Integrating a Modular Excavator as a Smart Tool into the Space Exploration Infrastructure using Small Satellite Systems Protocols

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Abstract: *sys*RAND is developing an industrial-class excavator for planetary surface exploration and development. This device is a bucket ladder with heritage derived from projects originally from the Colorado School of Mines. The current device will be used extensively to study the physics of digging in simulated Lunar conditions. A successor design which is expected to be more robust and remotely serviceable is on the drawing board.

Technical capabilities developed in the Small Satellite community are being translated to other space applications. Concurrent with the excavator project, the company is developing hardware and software tools for the Air Force Research Laboratory's Satellite Data Model (SDM) and *Space Plug and Play Avionics* (SPA). This capability is also consistent with international standardization efforts of the Consultative Committee for Space Data Systems' *Spacecraft Onboard Interface Services* (CCSDS SOIS).

The Excavator control system is based upon a COTS industrial controller to be augmented by AFRL's Satellite Data Model plus SPA-E and SPA-U Plug 'n Play interface standardization. The controls are further extended for realtime scientific data acquisition of environmental parameters such as plasma flux, magnetic and electrostatic field strengths, *etc*.

The excavator will employ a universal tool coupling which encourages the interchange of a wide variety of tools among a number of robotic arms and mobility turrets. This coupling will also connect the SPA-E (Ethernet derivative) from the vehicle to the excavator controller, which is consistent with NASA's extensive use of Ethernet throughout many of their architectures. The SPA-U (USB derivative) interface will be used for sensor interfaces and localized IO processing of excavator servo and sensor inputs along with sensors which are collecting scientific data on the ambient environment and the platform's interaction with it.

The goal for a fully operational system is autonomous and semi-autonomous operation, using a modest energy budget and minimal human supervision and intervention.

Applications include civil engineering and *in-situ* resource utilization in support of long-range logistical objectives. The excavator has been modeled at a production rate in the neighborhood of 1,000 kg / hr and will be integrated with a universal tool coupling, a robotic turret arm and a mobility platform.

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Introduction

Some of the technical capabilities under development in the Small Satellite community are being translated to other space applications. *sys*RAND is active in these and related developments. One of the very promising interface developments is *Space Plug and Play Avionics*, (SPA), and the *Satellite Data Model*, (SDM), a computing network definition which will ultimately permit integration of satellite bus and payloads with a minimum of application program development and design. SPA will enable satellite busses to be assembled in a matter of minutes, tested in hours and integrated with payload in days.

*sys*RAND Corporation has been developing an industrial-class excavator for planetary surface exploration and development, under a NASA contract. This excavator is intended to refine the art and science of digging on the Moon and Mars while enhancing the relevant physics models. Many of the operational issues are also being addressed as the Technology Readiness Level is advanced to TRL 4, and to at least TRL 5 by the end of the second phase contract.

In the course of preparing the excavator for laboratory shakedown and field trials, controls will be refined and the design iterated toward a flight-ready system. In order for the excavator to be useful the blade should be in constant motion. This is due to the void created in the regolith when it is scooped out – the device cannot get a second bucket of soil from the same space and the blade must be moved forward, sideways or deeper in order to gain purchase on the next full scoop of regolith. In order to achieve the modelled 500 to 1,000 kilograms of hourly production, the combined motion of the mobility platform, the robotic arm / turret and the excavator blade must keep the blade's nose imbedded in the trench, constantly addressing the workface of the regolith cut.

Since the Air Force Research Laboratory and NASA have an interest in incorporating the SPA and SDM in future mission spacecraft, it is logical that these two agencies participate in this development. The multi-disciplinary *sys*RAND design and development team is in the position to 1) assure that the *sys*RAND electronics and computer systems design does not preclude the insertion into the SPA / SDM domain, 2) define the field operations which maintain device productivity and safety, and 3) imbed the excavator controller within the SPA technology should the opportunity present itself. This capability is also congruent with the Consultative Committee for Space Data Systems' *Spacecraft Onboard Interface Services* (CCSDS SOIS) efforts for international standardization.

*sys*RAND's SDM and SOIS-based implementations are supported with a foundation of existing and pervasive standards such as TCP, Ethernet, CANbus, JTAG IEEE 1149, VHDL and RS485 Physical Layer – to cite just a few of the more common examples.

Figure 1 Excavator *Proof-of-Concept* Device

The excavator is representative of modular smart tools which will be developed for use on planetary surfaces. These devices will be employed to support civil engineering, *in-situ* Resource Utilization, search and rescue, spacecraft maintenance and servicing, structure construction and outfitting, manufacturing facilities installation and maintenance, and so much more. Many of these tools will resemble the excavator because they will be esoteric, special-purpose devices which do not generalize like a hammer or a socket wrench. These tools also have to operate for extended duration and when they malfunction, they may not be repairable for years – or at least until a shirtsleeves maintenance depot is erected.

Certain tools, such as manipulator grips and welding heads, will be found in applications on the surface as well as in orbit. Nearly every tool will feature electronics and intelligent software so that they may be used safely, effectively and indefinitely. ***Space Plug and Play Avionics*** and the companion ***Satellite Data Model*** are the first generation of systems which are intended to be prepackaged into functional partitions which may be parametrically controlled using preloaded software modules, or heuristically driven, eliminating conventional, and specialized computer programming for each and every instantiation on the bench or in the field.

Excavator Applications

The applications specific to the excavator meet long-range planetary surface exploration and development objectives. Short-term missions or those which are a one-time situation, *e.g.*: Apollo missions, have little interest in many of these tools because they imply permanence and growing an industrial plant to provide logistical mission support through the use of resources indigenous to the planetary surface. The principal applications for the excavator fall into two principal categories, civil engineering and *in-situ* resource utilization. A third application is scientific sampling, but there are many devices, such as corers, which better meet the need and are much easier to deploy. A first cut at the scaling the material flow for each application class is depicted in Figure 2.

The applications available to the blade are dependent upon the agility which is evidenced, or not, in its design and implementation. For instance, the excavator blade can be fixed to the mobility platform's *line-of-travel* and the 10cm kerf of the excavator takes advantage of the regolith's vertical *angle of repose / critical angle*, supporting trenches for cables, conduits and footings. The same blade can be swept on two axes for a larger effective cut (depth) and kerf (width), which enables larger volumes to be ingested for bulk processing in short horizontal runs. Civil engineering cable and pipe applications will require narrow kerf trenches, yet all other uses for the blade would make use of repetitive sweeping, including ISRU. This sweeping could be horizontal or vertical, or both motions, nested, as shown in Figure 3.

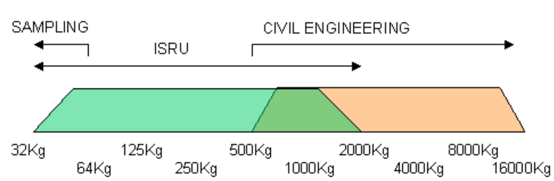

Figure 2 Scaling Excavator Applications

Civil Engineering applications for the excavator blade include berm construction and stabilization, trenching for sub-surface power cables, fluid conduits and footings, digging holes and trenches for structure emplacement, burial of structures for radiation, micrometeoroid and thermal protection, and leveling of surfaces for landing pad preparation. Civil Engineering also provides indirect support of ISRU by building the infrastructural facilities necessary to house processing and manufacturing.

In-situ Resource Utilization applications are centered on surface mining of regolith in bulk quantities sufficient to support oxygen separation, metals extraction, glass production and the capture of volatiles loosely imbedded in the regolith matrix. Mining regolith and volatiles will vary by soil compaction and related conditions.

Recursive trenching of the surface creates a rough stepped-trench which is easily smoothed by any number of methods, including metal frames which could have other uses before being converted to a drag-rake. Current estimates are that six feet of disturbed regolith provides adequate radiation shielding which may also prove sufficient for micrometeoroid protection. The depth at which a habitat, laboratory or garage is to be buried depends upon whether the structure may be practically unearthed and relocated. So it is likely that a cylindrical habitat would be lowered into a stepped trench to its equator, *i.e.*, halfway, and then covered over. The most economical approach would have the volume of extracted regolith at least equal the volume deemed necessary to bury the structure.

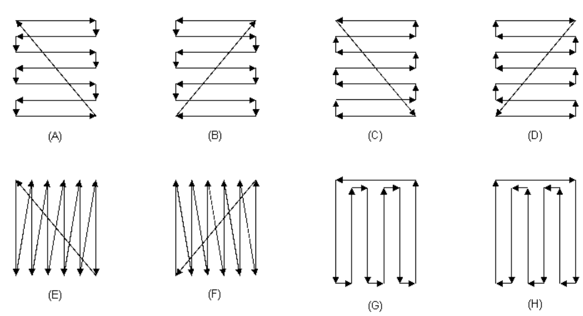

Figure 3 Various Iterative Blade Sweep Patterns

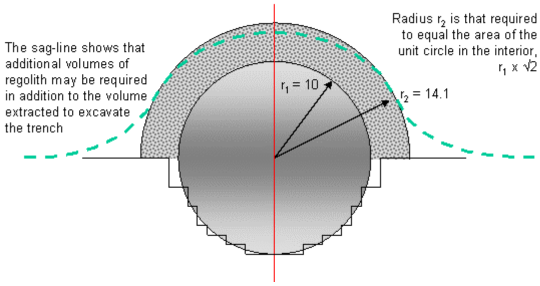

Figure 4 Matching Volumes of Excavation and Overburden

So to extract the trenched volume of regolith necessary for a two meter overburden, a habitat radius of ~5 meters is required. The access to the trench should likely be a ramp oriented towards the nearest Lunar Pole which is not covered over after the insertion of the structure, and an additional berm shields the ramp, crossing the "T."

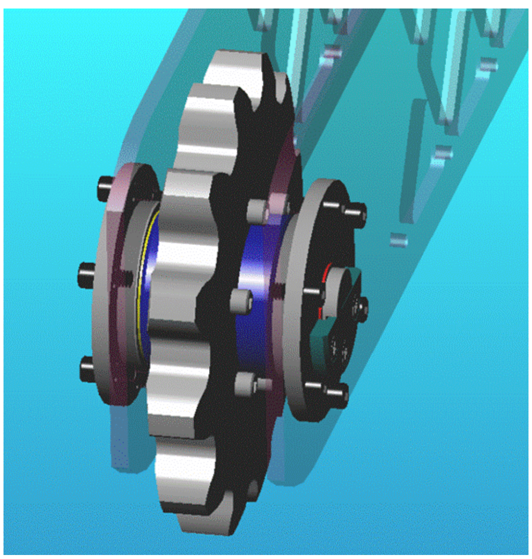

Figure 5 Excavator Nose with Sprocket

Application Objectives Drive Features

Design considerations include the power constraints of all-electric systems, temperature extremes, queueing issues, loose *vs*. compacted soils, system mass limitations, production rates, *etc*. Other desirable features are dust miti-gation and exploitation, plus imbedded volatiles capture from an undisturbed regolith "*plug.*" An assembly of modular assemblies is easier to integrate and operate than a monolithic device, an imperative device feature.

The digging end of the blade has the mounting and bearings for an idler sprocket upon which the Pintle Chain (ASME D662) is installed, as shown in Figure 6. K-1 platforms are welded to the chain at intervals of five links to which the buckets (scoops) are to be attached.

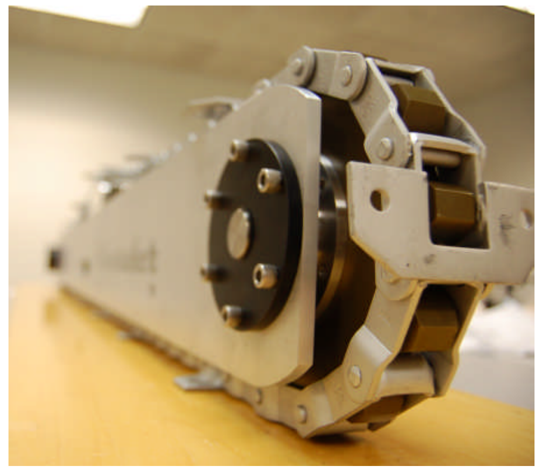

Figure 6 Design and Implementation of the Digging End

The drive motor is a high-torque device with digital controls. It will be replaced later with a motor which also features high-torque but more compact form factor. The excavator's drive end should remain above the surface and does not

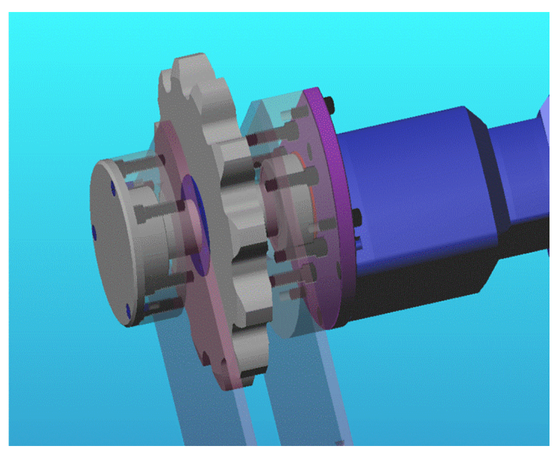

Figure 7 Modular Motor Mount and Rear Drive Sprocket

have to be as narrow as the nose. The 10cm buckets are slightly wider than the blade assembly.

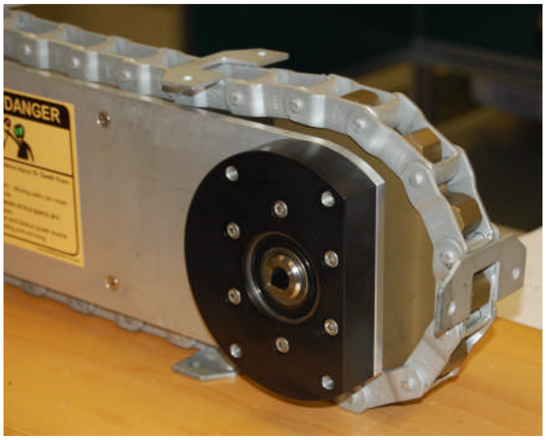

Figure 8 Design of the Driving End Characteristics

Several Computer Models have been developed which are encouraging and the excavator has been modelled for a production rate in the neighborhood of 1,000 kg / hr, a figure which will vary depending upon spillage and other loss factors. A relatively low-wattage motor (100 W_e) drives the device at a chain rotation rate of 7 rpm through a gearbox which delivers high torque to the drive sprocket, and is expected to consume 25 to 50 $W_{atts.}$ The chain is reversible although a practical appli-cation hasn't been identified, except to possibly clear a jammed rock.

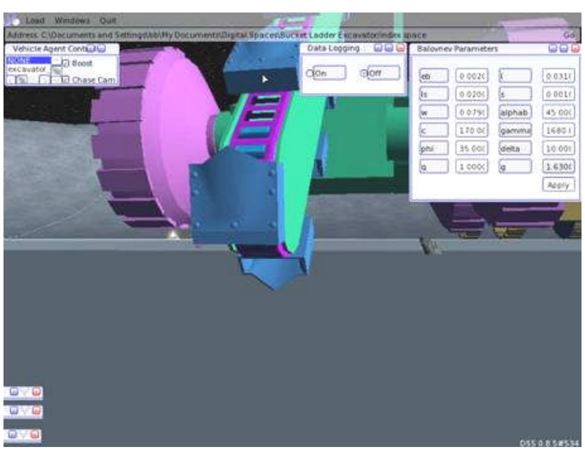

Figure 9 Simulation Rendering of the Excavator Contact Aspect

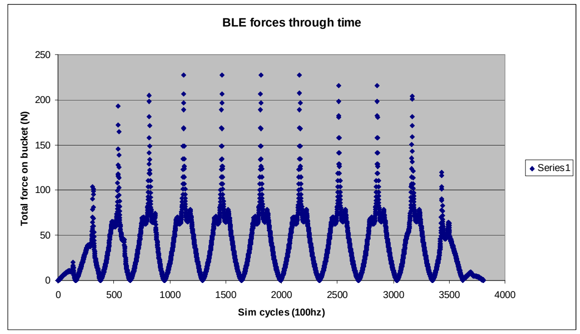

Figure 10 Rendering Physics Simulation Profile

A Notional Mobility Platform

A number of robotic mobility platforms have been surveyed in our search for a configuration suitable for excavator operation. One platform, which has the potential to be a very good fit for surface excavation operations, is Jet Propulsion Laboratory's All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE).

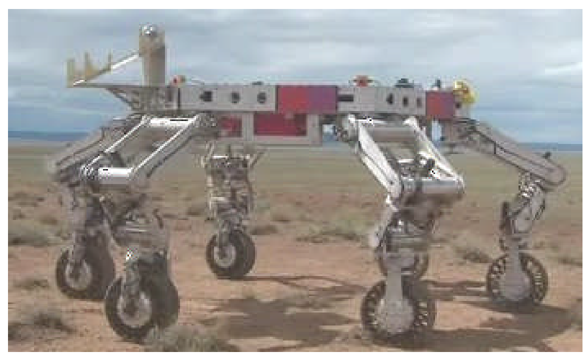

Figure 11 ATHLETE in a photogenic pose

There are three principal attractions to this particular platform. The relative mass ratio and sizes of the ATHLETE platform to our Excavator Blade seem *subjectively correct.* The vehicle's wide track allows the ATHLETE to straddle a trench, which prevents collapse of near-vertical trench walls from the vehicle load. The fact that individual legs may be partially retracted would further help to clear a trench. Any mobility plat-form appropriate to the excavator must have a wheelbase and track which is clear of the cutting operation.

The planned successor to ATHLETE is much larger and might not be as appropriate to the current excavator. Fortunately, the excavator design is deliberately scaleable.

Another platform of interest for the deployment of Moonraker is the Chariot from the Johnson Space Center, shown in Figure 12. The Chariot has a wide track which would prevent its toppling under an off-side load.

Figure 12 Front Quarter view of Chariot

A perceived disadvantage of this platform is that it is apparently a solid frame which could be a problem should a trench collapse. Chariot could better address ISRU applications were it articulated on two axes.

Figure 13 Starboard view of Chariot

Comparing Orbital Systems to Surface Systems

Most coherent distributed network architectures can support *Plug and Play* facilities and since the SPA / SDM is coded in C source, the system can be ported. The SPA family currently includes SpaceWire and USB networking. CANbus and Ethernet would seem to be the next popular network implementations.

Figure 14 depicts a typical small satellite network of Application Processors (AP), each with a complement of IO Processors, or Appliqúe Sensor Interface Modules (ASIMs). The APs perform the top-level tasks such as Command & Data Handling, Attitude Determination & Control System, Power, *etc*.

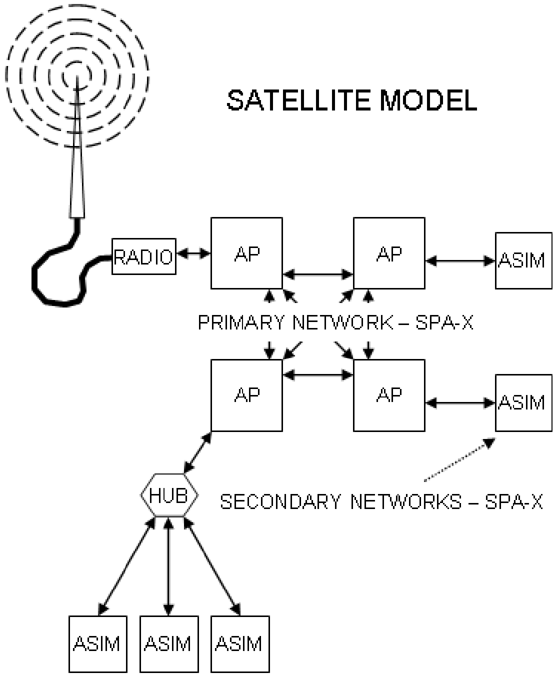

Figure 14 Satellite Implementation of the Model

Subordinate networks of ASIMs are usually linked to a task on the adjacent AP, and the ASIM's IO data streams are available to other processors through a SPA subscription service.

Cursory examination of the two abstracted system models of Figure 14 and Figure 15 reveals that they are nearly identical. The principal difference is that the satellite model is static after assembly and integration while the modular tool model allows the modular tool, robotic arm or the arm-and-tool to be arbitrarily removed or added, at will.

Another advantage of implementing SPA on modular tools is that some tools can be used both in orbit and in planetary contexts. Hybrid networks are probable, where some network nodes are SPA Avionics and others are not.

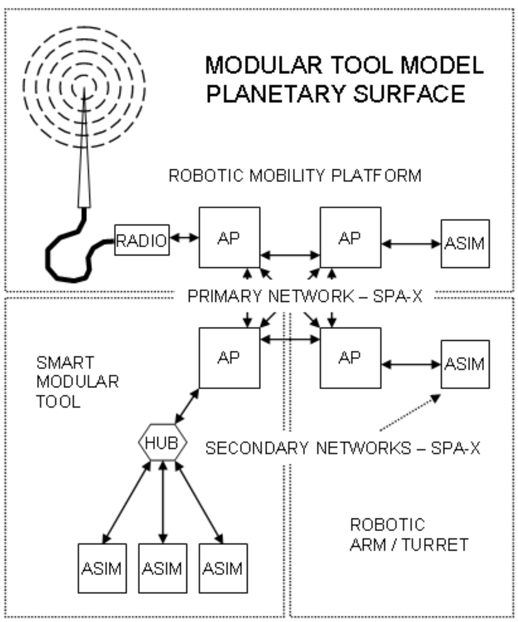

Figure 15 Representative SPA Models Differ only in Removable Componentry

Control Model

Modular Smart Tools are alternate components of a common *docking and locking* port on a robotic arm or turret installed on a robotic mobility platform. The Excavator Application is a specific example of a generalized and layered control architecture with components resident on each of the mobility platform, arm / turret and modular tool.

A Concept of Operations (CONOPS) is being designed specifically to support civil engineering and ISRU activities. Control centers communicate with the Excavator Applications Program (or other modular tool) through the Mobility Platform's RF links.

A Universal Tool Coupling connects the robotic arm / turret to the modular tool through a coupler which conveys power and network signals between them. A COTS industrial controller which features Ethernet and USB ports will be used to directly control the excavator. The ARM processor will support AFRL's Satellite Data Model (SDM) and *Plug 'n Play* interfaces, *SPA-E* (Ethernet) and *SPA-U* (USB). The controls are to be further extended for realtime scientific data acquisition of the planetary environment.

Science Data Acquisition

The Excavator is *closely coupled* to a planetary surface like few other devices. The excavator will have extensions for realtime scientific data acquisition of environmental parameters and some of the candidate sensors are:

- Plasma Flux,
- Magnetic Fields,
- ElectroStatic Fields, and
- Anomalous Sample Capture.

The Excavator will collect internal engineering data from which science can be developed. For example, the measure of current required to drive the blade's motor indicates the compaction and cohesion of the regolith.

Layered Control

A layered model is used to span the range of command authorities which may direct the excavator's activity. The autonomy granted to the decision software at each layer is a settable parameter in the model. Initially, a top layer (operator-in-the-loop) would exist to accommodate remote operations from ground stations on the Earth. It is likely that no autonomy is permitted early on.

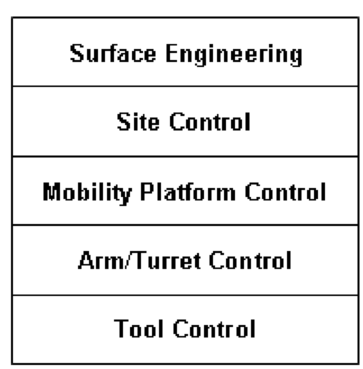

Figure 16 A Layered Control Structure

Other scenarios would select a strong autonomy on all but one layer, perhaps for operator training. Or the converse may be selected, where only one layer enjoys the confidence of high autonomy.

Concept of Operation

The methods and procedures anticipated by the design and development team, then later elaborated and focussed by the operations staff, is called the Concept of Operation (CONOPS). The design team always makes every practical effort to analyze and capture the operational context of a product or service. In the case of the excavator, generalized to a family of modular tools, many of the CONOPS procedures will find their way into program code or expert systems operational rules.

Therefore, a hypothetical operation following the strata of Figure 16:

- ✧ a Work Order is issued electronically by **Surface Engineering** which specifies operating parameters for a TASK, including autonomy levels for each layer, and
- ✧ the **Site Control** manages vehicle traffic, fixed feature layout, routing and sequencing of tooling paths, cable and fluid conduit insertion and excavation. Site Control enforces safety.

The Mobility Platform

- ✧ collects tools, power, and other provisions, such as marker beacons, spare parts magazines, *etc*.,
- ✧ the Mobility Platform extracts a Tool (Excavator Blade) from a Toolrack,
- ✧ the Mobility Platform confirms the mission package with the control center, and
- ✧ provides the transportation and deployment platform for the tool's operation.

The **Arm/Turret Control** is self-directed, following tool control algorithms to

- ✧ position the mobility platform, and
- ✧ position the tool's effector.

The **Modular Tool** has internal controls

- ✧ the Tool's Application Program is downloaded to the Robotic Arm / Turret,
- ✧ and the Tool's Application Program is downloaded to the Mobility Platform.

After which:

- ✧ the Mobility Platform departs the yard and proceeds cross-country to the worksite,
- ✧ arriving at the worksite, the Tool software assumes control and negotiates entry to the worksite,
- ✧ the Tool/Platform operates under the supervision of the Worksite control system, and
- ✧ upon exitting the worksite, control reverts to the mobility platform.

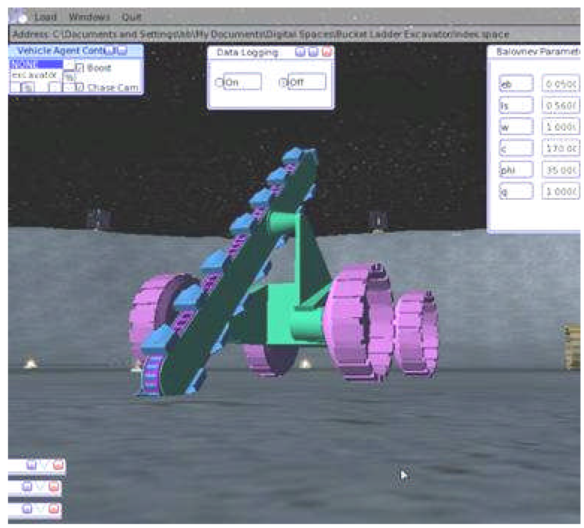

Figure 17 The Excavator Platform at Work

Principal Work Volumes

One of the factors which scales the computational load and sensor bandwidths is the robotic effector's work volume. This is the space which the working tip of the tool can reach while exercising its servoes in all of their intrinsic *degrees-of-freedom* (DOF). The computational requirements are highest for rectangular and lowest for spherical.

Other, hybrid systems such as the cylindrical, derive from these two canonical types. The coordinate systems represented by these volume shapes are Cartesian and Polar, and cylindrical uses Polar in the X-Y plane and

Cartesian in the Z-axis.

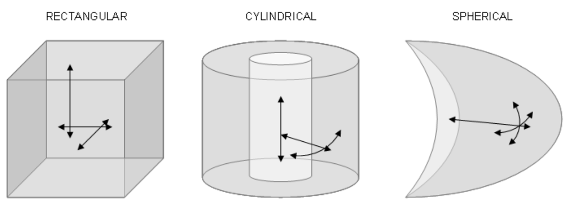

Figure 18 Work Volume Coordinate Systems

Each shape will require at least three effectors to maintain six degrees of freedom. The intent of our modular tool approach is to offer four DOF, or two actuators, for each of the arm / turret and the modular tool. This provides a total of eight DOF for the tool with respect to the mobility platform. The coordinate system to be employed by the Excavator is expected to be spherical.

Smart Tool Controls

A COTS Industrial Controller, depicted in Figure 19, is suitable for the Laboratory Context, and offers a Realtime Kernel with extensive libraries of COTS parameter-directed software modules. The system is an industrial computer in the PC104 form factor and modules have been procured to support our targetted Tool Control configuration. Using COTS for the early development stages usually enhances the development process, maintaining an applications focus.

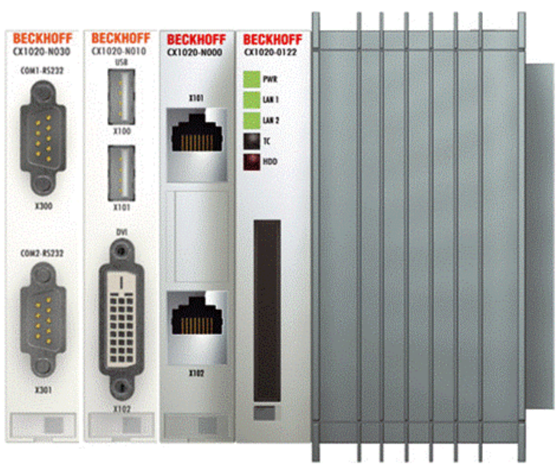

Figure 19 A COTS Industrial Controller

In the second stage, a ruggedized transitional platform, featuring an ARM on a PC104 form factor, will be used for field operations to implement SPA features in a realistic approximation of the Application, *e.g.*: under a Realtime Operating System (RT OS). This second implementation sheds PC peripherals (keyboard, mouse, display) and will be extensively tested in the lab and field trials.

The third version of the excavator controller will be a flight-ready controller which is code-compatible with the previous versions and has built-in SPA hardware. This unit will be rigorously tested as space avionics.

Defining the Tool Interface

The control system is based upon a COTS industrial controller augmented by the inclusion of AFRL's Satellite Data Model plus SPA-E and SPA-U *Plug 'n Play* interfaces. The excavator will be fitted with a Universal Tool Coupling (UTC) and a robotic turret arm for integration onto a robotic mobility platform. This coupling will also connect the SPA-E (Ethernet Derivative) from the vehicle to the excavator controller. All of the USB devices on the Excavator have local connection to the processor on-board the excavator and do not cross the UTC interface.

The SDM Services over the network include the Data Manager, the Task Manager, the Sensor Manager, and the Network Manager. These services are SPA functions which are a superset of conventional layered network functionality. The backbone of the function set is the ASIM Registers, which uses a contiguous block of memory as a scoreboard. Local processors post the data from their attached sensors to specific locations. The memory is approximately 256 x 16 Bytes, or 4 Kilobytes, in extent. Applications programs subscribe to data by reference and are connected to the appropriate network node and 16 Byte block of cells.

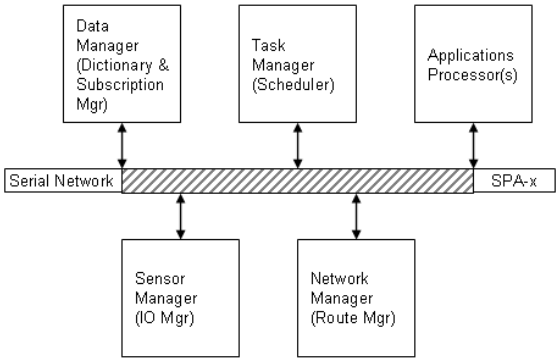

Figure 20 The Basic SPA Services Network

At least one instance of an Applications Processor is the Modular Tool Portal with a SPA subnetwork. The Modular Tool Portal resides on the mobility platform or other spacecraft and connects the platform's mobility functions to the *virtual command bus.* The Modular Tool Portal is a typical Applications Processor which is extended to the Robotic Arm / Turret / Modular Tool ensemble through a local SPA-E serial bus,

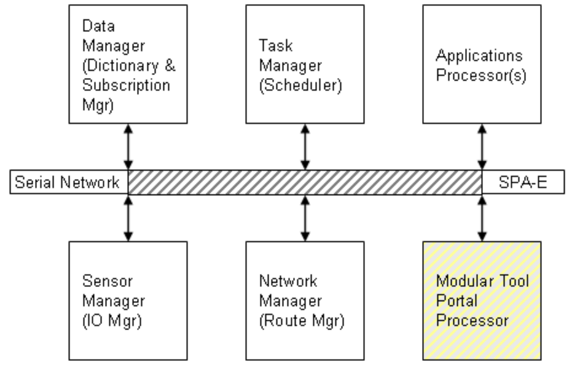

Figure 21 The Modular Tool Ap and SPA Utilities are Peers

observing the Satellite Data Model. The Modular Tool Portal Processor functions are not defined as SPA functions, but are a Generic Tool Application.

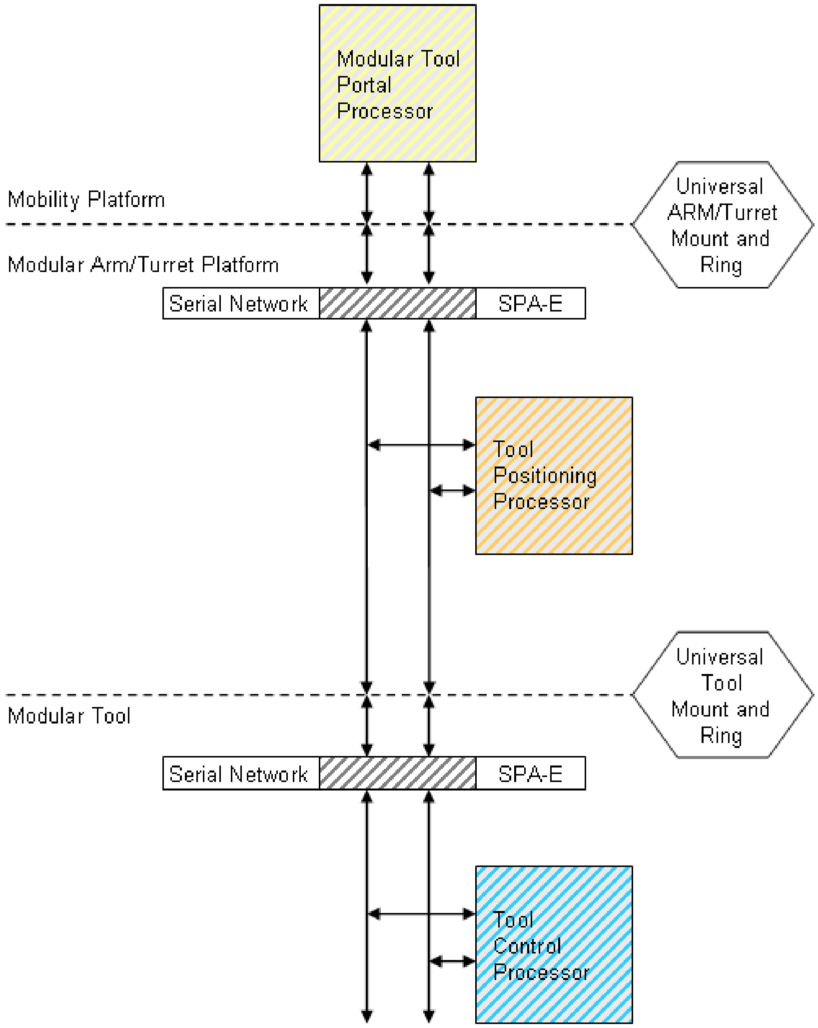

Figure 22 The Modular Tool Subsystem with Redundant SPA-E Links

Three-Tier Application

Three processors work the Modular Tool concurrently through a *virtual command bus*, where positioning of the mobility platform, the arm / turret and the modular tool are concurrent. Positioning and other command streams originate in the Modular Tool Control Processor, shown at the bottom of Figure 22.

When the Mobility Platform is outside the control authority of a worksite, the Mobility Platform directs the operation of the Tool Positioning Processor and the Tool Control Processor, to assure tool stowage.

When the Mobility Platform is within the control authority of a worksite, the Tool Control Processor directs the operation of the Mobility Platform Command Processor (via the Portal Processor) and the Tool Positioning Processor.

It is important to note that while the processes are concurrent, the previously-cited command hierarchy prevails. In the current view, the Tool Positioning Processor is never at the top of the control ranks.

Arm/Turret Subsystem Network

The Tool Positioning Subsystem is imbedded in the Arm / Turret and communicates with both the Modular Tool Portal Processor and the Tool Control Processor, exchanging power and signals across rotating couplers.

The Tool Positioning Processor has a subordinate SPA-U bus which includes actuators, sensors and servos which provide at least 4 DOF.

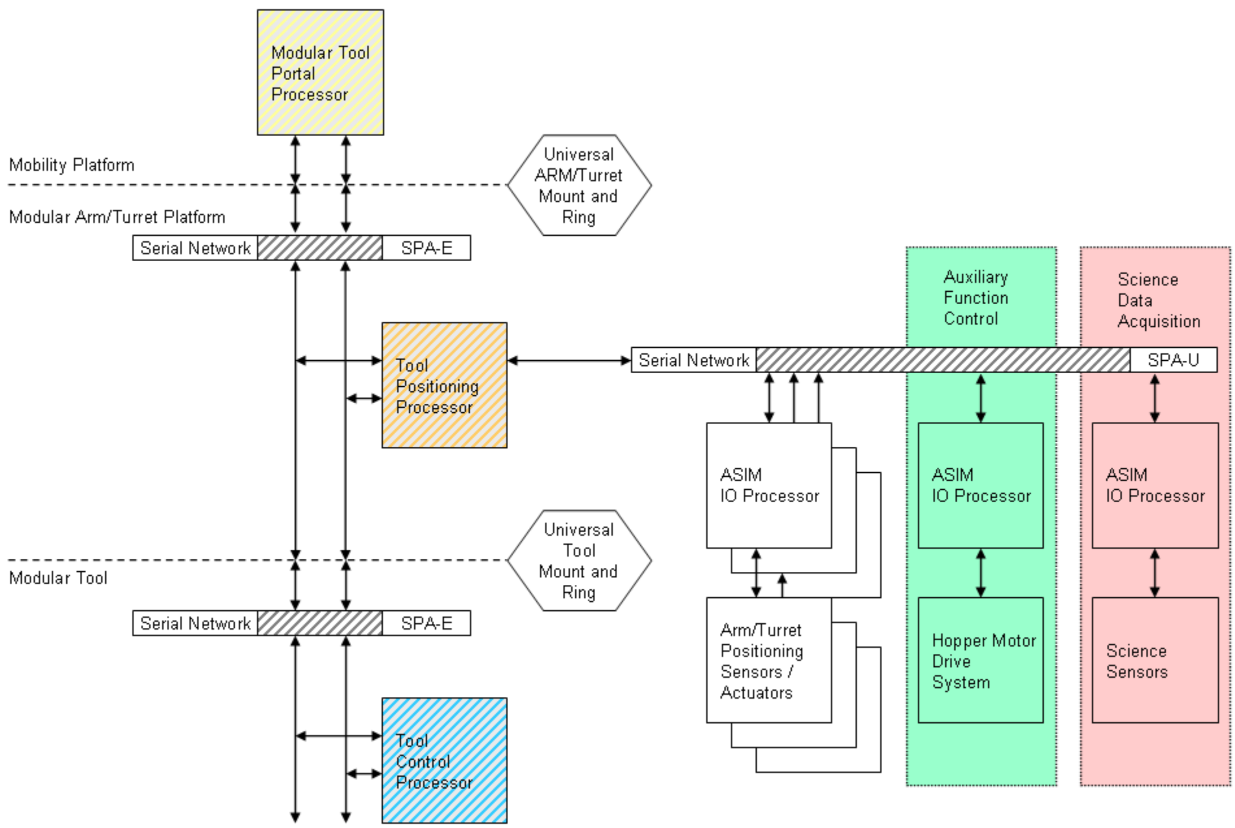

Figure 23 The Tool Positioning Subsystem SPA-U Bus

Modular Tool System Network

The Tool Control Subsystem is imbedded in the Modular Tool (Excavator) and communicates with both the Modular Tool Portal Processor and the Tool Positioning Processor, exchanging power and signals across rotating couplers.

The Tool Control Processor has a subordinate SPA-U bus which includes actuators, sensors and servos which provide at least 4 DOF.

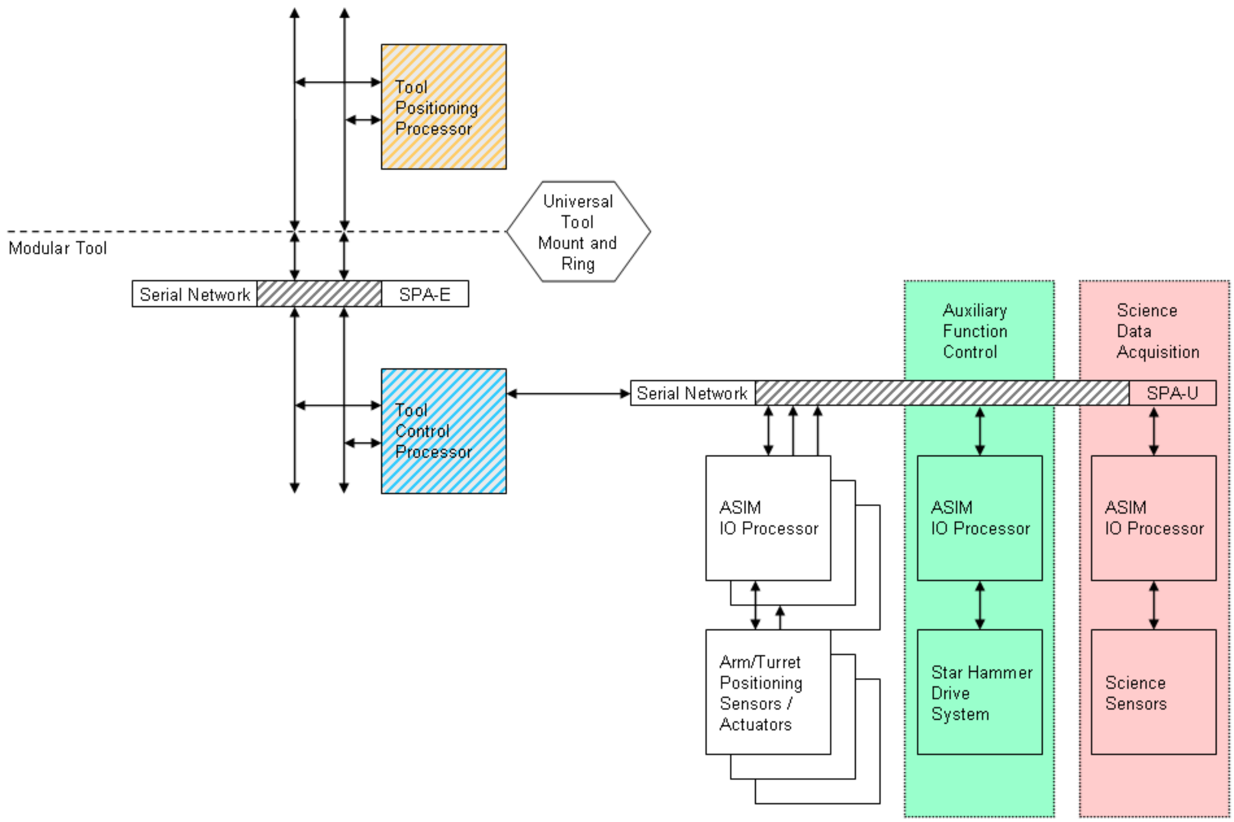

Figure 24 The Tool Control Subsystem SPA-U Bus

Integrated System

The Modular Tool System employs components of the Mobility Platform, the Robotic Arm/Turret and a Modular Tool. The *SPA Plug 'n Play* provides integration, versatility and operational flexibility. Most command flows are from the Modular Tool to the Platform while the unit is under the authority of the worksite. Outside of the worksite control authority, the mobility platform directs the stowage and dismount of modular tools, supporting system states including depot or *in-transit* (cross-country) CONOPS.

Test Bypass

Another feature of Space Plug ‘n Play Avionics is Test Bypass, a secondary, low-bandwidth simulation and maintenance network. This network provides a “back-door” access to the block of ASIM registers which are used to support sensor data scoreboarding. The Test Bypass logic allows a technician to overwrite locations of choice and lock-out any automatic updates from software. This method forces the sensor path to assume a static state which enables debug of downstream code and computational networks.

The Test Bypass Network is a tree of RS422 point-to-point links with a router which manages traffic. Test Bypass is only used on the satellite test bench and during integration. In orbit Test Bypass is *inert*, with no application or processor to drive it.

Enhanced Test Bypass

*sys*RAND is developing a software ensemble which provides robust support for spacecraft systems spanning development, bus integration, payload integration, launcher integration, *on-orbit* operations and decommissioning. The *sIDEreal™* package is an Applications-oriented Integrated Development Environment (AIDE) for realtime applications, and unlike conventional IDEs, supports a device for its entire product life cycle.

Foundational to the *sys*RAND AIDE is the redefinition of the Test Bypass Network and subsystem functionality. In a fashion merely similar to the basic Test Bypass, an Enhanced Test Bypass (ETBP) Network also connects SPA processor and network nodes (routers, *etc*.). However, the topology of the ETBP Network (ETBPN) can be an RS485 multidrop *bus* or RS485 driving legacy RS422 *point-to-point* nodes. The AIDE also works with SPA-U and Wireless USB (SPA-n) as delivery media.

ETBP directly supports or will soon support:

- Software Debug and Test
- Program Upload / Download
- Hardware / Software Diagnostics
- *Hardware-In-the-Loop* Simulation
- Health / Performance Monitoring
- Software Revision Control System
- and more.

Reiterating, unlike conventional IDEs, *sIDEreal*™ provides Life Cycle Support. *sIDEreal*™ also expects to provide support from the satellite bench to *On-Orbit* operations.

The block diagram depicted in Figure 25 shows that the Test Bypass Network is an independent resource and has its own topology, which will be present in Smart Modular Tools, including the Excavator family.

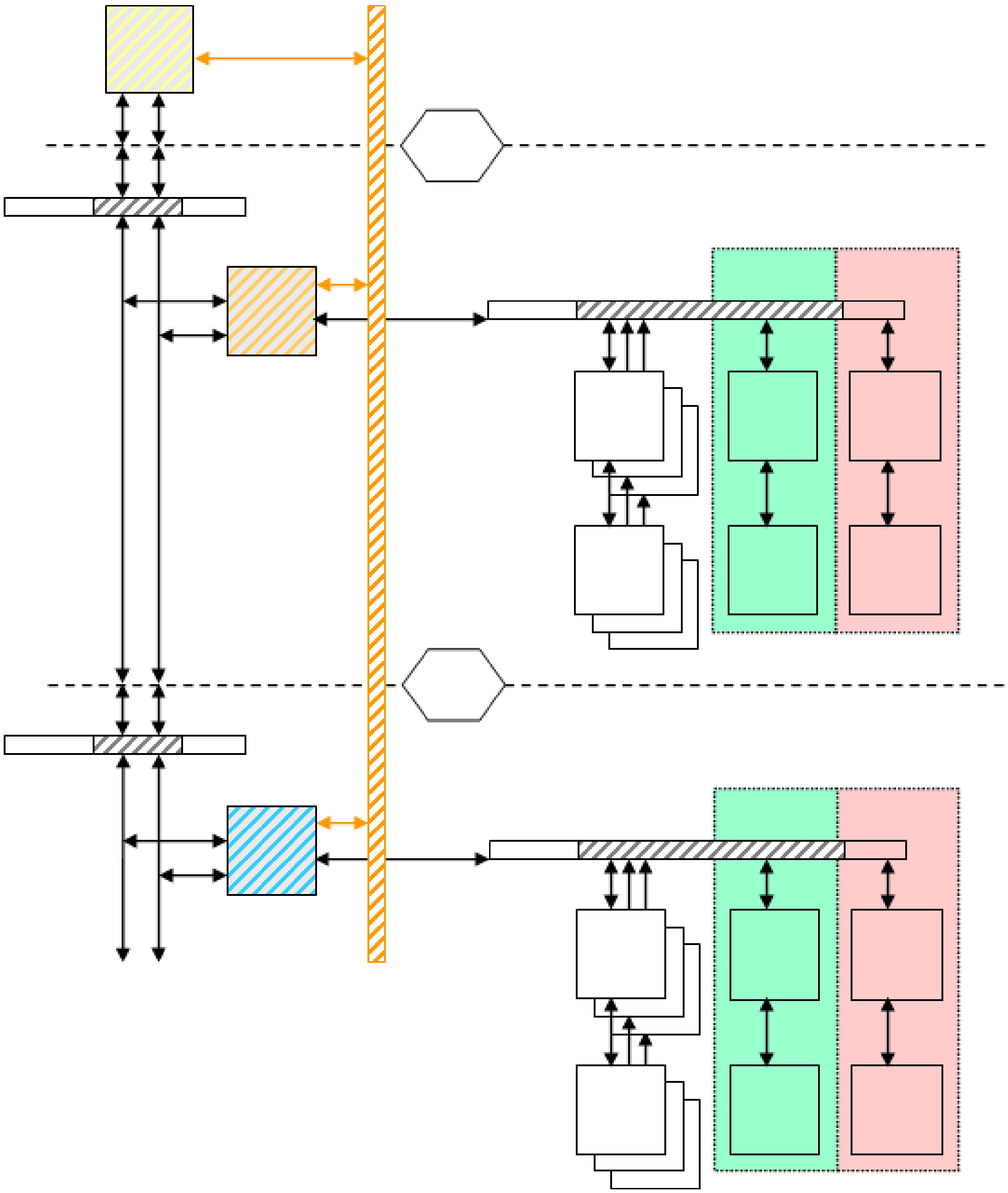

Figure 25 The Test Bypass Network (highlighted)

Reorganizing for Compatibility

Initial versions of the system will be installed in mobility platforms which do not support *Plug 'n Play* protocols. The Ethernet network will be otherwise compatible with SPA-E. Since the Arm / Turret and Tool processors will be SPA-compliant, the Modular Tool Portal Processor will provide SDM / SPA services on the downstream network. The SDM Services of Data Manager, Task Manager, Sensor Manager and Network Manager are necessary for the collaboration of the Smart Modular Tool and Excavator applications programs. This situation will require that the SPA network services will be hosted on the Modular Tool Portal Processor indefinitely. Contrast Figure 26 to the Modular Tool and SPA Services depicted in Figure 21.

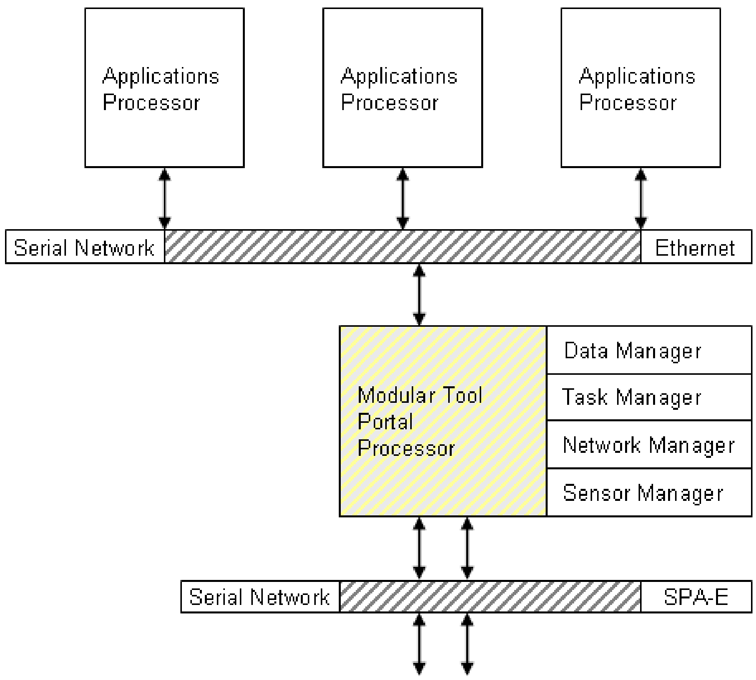

Figure 26 The SPA Service Managers Reside on the Tool Portal

Code Load over SPA-E

When a Robotic Modular Arm / Turret is inserted into a Robotic Mobility Platform, or a RESET occurs, the Tool Positioning Processor down-loads the Modular Tool (TURRET) code to the Mobility Platform Command Processor. The Turret Code is a generic program for servo control of the Turret by the Mobility Platform or the Modular Tool. Turret Code also computes trajectories within the combination of the platform's and the turret's work volume.

The Turret is capable of ***docking and locking*** to a compatible modular tool within its work volume, when the platform places the tool within reach, whether the tool is in a rack or otherwise positioned on the surface, as long as the docking port is exposed.

When a Smart Modular Tool is physically attached to a Robotic Arm or Turret, or a RESET occurs, the Tool Control Processor downloads the Modular Tool (EXCAVATOR) code to the Tool Positioning Processor. The Excavator Code is a program specific to the motion control of the Tool by the Positioning Processor. The Tool

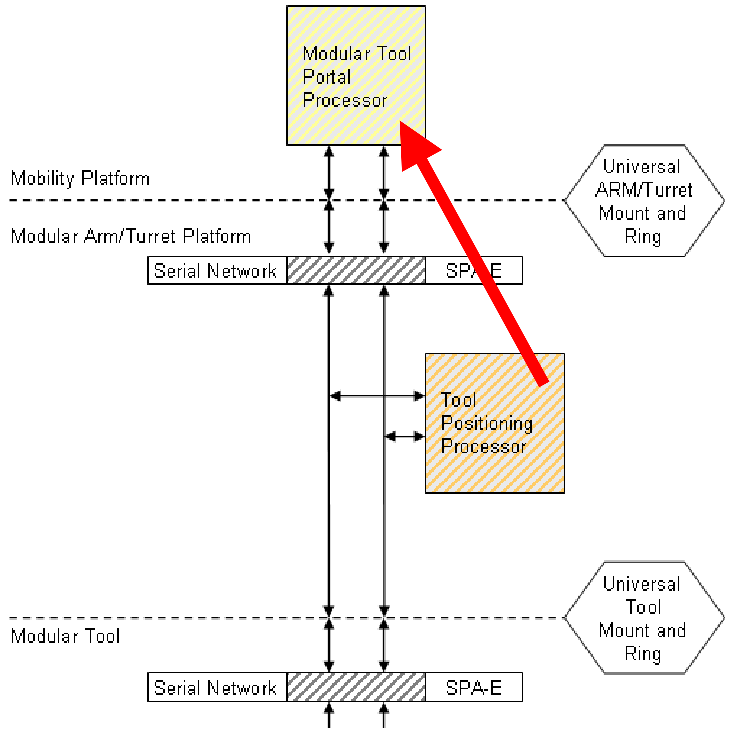

Figure 27 Tool Positioning Processor Downloads the Portal Processor

Code also computes tool trajectories within the combination of the platform, turret and tool's work volume.

All three subsystems are orchestrated to perform their functions simultaneously, delivering a smooth tool motion trajectory.

Universal Tool Coupling

The excavator team will develop or adopt a Tool Coupling which can be generalized to a large family of Modular Tools, hence 'universal'. A Tool Coupling has two major components, one on the end of the Arm / Turret and the complementary part attached to the excavator. In all likelihood the excavator may have a coupling which supports the mechanical loads and routes signals and power, and a second coupling which is used as leverage to position the excavator blade.

The Universal Tool Coupling incorporating the SDM Plug 'n Play model will likely find its way to orbital applications where a variety of tools, effectors, sensor platforms may be attached to satellites. The connections between the Modular Tool (Excavator), the Mounting System (Turret) and the Mobility Platform are SPA-E.

The PHY layer imbedded in the rotating couplers may be optical loops to avoid electrical contacts or copper cable loops within the UTC. The SPA-E and the ETBP Networks are bridged across the mechanical break between the blade and the turret. The UTC may be adaptable for use in orbital installations for the most general application of tools, although an *excavator in orbit* may prove the exception since such an installation has no utility.

Conclusion

The Excavator being developed for NASA can be generalized as a member of a class of Smart Modular Tools. The Air Force Space Plug and Play Avionics can be adapted to the Ethernet and the resulting Smart Modular Tool System will interoperate within a pure SPA environment or a mixed satellite network.

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Chariot at Moses Lake images are courtesy of K. Pratt, http://flickr.com/photos/kpratt/2585479219/

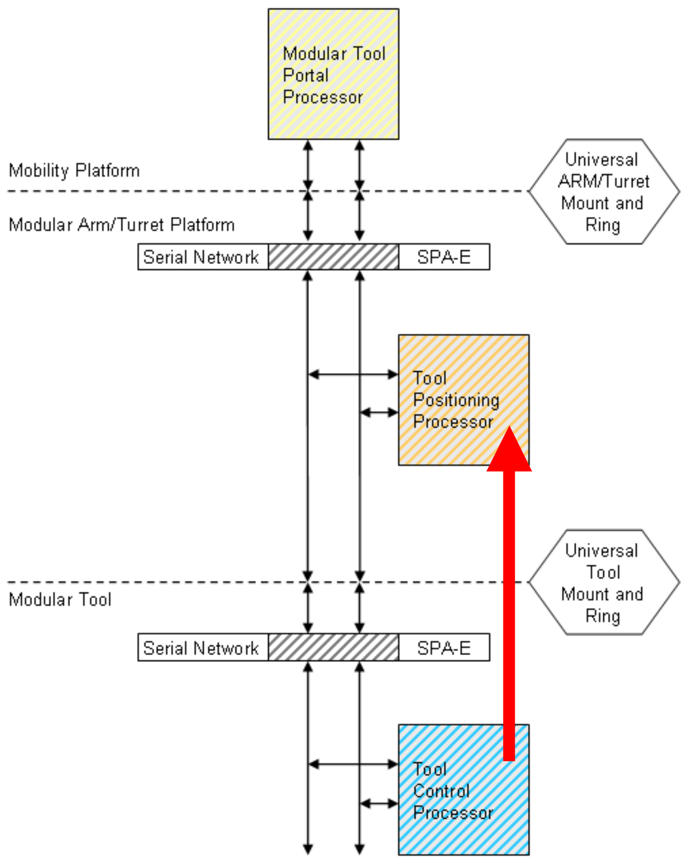

Figure 28 Tool Control Processor Downloads the Tool Positioning Processor