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Component-Level Electronic-Assembly Repair (CLEAR) System Architecture

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Executive Summary

This document intends to capture the system architecture for a Component-Level Electronic-Assembly Repair (CLEAR) capability. This architecture, hereafter referred to as the CLEAR system architecture, can be applied to electronic repair needs of the Constellation Program (CxP) in missions in Earth orbit and the Moon, and extendable to Mars. The CLEAR system architecture may be considered a precursor to a system functional requirements document and is intended to define the functions required to respond to the "Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept" (CLEAR–DOC–007). The operational concept was developed to respond to the "Component-Level Electronic-Assembly Repair (CLEAR) In-Space Electronic Diagnostics and Repair Needs Assessment" (CLEAR–DOC–006), and "Component-Level Electronic-Assembly Repair (CLEAR) Analysis of ISS On-Orbit Electrical Systems Problem Reporting and Corrective Actions," (CLEAR–DOC–005), which both use the existing International Space Station (ISS) as an analogy for the types of electronics used in spacecraft and the types of problems encountered.

The problem of electronics repair cannot be resolved by a simple monolithic solution. Instead, a solution must exploit existing capabilities while building new capabilities. This document considers the evolution or incremental growth in capability. The CLEAR system architecture is a semiautomated system, capable of the complete repair cycle that includes diagnostic, repair, and test processes. This architecture considers the role of ground support, teleoperations, and the information infrastructure required to achieve its capability.

A basic assumption is that the CLEAR repair process deals with flight hardware that is removed from the system as an orbital replaceable unit (ORU) and has been replaced with a spare ORU. The CLEAR strategy is to repair the faulty ORU and return it to service in the system or as a functioning spare.

The CLEAR system architecture is composed of four primary systems that have interactions with elements of the overall CxP architecture. Each system can be considered to involve both a Space segment and an Earth segment. The four systems for CLEAR are (1) Teleoperations, (2) Control and Data, (3) Diagnostics and Test, and (4) Repair Apparatus.

The CLEAR Teleoperations (CTO) system architecture is closely coupled with the CxP Command, Control, Communications, and Information (C3I) infrastructure. Repair involves problem diagnostics, the physical repair materials and processes (M&P), and functional test capabilities. CLEAR is highly dependent on detailed and complex information that requires specialized knowledge in a wide array of disciplines. The knowledge base exceeds that of our highly trained flight crews. Historically, the National Aeronautics and Space Administration (NASA) has augmented the flight crew by employing extensive telemetry, communications, and monitoring of systems by mission operations centers. Science payloads have been supported by remote payload operations centers that provide user access to science instruments and experiment payloads, without adding a burden on the primary flight system operations. CTO is an extension of this payload capability.

The CLEAR Control and Data (CC&D) system architecture serves as the data backbone of the Space segment. The CC&D system must provide for incremental development of the repair-related technologies. It must be established early and yet resist obsolescence. A local-area network (LAN)-based architecture is inherently an open architecture, less restrictive than proprietary architectures, and considered the best option for long-term stability. The LAN-based data backbone is consistent with a plug-and-play approach that provides ease of integration and incremental growth. To assure high performance, the project is adopting the Institute of Electrical and Electronics Engineers (IEEE) 1588 "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" (IEEE–1588) for precision synchronization of instruments, robotics, and machine control. This standard is already incorporated in *Orion's* primary control architecture.

The CLEAR Diagnostics and Test (CD&T) system architecture addresses the instrumentation of two repair-related activities. Diagnostics is used to determine and isolate a system malfunction to the component level and determine the root cause. Testing (functional) is aimed at verifying that the repair has restored full function and verifying that the repaired assembly is suitable to return to service. Although diagnostics and test are different activities, they often use similar functions and the same

instruments. Thus, diagnostic functions and test functions are considered different applications of a single CD&T system.

For diagnostics, CLEAR will adopt characterization techniques employed by the U.S. Navy that rely on "known-good" circuit signatures as a means of quickly isolating circuit faults. Functional tests require external power and emulation of external system interfaces. Emulation, along with a wide array of measurements, drives complexity and test system mass. To address the need for compact light equipment and the need for simple crew operation, the CD&T system will exploit the synthetic instrument (SI) approach. Synthetic instrumentation exploits advances in reconfigurable electronics and the ability to synthesize instruments on demand. Synthetic instrumentation is also consistent with the CTO approach.

The CLEAR Repair Apparatus (CRA) system architecture addresses the repair processes that are beyond the capability of manual tools and the crew skill level. Repair is driven by the design, materials, and fabrication processes used in the original circuit fabrication. Advanced high-density component technologies involve process cycles with control parameters and requirements that are beyond the capability of manual methods. Furthermore, spacecraft electronics require conformal coatings and conductive cooling features that impede the repair process. Fortunately, nearly all component replacement can be done by modern reflow techniques. The CRA system will employ flexible, programmable equipment that can be configured for each application. These repair processes will be validated on Earth before repairs are executed on critical flight hardware in space. Properly programmed and validated robotics control of thoroughly developed processes will create in situ repair capability for nearly all spacecraft circuit repair applications.

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1.0   Introduction

The Component-Level Electronic-Assembly Repair (CLEAR) task is part of the NASA Exploration Technology Development Program (ETDP) Supportability Project. CLEAR's objective is to develop technologies that enable a capability for future space-flight crews to perform in situ repairs of electronic hardware at the component level (Ref. 1). This document, which is one of many documents produced by the CLEAR task (see Section 2.0), identifies a proposed architecture concept for how to perform component-level repair of electronics within a spacecraft or habitat. This architecture is based on a documented diagnostic and repair needs assessment (CLEAR–DOC–006) and operational concept (CLEAR–DOC–007).

The CLEAR task responds to the general need to reduce the upmass of spare hardware and to empower the crew to respond to problems without dependence on a robust and timely logistics system. The CLEAR task has chosen to approach enabling component-level repair of electronics without expanding crew size or dramatically expanding flight crew training. This task has adopted a strategy to exploit teleoperations as a means of augmenting the flight crew with ground-based support on an as-needed basis. Previous documents (Refs. 1 and 2) have described this strategy.

2.0   Documents

The following documents contain supplemental information related to the CLEAR task.

2.1   Reference Documents

Document number	Document title
CLEAR–DOC–005	Component-Level Electronic-Assembly Repair (CLEAR) Analysis of ISS On-Orbit Electrical Systems Problem Report and Corrective Actions
CLEAR–DOC–006	Component-Level Electronic-Assembly Repair (CLEAR) Assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs
CLEAR–DOC–007	Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept

2.2   Applicable Documents

Document number	Document title
CLEAR–ANA–001	Component-Level Electronic-Assembly Repair (CLEAR) Life-Cycle Cost Impacts of Different Approaches for In Situ Maintenance of Electronics Hardware
CLEAR–ANA–002	Component-Level Electronic-Assembly Repair (CLEAR) Noncontact Coupling Techniques for Performing Signature Analysis
CLEAR–DOC–001	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Exp-1 (CRE–1) Flight System Requirements Document
CLEAR–DOC–002	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Exp-1 (CRE–1) Concept and Hardware Summary
CLEAR–DOC–003	Component-Level Electronic-Assembly Repair (CLEAR) Recommendations for the Design of Electronic Assemblies for NASA's Exploration Program
CLEAR–DOC–004	Component-Level Electronic-Assembly Repair (CLEAR) Trade Study: Current Technologies and Instruments for Electronic Fault Diagnosis and Repair
CLEAR–DOC–005	Component-Level Electronic-Assembly Repair (CLEAR) Analysis of ISS On-Orbit Electrical Systems Problem Report and Corrective Actions
CLEAR–DOC–006	Component-Level Electronic-Assembly Repair (CLEAR) Assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs
CLEAR–DOC–007	Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept
CLEAR–DOC–009	Component-Level Electronic-Assembly Repair (CLEAR) Recommendations for Enabling Manual Component-Level Electronic Repair for Future Space Missions
CLEAR–RPT–001	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Exp-1 (CRE–1) Systems Requirements Review (SRR) Panel Report
CLEAR–RPT–002	Component-Level Electronic-Assembly Repair (CLEAR) Soldering in Reduced Gravity (SoRGE) Mission Test Report
CLEAR–RPT–003	Component-Level Electronic-Assembly Repair (CLEAR) Analog Signal and Complex Signature Analysis Test Report
CLEAR–RPT–004	Component-Level Electronic-Assembly Repair (CLEAR) Synthetic Instrument Capabilities Assessment and Test Report

3.0   CLEAR System Architecture

3.1   Overview

The CLEAR system architecture is an organized functional system structure that establishes primary elements, the functional hierarchy, and dependencies of a system to meet the operational needs of the CLEAR concept of operations. The CLEAR architecture serves as a guide for the development and design of the actual system.

The CLEAR system architecture is intended to cover the complete system from ground-user interfaces to flight hardware and crew. Since the capability is aimed at supporting flight systems, there are many aspects of both ground and flight operations that must be considered. Where possible, the project intends to exploit existing ISS infrastructure or planned Constellation Program (CxP) infrastructure. This includes existing organizational capabilities that currently support the ongoing space shuttle and International Space Station (ISS) operations.

The overall architecture, as outlined in the CLEAR Operational Concept (CLEAR–DOC–007), is split into an Earth segment and a Space segment. The Earth segment involves information and database management, operational planning, and robotic and automated equipment programming and validation. The Space segment involves all the in-space equipment including diagnostic and test instruments, robotics, and repair process equipment with related controllers and crew interfaces.

This document defines three major system architectural elements, the teleoperations, the diagnostics and test, and the repair apparatus subsystems. As described in CLEAR–DOC–007, CLEAR depends on teleoperations to perform complex tasks with minimum impact on crew time and training. CLEAR Diagnostics and Test (CD&T) functions are performed by an integrated set of highly reconfigurable equipment. The CLEAR Repair Apparatus (CRA) includes the materials and processes (M&P) of repair and the robotic elements required to automate the processes. Each CLEAR subsystem has a distinct role, and this document describes functions and relationships between subsystems and users.

3.2   Assumptions

CLEAR is a task under the supportability project for CxP's ETDP office. Since much of the CxP architectures are still being formulated, the CLEAR team must make assumptions about future capabilities that will be provided by the program. Many assumptions are extrapolations of space shuttle and ISS capabilities. The CLEAR team acknowledges that assumptions are will be inherently inaccurate, and the architecture is expected to be revised and updated as program changes and new information becomes available.

Assumption.—The command, control, communications, and information (C3I) infrastructure is provided by CxP.
Rationale.—CLEAR is not responsible for developing independent C3I. The design will, however, be compatible with the C3I infrastructure provided.

Assumption.—The spacecraft systems for CxP will utilize a modular orbital replaceable unit (ORU) design philosophy similar to that used in the ISS.
Rationale.—Component-level repair does not negate the need for ORUs. ORUs make it feasible to quickly remove and replace malfunctioning hardware and return systems to full operation. Component-level repair affects how an ORU is processed once it has been removed from the system.

Assumption.—Removal and replacement of an ORU is handled by operations. CLEAR controls the hardware once an ORU has been disassembled or a faulty intermediate-level assembly has been removed from the ORU.

Rationale.—CLEAR relies on spacecraft operations to perform ORU remove-and-replace operations and any deintegration required to access electronic (intermediate-level) subassemblies. CLEAR diagnostics, repair, and test activities will be used to repair subassemblies by removal and replacement of components. Components will be repaired or reworked depending on the complexity of the tasks and the available M&P.

Assumption.—Communications for CLEAR equipment are handled as a payload rather than a spacecraft system.

Rationale.—This relaxes certain safety, reliability, and security requirements that are normally needed for real-time interaction with flight critical systems. It provides greater latitude in CLEAR equipment control. It also implies that CLEAR would be communicating through a payload host center that would handle the communications exchanges between the CLEAR Earth segment and the CLEAR Space segment.

Assumption.—A CxP logistics depot or equivalent logistics center will provide the main source of engineering support and management for the CLEAR Teleoperations Support Team (TEST) center.

Rationale.—Logistics depots provide ongoing support for on-orbit operations, including processing of hardware prior to flight integration and servicing ORUs. These depots are equipped to diagnose, repair, and test ORUs in preflight operations or as part of processing ORUs returned from orbit. Expertise and skills are distributed throughout the Agency and its contractors. A depot serves as the center for organizing the detailed responses to system hardware problems. It is assumed that such a depot would take ownership once the capability is developed.

Assumption.—The C3I infrastructure will expand the capabilities beyond that currently employed for the space shuttle and ISS.

Rationale.—According to the C3I CxP 70022: Constellation Program Command, Control, Communication, and Information (C3I) Interoperability Standards Book, Volume 1: Interoperability Specification, the system will be upgraded to better exploit existing legacy capability and incorporate non-Government assets. The routing of messages and data will employ an Internet-like protocol; therefore, CLEAR uplink and downlink transactions may be more like Internet transactions.

Assumption.—CLEAR will be operated as an independent payload; thus, a CLEAR TEST will be provided with communications interfaces and communications software development kits that will simplify teleoperations development.

Rationale.—To avoid the interference with primary spacecraft operations and allow the payloads to operate freely within a predefined envelope, the ISS program established separate communications channels. For ISS payloads, command and data communications between payloads and payload users, such as science experiments, are accommodated by the Huntsville Operations Support Center (HOSC) (based at the NASA Marshall Space Flight Center). The HOSC also provides a Telescience Resource Kit (TReK) to assist payload developers and users in developing an interface that will provide access to payload data and command uplink. A similar arrangement is assumed for CxP operations.

Assumption.—CLEAR hardware will be accommodated in a payload or multipurpose facility.

Rationale.—CLEAR repair operations will use techniques, materials, and processes that should be isolated from the crew's cabin environment. For CxP lunar surface operations, the repair apparatus and containment enclosure may share resources with science payloads. This would include utilities that support atmosphere containment, inert atmosphere supply, and a means of exhaust venting.
For the shuttle and ISS, many small microgravity experiments are performed in a small, rack-mounted facility called microgravity science glovebox. CLEAR assumes that CxP will provide functionally similar accommodations on the lunar surface.

3.3 Partitioning Into Segments

CLEAR will comprise an Earth segment referred to as "CLEAR TEST" (Teleoperations Engineering Support Team) and a remote (on-orbit) segment, referred to as semiautomated repair and diagnostics apparatus (SARADA).

3.3.1 Space Segment

CLEAR SARADA is a system that will operate in a manner similar to an experiment payload. Payloads often are supported with a mix of voice, video, and data communications. SARADA provides for both manual operations involving direct action of the crew and automated operations under the direct control of the CLEAR TEST team. SARADA will provide diagnostic, repair, and test equipment suited for isolating faults, performing repairs, and performing functional tests.

- SARADA will support both a manual diagnostic and test capability and a teleoperated automated diagnostic and test capability.
- SARADA will provide specialized equipment to support manual operations, such as removal of intermediate-level assemblies from ORUs and simple component-level repairs.
- SARADA will provide the specialized equipment and material handling capabilities needed to support the M&P required for automated component-level repair.

CLEAR SARADA integrates many discrete functions. It encompasses the flight CC&D system, CD&T system, and the CRA system.

3.3.2 Earth Segment

The ground-based CLEAR TEST center will be similar in concept to the Glenn Telescience Support Center (TSC) used to support science payload operations. Payload teleoperations allow NASA centers and institutions to interact with their payloads without posing a risk to the primary flight systems.

The CLEAR TEST concept will be consistent with the NASA logistics and repair depot system used for the space shuttle and ISS. Flight electronics problems will be tracked with the existing Problem Reporting and Corrective Action (PRACA) system, and flight system information will be accessible through the Vehicle Master Database (VMDB). By exploiting existing problem tracking and design information infrastructure, CLEAR can expand capabilities with minimum impact to current operations.

The CLEAR TEST center also will develop and validate diagnostic and test procedures, process kits, and software code required for performing the physical repairs. The CLEAR TEST center will develop and maintain a CLEAR library containing validated procedures and programming code for reuse in future applications.

3.4 CLEAR Systems

CLEAR involves four interdependent systems with their own architectures: the CLEAR Teleoperations (CTO), CLEAR Control and Data (CC&D), CD&T, and CRA systems.

3.4.1 CLEAR Teleoperations System Architecture

Regardless of the repair method (manual or automated), it is essential to define space and ground-based activities related to the repair process and the telecommunications infrastructure that links them. In many ways, repair is an off-nominal or contingency operation, and there may be considerable risks to the crew and mission. The wide diversity of systems makes it impractical to have each crew member familiar with the level of detail required to diagnose and repair flight hardware. The crew must be backed by ground-based expertise and a knowledge base capable of resolving the problem, creating and coordinating crew procedures, and programming equipment to execute corrective actions.

As described in the CLEAR Operational Concept (CLEAR–DOC–007), teleoperation involves people, information, and information and development tools. Section 4.0 will outline what information is acquired, what actions are formulated, and type of commands and information that pass between the ground and flight segments.

3.4.2 CLEAR Control and Data System Architecture

The CC&D system links directly to the spacecraft's onboard command and data system. The CC&D system serves as the Space segment of the overall CLEAR architecture and is the primary controller for the SARADA subsystems including the CD&T system and CRA system.

3.4.3 CLEAR Diagnostics and Test System Architecture

The CD&T architecture is tightly coupled with the overall teleoperations via the CC&D system. CD&T data will be passed from flight equipment to the Earth segment. The goals of diagnostic and functional test measurements have distinctly different objectives, but the measurement instruments are often the same. Therefore, diagnostics and test are considered to be different functional applications of a single architecture. At the component level, CD&T requires planning and is highly dependent on acquiring specific measurements, locating the specific measurement nodes, and properly setting up both target device and measurement instruments. All of these activities require planning and preparation prior to measurements and detailed examination of the resulting data.

3.4.4 CLEAR Repair Apparatus System Architecture

Component-level repair may be performed manually and will always be an option when human crews are available. However, many operations are best handled by dedicated preprogrammed equipment designed to reproduce many of the conditions used in manufacturing. Most high-density devices and particularly, modern grid array devices, require a solder reflow capability that is beyond the reach of simple manual soldering irons. One of the overlooked parameters associated with solder repairs is process timing. Since reflow processes have specific temperature profiles with heat ramp and soak periods, special programmable closed-loop controllers are required. The actual profile may have been developed by analysis or by actual experiments.

In low or zero gravity, normal heat convection currents are suppressed, which means heated objects will become hotter more rapidly. Overheating components is the main hazard in component repairs. Therefore, a manufacturer's heat profile cannot be used without accounting for gravity. The effect of low gravity on convective cooling requires adjusting profiles based on gravity models. For robotic component removal and replacement, a motion-control sequence must be programmed. Therefore, apparatus programming must be performed and validated offline before teleoperations.

Since repair may require removal of conformal coatings and application of flux and cleaning fluids, the repair apparatus must provide methods of containing vapors, liquids, and debris. Many process steps are easier to accomplish with simple crew intervention. Like CD&T, the actual CRA architecture is intimately tied to the CTO architecture via the CC&D system.

4.0 CLEAR Teleoperations System Architecture

4.1 Overview

CLEAR intends to provide a capability to perform in situ repairs of electronic hardware at the component level. CLEAR responds to the need to reduce the upmass of spare hardware and to empower the crew to respond to problems without dependence on a robust and timely logistics system. The CLEAR project has determined that this must be accomplished without expanding crew size or dramatically expanding flight crew training. The project has adopted a strategy to exploit teleoperations as a means of augmenting the flight crew with ground-based support on an as-needed basis. The previous CLEAR white paper, the CLEAR project plan, and CLEAR–DOC–007 described this strategy.

This section defines the role of teleoperations in the diagnosis, repair, and functional test of electronic hardware in future missions, defines the roles of various elements in the program, and identifies computer software components needed to create teleoperations.

4.2 Teleoperations Approach

CLEAR will be composed of the CLEAR TEST Earth segment and the remote (on-orbit) CLEAR SARADA segment. The ground-based CLEAR TEST center will be similar in concept to the Glenn TSC used to support science payload operations. Data communications and transfer rates given here are based on those available between the TSC and the ISS. The makeup of the CLEAR TEST will be consistent with the NASA depot system used for the space shuttle and ISS.

CLEAR is designed to keep the crew workload to a minimum. The key is to link the diagnostic and repair process to knowledgeable and skilled engineering staff through teleoperations. However, this support should not become a burden to the program by requiring a dedicated staff to perform repair and diagnostic teleoperations. The preferred approach is to provide a capability that can be called upon as needed.

The CLEAR concept is intended to minimize dependency on real-time interaction. Real-time interaction is possible and feasible for some operations. The process of diagnosing faults, testing, and setting up a repair is prone to long pauses while support staff assess data and consider the next step. Considering the frequent loss-of-signal events and the high value of both crew time and communications, it is more practical to perform as much of the process offline as possible. To accomplish this, CLEAR considers both NASA practices and industry practices in regards to automated operations.

From manufacturing, CLEAR borrows the approach used by relatively small or short-run manufacturing operations. To compensate for the high cost of labor, manufacturers will leverage engineering and machinist skills by capturing machine operating parameters in software data files. An early example was the development of computer numerical control (CNC) techniques where simple and compact machine "G-codes" are used to program and execute machine tool operations. Similarly, microgravity experiments aboard the space shuttle and ISS were extensively preplanned and automated with optional breakpoints in the experiment procedures to accommodate changes based on near real-time assessment of experiment data.

To provide efficient preprogrammed control and to accommodate flexibility, CLEAR TEST engineers will develop and verify pre-scripted diagnostic and repair routines that may include decision branches at key points. The process may employ manual crew operations in combination with a robotic mechanism.

CLEAR SARADA will be designed to accommodate both manual and automated operations. For the most part, CLEAR SARADA will not operate under remote real-time control. Programming and subsequent verification will be performed offline and will avoid unnecessary consumption of crew and teleoperations time.
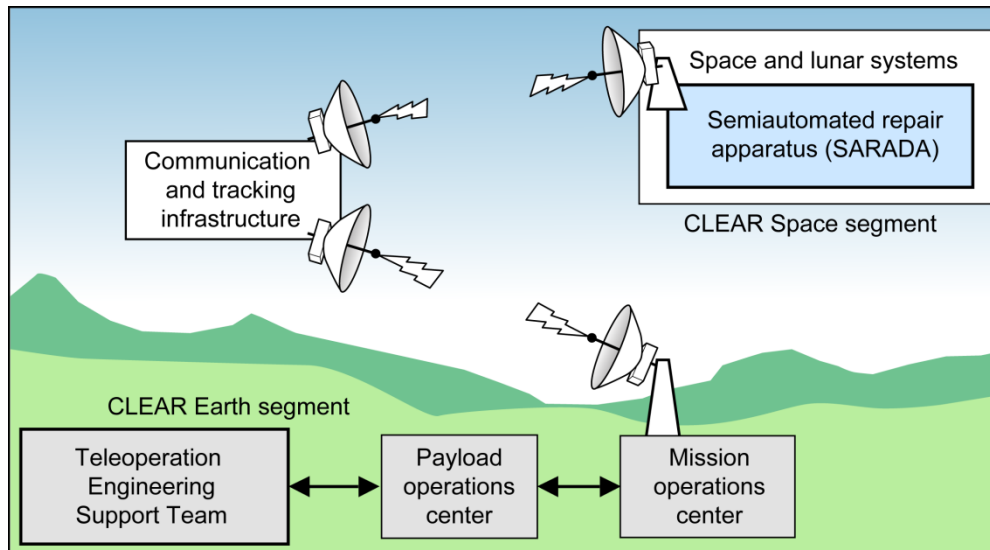
Figure 1.—CLEAR is composed of an Earth segment and Space segment that is linked via Constellation Command, Control, Communications and Information (C3I) infrastructure.

4.3 Teleoperation Segments

As described in the introduction, CLEAR is composed of two segments. For this document, the Earth segment is referred to as CLEAR TEST. The Space segment is referred to as the CLEAR SARADA. The following subsections delineate the roles of each segment (Figure 1).

Teleoperations must bridge these segments by relying on program assets, such as the deep space network and the tracking and data relay satellite system. As CxP evolves, new capabilities may be added to the system. Teleoperations must be transparent to the flight-hardware and ground-based users.

4.3.1 Space Segment: CLEAR SARADA Teleoperations

CLEAR SARADA represents the Space segment of CTO. SARADA's internal command and data system interfaces with the spacecraft Command and Data Handling (C&DH) system. The CLEAR command and data backbone supports teleoperations within the SARADA hardware.

4.3.2 Earth Segment: CLEAR TEST Teleoperations

CLEAR TEST represents the Earth segment of CTO. TEST is composed of people and the tools they employ for developing and validating repair operations. It also includes the information libraries required to support CLEAR and to capture and archive teleoperations

4.3.3 Communications Between Space and Ground Segments

Table I indicates the average and maximum data file sizes for diagnostic and repair operations. The files required to control the diagnostic and repair system are uplinked via the C3I system to CLEAR SARADA. The data are parsed out to the final subsystem controllers. The data downlinked will include diagnostic and test data files, digital images, and high-definition digital video.

TABLE I.—CLEAR PRELIMINARY FILE SIZE ESTIMATES[a]

File type	Maximum size, MB	Average size, MB	Uplink/ downlink	Comment
Huntron test file (includes CAD files)	50	25	Uplink	Compressed
Separate printed circuit board CAD files (Gerber format)	10	2	Uplink	Compressed
Functional test files (ref. LabView)	25	10	Uplink	Uncompressed
Acquired functional data files (DSO, etc.)	100	25	Downlink	Eight high-speed channels (compressed)
Still image files (lossless JPEG2000)	4	3	Downlink	2000- by 2000-pixel resolution
Motion image files (MPEG–4)	150	60	Downlink	60-s HDTV resolution

[a]File size depends heavily on board size and complexity. These estimates are conservative and assumed a multilayer, 6U-size board.

4.3.4 Teleoperation Computer Software

Teleoperation is software-intensive. Conversely, software development is highly constrained by the communication and security protocols imposed by spacecraft telecommunications. As noted in the assumptions, CxP will provide separate telecommunications channels to be used in the same manner that the ISS handles science payloads. In this way, CTO poses a minimum risk to flight system operations. For ISS, a payload developer or user may interact with their payload using local ground facility that is certified and linked to the HOSC, which provides telemetry services.

Teleoperation software will need to support the CD&H for diagnostics, repair, and functional tests. Major software functions are called computer software components (CSCs). CLEAR CSCs for diagnostic, repair, and test activities are tailored to each specific ORU application. Figure 2 illustrates some of the potential CSCs. Each CSC will have distinct development and validation requirements. To facilitate rapid development and validation, special software tools will be needed. For ISS, a TReK is provided to assist payload developers in developing a user interface that will provide access to payload data and command uplink.

4.3.5 CLEAR Teleoperations Data Transactions

Figure 3, which is based on the scenarios outlined in CLEAR–DOC–007, shows the data transactions that occur between elements of the Earth and Space segments. The figure is a diagram that is often referred to as a "swim lanes diagram" by software architecture designers. System elements are illustrated as lanes that represent elements domain. Rounded bubbles represent data, and rectangular blocks represent operations or processes. Each element owns certain processes and data libraries. Data files generated may require input data from other elements, and dependencies are illustrated.

In the illustration, information from VMDB and PRACA databases is used to help create diagnostic strategies. The programming of diagnostics also requires information regarding diagnostic capabilities. The data product is a diagnostic routine that was developed and validated for uplink to the Space segment. If synthetic instrument (SI) technology is employed, the code required to synthesize an instrument is included in the diagnostic routine. Any new code developed will also be sent to update the CLEAR library.
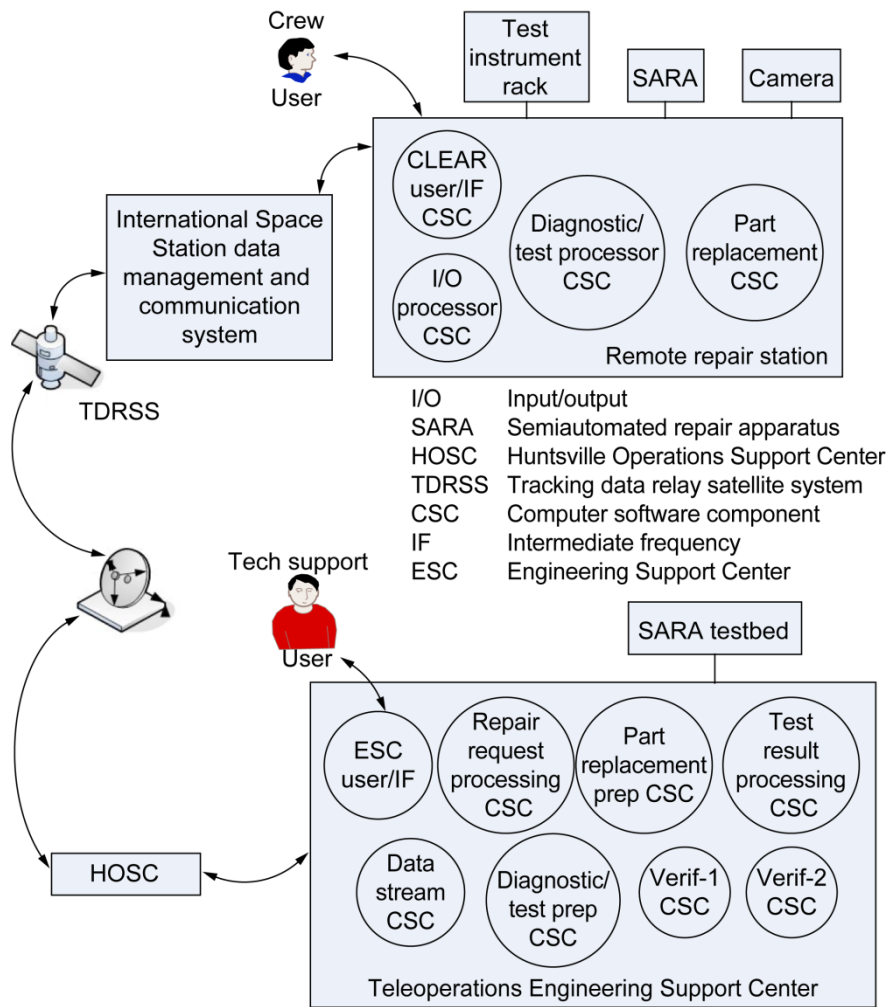
Figure 2.—CLEAR CSC using the International Space Station payload operation center model.
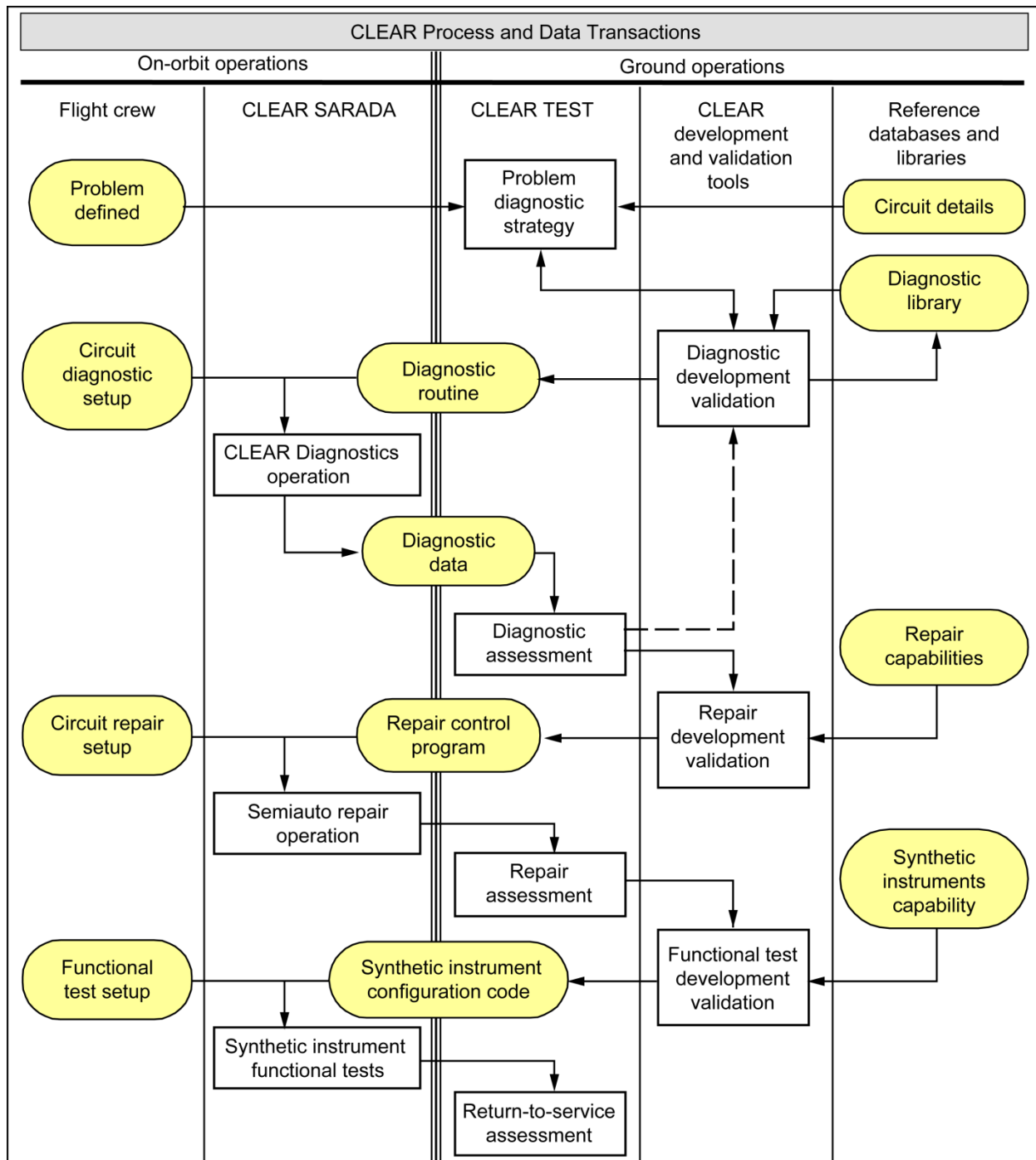
Figure 3.—Swim lanes model of the CLEAR data transactions.

As shown, the Space segment is composed of the crew and the CLEAR apparatus. Note that the Space segment activity is directly related to setup and execution of the diagnostic and repair operations. The time-consuming processes of creating and validating diagnostic and repair procedures, equipment control, and data processing routines are all done offline. This minimizes crew time and training requirements.

4.4 CLEAR Diagnostic, Repair, and Test Application Development

4.4.1 Merging System Information with Development Tools

Effective response to problems requires access to detailed design information and an understanding of the system history and its current configuration. The response also requires the ability to access, understand, and use the technical repair tools. The TEST will need an array of information and an array of technical options to formulate corrective action.

As illustrated in Figure 4, diagnostic, repair, and test operations will involve details provided by a complete set of drawings and documents. The emphasis on teleoperations and remote control will require special tools, particularly if robotic equipment is used. The following sections describe the database, library, and development tools required.

Figure 4.—CLEAR diagnostic, repair, and test application development.

4.4.2   Spacecraft Design Data

For shuttle and ISS, design details are captured in a design database called the VMDB. Diagnostic, repair, and functional tests will require detailed design and configuration information.

The design data must provide the following design information:

- Functional design requirements
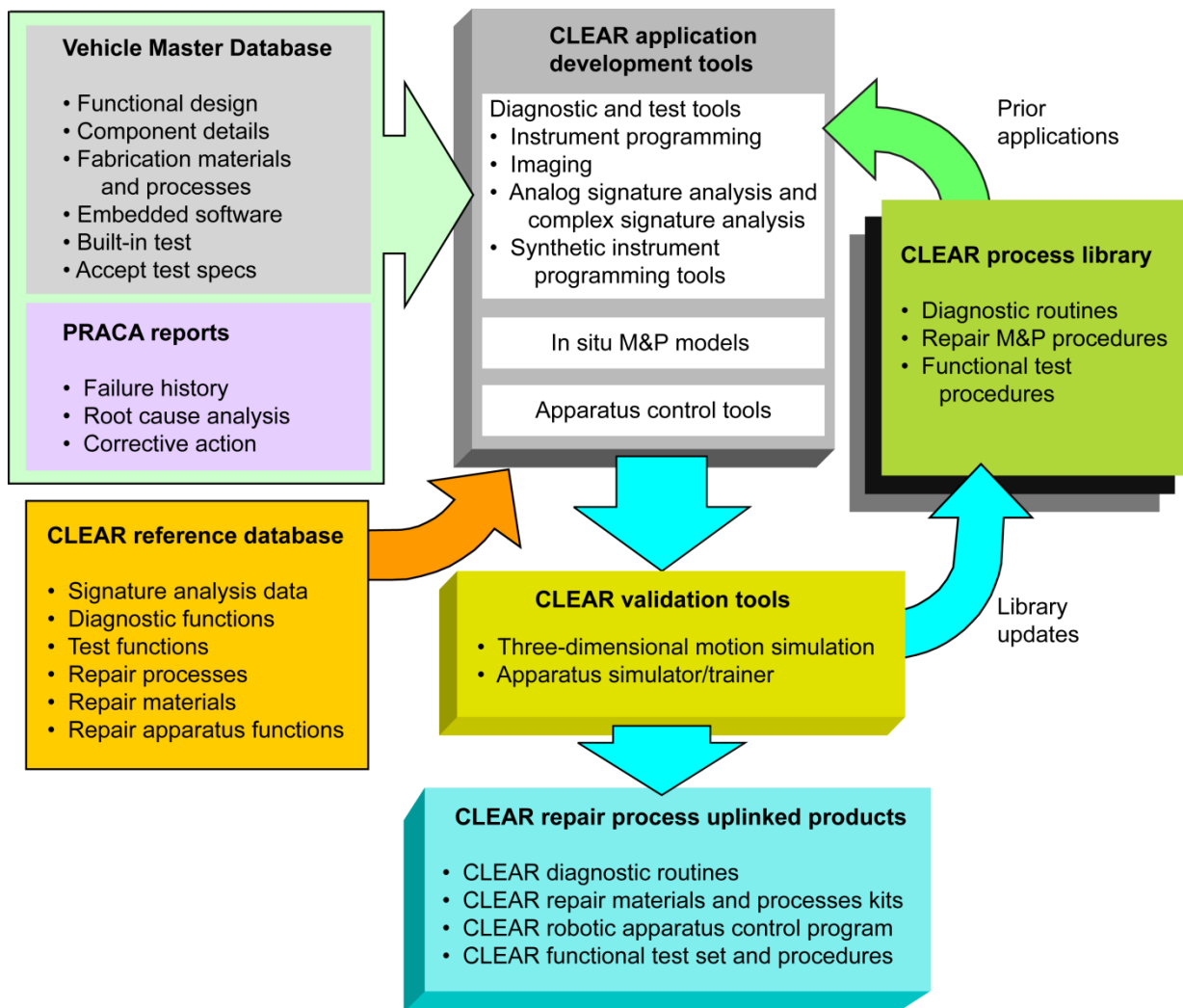- Assembly and component details (circuit-card assembly (CCA) digital drawing files)
- Fabrication details including materials and process information
- Software specifications
- Built-in test (including Joint Test Action Group (JTAG) tests)
- Accept test specifications

To facilitate diagnostics, repair, and functional tests, the VMDB can be expanded to include as-built and as-repaired configurations.

4.4.3   System Problem History (PRACA Database)

The PRACA system provides information regarding ongoing open-problem reports and historical closed-problem reports. The recent review of ISS PRACA reports in CLEAR–DOC–005 shows electrical systems problem reports were reviewed. The analysis was launched as part of an overall needs assessment for on-orbit electrical repair. The analysis indicated that roughly 42 percent of electrical and electronic system problems are ultimately resolved with component-level repairs.

The same report indicated that the existing telemetry and built-in tests are inadequate to resolve many problems. The "root cause unknown" statement in many electrical PRACA reports is an indicator of a need for greater diagnostics to resolve problems below the ORU level. The PRACA reports often refer to failure analysis reports that may involve a very detailed investigation and examination of a problem's root cause.

The PRACA system is very important not only as a problem archive but as a problem-reporting and tracking tool. The first time a problem is detected, a problem report is activated. From a CxP perspective, a problem report initiation will be the first indication that a CLEAR diagnostic repair and test process is needed. The problem report closeout will be the final indication that the CLEAR process is complete.

4.4.4   CLEAR Reference Database

The CLEAR reference database is composed of information not found in the design database or spacecraft problem reports. For example, circuit cards characterization information for "known-good" boards.

The CLEAR reference database will contain information unique to CLEAR operations and design capabilities.

- Analog signature analysis (ASA) and complex signature analysis (CSA) characterization data
- SI capabilities
- Test functions
- Repair process parameters
- Repair materials properties
- Repair apparatus functions and capabilities

4.4.5   CLEAR Process Library

The CLEAR process library represents the accumulated knowledge for the diagnostics, repair, and test of circuits. Unlike other databases, this library is intended to contain reusable control codes and

setup parameters. Much like an industrial CNC library, it will contain the programming code and parameters for specific component-repair operations.

Diagnostic Routines.—The developed diagnosis of a specific fault of a specific circuit will be stored in this library. Because diagnostic processes search for an undetermined cause, a variety of diagnostic routines may be used to determine a specific fault. Over the life of the circuit design, multiple independent faults may occur. Therefore, we expect to accumulate a large library of diagnostic routines.

Repair Procedures.—For any given circuit, a procedure may be needed for every component type. Therefore, like diagnostics, a significant library of repair procedures can be accumulated. It would be useful to have a template process that covers setup operations and contains commonly used processes.

Functional Test Procedures.—A delta (subset) of acceptance test procedures will be used to verify that the circuit has been successfully repaired. CLEAR will use the SI approach to synthesize interfaces required for a functional test.

4.4.6 CLEAR Application Development Tools

Diagnostic and Test Programming Tools.—These tools are aimed at programming the Space segment to perform various diagnostic and test functions for specific circuit applications. Since diagnostics and functional testing involve many of the same instruments, they will use the same tools. In some cases, the programming involves purely electronic functions while others, such as automated probing, involve robotic motion control.

Diagnostic and test functions often rely on basic conventional instruments, such as multifunction meters, oscilloscopes, and signal generators. A new generation of "panel-less instruments" minimizes space and weight by eliminating displays and adjustment knobs and by employing a common laptop computer as the user interface. Setup of instrument parameters and coordination between stimulus signals and signal measurement must be programmed into the hardware. Instrument vendors can provide the programming and interface software. Coordination will require programming of diagnostic and test controllers that will use an IEEE–1588 instrument triggering standard.

Imaging tools provide the ability to manipulate imaging cameras that are part of the flight apparatus. A remotely controlled digital camera will be used in visual examination and will provide imaging for both flight crew and CLEAR TEST. These tools will provide camera resolution, frame rate, and optical settings suited for circuit board examination. These tools also define the data processing and compression techniques.

The robotics programming tools will be used to preset the positions of imaging devices that are manipulated robotically. The positioning will be based on circuit computer-aided design (CAD) data for component location and identification and to locate registration points for the repair process. This same data will support advanced examination tools like infrared imaging or x-ray.

For safe operation, CLEAR will employ robotic motion validation tools, assuring collision-free motion control to minimize risk to hardware and crew.

Analog Signature Analysis and Complex Signature Analysis Programming.—ASA and CSA both rely on data from "known good boards" (Gold Boards). Similar to the U.S. Navy "gold disk" program, these "gold signatures" will be needed to support the diagnostics. If not available, a library of gold signatures will be acquired through actual tests of good circuits performed at a ground-based depot. These will be added to the CLEAR reference library for future reference.

Synthetic Instrument Programming.—SI technology provides a highly capable, but generic instrument, front end. This is described further in the diagnostics and test architecture. In many ways, synthetic instrumentation is based on the premise that many instrument functions are digital or can be performed by digital circuits, which implies that instrument functions can be operated as software. To achieve instrument-level performance, it is necessary to embed software into field-programmable gate array (FPGA) that allows designers to exploit data pipelines, parallel processes, and other signal processing techniques that give conventional instruments their high performance. A set of tools will be

needed to create an instrument model and then perform the hardware programming. Ground-based simulators of the flight hardware will be needed to develop and validate the code.

FPGA programming has a specific programming language called VHDL. VHDL is a compound acronym where V is VHSIC (very high-speed integrated circuit) and HDL is hardware description language. The Department of Defense (DOD) developed the VHDL language for logic synthesis applications. IEEE–1076 is the main standard governing the VHDL language syntax. Higher-level and easier-to-use tools have been developed that simplify the programming process. Products like MatLab (The MathWorks, Inc.) and LabVIEW (National Instruments) can generate VHDL code. Tools are available the can model and validate the VHDL code prior to committing it to hardware. To assure high performance, the code must be programmed and tested in real hardware before it is uplinked to the CLEAR SARADA's SI system.

Repair Material and Processes Modeling Tools.—Certain processes may have a significant dependence on gravity. In microgravity, voids in metal solder joints are more prevalent than 1-g and require certain adjustment to the process. Microgravity tools take the setting used for normal solder processes and compensate them for microgravity effects.

Solder reflow is used for removing components and installing new components. The process typically employs a solder paste with heat-activated flux. A predefined temperature profile is required to ensure proper flux activation and solder reflow, yet it minimizes the excess temperatures that may damage the circuit.

Many circuits are conductively cooled with integrated heat sinks that make reflow processes more difficult to achieve. Reflow process models will incorporate thermal models of each circuit card and will account for microgravity effects. The models will be used to adjust preheat cycles and component heating profiles to assure a reliable repair and prevent damage due to excessive heating. The final output is a reflow process profile that specifies the heat flux and wattage of each heating element along the timed reflow profile.

Apparatus Control Programming Tools.—The repair apparatus requires control software to perform robotic motion control functions and control the reflow process. There are several forms of robotics for general-purpose movement and manipulation of objects. The simplest and most widely used is a Cartesian or Gantry robot. This mechanism moves through space along three orthogonal axes and is often used in CNC machining centers where rotary tools carve complex shapes from simple base stock. The simple coordinate system gave rise to simple-to-use programming languages. The common International Organization of Standardization (ISO) standard uses the CNC G-code. G-codes are simple character codes that defined a specific point-to-point motion along with a specific motion or tool parameter, such as rotation rate, or feed rate. G-code was intended to be a compact text code that would be simple enough for a machinist with no computer background to program.

Sophisticated programs are now available that can model three-dimensional motion and can even show the process and an animation. These more advanced programming tools produce G-code as their primary output because most CNC machines have G-code interpreters that convert the code into motion control parameters. The motion controllers coordinate the motion along multiple axes simultaneously so that they can perform complex motion.

Like CNC, the CLEAR apparatus must be protected from motion-control errors that could result in hardware collision or potentially harm a crew member. Thorough code validation can be performed by industry-standard three-dimensional validation tools that check the robotic motion paths for collisions or process sequence errors. For Cartesian-style robotics, there is a wide range of programming and validation tools available.

Reflow process control programming would normally be developed by experiment. However the influence of the low-gravity environment makes it impossible to accurately duplicate the process in Earth's 1-g environment. M&P low-gravity models are, therefore, essential to creating an appropriate process heat profile. The criticality of the flight hardware and consequences of damage to the circuit are too great to allow a loosely controlled process.

4.4.7   CLEAR Integrated Validation Tools

Before complex commands are uplinked to the Space segment, the code must be validated. The complex interactions among the instruments, robotic hardware, flight crew, and repair targets involve so many details that it is easy to overlook a detail that results in damage to hardware or injury to a crew member. As described in the previous section, industry uses development tools that can also perform simulation and serve as an initial validation of the process. However, the interaction between robotics, instruments, and crew members will require a simulation of the overall process. Motion control may be performed by three-dimensional animation of the process as used by industry for robotic and CNC operations. If substantial crew interaction is required, then a live simulation using a high-fidelity mockup of the system will be needed. The simulator and/or trainer would support this simulation and also serve as a trainer for flight crews.

4.4.8   CLEAR Repair Process and Uplink Products

The final products of the CLEAR development and validation effort are primarily software to configure, control and acquire data. The products will also involve repair process M&P kits needed to perform the repair.

- CLEAR Diagnostics Software and Procedures
- CLEAR Repair Apparatus Software and Procedures
- CLEAR Functional Test Software and Procedures
- CLEAR Repair M&P kits

The content of the products, the software programs, and kits are further described in later sections.

5.0 CLEAR Control and Data System Architecture

5.1 Overview

CLEAR system architecture attempts to create a unified strategy that can also accommodate incremental growth. There are many individual operations associated with the diagnosis, repair, and testing of flight hardware. These operations must be sequenced and coordinated and must not demand excessive crew time. Such a system must also tolerate communications interruptions and maintain control, regardless of external events.

The CC&D system architecture is intended to serve as a backbone to which discrete functional elements are integrated into a fully teleoperational and semiautomated system. This architecture is also intended to accommodate incremental growth capability while averting hardware obsolescence. The CC&D system must provide the flexibility to accommodate new functions as they are developed.

5.2 CLEAR Control and Data Approach

Figure 5 illustrates a simplified hierarchy of the CC&D system, and Figure 6 shows many major CLEAR SARADA functions. The figure also illustrates the interconnections where commands, data, and power flow. The CC&D controller is both the main controller and master of the data network or data backbone of the system. This backbone function is essential to the incremental development strategy and must be defined explicitly prior to incremental hardware development.

The CC&D controller is the master control of the SARADA. It serves as the primary interface with the equipment, crew, and spacecraft. It is also the gateway for CLEAR teleoperations. Each block in Figure 6 has a smart subsystem controller that also provides network interfaces to the block above and below it in the system hierarchy. Ideally, the blocks would provide a plug-and-play capability that would allow additional blocks to be added without requiring a massive reconfiguration of the system. The best way to accommodate plug-and-play is with LAN protocols.

Spacecraft Interface.—The CC&D controller is linked with the spacecraft's C&DH network. For ISS, the connection would be a MIL–STD1553 serial bus. For CxP, the time-triggered gigabit Ethernet (TTGbE) would be the likely interface and incorporates features of the recently established IEEE–1588 instrument network standard. The channel on the spacecraft side would be the branch of the C&DH system that supports payloads. Using payload, instead of primary system channels, eliminates the concern that CLEAR transactions would consume bandwidth needed for mission support. Since the payload command and data channels pose no risk of system hardware interference, the CLEAR TEST center can operate independently.
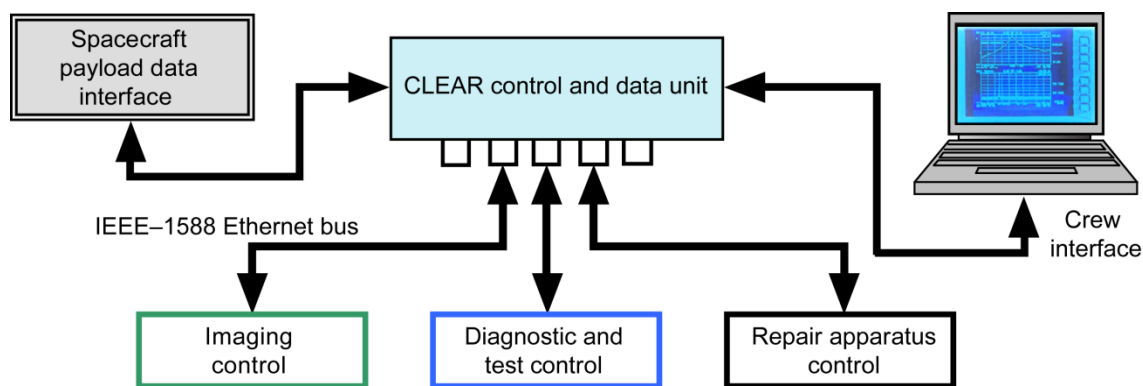
Figure 5.—CLEAR data backbone is a common Ethernet extension with IEEE–1588 protocols to make it deterministic and suited for high-speed instrumentation and robotics networking.
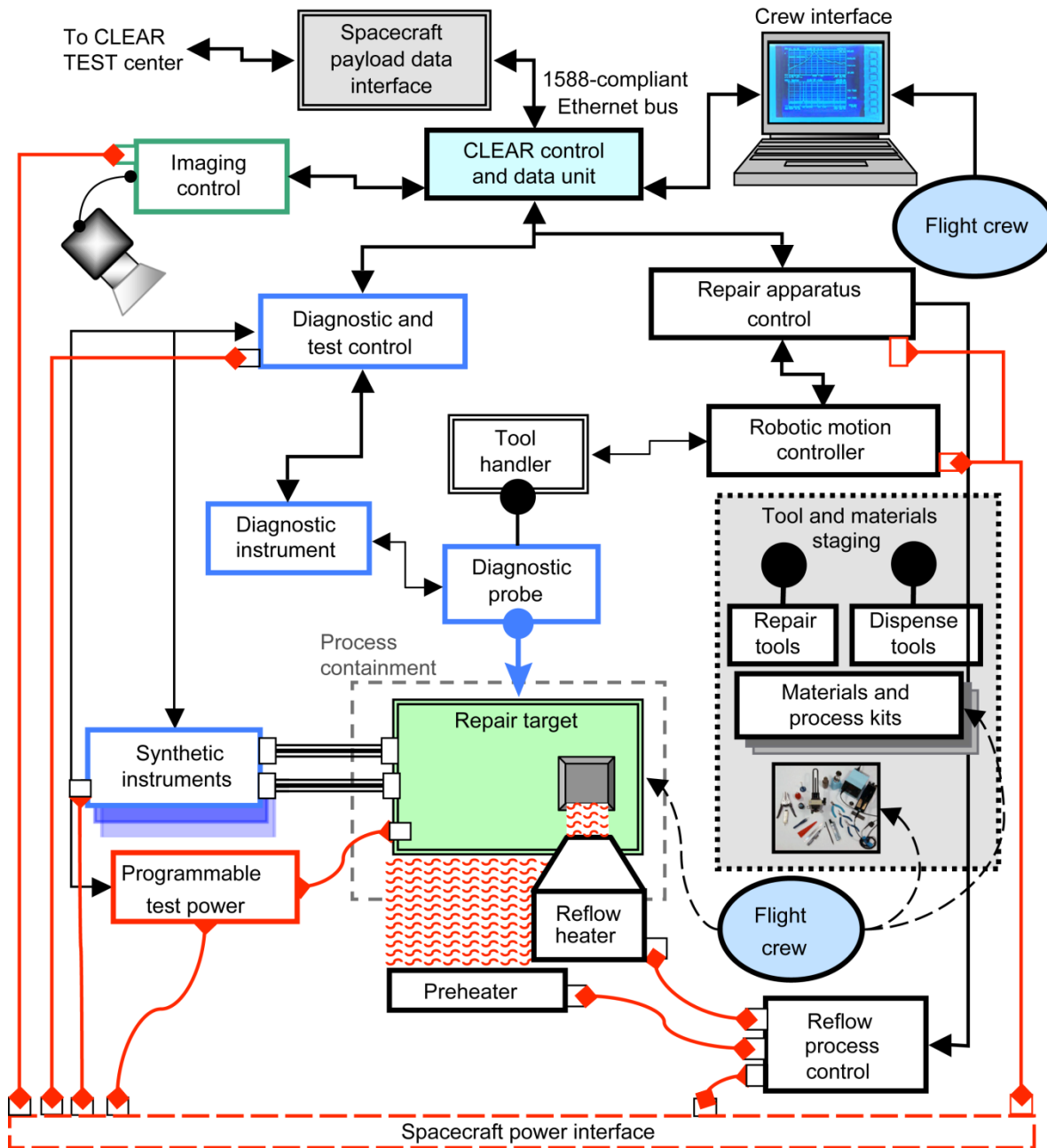
Figure 6.—CLEAR semiautomated repair and diagnostics apparatus (SARADA).

5.3   CLEAR Data Backbone: IEEE–1588 Enhanced Ethernet

Several architectures are considered to be part of the CLEAR data backbone. For a number of reasons, a high-speed serial network that also supports precise triggering is the preferred approach. The data backbone architecture will be based on a variant of the ubiquitous Ethernet. Ethernet is a LAN protocol and is the world's most widely supported standard. An unmodified Ethernet, based on network time protocol, is not normally considered to be adequate to support real-time control. However, industry has recently enhanced Ethernet to make it more "deterministic" and suited for systems with critical timing.

Enhanced Ethernet has been adopted in three relevant applications:

- **Constellation**.—TTGbE is the current standard for *Orion*. CxP originally considered STD 1553 and 1394B before selecting TTGbE.
- **Instrumentation**.—LAN extension for instruments (LXI) is an Ethernet-derived instrument network promoted by several instrument makers, including Agilent.
- **Industrial Motion Control**.—New Ethernet derivatives have appeared in industrial equipment applications, particularly, for multiaxis motion controllers like robotics and CNC.

The adoption of IEEE–1588 has been essential in making Ethernet viable for these applications. The protocol makes Ethernet deterministic; that is, it makes the timing and response of the equipment fast and predictable. It is even possible to employ universal time clock transmissions provided by the global positioning system. The IEEE–1588 relies on a master clock and synchronization protocol to keep various devices in sync and deterministic.

Military Analogy.—If a general is preparing a synchronized attack by multiple armed forces, all subordinate commanders synchronize their clocks to the general's master clock. Each commander is issued specific orders to execute at a precise time. When the internal clocks reach that precise point in time, each commander executes the assigned orders. The result is an attack that is coordinated, simultaneous, and not dependent on further signals. Likewise, the IEEE–1588 master unit can use the Ethernet to command actions of subordinate units without special external trigger lines. This also implies that subordinate or slave units are both "smart" and are equipped with accurate "slave clocks."

IEEE–1588 Synchronization Process.—Figure 7 shows how the network master device clock synchronizes a number of slave device clocks. The master and slave devices perform a series of message transactions that are intended to measure innate delays in the network and intervening connections. A precise characteristic delay is calculated and recorded by the slave device. When the master issues a "The time is now," the slave device knows that the time received needs to be adjusted by the calculated characteristic delay and adjusts its own internal clock accordingly. With each device precisely synchronized, the master can download specific instructions to each slave device to be executed at a specific time.
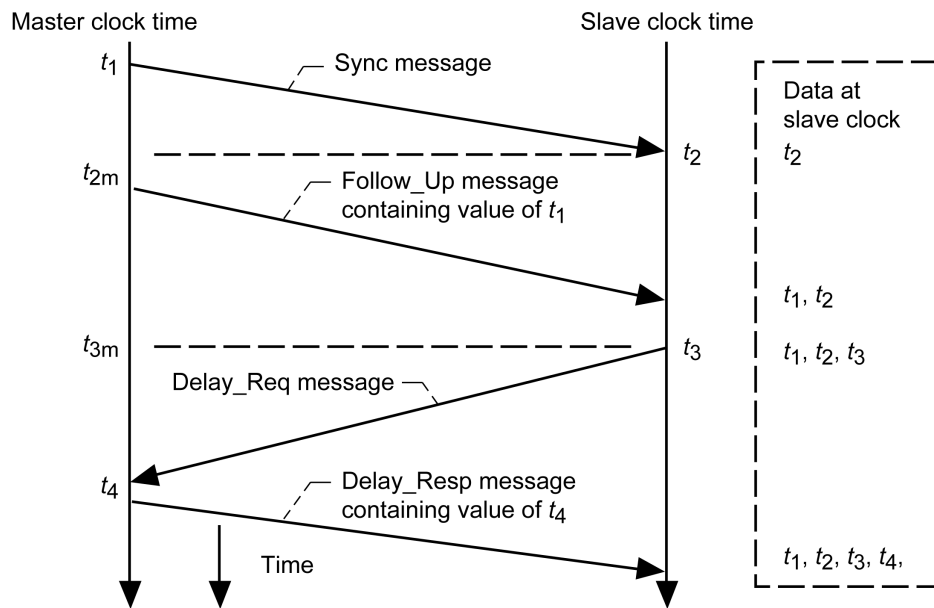

Figure 7.—Message transactions used to synchronize slave clocks with the master clock.

The master clock and network controller roles are performed by the CC&D controller. All other units within SARADA are slave units. The crew interface and the spacecraft payload data interface are external units and will have override authority. This is to assure that the flight crew and CLEAR TEST engineers can halt SARADA for safety.

5.4   CLEAR Control and Data Unit

This unit will perform the command and data handling functions.

- Mastering LAN
    - Master clock
    - Synchronization management.
- Command and data multiplexing and demultiplexing for uplink and downlink
- Command and data buffering
- Mass data storage
- Data compression and formatting
- System health and safety monitoring
- Manage external interfaces
    - Crew interface
    - Spacecraft payload interface
- Manage CLEAR SARADA subsystems
    - Image controller
    - Diagnostics and test controller
    - Repair apparatus controller

5.4.1   Crew Interface

The crew will interface the system through a Government-furnished laptop computer. The crew interface may be used for monitoring the CLEAR process, archiving instrument data, and performing data processing required to analyze and display data. The crew interface will provide the graphics display for CLEAR process setup and operating procedures. The crew interface will provide a CLEAR process library that will include background information and refresher training for the crew.

The crew interface also will provide the crew with an override authority to interrupt or halt CLEAR processes and will provide a software E-stop function for the crew.

5.4.2   CLEAR Imaging Controller

Imaging is essential for examination, process control, and postrepair evaluation. Imaging data usually demands high data rates and mass storage. As a separate controller, it provides dedicated circuits that minimize the impact on control loops and other instrumentation. Although there are a variety of imaging devices from visible light to infrared (IR) and even x-ray, the images can be converted to a common digital format.

Although the IEEE–1588 extended Ethernet bus is the primary conduit of data, specialized high-speed serial ports with plug-and-play capability, such as universal serial bus (USB) and 1394 FireWire may also be included for high-speed digital image transfers.

The high-speed bus may also pass imaging camera parameters such as frame rate, resolution, and exposure settings. Optical zoom and focus can also be performed by the controller. Crew access images can be passed to the crew interface via the CC&D controller or via a separate 1394B bus.

5.4.3   CLEAR Diagnostic and Test Controller

Diagnostic and test functions will require many of the same instruments particularly where SI technology is employed. The diagnostic and test functions will employ a mix of instruments linked by

the IEEE–1588-compliant networks. This provides a stable data environment that accommodates incremental growth in capability over several years. Individual complex multicard analyzers or SIs may employ backplane interconnections. However, backplane designs will likely become obsolete more rapidly than network links. Whenever possible, IEEE–1588-compliant network buses will be used.

The CD&T controller will manage the ASA/CSA characterization instruments (see Figure 8). It will house the setup parameters for the instruments and initiate any instrument triggering, if needed.

Data passed from the instrument will be buffered in the CD&T controller and transmitted to the main CC&D unit for further processing. Reference known-good data will be housed in the CC&D unit or in the crew interface for real-time diagnostic display. Similar functions will be provided for any IEEE–1588-compliant handheld equipment and high-speed data bus analyzers.
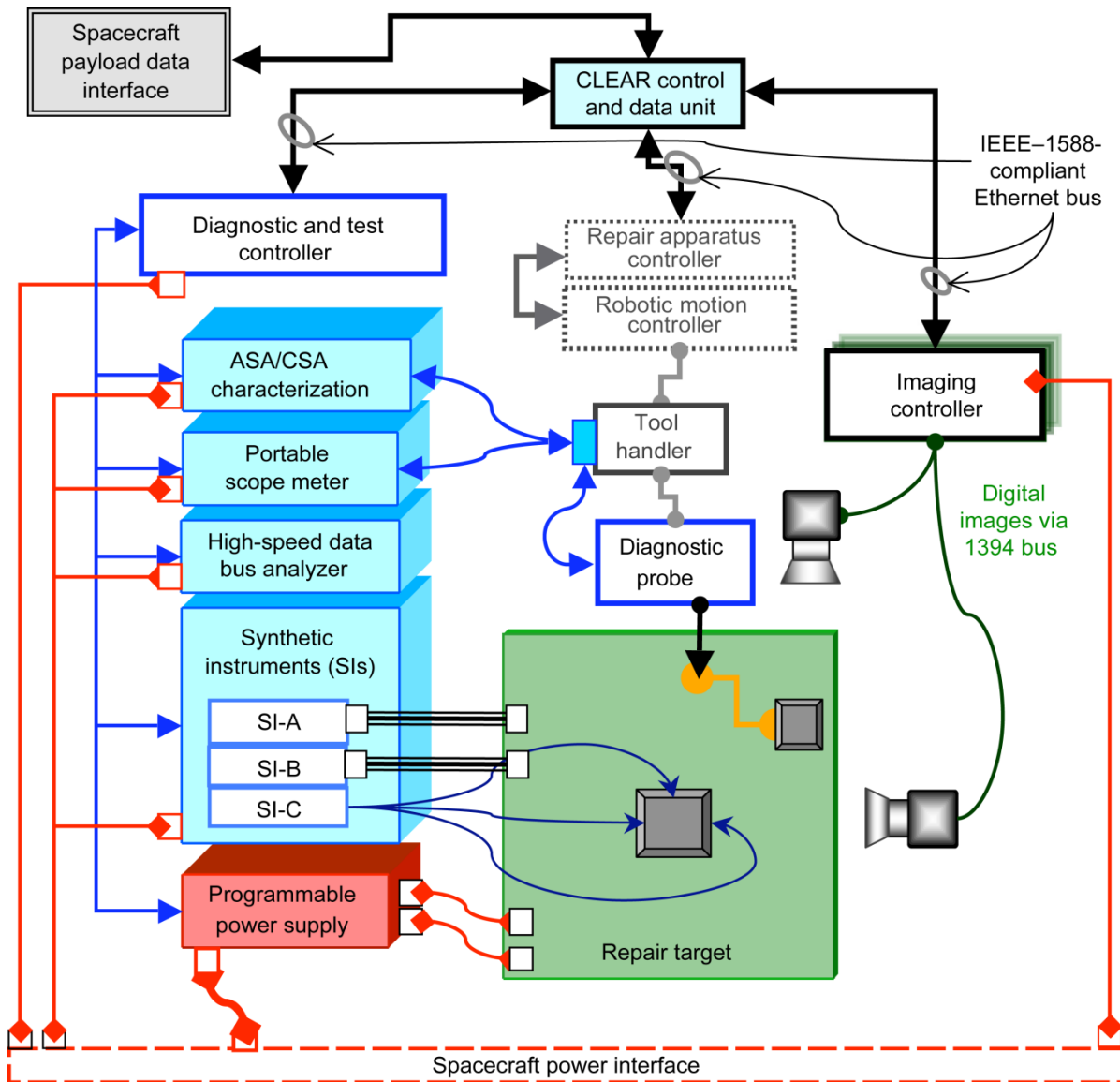

Figure 8.—Imaging control and diagnostics and test control functions (analog signature analysis (ASA) and complex signature analysis).

The CD&T controller will control the synthesizing process for synthetic instrumentation. The CD&T controller will program the FPGA, load software, and will manage the overall configuration and coordination of multiple SIs. The CD&T will act as the IEEE–1588 master clock unit for instrument triggering and synchronization. In addition, it will buffer and correlate instrument data prior to forwarding it to the CC&D unit for further processing, downlink, or crew display.

For automated diagnostic probing, the CD&T controller interacts with the CLEAR repair apparatus controller (CRAC). The CD&T passes node XYZ location coordinates to the CRAC via the CC&D controller or by direct network link. Automated probing of the circuit card will require manual setup by the crew. A card-specific setup routine would be executed to capture registration points and adjust the system alignment to assure that each diagnostic node is accurately located.

The imaging system may also support the alignment exercise. All alignment information is stored in the CD&T controller and merged with diagnostic node test parameters.

5.4.4   CLEAR Repair Apparatus Control

The repair apparatus involves robotic motion control for a variety of automated mechanical functions and process control for reflow and related processes (Figure 9). Motion control and process control will be handled by separate controllers. The CRAC will determine if there are any safety conflicts, such as open enclosure switches, which may indicate that the crew is not clear of the apparatus. The CRAC will not permit process operation unless all inhibit functions and safety limits are cleared.

Motorized robotics requires coordination of multiaxis motors to move a payload through a predefined motion path. A responsive closed-loop control is needed to assure that each axis accurately tracks its position and speed profile to achieve the needed complex motion. This is an example of a deterministic system where each axis must be at a specific location at a specific time. As noted earlier, Ethernet-derivative networks are being adopted in industrial systems partly because they are low-cost and partly because they modularize the functions so that the system can be easily expanded. IEEE–1588-compliant networks may provide sufficient deterministic control to support both motion control and process control.

Motorized robotic motion is usually provided by stepper motors or servo motors. Each motor type requires a distinctly different motor-drive modulation and feedback scheme. Many motion control architectures separate the high-power motor-drive electronics from the controllers, creating distinct drive modules tailored to the motor type. This modularization also allows a single controller to manage a variety of motor types.

Tool handler control is needed when general-purpose robotics are coupled with special functions such as material dispensing, component pick-and-place, and special tool handling, each requiring unique control. These devices at the tool end of the robotic apparatus are often referred to as end-effectors. End-effectors may include grippers and vacuum pick up tools, paste-dispensing syringes, and coating applicators. Feedback signals may be required for closed-loop control that may include temperature sensors, position sensors, and pressure sensors.

End-effectors, such as vacuum-dispensing tools, depend on both pneumatic supplies and valves for actuation. Pneumatic actuation is considered to be an alternate method of delivering actuation power. Grippers may be either motorized or pneumatically actuated. Pneumatic actuators will still require a motorized vacuum pressure pump. Like the motor drives for motion control, these ancillary devices must have separate drive units. Pneumatic actuation will require flexible feedlines routed similarly to the electrical lines.

End-effector tools are interchangeable and may be changed manually or by automated means. To accommodate quick and simple tool changes, a standardized tool handler is needed. This device not only holds a particular tool, but it may also conduct power and provide an interface for special devices and sensors. All potential end-effectors and their related power and control-loop requirements must be considered to define the tool handler requirements.
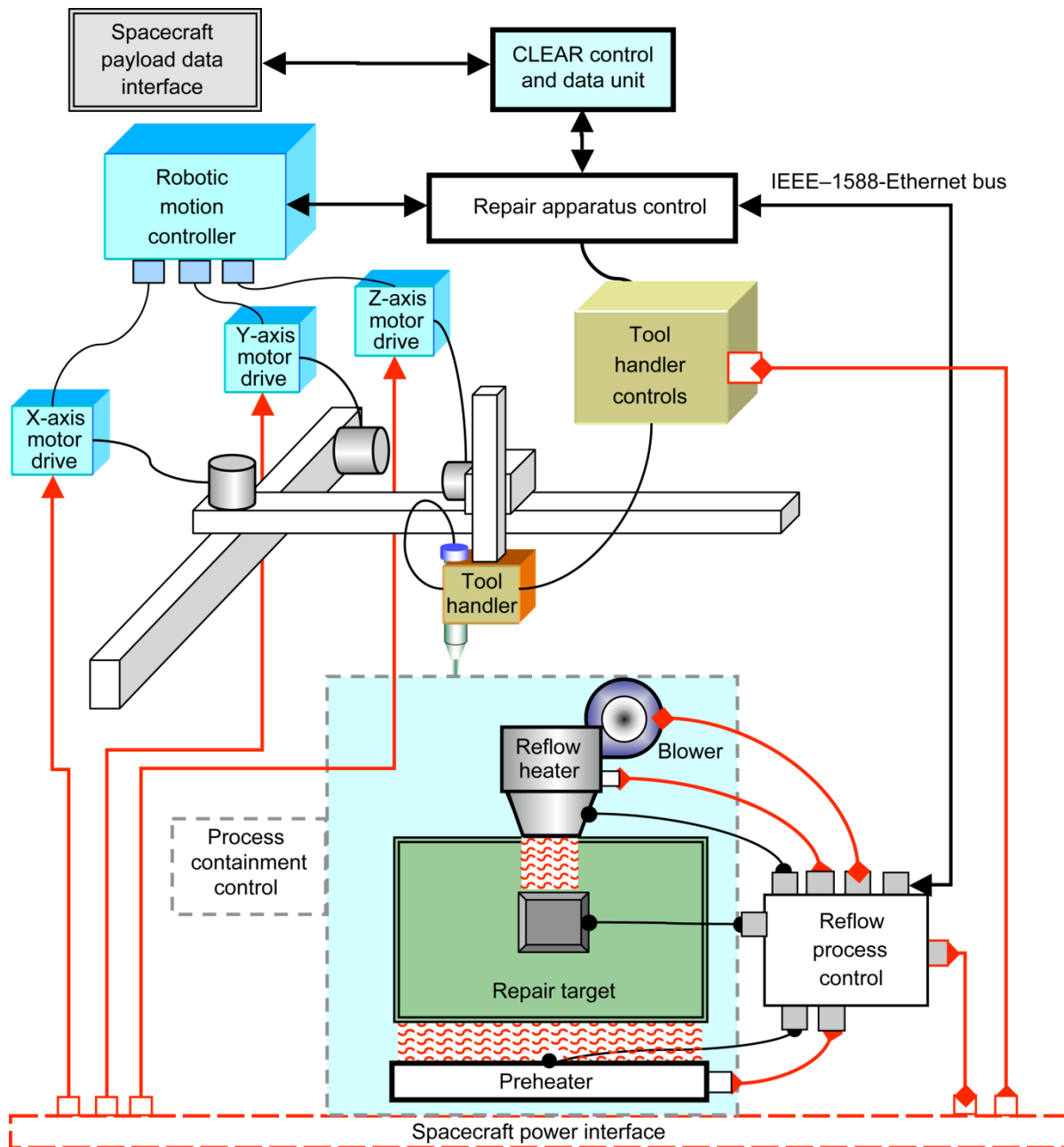
Figure 9.—Repair apparatus control functions.

Reflow Process Control.—Reflow heat may be delivered as hot gas or as IR radiation. Some circuit-card fabrication facilities use a combination of hot gas and IR. A conventional industrial temperature control is usually employed in rework stations. Because spacecraft circuits are often conductively cooled, the cards may have added metal layers to enhance conductivity. The added metal will make localized heating of the components more difficult. Therefore, the circuits must be preheated to reduce the heat loss during reflow.

The reflow process will need a closed-loop control, and thus temperature readings may be needed on the circuit card, the component, and the reflow hardware.

Repair Process Containment Control.—Process containment and its related control functions depend on the process and on the accommodations provided. If a general-purpose glovebox is available with purge and vent capability, then the CLEAR repair apparatus will be designed to operate in the provided accommodations. However, if no glovebox is provided, then CLEAR will need to develop a containment enclosure that captures vapor, liquid, and particle debris.

6.0 CLEAR Diagnostics and Test System Architecture

6.1 Introduction

The CD&T system is perhaps the most ambitious in terms of reducing a complex system down to a light, compact, and simple-to-use system. Diagnosing and testing complex flight systems demand an understanding of the internal details of the system. In effect, diagnostics and testing require expertise in both the device under test and the test equipment.

When electrical problems occur in the field (or in space), the first process is to isolate the problem to specific hardware. System telemetry can locate a specific ORU. Furthermore, telemetry combined with built-in tests, can refine the isolation down to a specific CCA. Isolating a problem down to a single component usually requires external diagnostic equipment.

Visual examination or imaging equipment can reveal physical flaws like broken leads, bad joints, or damaged components. The U.S. Navy (Naval Sea Systems Command (NAVSEA)) considers visual inspection a simple and effective initial screening method. Image examination techniques are described in Section 6.2.

The U.S. Navy has successfully simplified component-level diagnostics in the field by employing comparative characterization techniques. ASA, developed by Huntron, Inc., allows a relatively unskilled user to distinguish good circuits from faulty circuits by using a side-by-side comparison. For CLEAR, this approach can be used as a screening technique that may be sufficient to isolate components in many situations. This and more advanced techniques are described in Section 6.4.

For complex devices like microprocessors and high-density integrated circuits, special methods are needed to access internal features. When systems involve software, the ambiguity between software and hardware behaviors further obscures the root cause of problems. This means special access ports, such as JTAG ports, and boundary scan techniques are needed.

Often emulation of a circuit's external interfaces is needed to reveal subtle transient problems or errors in software or communications protocols. Techniques that involve emulation of functions are described further in Section 6.5.

To isolate the root cause of a component fault, the CLEAR team may need special diagnostic testing, and the component may need to be placed under operating stress to expose the root cause. Circuit stress under power loading is often required to expose power supply instability, radiofrequency (RF) tuning problems, or heat-related problems.

The incorporation of all these techniques in a weight- and volume-constrained environment, compounded by low crew availability, is driving the architecture toward a highly reconfigurable SI architecture.

6.2 Examination by Imaging Functions

Imaging provides direct data or supporting information throughout the repair process. A good visual examination can eliminate substantial diagnostic setup and programming. High-resolution closeup imaging can reveal subtle problems like corrosion and contamination that may not show up with electrical diagnostics. A visual inspection that discovers frayed lead wires, cracking solder joints, or tin whisker growth can preempt a developing problem or isolate frustrating transient problems.

6.2.1 Imagers

Image processing is easily handled by the crew interface computer. High-resolution images will create large files and may be time consuming for downlink operations. A field of view of a few millimeters and a 2000- by 2000-pixel imager array, shown in Figure 10, is expected to satisfy most imaging needs.
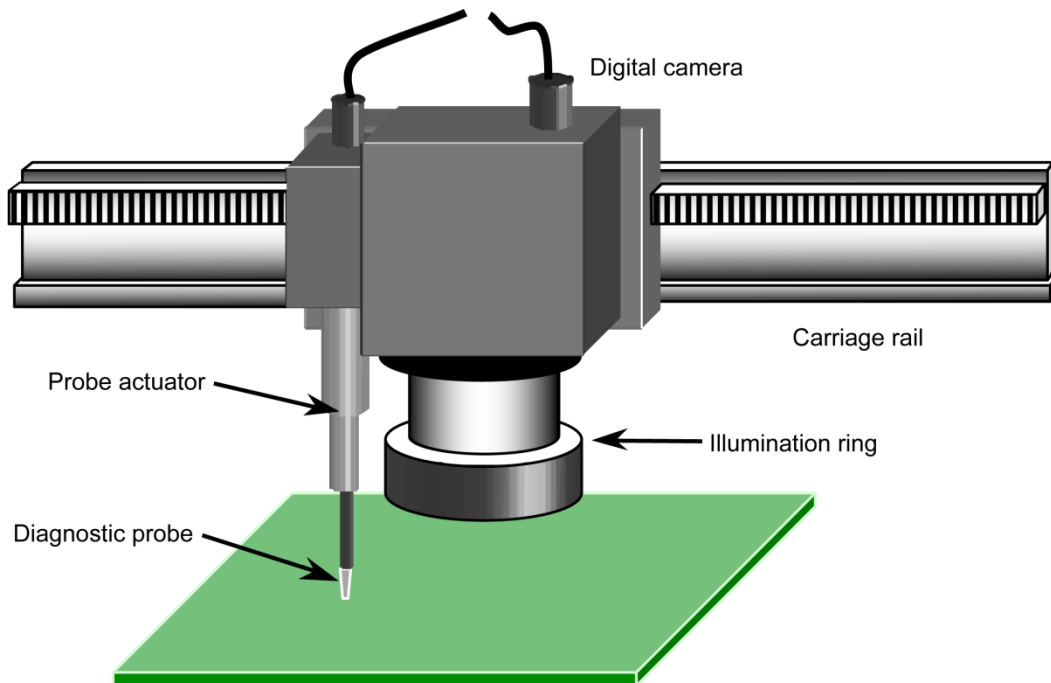
Figure 10.—A digital camera with integrated illumination is mounted along with a probing device on a robotic carriage. The camera provides inspection and verifies registration and process monitoring.

Lossless compression will be used to reduce file size and bandwidth while maintaining image quality.

The widespread adoption of digital high-definition television (HDTV) may provide a low-cost commercial-off-the-shelf (COTS) solution. HDTV has multiple resolution modes. The 1080- by 1920-pixel resolution mode will suffice for most imaging applications.

The 30-frame/s rate of HDTV may pose a problem for downlink data transmission. This frame rate is not necessary for most applications, and the transmission rate needs may be reduced by using a reduced frame rate or employing a still frame mode. HDTV employs lossy compression techniques, and HDTV camera performance should be evaluated to determine if the loss is significant.

6.2.2 Optics and Illumination

Imager optics will have a zoom and field of view of a few millimeters, equivalent to a microscope used in circuit fabrication and inspection. The 24-bit color will be standard, but conversion to grayscale may be used to reduce memory and bandwidth when necessary.

Although general lighting will be available, an adjustable high-intensity lamp will be used for very close work. In some cases, imaging is enhanced by polarization of the light source and the camera optics. The lighting should be positioned separately from the camera in order to optimize reflections for the clearest image and best contrast.

6.2.3 Nonvisible Examination Technology (Ultraviolet, Infrared, and X-ray)

Nonvisible radiation can provide information beyond visible methods.

Infrared imaging.—IR emissions from a circuit can diagnose thermal problems on operating circuits. The weight and complexity varies with wavelength. For imaging temperature, profiles on circuits a mid-range IR unit with internal cooling is required. IR imaging may also support the repair process if IR radiant heat is used in reflow operations.

Ultraviolet imaging.—Ultraviolet (UV) is used for certain types of conformal coatings, such as Paralene, that may be too thin to detect visually. Normally a strong UV light source is used for visual inspection, which can harm the user's unprotected eyes. A UV-range camera may be used to detect fluorescence using a much weaker UV light source.

X-ray.—The electronics industry is increasing its reliance on x-ray for diagnosis of ball grid array (BGA) and land grid array (LGA). The recent CLEAR program needs assessment determined that the BGA and LGA will likely replace many surface-mount technology integrated circuit (IC) packages in future avionics. For BGA and LGA devices, x-ray inspection may be the only viable technique.

A number of ISS electronics problem reports also included x-ray examinations to reveal critical circuit flaws. X-ray applications range from full-size circuit boards to small hybrid assemblies. Some x-rays use x-ray fluorescence techniques, whereas others use very small scanning x-ray point sources suited to a two-axis scanning method.

6.3   Compact Conventional Instruments Functions

6.3.1   Meters

After visual examination, many simple problems are isolated by a simple handheld multimeter. The most common measurement is to test continuity in a connector or cable harness. Voltage and current measurements can quickly determine if power is reaching the faulty component and if shorts or open circuits exist.

6.3.2   Oscilloscopes

Oscilloscopes require greater operator knowledge to setup and are often very difficult to interpret. Recently industry is tending toward panelless instruments. The user controls and display functions have been offloaded to a laptop computer, and the instrument is reduced to a simple box with connectors and a data port. The unit weight may be reduced by half. Since a panelless instrument is already networked, it is simple to extend the data flow to include uplink and downlink functions.

6.3.3   Signal Generators

Many diagnostic and test techniques require injecting a stimulus signal-to-target circuit and observing its response. For example, ASA requires a small signal injection. The trend is toward direct digital synthesis, where single-chip devices are used to synthesize signals from high-frequency clocks. Direct digital synthesis is a suitable application for synthetic instrumentation.

6.3.4   Analyzers

Generally an analyzer is a compound instrument that incorporates a specific stimulus signal, a response measurement, and signal processing and display function. The Huntron ASA and the CLEAR CSA techniques can both be described as analyzers. Many of these analyzer functions could be synthesized by SIs.

The most effective compact stand-alone analyzers are used for diagnosing high-speed networks, such as Ethernet LANs, RF cables, and optical networks. Although very specialized, they are often handheld and simple to operate, making them an attractive option.

6.4   CLEAR Diagnostics by Characterization

6.4.1   Analog Signature Analysis Function

A power-off technique called ASA was developed by Huntron (see Figure 11) as a simple but effective form of diagnostics, based on comparison with a known-good board. It provides the advantage of diagnosing a circuit in the power-off condition, which negates the need for power supplies and the risk posed by powering up a faulty circuit.
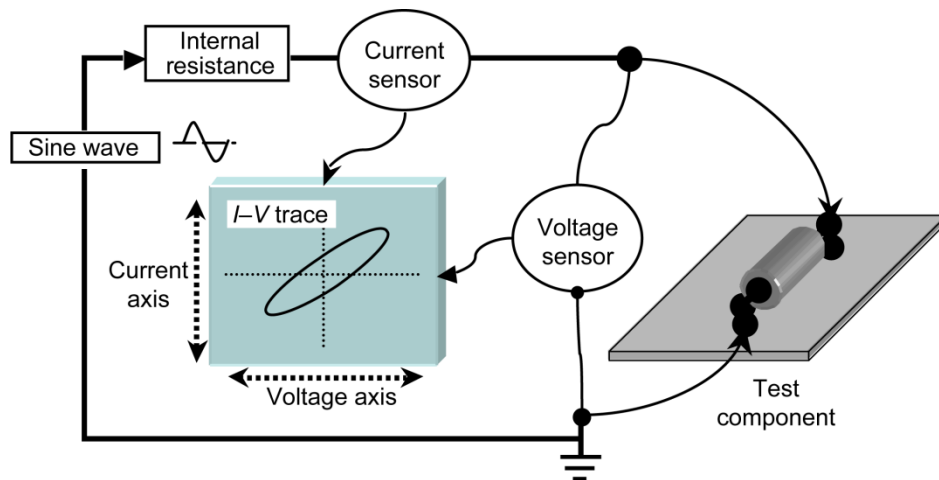
Figure 11.—Analog signature analysis (ASA) relies on measuring the response to very low-power sine wave signal, I–V, current-voltage.
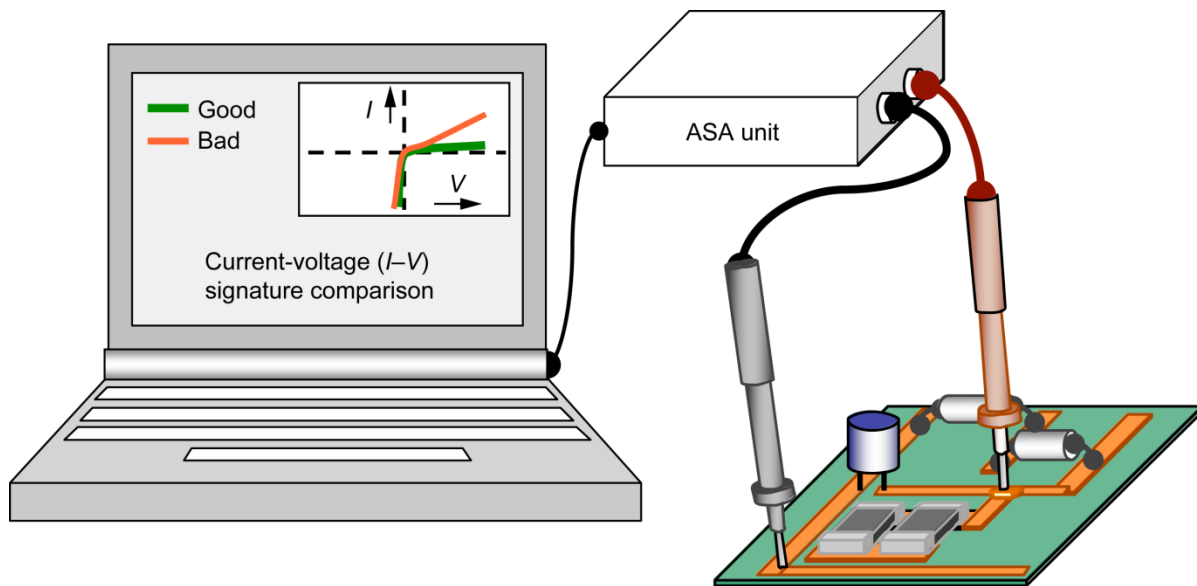
Figure 12.—Analog signature analysis (ASA) characterization may involve several individual devices contributing to the node's characteristic signature. A fault in any one of them alters the signature.

The ASA technique applies a current-limited sine-wave voltage to an unpowered circuit or electronic component (Figure 12). The resulting current (I) and voltage (V) characteristic (analog signature) is then stored and displayed for comparison with signatures of a known-good circuit card or electronic component. Thus, circuit cards and electronic components can be diagnosed without applying external power.

A single component that can be isolated provides a very predictable curve. Circuits usually have multiple devices on each node; thus, a node will have a signature that is a composite of multiple devices.

As long as the settings and probe positions are consistent, the signature should accurately duplicate the known-good-board signature.

A personal computer (PC) workstation with ASA software graphically displays the analog signature. This approach can be applied to any type of passive component like a resistor, capacitor, or inductor. It can also be applied to solid-state semiconductor components like a diode, a transistor, a silicon-controlled rectifier, digital, analog, or mixed-signal IC.

Alternatively, the signature can be compared with "known node faults," where individual components with various fault modes can be precharacterized, providing a more precise diagnosis. A skilled user that is familiar with the circuit design and each component's function, may use the signature to determine exactly which component is faulty. If the user is not skilled and no known-good reference is available, the results will be ambiguous.

6.4.2   Complex Signature Analysis Functions

CSA is an extension of ASA that uses capability a vector network analyzer. Not to be confused with network protocol analyzers, a vector network analyzer tests networks of components in high-frequency alternating current (AC) signal circuits. Vector network analyzers share certain capabilities with a spectrum analyzer. These devices are generally used for high-frequency or RF circuits, where operating frequencies can range from 10 kHz to 110 GHz.

A vector network analyzer measures the frequency domain properties of component networks rather than single components. It injects a signal into the network and measures the signal reflecting back from the circuit and the signal transmitted through the circuit. These analyzers are commonly used to test high-frequency amplifiers, filters, and tuning networks and can also test piezoelectric devices like crystal resonators. They operate at very low wattage and inject signals into passive networks or active devices like amplifiers.

For CLEAR, the vector network analyzer provides a complex impedance measurement. Network analyzers make their measurements relative to a reference impedance value (typically 50 Ω for RF systems). The scale can be very large; a log scale is used, and impedance ratio (expressed in dB) is displayed.

Complex impedance Z is a complex value; that is, it is composed of a real value R and an imaginary value X.

$$Z = R + Xi$$

The resistance term (R) is measured with a common direct current (DC) resistance meter. The reactance term (X) typically involves inductors or capacitors and is only meaningful for AC signals. Beyond this, the explanation involves amplitude and phase relationships, which are difficult to grasp. Complex impedance measured over a frequency sweep reveals resonant behaviors for both the entire network and individual component resonance. By performing a wide sweep, one can identify specific components. By comparing the sweep signature to a known-good or gold signature, one can quickly spot a failed component. As shown in the plot, the data may be very difficult to interpret directly, but it provides a very distinct, unique signature.

As shown in Figure 13, a filter composed of several LC (inductor capacitor) nodes has a distinct resonant condition for each node. The plots produced by the network analyzer could be used to characterize the network. The actual measurement can be taken at the input or output end.

In Figure 13, note that markers 1 through 5 indicate distinct nodes and each node's contribution to the characterization curve. Therefore, it is possible to characterize the network without measuring every node. This is particularly useful when parts of a circuit are inaccessible. The measurement is taken from the signal injection side of the circuit rather than from the output side. In Figure 13, the blue trace is the characterization of a known-good reference network. The red trace is a test trace from a network where node 2 has a faulty component.

This illustrates that any device fault will appear as a distortion of the curve at that point.
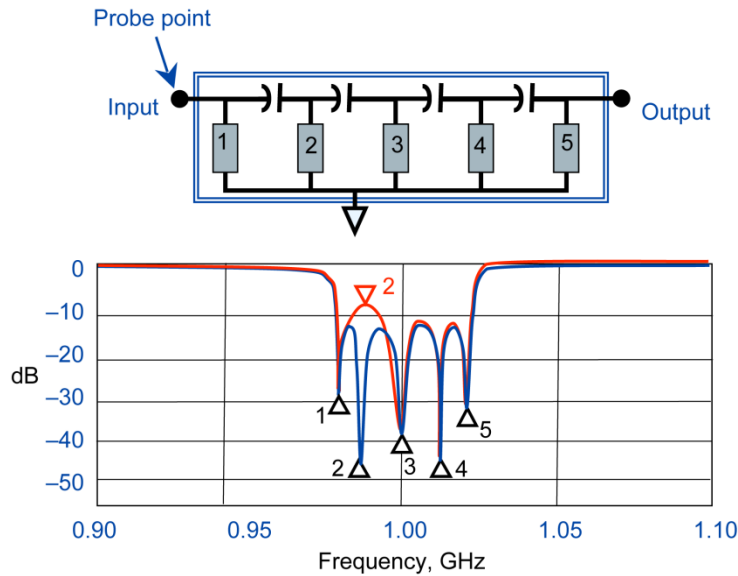
Figure 13.—Each marker indicates a normal resonance of a "known-good" network composed of five components. The red trace indicates that element 2 of the test circuit has a faulty component and therefore does not match up with the expected known-good trace.

6.5 CLEAR Synthetic Instrument Architecture

The motivation behind synthetic instrumentation is the need to reduce the size and weight of instruments and related hardware used in the diagnosis and test of electronics. It is not uncommon for a specific ORU to require multiple racks of equipment. DOD studies consider automatic test equipment (ATE) as a primary contributor to the high life-cycle cost of avionics equipment. ATE life-cycle cost can become an increasingly expensive part of avionics cost over time as hardware becomes obsolete. The studies also determined that test software is a major component of avionics and test equipment cost. Hardware and software obsolescence also tends to drive up cost, particularly for proprietary systems. These DOD studies prompted development of nontraditional concepts for ATE to keep life-cycle cost down. SIs are conceived as a way to make ATE equipment more universal and easier to update remotely.

6.5.1 Conventional Automatic Test Equipment Functions

To define the CLEAR SI functions, it is essential to first define the basic capabilities of a conventional ATE for functional test. Simple measurements are inadequate to fully diagnose or functionally test complex systems that are distributed over many circuit cards.

Generation of Stimulus Signals.—Diagnostic and test equipment generally requires a stimulus signal injected into the test target. For ASA or CSA diagnostics, injecting a signal is an essential step in characterization. The response is measured on the same line as the injected signal. The characteristics of the injected signal must be identical in the known-good circuit reference and the test target, otherwise the method is unreliable.

Functional tests require a variety of stimulus signals.

- Input clock for clocking or triggering digital functions
- Signals from sensors and transducers
- RF communications signal
- Parallel and serial data bus signals
- Analog signals from the audio through the RF range
- Amplitude modulation (AM), frequency modulation (FM), frequency shift keying, pulse-width modulation, and other modulation methods
- Analog feedback signals in control loops

Capture of Response Signals.—For every stimulus signal there is a circuit with a like output signal. Diagnostic and test equipment must match signal generation with similar signal capture capability. Overall, this implies that the signal-generation channel count should match the captured-signal channel count.

Monitoring Measurements.—Diagnostic instruments are mounted to serve as a nonintrusive or transparent monitor of circuit behavior or signal traffic. Secondary effects, such as heat generation during various operating modes, are also monitored to locate heat-related problems.

Emulation of Interfaces.—For electronic circuits that are part of a much larger system, the largest consumer of capability is the need to emulate external circuits. This can involve emulating hundreds of individual signal channels. Emulators often serve as indirect points for stimulus signal injection or provide breakout channels for receiving and collecting system data.

Spacecraft Power Simulator.—A power supply that emulates the spacecraft power is needed to perform functional tests. Spacecraft power can be the source of many problems in avionics. Functional testing often includes testing the ability of a circuit's internal power supply to tolerate occasional spacecraft power system transients. The power supply needs to be programmable to simulate these transients.

Power Load Simulator.—Power systems and RF systems cannot be fully tested without external loads to absorb power. These loads stress the test circuit so the components are tested in actual conditions.

6.5.2 CLEAR Synthetic Instrument Functions

Figure 14 illustrates the complexity of a test setup required to fully functionally test a circuit. It shows how emulation requirements drive the scale of ATE. A conventional system intended to perform automated functional tests can result in a multirack system too massive for space applications. Likewise, the software code developed to exercise and coordinate various test functions is usually much larger than the code installed in the flight avionics.

A system is needed that can be configured to diagnose and test virtually any form of electronics on the spacecraft and fit within the small accommodations. Furthermore, the system must not create a substantial workload for the flight crew or significantly increase training requirements. So far, the SI concept appears to be the best approach.

CLEAR SI strategy involves

- Partitioning the functions between Space and Earth segments
- Allocating (offload) data processing and analysis functions to the Earth segment
- Employing analog front-end hardware with greatest possible range and bandwidth
- Exploiting digital functions instead of analog functions where possible
- Employing FPGA technology to synthesize the digital functions
- Employing signal routing capability to match instruments to specific circuit connections
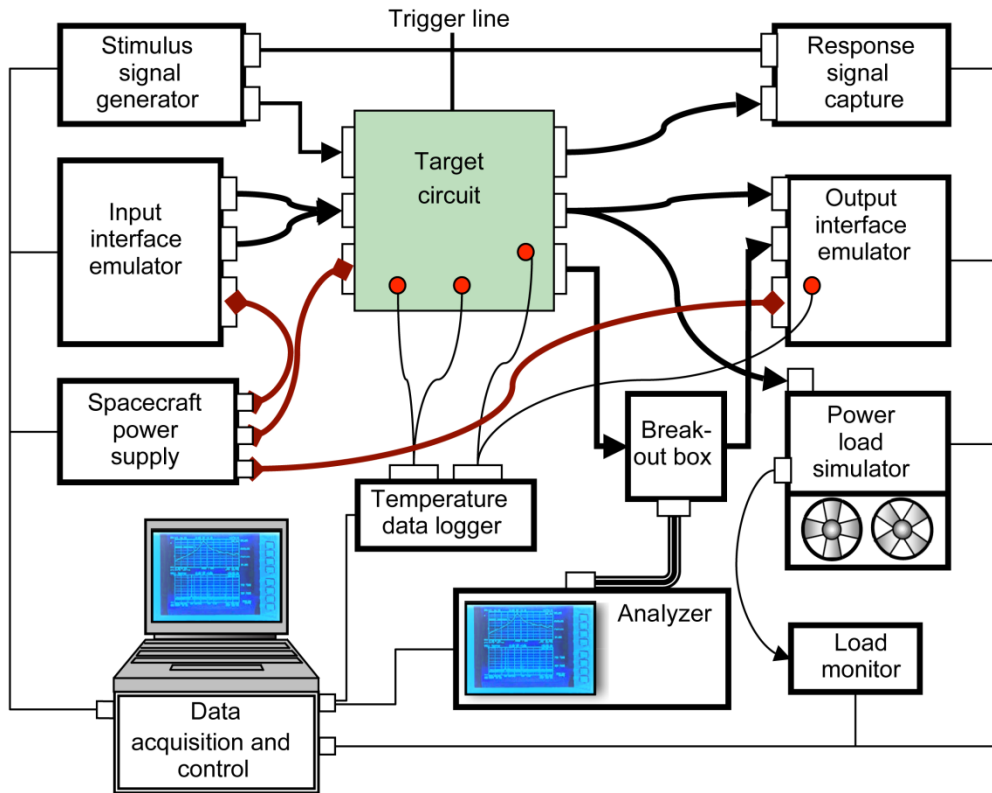
Figure 14.—Conventional automatic test equipment functional test systems involve interface emulators, data loggers, signal monitors, signal stimulus sources, measurement instruments, power supplies, and load simulators (with cooling).

6.5.3   Allocating Space and Earth Synthetic Instrument Functions

As described in CLEAR–DOC–007, CLEAR is composed of a Space and an Earth segment for both hardware and software. CLEAR synthetic instrumentation is also partitioned in that manner. The intent is to provide the essential signal capture and generation capability on orbit and to offload the signal processing related to analysis and display to the Earth segment.

Earth segment functions are already described in the teleoperations architecture. The Earth segment, or CLEAR TEST center, processes the raw data sent by the Space segment and performs the analyses, assessment, decision making, and action planning for the next phase of the process (see Figure 15). This segment is well within the current technology base.

Earth Segment Functions
- Data processing and storage
- Data analysis
- Data assessment
- SI control programming
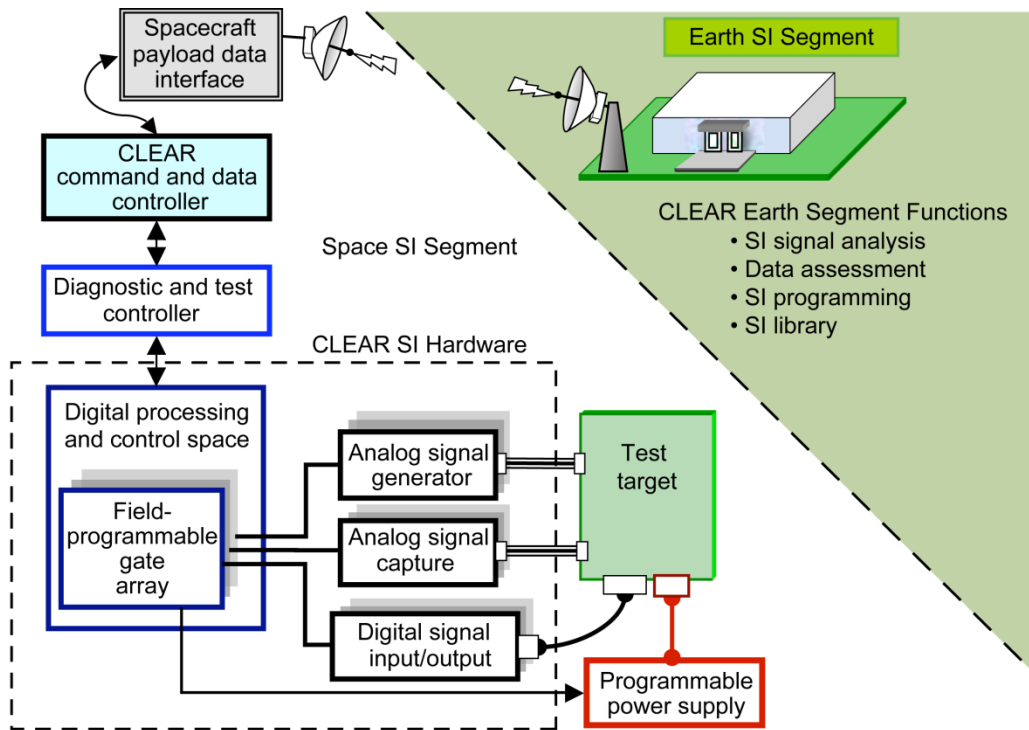- SI library (database management)

Figure 15.—The synthetic instrument (SI) architecture is partitioned into Space and Earth segments.

The Space segment can be considered the front end of a diagnostic and test system, providing the interface with the test target and acquiring the raw data. For a complete solution including the postrepair functional tests, the Space segment will need to provide the supporting emulation capability.

Space Segment Functions
- Measurement capture including signal conditioning, analog-to-digital conversion (ADC)
- Stimulus generation including digital-to-analog conversion (DAC) filtering
- Timing and triggering
- Input/output (I/O) interface emulation
- Signal routing
- Crew and spacecraft interfaces

6.5.4 Synthetic Instrument Functions and Technology Options

Flight Segment Analog Front End.—Although SI technology relies on exploiting digital domain capabilities, instrumentation and measurements are started in the analog domain. Analog hardware is the primary restriction on SIs, and the sooner signals are converted to digital, the easier it is to exploit synthetic instrumentation. The analog front end refers to both analog input and output. For an all-purpose system, these devices must have an inherent ability to be configured over a wide range of parameters.

When a specific application cannot be accommodated by a reconfigurable or programmable device, then add-on modules may be inserted into the system as a temporary means of extending capability. Generally, the add-on approach is how variations of physical contact or sensors are handled. For example, a high-voltage measurement that is beyond the safe range of the analog front end may be required for a specific instance. An add-on solution would be to provide a high-voltage probe that preconverts the voltage down to a safe level. Similarly, it is common to use RF upconverters and

downconverters to convert extremely high RFs to a range that common equipment can handle and to avoid extremely expensive RF instruments (Figure 16 and Figure 17).

Analog Signal Conditioning.—Signal conditioning involves the analog manipulation of the signal to make it suitable for measurement by electronic devices. Raw signals may include low-voltage thermocouple measurements, high-voltage power measurements, high-impedance logic, or 50-Ω impedance-frequency RF signals. Each type of measurement requires specific input conditions to prevent signal distortion or damage to the instruments. The input signal must be preconditioned for the measurement instrument. Signal conditioning involves signal amplification or attenuation and filtering. For flexibility, the instruments must have a fully programmable signal-conditioning section.

Signal amplification improves the signal-to-noise ratios of measurements and increases the resolution and sensitivity of measurements by matching signal magnitudes to the acquisition ranges. Signal filtering will allow signal shaping and rejection of unwanted noise from power lines and prevents signal aliasing. In many cases, signal isolation may be built in to remove common-mode voltage errors caused by differences in grounding potentials. The sample-and-hold function will be the last point where the signal is analog. This function will sample the continuous signal and hold it, upon triggering, at a steady value so that the ADC can read it in and convert it to digital. Once the sample is read into the converter, the sample and hold circuit will be retriggered to capture another sample.

Analog to Digital Conversion.—The analog-to-digital converter will receive the preconditioned signal and perform a conversion to digital data. The digital word generated will depend on the device, but is typically 8-, 10-, 12-, or 16-bit word. The word size will define the resolution of the measurement. Once converted to digital format, the remaining processes will be handled in the digital domain.

Digital Signal Processing.—Data can be stored in both raw form and in a processed form. Storing raw unprocessed data is important since there may be many alternate ways of processing data to reveal different signal properties. For conventional instruments, considerable computational power is dedicated to processing and presenting the data to the user in an understandable format. For CLEAR, most of this will be deferred by the Space segment and performed by the Earth segment. This will allow the flight system to focus on controlling the analog section, routing signals, and packaging and transmitting raw diagnostic data.

On the ground, data analysis will involve processing and presenting diagnostic data for the CLEAR TEST team. This is also where the TEST team can employ analysis tools to extract characteristics not easily visible in the raw data.

Digital Control of Analog Function.—There are several instances where a digital device can enhance the range and function of a dedicated analog device.

- Amplifier gain and attenuation control
- Absolute voltage and differential voltage
- Input impedance
- Temperature compensation
- Voltage reference (calibration)
- Input filter frequency band
- Sample rate, sample resolution, and sample hold time
- Signal multiplexing control
- Trigger source, trigger delay, and trigger level

Virtually any adjustment that can be made on the front panel of an instrument can be handled by digital control of an analog device. In some cases, an analog function can be replaced completely by a digital function. For example, certain forms of digital filtering can eliminate equivalent analog filters. The digital filter may actually be a mathematical algorithm that filters digitized data in a digital signal processor. Again, CLEAR would handle this digital process on the ground.

Digital Input/Output and Interfaces.—Most avionics ORUs have a mix of analog and digital I/O signals. At the ORU level, the digital signals may take the form of a serial data bus. For ISS, the standard

is the STD 1553 bus that was developed and deployed in the 1970s for aircraft avionics and fly-by-wire control systems. For CxP, the current data bus is a LAN known as the TTGbE, which is described in Section 5.0. These interfaces, although physically simple, have complex protocols and driver software. A specialized TTGbE digital network analyzer with preprogrammed test functions may be the simplest option.

At the shop replaceable unit or circuit-card level, digital interfaces are more likely to require large backplane connections with dozens of data, address, and I/O lines. These connections employ parallel data bus architecture. This is an application where SIs can be most effective. Digital instruments do not need analog signal conditioning and only require digital buffers or isolators to protect the instrument from circuit faults. The SI can bypass the analog section and link directly to the digital test target.
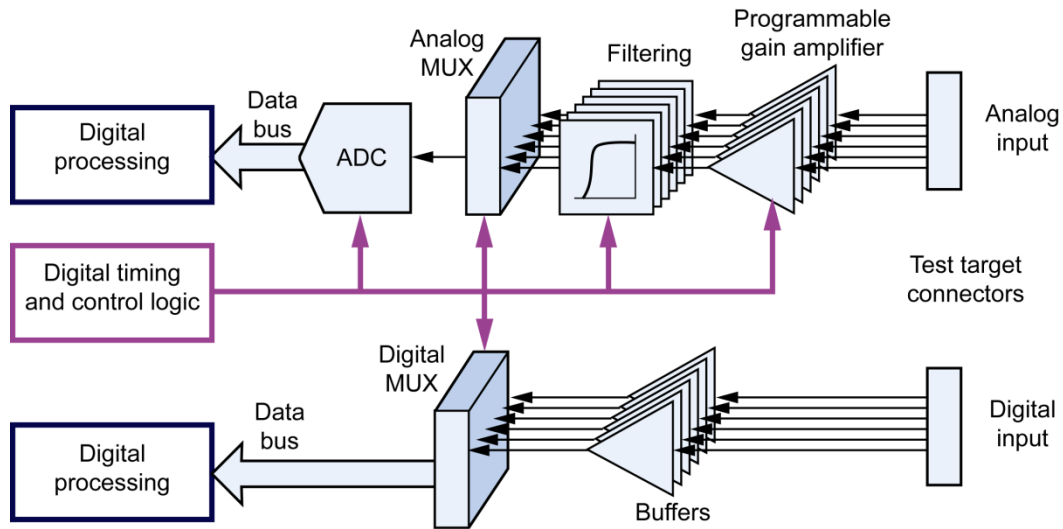
Figure 16.—Signal capture (analog-to-digital conversion (ADC) and multiplexer (MUX)).
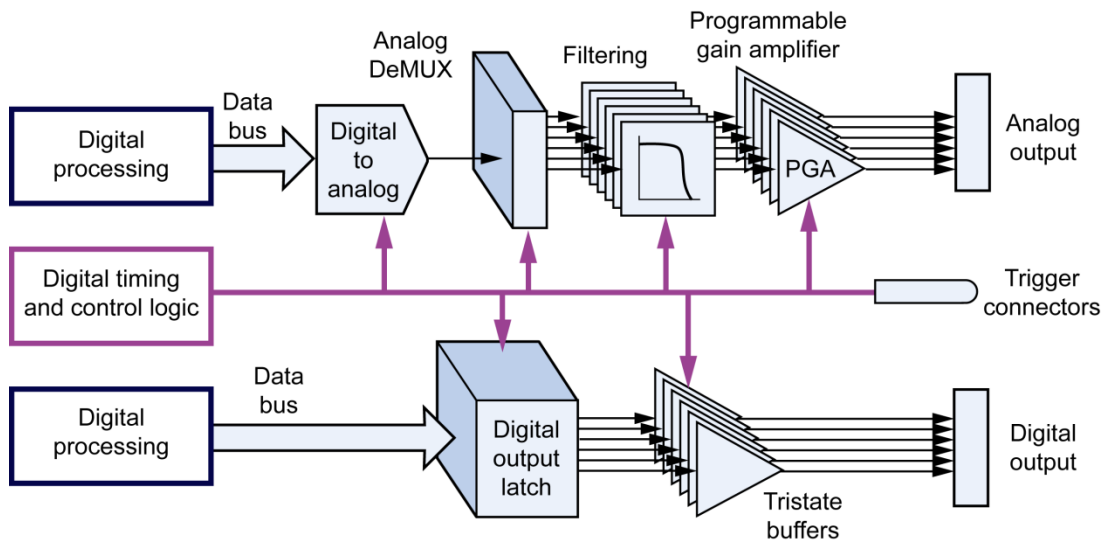
Figure 17.—Signal generation.

SIs can be setup as traditional logic analyzers to test digital I/O. The most common application will likely be to serve as a digital emulator. The emulator can be programmed to interact with the target by emulating a device that would be attached to the target in normal operations. Emulators are frequently used in embedded computer development. The emulator transmits signals and interacts like the original device, but it has added instrument capabilities to capture detailed measurements. This technique can capture timing and triggering errors down to nanosecond resolution. It can capture handshake or protocol errors, and detect abnormal transients or slow I/O faults.

Stimulus Signal Generation.—For every signal type used, there is a signal-generation need. Signals are generally categorized as analog, digital, or RF. Digital signals are based on binary logic state voltages, nominally 0 to 5 V for transistor-transistor logic. Analog signals can range from simple AC waves to waves with complex amplitude and frequency content such as audio. RF signals are analog signals with high enough frequency to be effectively transmitted via antenna. Each signal type has its own signal modulation techniques and impedance characteristics.

SI can produce digital and analog signals, as shown in Figure 18. RF signals are more difficult to measure and produce because of the extremely wide range of frequency and power levels. RF systems employ antenna technology to transmit across space where voltage and current measurements are meaningless.

Field Programmable Gate Array Technology.—In SI, the FPGA is an enabling capability because it provides the user a "sea" of available logic gates that can be programmed to synthesize the desired digital functions. Because these logic gates can be arranged to provide highly parallel pipeline processing, they can achieve very high performance. In contrast, a PC microprocessor-controlled data acquisition instrument performs many sequential functions and must perform memory fetches and must also support operating system overhead. As a result, microprocessor-controlled instruments usually have poor performance. The FPGA can provide signal processing performance near that of a benchtop instrument.

Ultimately, the SI will support low- to moderate-frequency or baseband analog signals, high-frequency or RF analog signals, and digital signals. For RF, the frequency required for radio transmission is normally well beyond the internal data rates, and it is normal to use RF upconversion and RF downconversion.
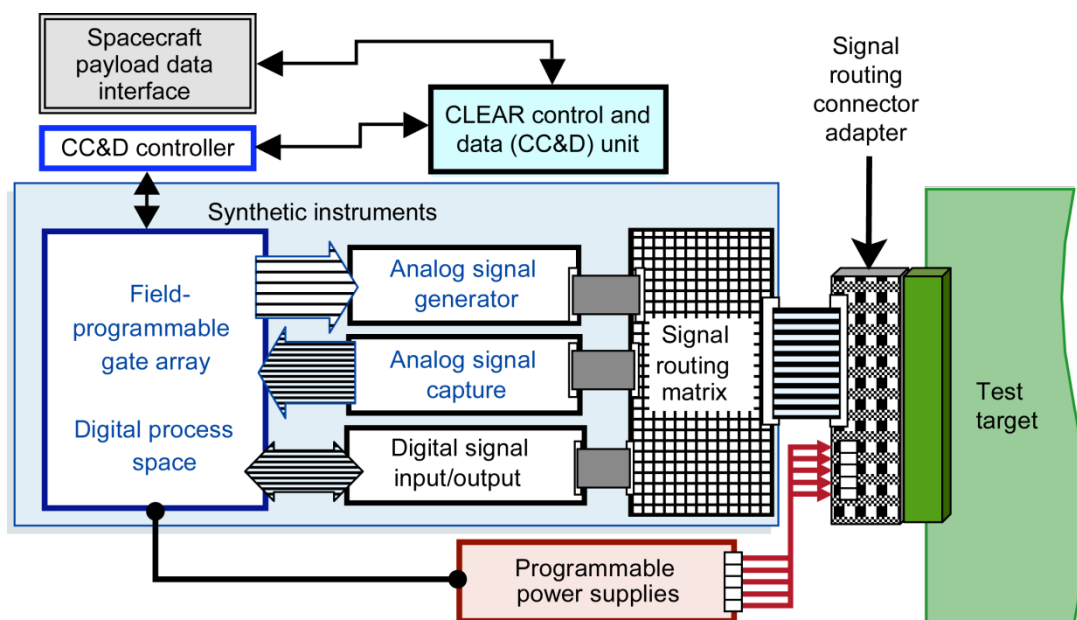

Figure 18.—Routing signals from various test targets may be accomplished by combined internal signal routing matrix and intermediate hardwired signal routing connector adapter.

Signal Routing.—The signal router will route all signals going to and from the test target. It is a means in which signals will be aligned to pin outs of each target. This routing function is needed to accommodate large ORU connectors and circuit-card backplane connectors. Unless the target circuit is part of a standard backplane assembly, each target is expected to have unique pin-out arrangements that may mix input, output, analog, digital, and power in a single connector.

In conventional automatic test systems, it is common to employ special test cables that mate with the ORU connector but attach to multiple instruments. A similar scheme can be employed for CLEAR, but there are crew time and stowage penalties for this approach. The analog section limits the routing flexibility. Unlike digital circuits, where bidirectional buffers can change direction on command, analog input and output circuits are distinctly different. Therefore, routing analog input and output requires external routing capabilities.

Analog switches can be used to route a signal to the appropriate analog input or output. Digital timing and control logic can configure the analog front end and switching to reassign channels. The generic SI block diagram includes a signal routing connector adapter and a front signal routing matrix. Recent studies regarding plug-and-play satellites indicate that microelectromechanical-systems-based reconfigurable manifolds may be best suited for flexible signal routing.

Alternatively, FPGAs with large-field open gates, can provide an option to relocate or resynthesize an SI into a location that is more accessible for a given signal channel.

7.0 CLEAR Repair Apparatus Architecture

7.1 Overview

The CRA borrows heavily from industry experience with automated and robotic technology. Industrial robots, unlike NASA robots, are typically stationary and focused on moving hardware instead of robot mobility (see Figure 9). The distinction between robots and automated equipment is the need for flexibility in motion and function. Automated equipment tends to involve a series of simple devices that perform only one task, where robots are complex and perform a series of tasks. Robot flexibility is extended by interchangeable end-effector tools. Robot motion ranges in complexity from simple Cartesian (XYZ) robots to complex multiple joints with multiple degrees of freedom.

All robots must be programmed, but in recent years the availability of three-dimensional programs and simulation tools has made it much easier to both program and validate the robot motion-control system. Three-dimensional computer programs allow the user to execute a robot program in a virtual three-dimensional environment to reveal errors and hazards. This reduces the risk of program errors causing collisions that damage hardware and harm workers. These programs also can predict the effect of different tools.

Because CLEAR repair involves materials and a variety of processes in a space environment, process modeling must be employed to convert 1-g processes to low-gravity applications. Materials must be properly staged in an area accessible to the robot. Once again, low-gravity will affect how materials are staged and dispensed. As with many repair processes, debris, vapors, and liquid byproducts may be produced, and these must be contained. Therefore, the repair apparatus architecture includes process containment.

7.2 Repair Apparatus Robotic Functions

7.2.1 Robotic Motion

Robots for semiautomated repair and diagnostics can be categorized as an industrial robot. ISO defines an industrial robot as an "automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes."

For fabrication and repair operations, robotic motion can be accomplished by various configurations. The simple Cartesian robot (Gantry robot) illustrated in this document is akin to flat-bed plotters and CNC machining centers. The Cartesian robot translates on three orthogonal linear axes to achieve a full range of motion. Two other common robot types include the selective compliant articulated robot arm (SCARA) and articulated (arm) robots. The SCARA uses a combination of rotary joints and linear telescoping slides. The articulated arm has compound rotary joints that tend to emulate the motion of a human arm. The remote manipulator arms used on the space shuttle and ISS are articulated arm robots. Another class is the anthropomorphic robot, which is intended to emulate the motion of a human and have at least two arms. These are most useful when used by a remote human operator often using haptic (touch) feedback. NASA's Robonaut is an anthropomorphic robot.

Cartesian and the SCARA robots are effective for motion that is simple, planar, and repetitive. These robots are widely used in pick-and-place operations for electronics assembly. Articulated arm robots are more effective when long complex paths are required such as spray paint and welding applications. Articulated arm robots are more likely to be used when multiple robots are used in a cooperative arrangement.

7.2.2 Robotic Motion Parameters

Tradeoffs to consider for robotic motion include the following:

- ***Degrees of Freedom***.—For CLEAR, the repair target normally will be a planar circuit card and three translation degrees of freedom will suffice.

- *Working Envelope*.—The planar circuit card will have a simple envelope; however, access to multiple tool, component, and material pallets will expand the needed envelope.
- *Kinematics*.—The combination of linear and rotary degrees of freedom and the length of each arm between joints will define the possible motion paths. Robot kinematics becomes important when complex motion paths are required, such as reaching into a constrained space or around obstructions.
- *Payload, Speed, and Acceleration*.—In low gravity, payload inertia is a primary concern. Minimizing speed and acceleration requirements minimizes motor horsepower and braking requirements. Inertia is a major factor in motion overshoot, vibration, and the required damping in a control system. It is also why industrial Cartesian pick-and-place robots require massive bases. Lightweight payloads (tools), in combination with low accelerations, minimize the overall system mass for CLEAR.
- *Accuracy and Repeatability*.—Accuracy refers to how precisely a robot will move to a commanded position. Repeatability refers to how consistently the robot achieves the same intended position. For CLEAR, accuracy and repeatability must be consistent with industrial electronics assembly equipment. Compound kinematics and cantilever beam segments make articulated robots the most prone to accuracy and repeatability problems. Simple kinematics and an end-supported beam structure make Cartesian robots the most accurate and repeatable.
- *Backlash and Compliance*.—Backlash is the natural play in mechanical gears and drive screws in motorized motion and directly affects accuracy and repeatability. True zero backlash in conventional drives is nearly impossible. Compliance is the natural deflection of the robot beam structures. The combination of backlash and compliance define the inherent rigidity of the apparatus. For CLEAR, probing, pick-and-place, and dispensing will not be dramatically affected by backlash and compliance as long as absolute position feedback is used to compensate for these effects. Rotary cutting and grinding tools will require substantial stiffness to prevent tool chatter and vibration throughout the system.
- *Tool Handling End-Effectors*.—The ability to accommodate a wide range of end-effectors provides a wide range of utility. Mechanical end-effectors are constrained by the supporting lines for power, control, and instrumentation. Routing of these lines is simpler in rotary joints. The pure translational motion of a Cartesian robot means electrical lines need to be housed in a folding cable tray or to employ a cable suspension system.

7.2.3 Robotic Operating Environment Constraints

For CLEAR applications, there are further operational and environment tradeoff considerations.

- *Heat Tolerance*.—It will be difficult to avoid exposing the apparatus to heat during solder reflow cycles, particularly if the component handling (pick-and-place) and solder reflow functions are combined. The robotic mechanism, particularly the tool handler, must be heat tolerant. Furthermore, moderately high heater current must be conducted through the tool handler's electrical interface.
- *Atmosphere*.—The robotic apparatus may be exposed to multiple atmospheric environments. Normally, a rework station operates at normal atmosphere; however, it is not uncommon to use inert nitrogen atmospheres to reduce oxidation, which in turn reduces the need for flux and improves quality. For CLEAR, an inert atmosphere may be employed to reduce solder porosity and the need for flux fume containment. The robotic apparatus may need to tolerate vacuum venting as a means of evacuating process vapors.
- *Payload Mass and Volume*.—Weight is important from an initial launch weight consideration. The unit must minimize volume, particularly when not in use. A unit that can be reduced to a very small stowed volume is very desirable.

7.3   Repair Process Functions

7.3.1   Reflow Soldering Process

The solder reflow process is the most likely method of repair beyond simple soldering iron repairs. The process will have to apply heat carefully in a series of ramp-and-hold steps, where the heating rate and hold times are established to prevent thermal stress damage.

Figure 19 illustrates a representative reflow temperature profile. An initial ramp-up is used to heat the circuit followed by a stabilizing soak that assures a uniform temperature. The solder flux is activated during the second ramp-up, and then the solder is reflowed. Reflow dell time is enough to assure thorough melting but to minimize excessive intermetallic growth in the solder joint and minimize circuit card material degradation. Blowers may be used to accelerate the cooling-down process until the soak temperature is reached again.

Compared with the reflow process used in the original manufacture of the circuit, reflow connected with repair or rework is more complex. In repair, the reflow process occurs twice, once to remove the component and a second time to install the new component. Another problem is the need to restrict the heating so that reflow only affects the component being replaced. Most circuit boards are designed to tolerate one or more rework cycles.

Reflow heat may be delivered as hot gas or as IR radiation. Hot gas requires a pneumatic supply or a motorized blower. Generally, a specific nozzle that restricts the hot gas flow to the desired component is selected. IR heaters also can be used, and they provide a standoff distance that makes it easier to view the process. IR heat sources do not readily form square or rectangular heat zones without optical masking on either the IR source or the target circuit. The mask may be simple custom-cut foils. Many industrial rework stations use a combination of IR and hot gas. Figure 20 illustrates a reflow system integrated into a Cartesian robot.
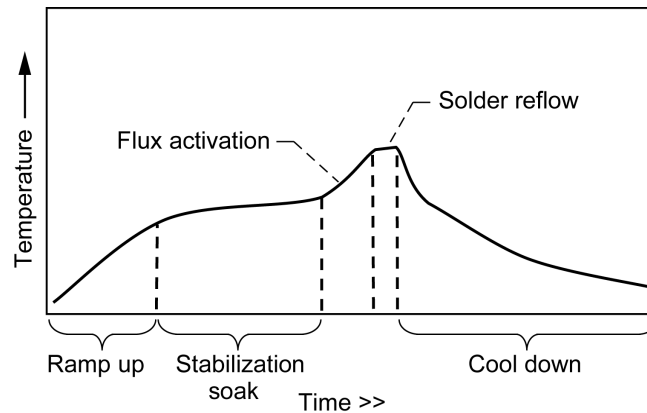
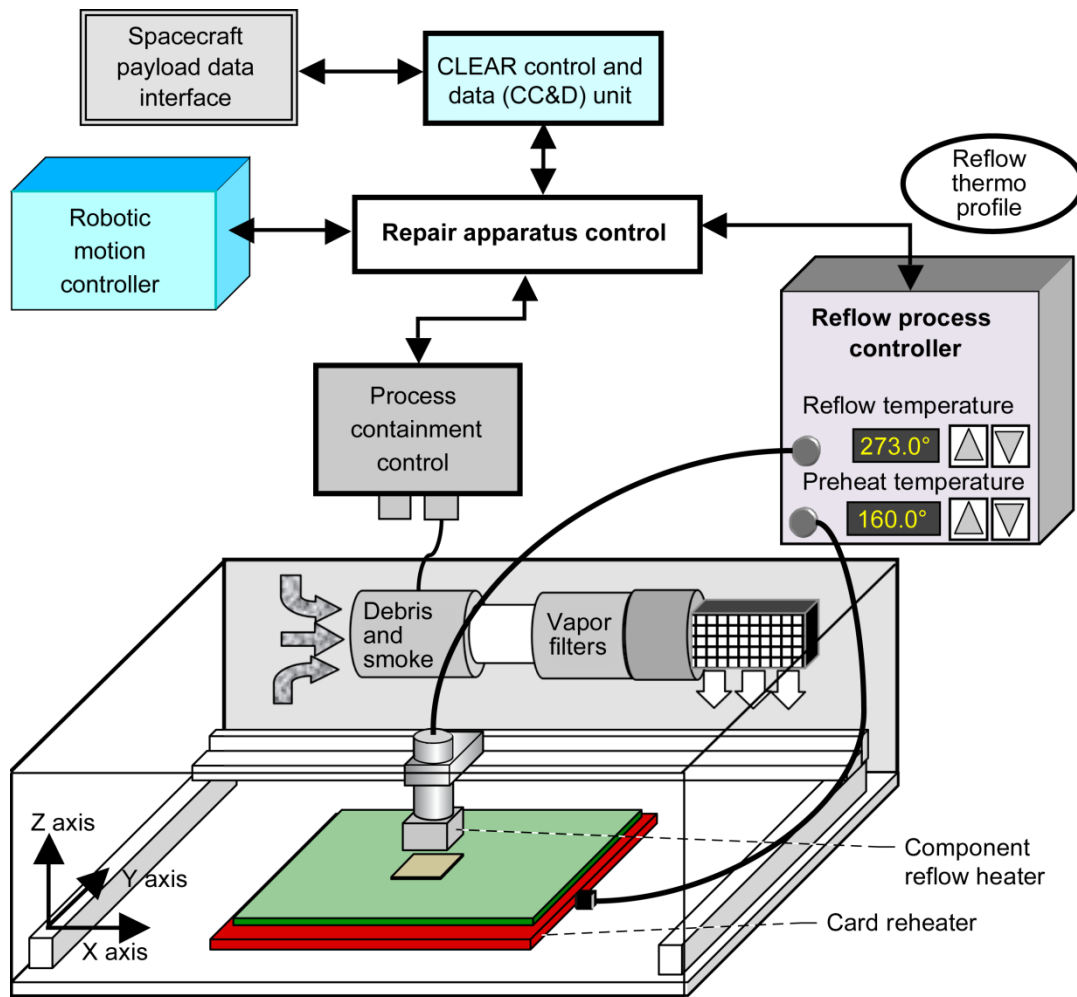Figure 19.—Reflow temperature profile.

Figure 20.—Reflow repair with process containment.

7.3.2   Repair Process Containment

Throughout the repair process, there are operations that create debris, vapor, and smoke. The basic glovebox containment will suffice for most applications. The containment shown in Figure 20 also will include glove ports for manual operations. On ISS there are existing facilities, such as ISS microgravity science glovebox. CLEAR SARADA could be simplified to fit into the glovebox and reduce the overall upmass required. It is likely that the lunar facilities also will have glovebox containment systems available.

An important CLEAR M&P objective is to develop technologies that make in situ repair more viable through elimination of unique consumables. The process containment of debris and vapor hazards also provides an opportunity to control the process environment. An inert atmosphere process environment is known to improve reflow solder processes by eliminating atmospheric oxidation and dross buildup. Because oxidation is eliminated, less solder flux, and thus less cleanup is needed. It may be possible to use light abrasives to mechanically remove any existing oxides and further reduce the need for flux agents.

The majority of solid debris and vapors can be controlled by circulating the air through filters. Filters are consumables, so processes must minimize debris and vapors. Containment of the small amount of cleaning and rinsing liquids can be controlled by using saturated wipes.

7.4   Staging and Handling Functions of Tools, Components, and Materials

7.4.1   Resource Staging

Repairs performed by manual or automated means will benefit from proper staging of the hardware. Tools used by the tool-handling robotic mechanism need to be staged in preassigned positions so that a robotic mechanism (or human) can quickly locate them. Unneeded items will have to be kept clear of the workarea. Since space will be limited, components, tools, and materials should be palletized so that they can be placed in the workarea quickly and removed quickly.

Palletized Items
- Diagnostic probes
- Imagers
- Tools (manual and motorized)
- Reflow hardware
- Repair consumables
  - Components
  - Process materials

7.4.2   Diagnostic Probe Handling

Automated tool handling includes the manipulation of diagnostic probes. In some cases, probes may need to operate in concert with imaging cameras. The probes may be passive meter or scope probes or they may be actively injecting signals for ASA and/or CSA applications. In addition, special probes may be needed for high voltage and high frequency. As noted earlier, the tool handler may provide wiring and connectors for common electrical and instrument needs. If additional conductor cables are required, then special flexible cable ways would be needed to keep them clear of mechanisms. Probes may be manually mounted or automatically mounted by the tool handler.

7.4.3   Imager Handling

Imaging cameras will support visual examination and process monitoring needs. The imagers will be used in setup to locate key registration points and check the alignment of the target circuit with the repair apparatus. This will require the camera to ride along on the tool handler as seen in commercial probing stations and certain pick-and-place machines. Using the vertical Z-axis with and fixed focal length is a noncontact method of measuring height. This will be used to check the level and flatness of the circuit and to check the clearance height of potential obstructions like circuit wiring or instrument cables. Imagers may be manually or automatically mounted.

7.4.4   Tool Handling

Many of the tasks and tools used in manual repair will need to be duplicated for semiautomated operations. Many motorized rotary tools for drilling, cutting, grinding, and cleaning are safer and more precise if performed robotically. The human arm-hand system is simply too unsteady and compliant to rigidly grip high-speed tools. Small rotary tools are best handled by a rigid robotic carriage that resists tool torque, the tendency to climb the work, bounce, and chatter effects. For example, using rotary tools to remove conformal coatings without damaging the underlying circuit requires a rigid tool handling carriage and precise depth control. Semiautomated motorized rotary tools may support automated cutting of component leads. The same rotary tool using an abrasive disc or drum may remove coatings and prepare PC board surfaces for solder reflow. This type of tooling is consistent with CNC machine tool operations. Linear actuated tools driven by electric solenoids could provide pick-and-place along with pulling and cutting.
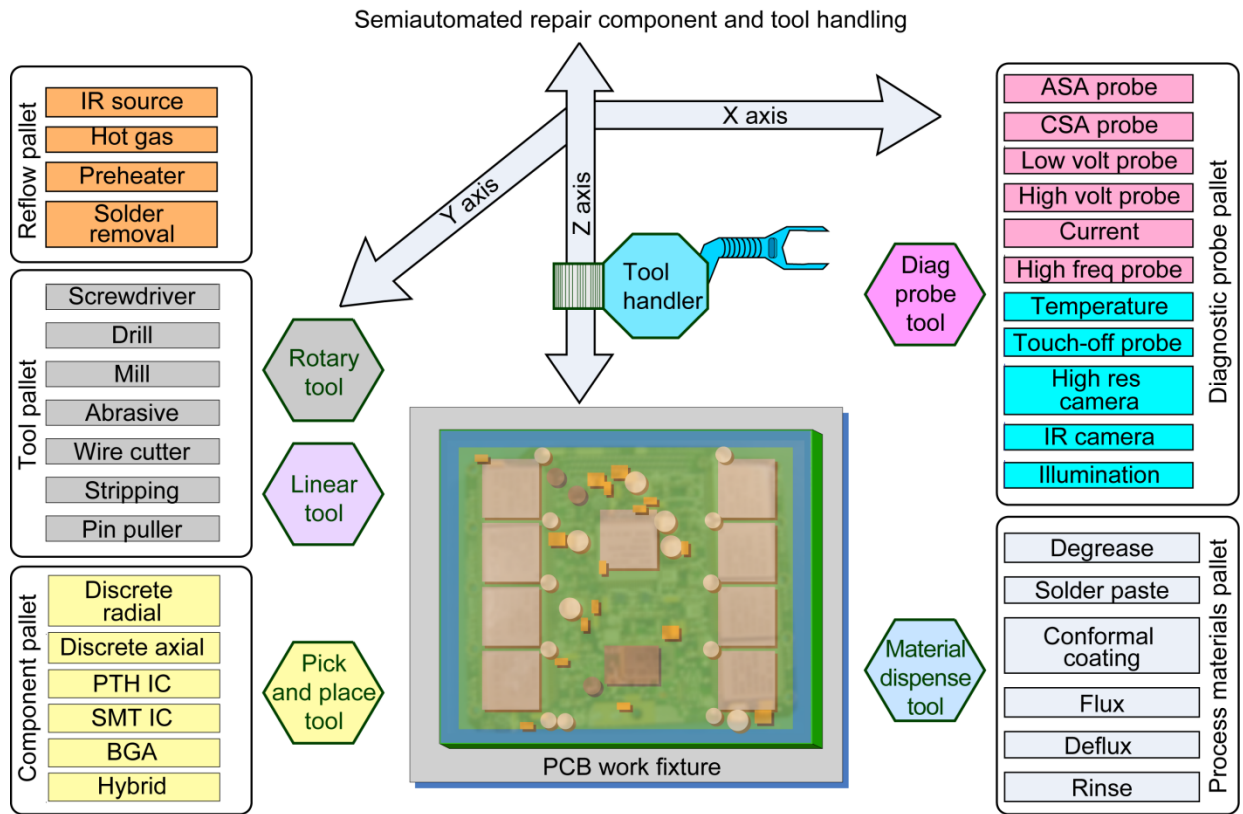
Figure 21.—Robotic tool handling requires tool, component, and materials staging. Palletizing keeps hardware organized and accessible (infrared (IR), plated through hole (PTH), integrated circuit (IC), surface-mount technology (SMT), ball grid array (BGA), analog signature analysis (ASA), and complex signature analysis (CSA)).

7.4.5 Reflow Hardware Handling

The solder reflow process hardware will be the most bulky and power-consuming element of the robotic system (Figure 21). Commercial rework stations use varied combinations of motion and heat application to assure proper alignment and reflow of complex ICs. Some systems move the component independently of heat sources, whereas others move the heat sources into and out of position as needed. In some instances, the pick-and-place device and component heater are integrated. CLEAR will seek an appropriate combination to assure the most reliable process within the constraints.

7.4.6 Component Staging

In circuit manufacturing, automated pick-and-place is essential to accurate high-speed placement of components. Component feeders in the form of tape reels, feed tubes, and pallets present the components for easy pickup by the pick-and-place component handler. Controlling small components and preventing dropped or lost components means that each component must be properly retained until needed. In space, there is no gravity to aid in containing materials and parts. On the lunar surface the low gravity will make it easier to control components, but there is some risk of contamination because of the lunar dust environment.

For specific ORU and subassemblies, palletized repair component kits could be preassembled and stored in stowage. Most repairs will consume only a few pieces of any repair kit and could be replenished on an as-needed basis.

7.4.7   Process Material Dispensing

Solder pastes, adhesives, and coatings each have special dispensing and application techniques. Most materials are in liquid or paste form and are typically applied by masking techniques to control distribution.

For short-run production or rework, small Cartesian robots with pneumatically driven dispensing syringes are employed. This type of dispensing could provide suitable accuracy for solder-paste dispensing. Conformal coatings are sprayed or dipped, which is not well suited for robotics. Thus, we expect manual brush-on dispensing to be the best option for coating materials. As an alternative, CLEAR is considering the development of special tapes as a replacement for conformal coatings and their dispensing.

Materials should be staged as premeasured packages, to minimize waste and the subsequent cleanup process. Many of the materials have a short shelf life (6 to 12 months). Methods to extend shelf life include minimizing exposure to light, packing in an inert atmosphere, and refrigeration. Note that refrigeration implies that a preheat or thaw cycle must be included in repair procedures.

8.0   Concluding Remarks

This architecture document was developed as a response to Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept (CLEAR–DOC–007). The architecture is defined in the context of the overall Constellation Program and organizes the various functions identified in the operational concept. Also, the architecture establishes the relationships between crew, ground support, flight equipment, and ground development with validation equipment. Finally, the architecture is defined to minimize the payload mass of the equipment, minimize logistic resources, and minimize the time and skill requirements of the flight crew.

The teleoperation and automated capabilities outlined in this document are intended to let the ground engineers and technical experts reach out and interact with the physical hardware while offloading time-consuming crew labor. By leveraging teleoperations, the ground crew, in effect, augments the flight crew. This support of the flight crew is essential for lunar surface operations where the vast distance and extreme payload constraints make it critical that every physical resource be fully exploited.

The architecture is also intended to provide flexibility and permit incremental growth. The initial modest capability is expected to expand over a number of missions spanning several years. It is particularly important that electronic equipment does not become obsolete during that period. To prevent obsolescence CLEAR will exploit modular equipment that is linked by a long life network that is upgradeable yet tolerant of legacy hardware. For CLEAR, a hardened network employing the IEEE–1588 standard is deemed the standard of choice.

Teleoperation and command and data handling requirements must flow down to the lowest levels so that ground crews can have complete control of the equipment. The architecture, however, is not intended to be exclusively dependent on real-time control by ground-based operations. Rather, the CLEAR approach allows the crew to operate the system independently in the event that communications is lost. The processes will be automated and specific diagnostic, repair, and test programs will need to be developed and fully validated in ground tests and simulations. A library of validated control programs can be uplinked and stored at the lunar site and loaded by the crew as needed. The CLEAR Teleoperations Engineering Support Team (TEST) center provides the development and validation tools in a dedicated support facility. The CLEAR TEST facility may be housed in existing NASA logistics depot or operations facility.

The CLEAR semiautomated repair and diagnostics apparatus (SARADA) will provide diagnostics, physical repair, and functional test capability for the crew. The equipment is semiautomated so that certain operations that are easily performed by the crew can be performed and reduce the complexity of the apparatus. Once set up by the crew, the SARADA performs the tedious diagnostic probing operations. The SARADA crew also performs automated repair operations such as reflow solder of large integrated circuits that cannot be done manually.

To distill the vast number of test instruments normally required for avionics testing to a minimum set, CLEAR will employ the synthetic instrument approach, which relies on very flexible measurement and signal routing technology and the flexibility and performance of field-programmable gate array devices. Synthetic instrumentation will support the diagnostic measurements and provide the emulation of external hardware that is essential for functional tests.

To quickly determine the location of a faulty circuit and reduce the complexity of test procedures related to power-on testing CLEAR will exploit diagnostics based on circuit characteristics in an unpowered state. Analog signature analysis and complex signature analysis will be used to inject signals into unpowered circuits and compare the response with "known-good signatures." This form of analysis is very simple for a crew member to perform and interpreting the results does not require electronics expertise.

Based on Constellation Program needs, the limits in logistics, equipment accommodation, and crew time, the CLEAR system architecture based on the technologies described will make component-level repair of spacecraft electronics viable for lunar missions and beyond.

Appendix.—Acronyms and Abbreviations

AC	alternating current
ADC	analog-to-digital conversion
AM	amplitude modulation
ASA	analog signature analysis
ATE	automatic test equipment
BGA	ball grid array
C&DH	Command and Data Handling
CAD	computer-aided design
CCA	circuit-card assembly
CC&D	CLEAR Control and Data
CD&T	CLEAR Diagnostics and Test
CLEAR	Component-Level Electronic-Assembly Repair
CNC	computer numerical control
COTS	commercial-off-the-shelf
CRA	CLEAR repair apparatus
CRAC	CLEAR repair apparatus controller
CRE–1	Component Repair Experiment 1
CSA	complex signature analysis
CSC	computer software components
CTO	CLEAR Teleoperations
CxP	Constellation Program
C3I	Command, Control, Communications, and Information
DAC	digital-to-analog conversion
DC	direct current
DOD	Department of Defense
ETDP	NASA Exploration Technology Development Program
FM	frequency modulation
FPGA	field-programmable gate array
HDTV	high-definition television
HOSC	Hunstville Operations Support Center
I/O	input/output
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	intermediate frequency
IR	infrared
ISO	International Organization of Standardization
ISS	International Space Station
JTAG	Joint Test Action Group
LAN	local-area network
LGA	land grid array

LXI	LAN extension for instruments
M&P	materials and processes
MUX	multiplexer
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
ORU	orbital replaceable unit
PC	personal computer
PGA	pin grid array
PRACA	Problem Reporting and Corrective Action
PTH	plated-through-hole
RF	radiofrequency
SARA	semiautomated repair apparatus
SARADA	semiautomated repair and diagnostics apparatus
SCARA	selective compliant articulated robot arm
SI	synthetic instrument
SMT	surface-mount technology
SoRGE	Soldering in Reduced Gravity Experiment
SRR	Systems Requirements Review
TDRSS	tracking data relay satellite system
TEST	Teleoperations Engineering Support Team
TReK	Telescience Resource Kit
TSC	Telescience Support Center
TTGbE	time-triggered gigabit Ethernet
USB	universal serial bus
UV	ultraviolet
VHDL	very high-speed integrated circuit hardware description language
VHSIC	very high-speed integrated circuit
VMDB	Vehicle Master Database

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14. ABSTRACT
This document captures the system architecture for a Component-Level Electronic-Assembly Repair (CLEAR) capability needed for electronics maintenance and repair of the Constellation Program (CxP). CLEAR is intended to improve flight system supportability and reduce the mass of spares required to maintain the electronics of human rated spacecraft on long duration missions. By necessity it allows the crew to make repairs that would otherwise be performed by Earth based repair depots. Because of practical knowledge and skill limitations of small spaceflight crews they must be augmented by Earth based support crews and automated repair equipment. This system architecture covers the complete system from ground-user to flight hardware and flight crew and defines an Earth segment and a Space segment. The "Earth Segment" involves database management, operational planning, and remote equipment programming and validation processes. The "Space Segment" involves the automated diagnostic, test and repair equipment required for a complete repair process. This document defines three major subsystems including, tele-operations that links the flight hardware to ground support, highly reconfigurable diagnostics and test instruments, and a CLEAR Repair Apparatus that automates the physical repair process.

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