Instrument Technologies for the Detection of Extraterrestrial Interstellar Robotic Probes

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Abstract

In the continuing endeavor to detect evidence of ETI (Extraterrestrial Intelligence) in the solar neighborhood, instrument technologies now exist that allow the formation of a scientific method to carry out a search for interstellar robotic probes of possible extraterrestrial origin. The range of currently observable probe features/manifestations will be shown and how they influence search space, instrument selection and deployment. Autonomous instrument platforms (i.e. robotic observatories) to search for anomalous energy signatures can be designed and assembled using Commercial off-the-shelf (COTS) hardware and software. The COTS approach to observatory design provides an economical, flexible and robust path toward collecting reliable data. The present variety of COTS instruments permits the necessary observational sensitivity, bandwidth and embedded processing speed to establish a nearby robotic probe detection envelope. A survey of these instrument technologies will be presented and how they can be applied to the challenge of collecting enough scientific data on anomalous observational phenomena to determine whether or not a robotic probe was detected.

Keywords: SETI, OSETI, interstellar probes, instruments, sensors, embedded computing, detection platforms.

1. Introduction

It is clear our civilization's space program is becoming more dependant on the use of exploratory robotic probes to unlock the secrets of the solar system. Some of the best discoveries have come about by direct investigation. We now possess the technology to explore nearly every body in our solar system using either remote-sensing or in-situ approaches. Before the year 2020 Voyager 1 should move into the heliopause and become our first interstellar probe. Sensor and computer technologies for aerospace, military and commercial applications are rapidly improving in terms of reliability, speed, miniaturization, lower power consumption, improved sensitivity, and robust thermal and radiation tolerance of the environment. With the phenomenal improvement and availability of digital computers and software, what were previously formidable engineering problems are now in some cases cookbook tasks. Take for example the use of Maxwell's equations to solve for Poynting vectors having the analytic form: $-\oint_S (\mathbf{E} \times \mathbf{H}) \bullet dS$ in electromagnetic circuits. Fifteen years ago it would have taken a workstation computer a few hours to calculate the field intensity at a boundary and display it as a color-weighted contour plot. Today commercially available software for the PC (e.g. Ansoft HFSS High Frequency Structure Simulator) can, in minutes, efficiently solve for fields in 3D electromagnetic (EM) structures using optimized numeric finite element methods.

The computing power of commercially available microprocessors has increased in lock-step with Moore's law, and the term "deterministic real-time" is commonplace in the domain of computer operating systems. Scientific instruments are significantly better than 10 to 15 years ago. Instrument sensitivity and bandwidth has vastly improved by using sensors having arrays of micron or sub-micron semiconductors, Micro-Electro-Mechanical Systems (MEMS) or nanostructures. When certain key technologies converge, they lend themselves to exploring new, unusual and anomalous phenomena, or augmenting existing research. The existing convergence of technologies allows scientists and engineers to seize the opportunity to broaden SETI's horizons. This paper will show what these key technologies are and how they can be used to carry out a search for extraterrestrial interstellar robotic probes. This strategy is one of several "fresh SETI strategies" contributed by Tough[1] and intended to expand existing SETI endeavors.

The Search for Extraterrestrial Intelligence (SETI) in the Optical Spectrum III, Stuart A. Kingsley, Ragbir Bhanthal, Editors, Proceedings of SPIE Vol. 4273 (2001)

2. Rationale to Search for Robotic Probes

Why does a search for interstellar robotic probes need to be part of SETI? Arguably we are not certain that ETI civilizations even exist or what the leading manifestations of ETI technology are. We do know ETI technology is based on the same fundamental physics as our own, but the ETI technology we first encounter will be profoundly different, advanced and alien. It is postulated that intentional omni-directional beacons either at optical or radio wavelengths are one obvious manifestation of ETI technology. Another is unintentional or random telecommunications leakage from advanced civilizations, or long-range scanning at RF or laser wavelengths. These are sensible first-order assumptions regarding ETI manifestations that are being actively investigated by several professional and amateur microwave and OSETI (optical) scientists. Manifestations of our own civilization, within the solar system and stretching out about 70 light years, are TV and radio broadcasts, pulses from planetary radar systems, spacecraft telecommunications transmissions from Earth, the presence of several active deep space probes, and derelict artifacts in the form of space debris like rocket booster stages or defunct spacecraft. The observable features of our own robotic probes are well known and have a familiar shape which includes a large dish antenna, gold-metalized thermal blankets, and appendages like a boom magnetometer, solar panels or RTG's.

However, this space probe stereotype is temporary. The current trend in probe design is lower mass, smaller volume, lower power (more energy efficient), wider communications bandwidth and increased autonomy. If spacecraft evolution continues the solar system will some day contain multitudes of small autonomous robotic probes responsible for monitoring specific regions or bodies in the solar system, linked via an optical communications network. Future perspectives surrounding robotic probe technology will be much different primarily because robotic probes will be an integral part of our society and at the pioneering edge of our expanding civilization.

It is argued by SETI advocates that the first ETI civilization we encounter will be much older than our own. The estimates of L (lifetime of a technological civilization) range from $10^2 < L < 10^8$ years. Older technological civilizations are expected to be advanced on all fronts, including the robotic exploration of interstellar space. When considering ETI robotic probes we must be mindful that the physical features will be remarkably different compared to our own probe designs, probably surpassing what we can imagine our own spacecraft evolving into.

One of the first things our young civilization did once rocket technology became sufficiently advanced was to launch probes to explore the solar system. Interestingly, the radio search for ETI began around the same time we launched the first exploratory probes. Since 1958 our civilization has launched approximately 125 space probes (lunar missions inclusive) to explore the solar system. If we continue to launch 125 probes every 40 years, that equates to 312 probes every 10^2 years. In 10^4 years of deep space probe exploration the number of probe launches could exceed 31,000! In the last 23 years of launches a more conservative extrapolation of future launches is about 110 probes every 10^2 years. For this rate, in 10^4 years of deep space probe exploration the number of launches could exceed 11,000. Figure 1 is a graph of these projections along with the actual launches between the years 1958 and 2000 (based on NASA historical statistics). These linear projections are very conservative and factors like technological declines, advances or breakthroughs are not considered. If the very best robotic probe velocity achievable by any advanced extraterrestrial civilization is 10% the speed of light (0.1c)[2], then in 5000 years a civilization could reach out to a distance of 500 light years. If this civilization followed a launch rate of 110 launches per 100 years it could have 5,390 probes at selected star systems between 10 and 500 LY. Or, if the launch rate was 312 per hundred years then the quantity increases to 15,288.

From our location in the galaxy there are an estimated 1.6×10^6 star systems within 500 LY. There is a 0.9% chance that any particular star system within that volume would get a probe visitation by a civilization launching 0.1c velocity probes for 5000 years. If potentially life bearing star systems are sought more often, the probabilities increase. A more detailed treatment of the probabilities of robotic probes in the solar system are given by Freitas[3] and Burke-Ward[4]. From these simple numbers, based on actual exploratory space probe trends on Earth, it is rational to presume that any advanced ETI civilizations, within 500 LY of our solar system, might have sent a probe to explore our star system. Deep space launches for our civilization are now common and interstellar missions are within our grasp. Combining that ingredient with the fact that an ETI robotic probe mission to our solar system has a non-zero probability, SETI is obligated to explore that possibility by carrying out a search for robotic probes. The question then arises, what should we search for and how.

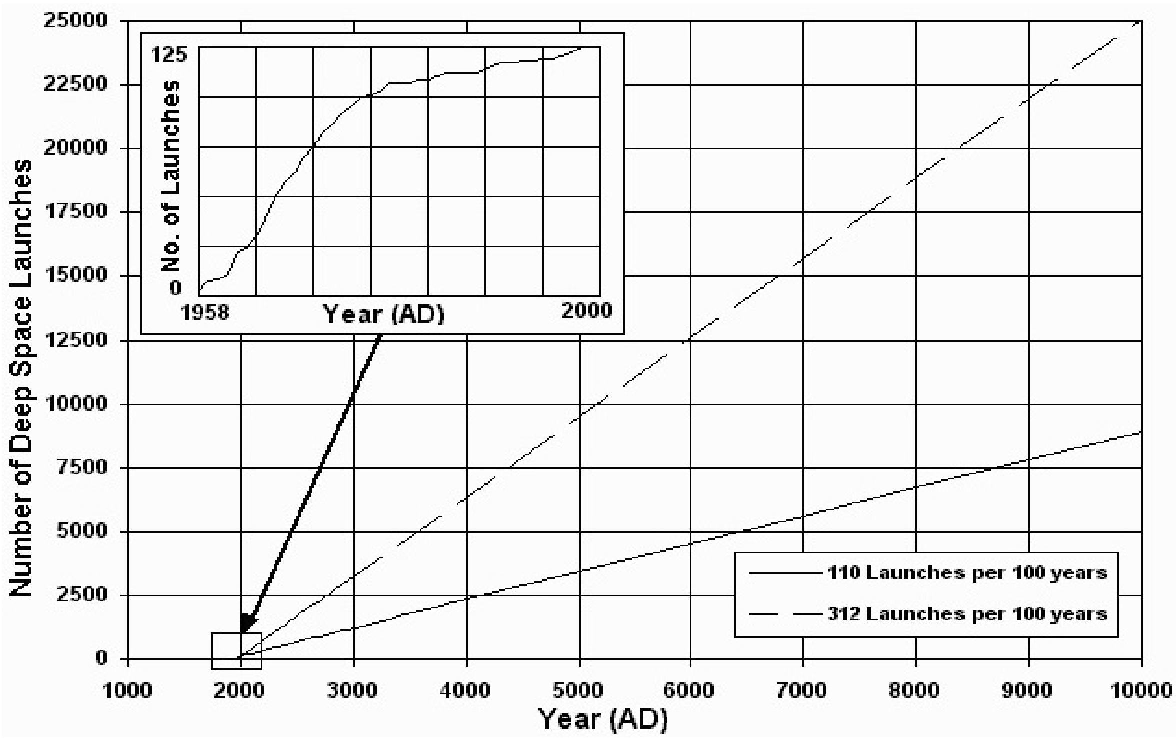

Figure 1. Actual Robotic Probe Launch es and Future Projections

3. Possible ETI Robotic Probe Features

First a set of presumed features for ETI robotic probes must be established. These features are expected to appear artificial when compared to the natural background. In the case of radio and OSETI, artificial is any electromagnetic signal that is clearly unnatural and only possible if ETI technology is at work. Aside from having to filter out known and previously unrecognized natural causes, SETI is constantly faced with distinguishing the detected EM energies from Earth-originating sources.

Trying to detect the physical presence of a robotic probe faces many of the same challenges. It's features must be distinguishable from natural causes and from manmade causes of interference. Natural sources include phenomena like asteroids, meteoroids, meteors or bolides. Potential causes of artificial interference take the form of space debris, artificial satellites, aircraft, balloons, etc. The amount of air traffic and space debris represents a rather large amount of interference making separation of unique ETI probe characteristics a formidable task. Fortunately it is not an impossible task. First let's examine possible large-scale features. The evaluation of several observable features of ETI civilization's has been done by Freitas[7] and others. Table 1 lists some of the possible manifestations.

These are considered manifestations of large-scale Kardashev[8] type II or III civilization activities and would not go unnoticed for long if occurring within our solar system. Since no obvious signs of type II or type III civilization astroengineering activities have been detected nearby, it is safe to say no large-scale ETI projects are taking place in our solar system. This leaves SETI searching for other observable features that might suggest an ETI robotic probe is present. Table 2 lists some of these observable features.

1. High energy leakage from fusion power sources
2. Optical emission/absorption lines from artificial effusion clouds
3. Anomalous radio emissions from recombination's in gas clouds
4. Artificial hyperfine transition lines (He isotopes and tritium)
5. Anomalous blackbody radiation
6. Unusually large x-ray and gamma ray bursts
7. Unusual magnetic fields
8. Large scale planetary, moon or asteroid belt[5] mining
9. Emissions from antimatter, fusion or mag-sail propulsion systems[6]

Table 1. Large Scale Manifestations

1. Infrared, visible or ultraviolet emissions
2. Ionized gases–hot or cold plasmas
3. Soft x-ray or gamma bursts
4. Anomalous electrophonic, ultrasonic or infrasonic emissions
5. Anomalous telecommunications activity (radio or optical)
6. Radioactivity
7. Varying albedos (radar or optical) from peculiar orbiting structures
8. Physical artifacts or waste products of non-earthly origin
9. Visible signs of intelligent macro, micro or nano structural design
10. Obviously artificial structures on the moon[9] or other solar system bodies
11. Intelligent and/or autonomous behavior
12. Statistical anomalies in observed meteor activity or cometary patterns
13. Neutrino emissions

Table 2. Observable Manifestations

This list is not complete and other features may need to be considered. At this time, with no observational guidelines or *a priori* knowledge about ETI probe technology, it is only possible to investigate features that we are capable of observing and recording with existing technologies. Admittedly, ETI technology may be so advanced and alien to our senses that detecting it is beyond our present reach. If a probe is not intended to be discovered with our level of technology it will not. Speculation about advanced ETI probe technologies that indulges expectations like cloaked nanoprobes or faster-than-light travel only serves to fuel pessimism and apathy. In order to avoid these pitfalls, this research paper stresses optimism by proposing that certain ETI probe features *are* capable of being measured with existing instrument technologies – action is preferable to apathy. While particular measurable features are sought, the factors listed in table 3 have limited or no significance to the search. It is highly unlikely given the expected size and age of a probe, that intelligent organisms will be present. One reason transporting multi-celled intelligent organisms is undesirable is the added mass, volume and complexity of life support systems even if the journey is short. Also, when exploring unknown territory, risking the destruction of a certain percentage of robotic probes is acceptable; sacrificing the lives of intelligent beings is not. Even if probes contained living biomatter we could not know this from a distant observation.

Determining the age and origin of a probe has limited value. The length of time a probe takes getting here is interesting but irrelevant. It is improbable a robotic probe would see any benefit communicating such information because its method of time-keeping would only have meaning to itself. Also, for obvious security reasons a probe will not disclose its point of origin. The time it takes to become technologically wealthy and the amount an ETI civilization spends in terms of joules of energy to explore interstellar space also does not influence the search. Type II or III civilizations spend what they can afford on interstellar exploration.

1. Intelligent living organisms.
2. Age of the probe.
3. Origin or the probe.
4. Technological and energy costs to build and launch interstellar probes.
5. Exploratory motives and incentives.

Table 3. Factors of Limited Significance

Nascent ETI technological civilizations will eventually determine rocket propulsion is impractical across interstellar distances. If ETI are sufficiently motivated, given enough time they will find a practical means to increase spacecraft velocities to 0.1c or faster.

The factors motivating ETI civilizations to launch exploratory probes has meaning in a behavioral context. No matter what the motives may be, it is necessary to observe any probe's technological features and behavior to the fullest possible extent.

Architects of interstellar robotic probes have undertaken a monumental task by first developing a practical means to remotely explore the galaxy and then actively doing so. Arguments made opposing interstellar travel and ETI interstellar exploration are irrelevant to the search and will not change the fact that interstellar travel is physically permissible. Again, the possibility that interstellar probes *can* exist at all merits a SETI investigation using carefully planned and implemented observational experiments. As Cocconi and Morrison pointed out for radio SETI: "The probability of success is difficult to estimate; but if we never search, the chance of success is zero."[10] Following this examination of the range of possible robotic probe features it is time to investigate a search methodology.

4. Search Methodology

When looking over the list of possible observable probe features it is clear that the available instrument technologies favor a search for electromagnetic signatures. In many ways the search for interstellar probes has more in common with OSETI than radio SETI. Fundamentally the search method for interstellar robotic probes involves following the steps in table 4.

A partial list of observable ETI probe characteristics has been defined. From the list, the first five features have the potential of being detected with existing technologies. A search in the IR, optical and UV ranges is favorable as is soft x-ray, ionizing radiation, electro-phonic emissions and anomalous telecommunications signals. ETI probes could be anywhere within the solar system, orbiting a planet, making a survey of all planetary bodies and moons, searching for life, searching for resources, passing through at high velocity or drifting through. The search volume could be boundless, but a practical observational limit is a 50 AU radius. That volume of space encompasses the orbit of Pluto and is about the observational limit at which our ground and space-based optical or radio telescopes could possibly detect a rather large, or bright, robotic probe. Searching for ETI probes in the solar system is possible using existing astronomical and surveillance systems. However, capable instruments, like the Hubble Space Telescope FOC, the DSN planetary radar, NEAT (Near-Earth Asteroid Tracking), NORAD/NAVSPASUR or HAARP are very specialized and expensive, which excludes all but the most affluent governmental space science or military programs from using them effectively. Unfortunately, these resources cannot be freed to assist in a search for robotic probes, which effectively reduces the practical observable search space.

In 1979 and 1982 an team of SETI researchers briefly used existing ground-based optical telescopes to search for probe artifacts at the stable Sun-Earth and Earth-Moon libration orbits[11,12]. One of the participants worked at the observatory which undoubtedly played a role in securing observatory time. For most SETI researchers negotiating for "prime" observatory time is very difficult and, if successful, the observing program would be of short duration, or a "piggyback" effort. These researchers found no evidence of artifacts, but did establish that longer, more dedicated, searches are necessary. They proposed a "*limiting artifact*" size of ~1 to 10 m and limiting magnitudes to +19 [13]. A practical magnitude range, with present commercial sensor technologies, is between -12 and +11 (~85° FOV, megapixel CCD sensor with 24cm^2 imaging area). By adopting these limits and using available instrument technologies a team of SETI researchers could carry out a long-term nearby automated search for ETI probes in cislunar space, Earth orbit, or passing through Earth's upper atmosphere.

1. Decide what probe features to search for.
2. Establish a bounded search space or volume, limiting artifact size and limiting magnitude.
3. Survey the available instruments and sensors.
4. Match the predicted robotic probe features with the available instruments.
5. Develop a set of design requirements and specifications for an observatory platform.
6. Select a data management and analysis strategy.
7. Derive testable hypotheses.
8. Design and build the observatory and begin the search.

Table 4. Search Methodology Steps

5. Instrument Technologies Available to Detect ETI Probe Features

The search observatories should be robotic or autonomously operated. Why a robotic observatory? There is a growing trend in astronomy[14] and OSETI[15] to automate the data collection process. The emphasis on building robotic observatories[16] is to improve parameters like scheduling, reliability, repeatability, precision and efficiency, while reducing cost, workforce and researcher fatigue or stress. Presently there are over 35 robotic observatories worldwide under operation or construction by government agencies, universities or astronomy groups. One distinguished observatory is ROTSE (Robotic Optical Transient Search Experiment)[17] operated in collaboration with the Los Alamos National Laboratory, Lawrence Livermore National Laboratory and the University of Michigan. ROTSE is now at a third working configuration and the platforms are currently being operated at Los Alamos, New Mexico. ROTSE and the many other functioning autonomous observatories, underscores the fact that robotic observatories have proven scientific value, are cost effective and can be designed using many commercial components. Robotic observatories can not only be used to experimentally study anomalous observational phenomena[18] to determine if it is connected with ETI technology, the observatory can host other experiments relating to meteorology, atmospheric research, astronomy and meteor studies. To adequately search a large portion of the space overhead, several observatories need to be built and operated in different geographic locations. Platforms should be placed in remote locations with *good seeing*, low levels of light pollution and where they won't be disturbed or tampered with. A portable, modular, rugged design makes good sense if the observatory is to be operated in a remote location.

5.1 COTS Instruments

One crucial aspect of the process is surveying the hundreds of commercially available instruments, sensors and computer hardware/software to determine what can be used to design and build the observatory. The most affordable instruments are the ones that already exist commercially and can be purchased off the shelf. There is a significant effort by the US government to use Commercial-Off-The-Shelf (COTS) instruments, sensors, computers and software wherever possible. Some NASA centers (e.g. Goddard and JPL) have funded COTS evaluation programs to "upscreen" plastic encapsulated microcircuits, to determine their radiation and thermal performance and potential use in flight missions. Stemming from a mandate in 1991, the United States military has taken a serious interest in using COTS computer hardware and IC's. To characterize COTS hardware, funding has been provided to such programs as the University of Maryland's CALCE (Computer Aided Life Cycle Engineering) program[19]. Because of increasing demands, a large variety of COTS electronic instruments are available with embedded microprocessors, high-capacity solid-state memory, FPGA's (Field Programmable Gate Arrays), DSP's, integrated A/D (analog-to-digital) converters and built-in high speed, serial or Ethernet communications ports. What does COTS mean for SETI research? Using mainly COTS components provides flexibility, reduces cost, design time and customization. Using COTS makes it possible for other SETI researchers to more readily build and replicate similar SETI experiments. The goal for SETI is to use these technologies to build autonomous observatories to gather the necessary data.

Robotic observatories must be reliable and "fault tolerant." Fault tolerant systems are "host failover" capable, meaning they have redundant system processors or hardware controllers. Due to the long-term nature of the search and the possible remote locations of the platforms, they must be designed for extended up-time and "high-availability." This means that down-time needs to be minimized with a goal of "5 9's (99.999%)" system reliability. 5 9's equates to between 5 and 10 minutes of down-time a year. By necessity, the telecommunications industry has embraced high-availability for its hardware, and is now striving for 6 9's system reliability. The fact that such high-availability systems are in operation bodes well for the design of a reliable robotic SETI observatory. Table 5 lists some of the existing COTS instruments that should be used in the design and construction of the observatory.

Instrument or System	Function	Suppliers*
Weather Station (Computer Interface)	To collect various meteorological data and monitor environmental conditions around the observatory.	> 10
GPS Receiver (Bus/computer Interface)	To collect geographic self-location data, precision time-code and generate reference clock signals.	> 22
Optical Telescopes and Lenses	Used to gather and magnify the light from a distant source to resolve its features.	> 93
Telescope / Sensor Mounts (Computer Interface)	Pan-and-tilt or Az-El motorized positioner to point or steer the optics and sensor arrays.	> 9
Spectrometers or Spectroradiometers	Used to measure and characterize the IR-Vis-UV emission spectra and from a light source, like a star or planet.	> 40
Photometer System	Used to measure the eye-weighted light in the visible band.	> 24
Magnetometer	Flux-Gate or Photon Precession to measure localized geomagnetic properties of the Earth's magnetic field.	> 12
Electronic imagers	Digital UV-Vis-IR imagers that can be added to the sensor platform, or integrated with a telescope.	> 30
Power Systems	Rechargeable batteries, solar panels and wind generators to provide remote/stand-alone power for the observatory.	> 18

* Approximate and based on available online sources

Table 5. COTS Instrument Selection

5.2 COTS Sensors

Along with a large selection of COTS instruments there exist many discrete sensors that can be used with the instruments or to design a particular instrument. Most notable are COTS multi-spectral FPA (focal plane array) sensors, used in the construction of visible and IR staring arrays, and sensitive high-speed imagers. PHILLS (Portable Hyperspectral Imager for Low Light Spectroscopy), an NRL funded project, is an example of a system built with multiple COTS intensified-CCD FPA sensors, optical lenses, digital signal processing (DSP) components, and computer software. If a certain kind of instrument is needed and it is not available commercially, it is possible to build such an instrument with COTS sensors and components.

It must be emphasized, the difficulty arises not in obtaining the sensors, but finding a reasonable match between what's available and the system requirements. For this search, the primary sensors are for detecting EM radiation from 1000Å (UV) to 20000Å (SWIR). The associated sensitivity, quantum efficiency, inherent noise and spectral response of the sensors should match the proposed limiting artifact size and limiting magnitude ranges. Sensors can be applied to the design of staring arrays to detect motion, record spectra, images, and aid in tracking. Table 6 lists the existing COTS sensors that could be used in the construction of an automated robotic observatory.

Sensor	Function	Suppliers*
CMOS Active Pixel Sensor	Visible spectrum "camera-on-a-chip" sensor, low power, high dynamic range, moderate quantum efficiency. Useful for motion detection, imaging and electronic tracking.	> 8
CCD Sensor, Intensified	Large formats, high quantum efficiency in the UV to NIR spectral range. Used for motion detection, imaging and spectroscopy.	> 44
Amplified Photodetector	InGaAs, InP, InPb, PbS, PbSe or doped Si semiconductors, good for detecting fast risetime pulses in the SWIR spectral range.	> 12
IR FPAs and Imagers	PbS, PbSe, HgCdTe, and other semiconductors, $6 < \lambda < 12$ μm. Used to image thermal emissions in the LWIR band.	> 20
QWIP (Quantum Well Infrared Photodetector)	GaAs, AlGaAs, narrow and double band, $8 < \lambda < 12$ μm, VLWIR > 15 μm, intrinsic, extrinsic types, usually requires thermo-electric or active cooling. Used to measure thermal emission levels.	> 4
Microbolometer	HgCdTc, SiO_2, metal oxides, $6 < \lambda < 14$ μm, cooled and uncooled operation, evacuated sensor surface, 100 Hz frame rates for uncooled arrays. Used for imaging and to measure thermal emission levels.	> 8
UV Photodiodes	Si, SiC, GaN, GaP PIN and heterostructures, spectral response $100 < \lambda <$ 440 nm; narrow-band filters; used to measure UV emission levels.	> 14
Accelerometers	To monitor the optical stability of the sensor and telescope platform. Milli-g to >5000 g sensitivity ranges, frequency responses from DC to 10 KHz. Single, dual and 3-axis outputs. Ultra-small modules, MEMS and surface mount IC versions.	> 11

* Approximate and based on available online sources

Table 6. COTS Sensors Selection

5.3 COTS Computer Hardware

COTS computer hardware is the engine that powers the robotic observatory. The fuel of that engine is embedded computing. The embedded computing thrust, fueled by market demands, has not only revolutionized computers but has played a huge role in instrumentation. What is embedded computing and why is it important to SETI research? Basically embedded computing is the use of microprocessor units (MPU) or microcontroller units (MCU) to carry out specific sets of commands and functions inside the instrument being used with little or no user interface capabilities. Embedded computing typically has more to do with "intelligent control" than general purpose computing.

For example, one COTS pan-and-tilt positioner uses an embedded 32-bit MCU to process pointing commands and control gimbaled stepper motors. Many COTS weather stations rely on embedded microcontrollers. Embedded MPU's and MCU's used today are based primarily on the Intel 8051/8052 or x86, the Motorola 68K series, the AMD E86™ series, Texas Instruments and MIPS. Several other companies also sell embedded MPU's. Processors are now offered in small form-factor modules like PC/104+, PCMCIA and EBX. Using embedded computing hardware greatly simplifies the operation of the observatory platform by letting the individual instruments perform computations, formatting, control and house-keeping internally, thereby freeing up the main computer to manage the entire system and make high-level decisions.

Taking advantage of embedded computing features reduces customization, allowing the SETI researchers to more quickly design, build and program the observatory. There are several ways to interface to the host computer, peripheral devices and instruments. A partial list of interfaces and bus architectures includes: Compact PCI (cPCI), Fibre-Channel, FPDP (Front Panel Data Port), I2C, IDE, IEEE 1394 (FireWire), InfiniBand, ISA, MIL-STD-1553, P2CI, parallel port, PC/104, PC/104+, PCI (Peripheral Component Interconnect), PCMCIA, PMC (PCI Mezzanine Card), PXI, RACEway, RACE++, RS232/RS422 serial, SCSI, SKYchannel, STD-Bus, USB, VME (VersaModule Eurocard), VME320, GigaBus VME and VXI (VME eXtensions for Instrumentation).

Many of the modern bus and microprocessor architectures support fast signal I/O, wide data bandwidths with high burst and data transfer rates. Multiprocessor connectivity architectures continue to improve via technologies like LVDS (Low Voltage Differential Signal) and the current trend is to balance aggregate processing performance with reduced power consumption and high reliability. At first sight, the choice of interfaces and bus connectivity technologies is dizzying. The three that stand out are: VME, cPCI and PC/104+. All three are standards and have well established markets. Within those markets price, availability, speed and functionality are competitive.

The VME bus, based on a 32-bit architecture, was introduced in 1981 and has gone through several standardization phases; with each one came an increase in performance. VITA (VMEbus International Trade Association) oversees the VME standards and improvements made to the VME bus. In many cases ANSI has also adopted the VITA standards. There are over 300 manufacturers of VME products worldwide and VME has been the workhorse for many years in both military and ruggedized commercial systems.

The 32-bit PCI bus is well known to PC owners. cPCI is a relative newcomer, being introduced in 1994, and is the modularized cousin of the PCI bus. cPCI has many advantages that are seen as complimentary to VME. The cPCI market share, especially in telecommunications, is rapidly increasing with the introduction of many new processor and peripheral boards. Remarkably, the cPCI bus is being seriously considered for some spaceflight missions (e.g. JPL X2000).

Computer Hardware	Function	Suppliers*
Single Board Computer (SBC)	The primary computer used to run the observatory, interface to and instruments, and manage the recorded data.	> 22
Data Storage	Magnetic recording devices function as reliable, long-term, high volume data storage.	> 18
Chassis and Backplanes	Used for housing, mounting and powering the various modular computer board, and peripherals.	> 77
Digital I/O and Interface Controllers	Hardware that is used to move data bits between peripherals and the host SBC or to control their function.	> 59
Memory	Solid state memory devices serve as temporary data storage or high-speed temporary data buffers.	> 24
VME Bus Products	Versatile, mature, standard 32 and 64-bit wide computer data bus that supports data transfer rates from 40 to 500+ Mbytes/sec. 21 slot backplanes. Products available include SBC's, Digital I/O (DIO), Data Acquisition, DSP, Imaging, Telecom, Ethernet and many others.	> 300
cPCI Bus Products	A 32 and 64-bit wide computer data bus that supports maximum data transfer rates from 133 to 533 Mbytes/sec. 8 slot backplanes, up to 16 with PCI bridges. Certain products available for VME will soon become available for the cPCI bus.	> 130
PC/104, PC/104+ Bus Products	Compact form-factor; self-stacking bus, no backplane, well suited for embedded PC applications; supports data transfer rates from 5 Mbytes/sec up to 132 Mbytes/Sec for PC/104+. Modules include SBC's, DSP's, disk controllers, DIO, video, and others.	> 160
DSP Products (boards and processors)	Used for numerically processing raw digitized sensor data and signals using 1D and 2D DFTs, FFTs and digital filtering algorithms. Supported on many bus types.	> 150

* Approximate and based on available online sources

Table 7. COTS Computer Hardware Selection

The PC/104+ is the other notable bus architecture. PC/104+ is a standard that is pin compatible with mezzanine stackable PC/104 8-bit and 16-bit ISA modules introduced in 1992. PC/104+ has added 32-bit PCI bus connectivity to the module increasing its performance and enhancing its use in embedded applications. In operation the hardware boards plug into a passive backplane housed in a chassis. The backplane is a large PC board with inter-connect sockets for VME, cPCI, etc. and provides multiple slots for the different form-factor boards (3U or 6U). It has minimal "glue-logic" circuitry and provides DC power for the boards. An example of a VME hardware board is a RAID disk controller for removable SCSI-3 hard drives. Not to be overlooked is the availability of COTS DSP hardware that is used to numerically process huge volumes of digitized raw sensor data. Table 7 lists the existing COTS computer hardware that could be used in the construction of an automated robotic observatory.

5.4 COTS Software

There are several COTS operating systems (OS) available. The OS's of choice are VxWorks®, and Linux. They are robust and well suited to run a robotic observatory. VxWorks is a development and execution environment for complex real-time and embedded applications and runs on a wide variety of target microprocessors some of which were listed in section 5.3. VxWorks is a mature well structured and modular operating system. Among the modern operating systems available to the SETI researcher Linux offers the largest variety of software.

Linux has enjoyed phenomenal growth in the past few years mainly because of its open-source architecture, stability and a concerted effort to keep the features of the OS kernel small, fast, extensible and stable. The modularity of the Linux OS means that software modules can be loaded when needed. The open-source aspect provides programmers an avenue to write hundreds of device drivers for hardware interfaces, OS API's (Application Program Interfaces), new applications and porting other/older programs written in languages other than C/C++ to Linux. Nearly all Linux source code is free to download and use. Linux has the following advantages: many open-source software products are regularly controlled either by a single individual or a small group of developers; source-code availability diminishes the dependency on key individuals; commercial support is available for many open-source products and source-code availability reduces the risk of "splintering and Balkanization"[20]. Both OS's have real-time capabilities. Tornado™ for VxWorks and RTLinux are POSIX (Portable Operating System Interface) 1003.1b compliant, and excellent choices for a RTOS (real-time operating system).

Why an RTOS for the observatory? An RTOS is needed to be able to ensure a deterministic, low latency response to triggers generated by hardware interrupts. Some robotic probe manifestations may be of limited duration or transient, so the OS must respond accordingly. If an EM emission is detected by an FPA sensor, the host OS must respond to that detection immediately and execute a programmed set of instructions designed to cause the observatory to collect more detailed data. Aside from COTS RTOS's there are real-time software programs, device drivers, data processing/analysis programs and numerous utilities available commercially or as shareware or freeware.

COTS software is very advantageous, and arguably the single most critical element of the robotic observatory The necessity to adapt or mold it to the observatories requirements and rigorously validate its functional modes must not be overlooked. Table 8 lists the existing COTS software that could be used in the construction of an automated robotic observatory. Figure 2. is a simplified system block diagram of a robotic scanning platform that could be built with existing COTS components.

Computer Software	Function	Suppliers*
RTOS	To provide a deterministic, "low latency" system response to emissions detected by the observatory	> 22
Real-time Software	Functions and code than run on the RTOS environment	> 16
Device Drivers	Programs used to control or interface to peripheral devices connected to the host computer.	> 500
Data Processing and Analysis	Programs to numerically process and extract information from the data and present it for high-level analysis.	> 140
Utility Programs	Programs to assist with data management, compression, archiving, formatting, diagnostics or system maintenance	> 850

* Approximate and based on available online sources

Table 8. COTS Software Selection

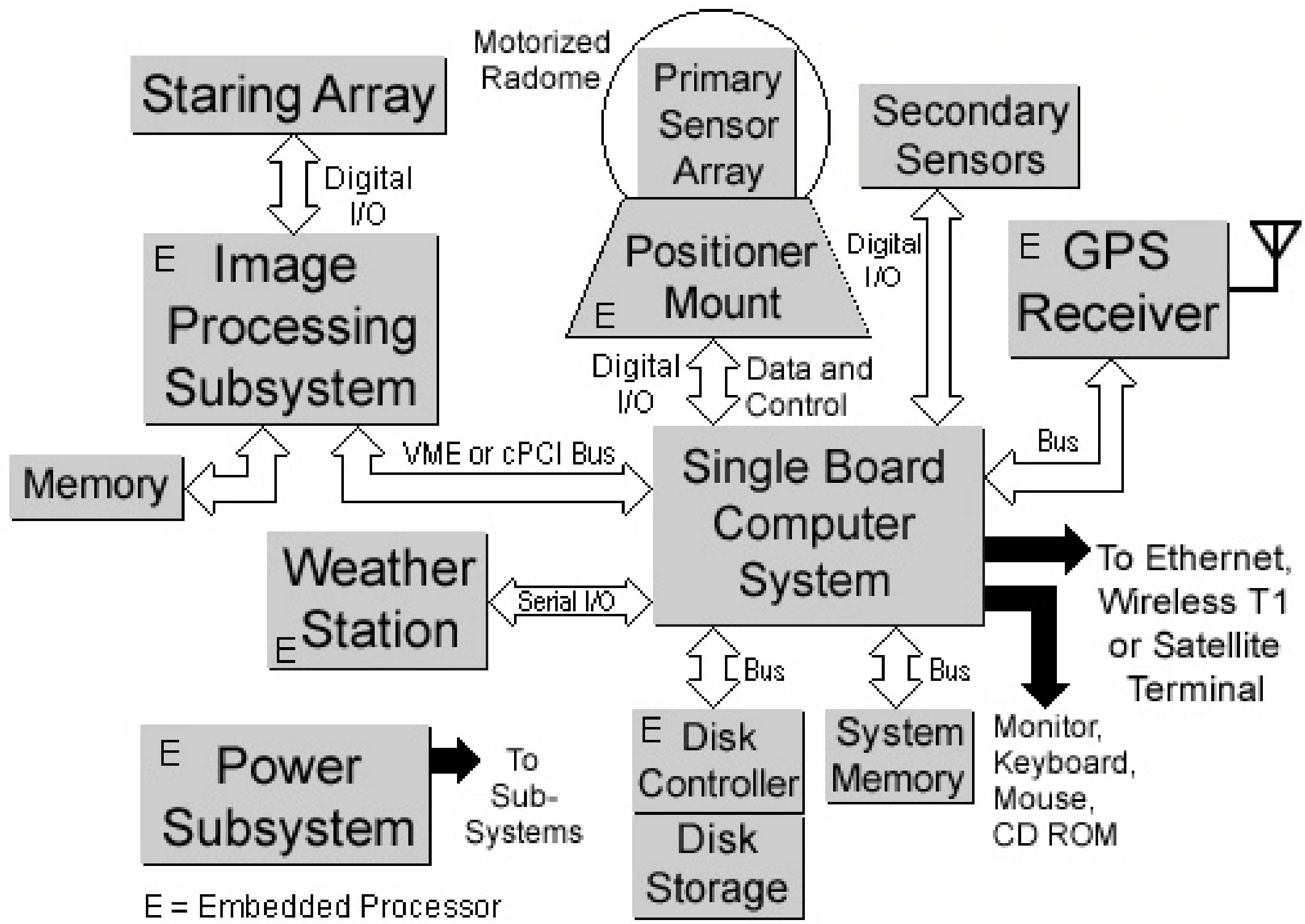

Figure 2. Automated Robotic Observatory Basic System Block Diagram

6. Proof is not Real-Time

The arguments in favor of robotic probes and the need to use COTS components for the search has been shown. Now some consideration of the methodology is needed. The search for robotic probes must wrestle with the same issues of observatory design, data acquisition, validation, evidence, and protocols as all other scientifically based searches for ETI. Therefore, the method of searching for robotic probes must be modeled after Radio SETI, OSETI and SETA (artifacts)[21].

Presently, we cannot expect to construct a single SETI experiment that would guarantee detection within an average persons lifespan. Searches will overlap multiple generations of SETI investigators. Thus, any search for ETI probes is expected to require time, patience and determination. An effective search for probes depends on using multiple corroborating instruments in conjunction with sensors and data processing software. A *single* telescopic camera or spectroradiometer instrument, however well automated, will not be able provide enough convincing scientific evidence to prove a probe was detected. Due to the possible ramifications of the discovery, one observation alone is not good enough!

The requirement for multiple instrument types is different from optical and radio SETI which depend on a single type of instrument, with speedy verification by other SETI stations. OSETI relies on the optical telescope with photomultiplier tube and narrow band filters; radio SETI, the parabolic radio-telescope with mega-channel narrowband heterodyne receiver.

SETV, a scientific search method for robotic probe visitation, must use multiple instruments concurrently because multiple manifestations may be present. With multiple instruments and sensors, the data fusion, management, and organization process is more complicated and analytically challenging. Hypotheses such as the "SETV Hypothesis" [22], which postulates: "*Technologically advanced extraterrestrial civilizations have deployed interstellar exploratory probes, and there is a non-zero probability that functioning probes have reached our solar system and are detectable or contactable using existing terrestrial technologies.*", are adequately testable with properly designed experiments using the appropriate data fusion, management and analysis methods. Data fusion and management is an in-depth topic covered excellently by Blackman & Popoli [23], Strömberg [24] and others.

Because a single real-time event cannot be proven to be a robotic probe, statistical techniques like Bayesian inference or Meta-analysis can be used once the observational data set is sizable and coded or organized properly. Because of the multiplicity of measured parameters and the need to statistically analyze the data sets to test the hypotheses, proof of robotic probe visitation can not happen in real-time. It may take decades to collect enough data to conclusively announce ETI technology has been found or not.

7. Conclusions

The search for extraterrestrial interstellar robotic probes is a necessary element of SETI and its inclusion improves the overall chances of success. It has been shown that existing COTS technologies give SETI researchers the means to carry out a proactive, rigorous and methodical scientific search for robotic probes within the solar system. The COTS approach is necessary for building an affordable, robotic observatory platform. COTS instruments and sensors placed on the observatory are matched to specific predicted manifestations of ETI probe technology, limiting artifact sizes and visible magnitudes. Robotic observatories can also gather data for other scientific disciplines unrelated to SETI. The search for robotic probes must be modeled after current SETI methods. Confirmation that a probe was detected will not happen with a single observation. It will require time and researcher patience due to the complexity of collecting, organizing and analyzing the different kinds of recorded data needed to experimentally test proposed hypotheses such as the SETV hypothesis.

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