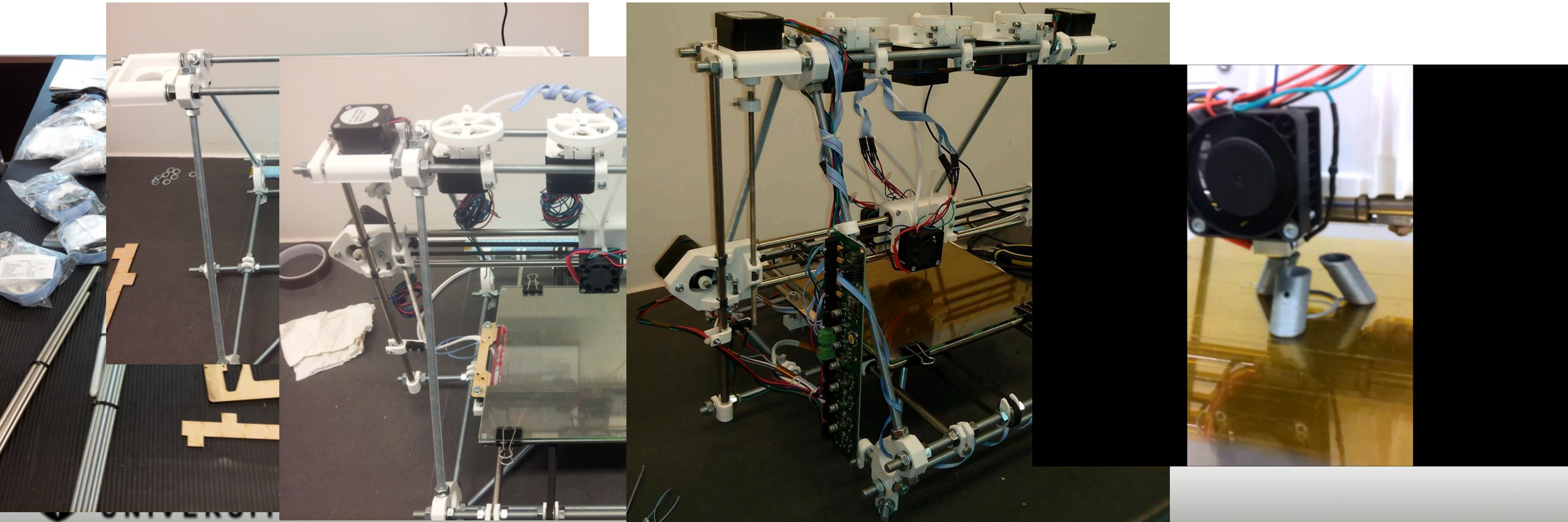
SLS is laser-based process suited to many different materials but laser is difficult to manufacture from lunar resources



- We are exploring SLS with **Renishaw** as a demonstration platform for our 3D printable **motor**
- **Thermal lance** is more efficient than laser (TBD)
- **EBF3** uses as **electron gun** and is restricted to metals
- Electron gun is a high voltage **vacuum tube**
- Different 3D printers mounted around a carousel for multiple material product manufacture, eg. electric **motor**

Replicating Rapid Prototyper (RepRap)

- Hobbyist 3D printing is based on fused deposition modelling and is restricted to plastics – zero-g 3D printer on ISS - industrial/hobbyist 3D printing will be merging
- Rep(licating) Rap(id Prototyper) – open source brainchild of Adrian Bowyer formerly of University of Bath UK
- It can print its own plastic parts (including silicones) **but** it cannot print: (i) metal bars (we are building a metal welder version with EBF3 head), (ii) joiners (which can be replaced with cement/adhesive) (iii) **motors** and (iv) **electronics** and **computer**; nor can it **self-assemble**



Mechatronic Systems

- All 3D printers are **cartesian robots** comprising an XY deposition table and a Z printing head
- I propose that they constitute **Universal Constructors** – they must construct mechatronic systems as the basis of all mechanised machines
- A 3D printable **motor system** including **actuators**, control **electronics** and **sensors** provides the basis for:

(i) construction of additional manufacturing tools – lathes, milling stations, drill presses, bending presses, etc (**FabLab**) – SEED factory

(ii) printable **3 DOF wrist** to replace the print head for parts assembly

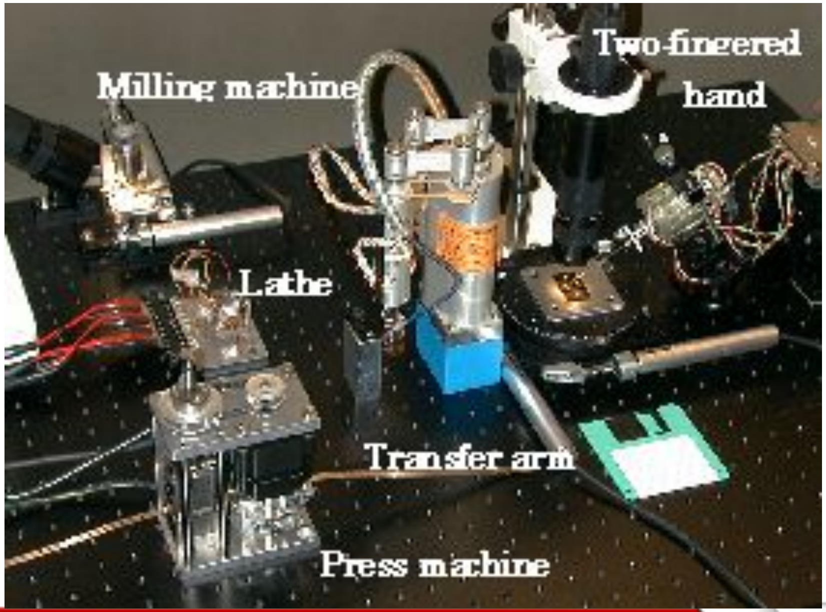
(iii) reconfigure serial **manipulators** with hands/tools

(iii) printed actuators for **pumps** and stirrers for unit chemical processes

(iv) **beneficiation** with crusher jaws and/or centrifugal ball milling for **surface finishing**

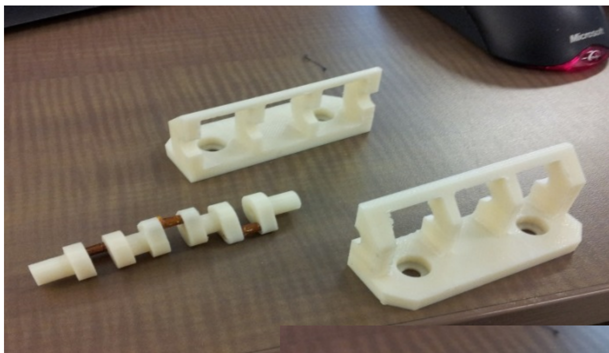
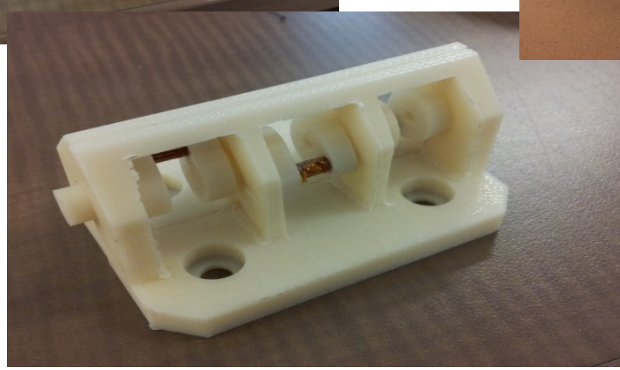
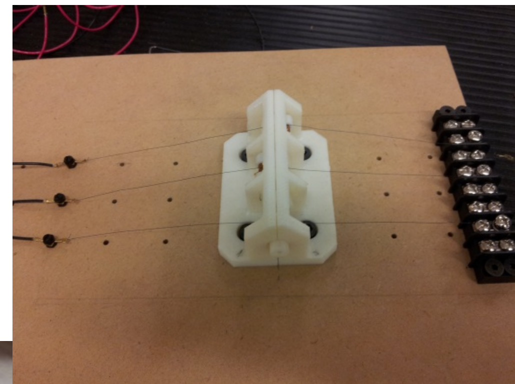
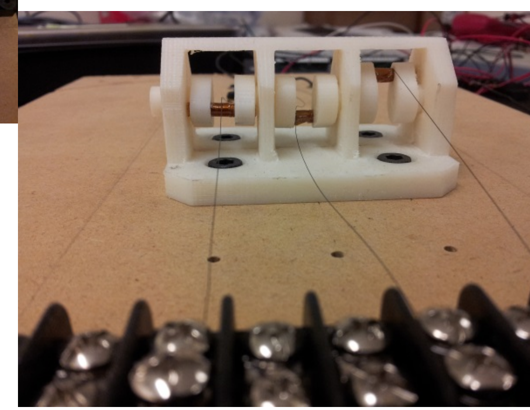
(iv) motorised **flywheels** for power storage

(v) vehicle **mobility** and drilling/trenching/excavation



3D Printable Motor – Prototype 1

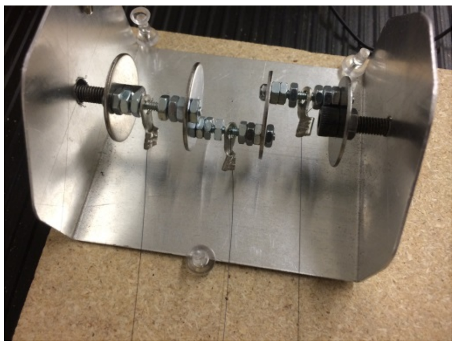
- Nitinol wires as artificial muscles operating in antagonistic pairs with a cam-based system to convert linear contraction/extension into rotary motion

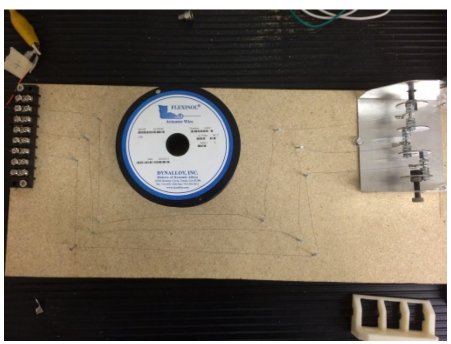





- This first design iteration did not work efficiently – coarse layering resolution exhibited excessive friction

3D Printable Motor – Prototype 2

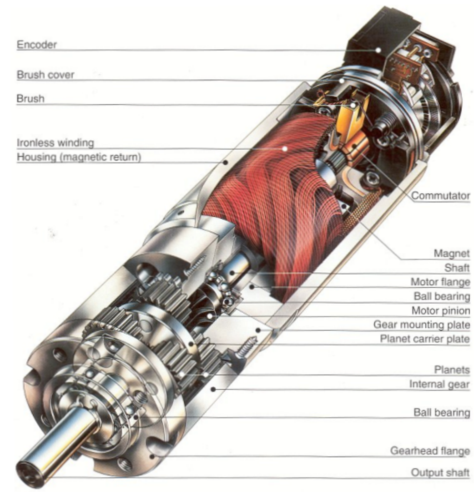
- The 3D printed plastic was replaced with steel to demonstrate the proof of principle



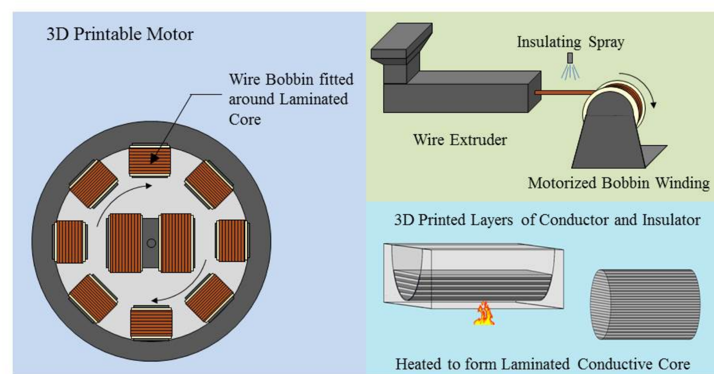


- It worked with good torque output! But it is limited by its thermal inertia
- Short stroke due to 5% strain introduces problems with compaction

3D Printable Motors – Design Concept 4

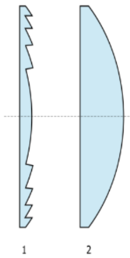


- Modern motors are complex, eg. Maxon motor
- However, electric motors can be simplified
- We have adopted a universal motor concept which uses coils to energise both rotor and stator poles – both must be constructed from plastic laminated layers of silicon electrical steel (up to 3% Si and 97% Fe)
- 3D printer carousel to apply multiple interleaved metal/plastic layers – demonstrate **multi-material 3D printing**
- **Plastic-coated wires** are **coiled** around grooved **plastic bobbins** which are sheathed over the [redacted] rotor and stator poles - [redacted] complex assembly [redacted] tasks



Power Generation on the Moon

- Photovoltaic cells of amorphous Si extracted from lunar silicates with only η~1-5% – most energy required is thermal for material processing
- Lunar solar furnace is based on parabolic trough mirrors or Fresnel/normal lens to create 1600°C and 2700°C respectively – R_{Ni}~90%, R_{Steel}~75%

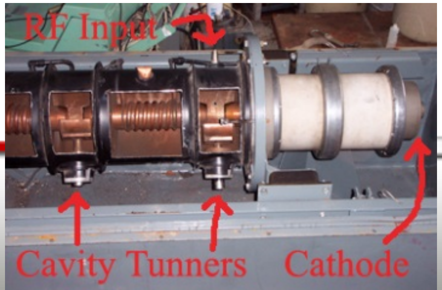


- **Tungsten** crucible is required for ceramic processing
- There are several options for conversion to electrical energy:

  (i) Mg_2Si is a potential thermoelectric conversion material

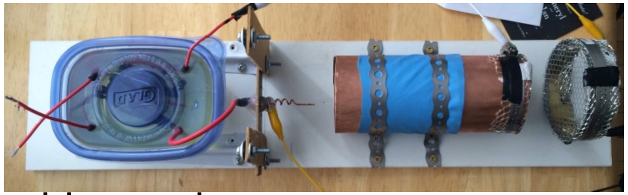
  (ii) Dynamic power conversion requires high thermal capacity liquid (such as Na(K) for AMTEC or high pressure water) or gas cooling (such as He) with Brayton cycle (eg. Magnox)

  (iii) **Thermionic emission** is used in nuclear reactors η~5-20%
- Thermionic emission from hot cathode is based on **vacuum tubes**
- Adaptable to spacecraft energy generation and solar power satellites – thermally powered klystron and/or magnetron
- **Motor**ised flywheels offer energy storage mechanism

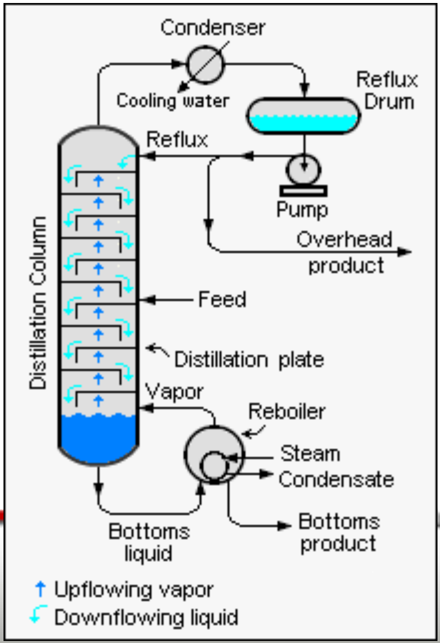


Lunar Volatiles

- RPM will demonstrate extraction of volatile from the lunar regolith, particularly water ice from lunar pole region
- Solar wind has impregnated regolith with 96% hydrogen (~120 ppm), almost 4% He and trace amounts of H_2O, **C**O, **C**O_2, **C**H_4, $\mathbf{N_2}$, **N**H_3, H_2**S**, **S**O_2, and noble gases such as **Ar**
- Gases are **preferentially adsorbed** onto small particles of ilmenite



- Mining is simple – scoop regolith into hopper
- Beneficiation may be achieved through **motor**ised rock-jaw crushing and magnetic separation (not RPM)
- Heating regolith to 700^{o}C releases 90% of volatiles
- Fractional distillation may be employed to separate gas fractions
- Reaction chambers require **motor**ised pumps and valves to control flow
- Regolith can also be sintered into glass at 1300^{o}C to form thermal and electrical insulation material
- Compressive structural materials – cast basalt and cement (as binder) – are available



Plastic Surgery with Silicone

- Plastic is restricted to **flexible electrical insulator** but we need to reduce C inventory imposed by hydrocarbon plastics
- **Silicones** $(R_2SiO)_n$, have O-Si-O backbones - simplest is PDMS silicone oil
- Silicones are radiation-tolerant and temp resistant to 350°C (cf. 120°C)
- **Syngas** is converted to methanol over Al_2O_3 catalyst (?) at 250°C and 5-10 MPa:
  $CO + H_2 \rightarrow CH_3OH$
- Chloromethane by reacting methanol with HCl over Al_2O_3 (?) catalyst at 350°C:
  $CH_3OH + \mathbf{HCl} \rightarrow CH_3Cl + H_2O$
- CH_3Cl is reacted with Si at 370 degrees with Cu (?) catalyst:
  $2CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2$
- This is hydrolysed to PDMS:
  $n(CH_3)_2SiCl_2 + nH_2O \rightarrow ((CH3)_2SiO)_n + 2nHCl$
- **HCl is recycled**
- Reagent **Cl must be imported from Earth**
- Silicone oil may be used for **hot isostatic pressing** of metal powders

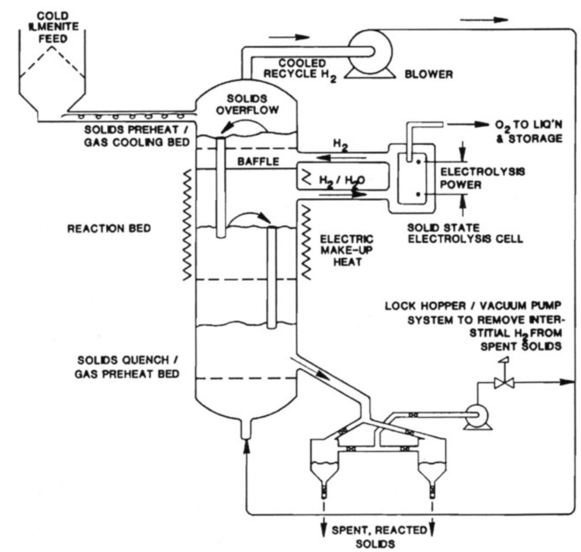
Any Old Iron?

- RPM will demonstrate **hydrogen reduction of ilmenite** at ~1000°C to create oxygen, iron and titania

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

$2H_2O \rightarrow 2H_2 + O$

- Hydrogen is recycled
- Regolith and TiO_2 fibres for thermal insulation
- Ceramics/glass for compressive structures/optics
- **Wrought iron** is tough but malleable
- **Cast iron** with ~2-4% C and 1-2% Si is more brittle but suitable as a structural material (eg. Iron Bridge for 200
- **Tool steel** with <2% C + 9-18% **W** for cutting tools
- **Kovar** is high electrical/thermal conductivity Fe alloy (53.5% Fe, 29% **Ni**, 17% **Co**, 0.3% Mn, 0.2% Si and <0.01% C) – one of a family of Fernico alloys
- No requirement for complex Al and/or Ca extraction for structural or electrical applications – iron-based technology only

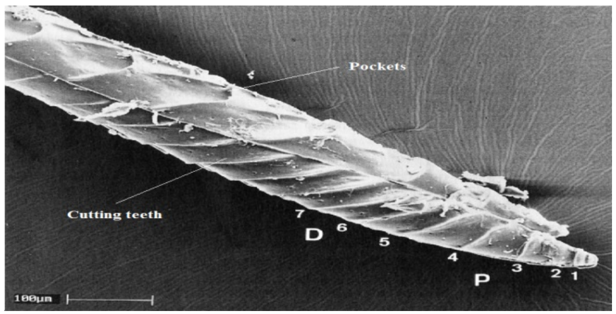


Nickel-Iron Meteorites

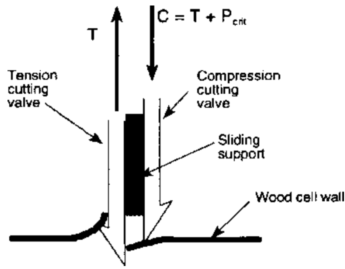
- Mascons in impact craters indicate location of NiFe meteorite ores – detectable as magnetic anomalies, eg. rim of South Pole Aitken crater - similar to Sudbury astrobleme
- Kamacite/taenite (NiFe alloys) is typically contaminated with Co
- Mond process at 40-80^{o}C reacts impure Ni with CO and S catalyst which is reversed at 230^{o}C/60 bar: $Ni(CO)_4 \leftrightarrow Ni + 4CO$
- S catalyst recovered at 750-1100^{o}C from troilite (FeS) in meteoritic inclusions, lunar regolith (~1%), or lunar volatiles
- Co fraction of NiFe alloy adjusted by mixing recovered Fe and Ni metal
- Permalloy may be used as mu-material for magnetic shielding comprising 80% Ni and 20% Fe with $\mu_r \sim 10^5$ (replace 5% Ni with Mo gives supermalloy with $\mu_r \sim 10^6$)
- Highland rock has ~0.3 μg/g W but W is difficult to extract from wolframite ($Fe,Mn(WO_4)$)
- Meteoritic NiFe alloys enriched in W microparticle inclusions which can be crushed and separated by froth flotation (W has high density of 19.3)

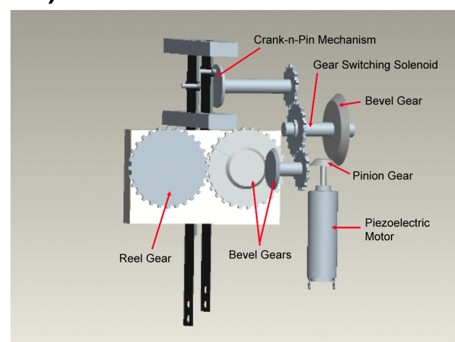
Subsurface Drilling

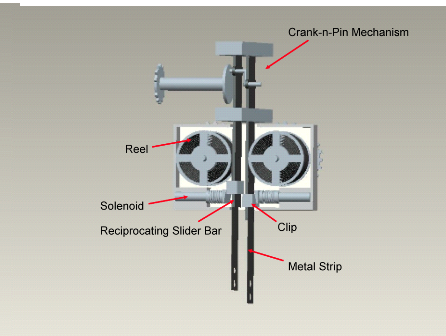
- Extraction of asteroid material may require more sophisticated mining techniques than surface scooping – deep drilling into compactified regolith >3m depth
- Our work on bio-inspired drilling based on the percussive woodwasp ovipositor mechanism provides one possibility (for ESA)



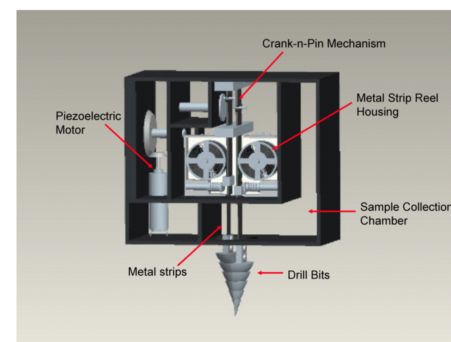
Wood wasp ovipositor





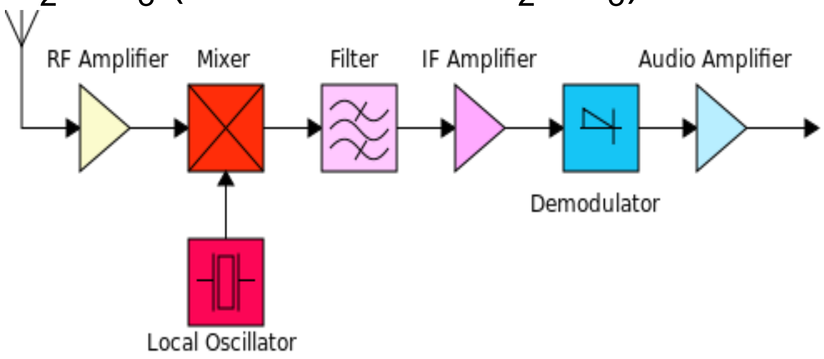


- Eliminates weight-on-bit infrastructure and drill string assembly
- New development - sonic drilling “liquefies” consolidated rock and soil through vibratory action ~150 Hz
- Piezoelectric drive motors offer a hammer-in-hole variant on NASA’s USDC
- Problem – vibration isolation of each drill blade from each other



Simple Sensors from Lunar Resources

- Displacement sensing is the most fundamental mode from which velocity, acceleration, force, pressure, etc are derived
- Simplest displacement sensor is a potentiometer (rheostat)
- **Piezoelectric quartz** as basis of more accurate displacement (and derivative) sensing – it is also a short-stroke high frequency actuator (eg. USDC)
- Quartz does not occur naturally on the Moon but it may be grown from **silica** (?)
- Melt silica at 2000°C followed by seeding in Na_2SiO_3 (formed from **Na_2CO_3**) at 350°C and 150 bar
- Quartz is an ideal rf oscillator in rf processing chain
- Pierce rf oscillator constructed with minimum components – one inverter, two resistors, two capacitors and one quartz crystal



- Convolution (channel) coding may be implemented through a bank of XOR gates
- **Na requires import from Earth**

Vision Sensor from Lunar Resources

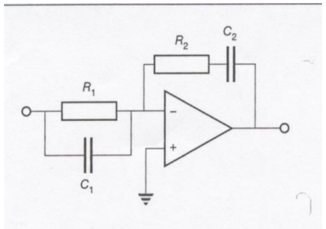
- Imaging array is fundamental as a remote distance sensor – **iron oxide** (TBD)
- Light-sensitive p-type semiconductor **selenium** was used in Victorian photophone
- Se is found in association with metal sulphides but these are **rare on the Moon** but there exist chalcopyrite (Cu-Fe-S) deposits
- S/Se ratio in carbonaceous meteorites is ~2450 with S~5% content of same
- In NiFe meteorites, Se is associated with troilite (FeS)
- Copper selenide may be smelted with soda $\mathbf{Na_2}CO_3$ and saltpetre KNO_3 (from KREEP?):

  $Cu_2Se + Na_2CO_3 + 2O_2 \rightarrow 2CuO + Na_2SeO_3 + CO_2$
- Selenite Na_2SeO_3 is acidified with H_2SO_4 that precipitates tellurite impurities out of solution leaving selenous acid (H_2SeO_3) from which Se may be liberated:

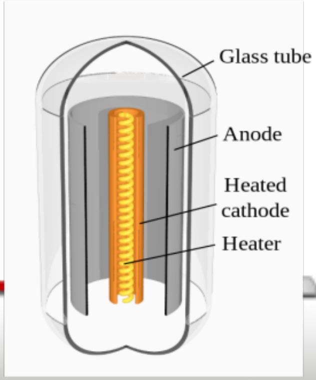
  $H_2SeO_3 + 2SO_2 + H_2O \rightarrow Se + 2H_2SO_4$ with sulphuric acid recycled
- Photocathode and photomultiplier are derived from **vacuum tube** technology using electrodes coated with Se
- **Imported reagent Na** is necessary for Se extraction
- The only **imported reagents** required are **salt (NaCl)**
- We can implement a **salt contingency** against uncontrolled replication

Simple Electronic Components

- Most solid state electronics requires ~30 different complex physical and chemical processes, eg. vapour deposition, epitaxy, etching, etc
- We focus on **RCL circuits** which involve simple printable components, eg. RC filters, LC oscillators, PID controllers, etc

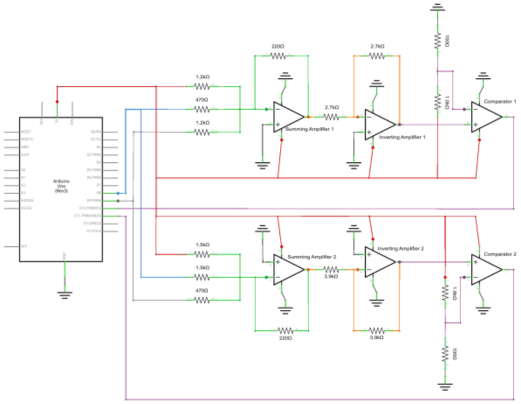


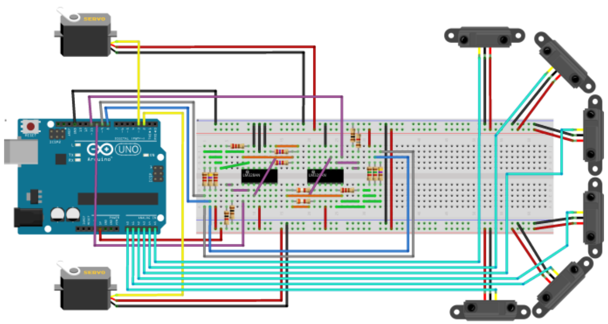
- **Vacuum tubes** are less susceptible to radiation than solid state electronics
- First differential amplifier and original op-amps were based on vacuum tubes
- Vacuum tubes are **thermionic diodes** which use resistance wire to heat cathode to 800-1000^{o}C in a evacuated envelope
- Cathode material has high melting point, eg. **sintered tungsten strip** that may be coated with CaO to reduce work function threshold (not essential)
- Spacecraft use vacuum tube-derived TWTA in transponders
- Vacuum tubes maintained at power-on state in thermally stable environment gives **reliable performance**
- First programmable electronic computer – **Colossus** – at Bletchley Park (1943) comprised 2400 vacuum tubes
- Problem: circuit complexity growth with task program, eg. ENIAC took up large room



Neural Computing

- Recurrent neural nets are Turing-equivalent; analogue neural nets have super-Turing capacities to compute “non-computable” functions
- Neural nets act as **compressed programs** with reduced footprint over general purpose architecture – 3D printer acts as universal Turing machine
- Our modified **Yamashida-Nakaruma** hardware “printable” neuron comprises a weighted input, summing integrator and signum output

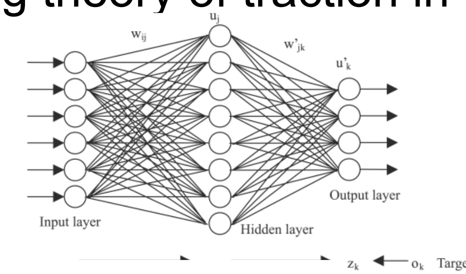


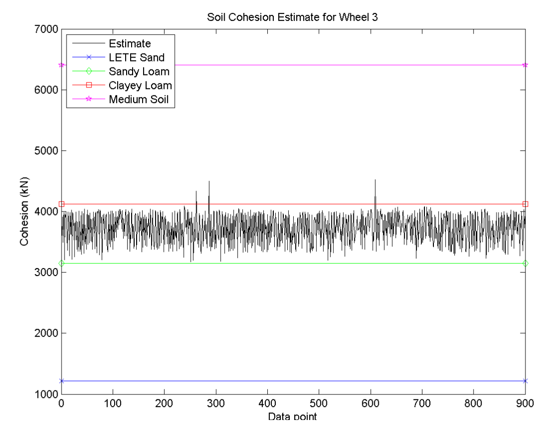


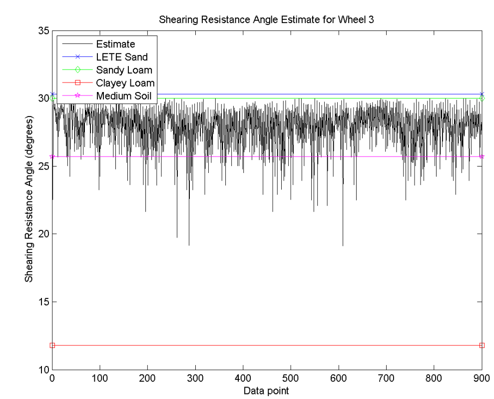
- We are investigating implementation of online BP learning in hardware

Neural Computing for RPM

- We have demonstrated neural network models of Bekker-Wong theory of traction in order to extract soil physical parameters during rover traverse







Tentative Conclusions

- Universal constructor (ergo self-replicating machine) does not appear infeasible in a lunar context
- All the major elements of a “generalised spacecraft” have been addressed – propellant, structure/mechanisms, power, thermal, orbit/attitude control, avionics (CDH/TTC) and payload (optical sensors)
- Lunar launch by linear mass driver – same principle as electric motor
- If successful, self-replication technology has the potential to revolutionise space exploration
- Two applications are constellation-based approaches to space-based geoengineering using a solar shield (short-term solution) and solar power satellites (long-term solution)
- Space exploration requires a *raison d’etre* of relevance to people on Earth – this is it – to solve environmental problems rather than just monitoring them
- This migrates baseload energy generation industry off-Earth, thereby protecting biosphere
- Huge productive capacity may be exploited by private sector
- There are many challenges to be addressed - autonomy in unstructured environments, eg. drilling for asteroid material
- Key aspect will be to define a controlled internal environment separate from the external environment