

## The NEAR Command and Data Handling System

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**T**he Near Earth Asteroid Rendezvous (NEAR) spacecraft's command and data handling (C&DH) system is designed to manage complex operations and to collect data when the spacecraft is out of contact with ground control. During ground contacts, the C&DH system accepts uplink commands and memory loads that describe a time-ordered set of events to follow, and it transmits previously recorded data back to the ground station. This article describes the overall C&DH system, gives details on each of the components, and tells how the system was tested prior to spacecraft integration. Solid-state data recorders and flight computers are also discussed.

(Keywords: Autonomous spacecraft, CCSDS, Deep space, Spacecraft, Telemetry.)

### INTRODUCTION

Although the Near Earth Asteroid Rendezvous (NEAR) spacecraft is in ground contact at least several times a week, the spacecraft does most of its work independently; that is, it operates on sequences of commands that are received via the X-band radio frequency (RF) uplink and stored onboard. Scenarios range from minimal housekeeping during cruise mode to recording data continuously during a 16-h cycle of science measurements at the asteroid Eros. Normally, ground contacts are needed only to send recorded data back to Earth and to receive the next series of commands to be executed. However, onboard autonomy rules will sense events that threaten the health of the spacecraft. The strategy in these cases is to enter a safe mode and wait for ground commands to direct a recovery. The command and data handling (C&DH) system communicates with the ground via the X-band RF system,

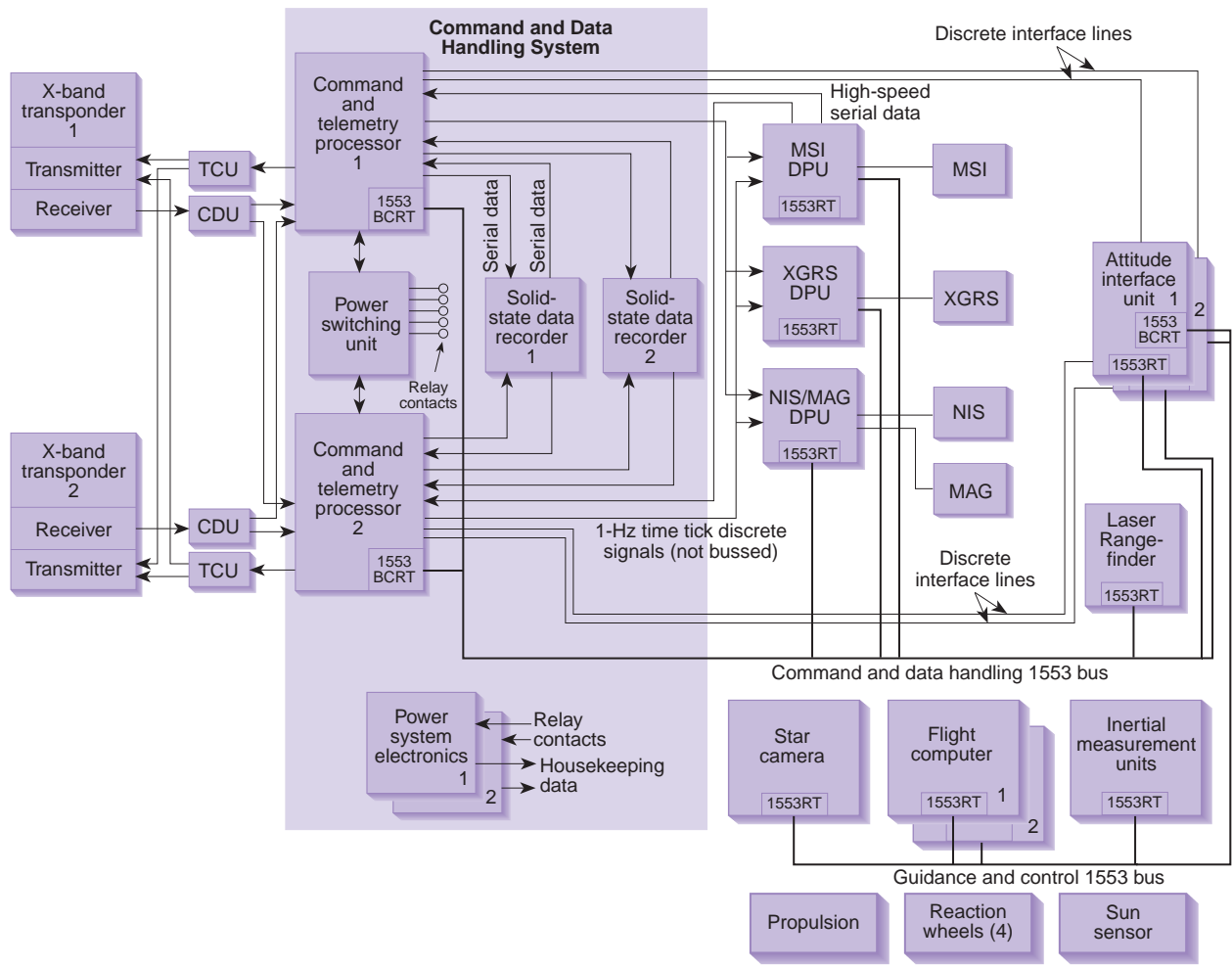
processes commands, formats and stores data, and autonomously protects the health of the spacecraft.

### OVERVIEW

#### Data Flow and Spacecraft Interfaces

The NEAR C&DH system has electrical interfaces throughout the spacecraft. Figure 1 shows the C&DH system in relation to the other packages onboard the spacecraft. The flow of data and electrical power over these interfaces is managed by the embedded computers in the command and telemetry processors (CTPs).

Command and telemetry signals pass between the RF receivers and transmitters and the C&DH system as serial streams. Table 1 shows the bit rates supported by the NEAR RF links. Formats of these serial streams



**Figure 1.** Data interfaces among NEAR components. (BC = bus controller, RT = remote terminal, CDU = command detector unit, DPU = data processing unit, TCU = telemetry conditioning unit, MSI = Multispectral Imager, XGRS = X-Ray/Gamma-Ray Spectrometer, NIS = Near-Infrared Spectrometer, MAG = Magnetometer.)

are based on standards published by the Consultative Committee for Space Data Systems (CCSDS).<sup>1-4</sup> NEAR follows CCSDS standards regarding headers for transfer frames and packets, Reed-Solomon coding, convolution coding, and command operating procedure version 1 (COP-1) for the “handshake” between ground station and spacecraft for commanding. Commands use CCSDS telecommand transfer frame structures containing nonpacketized NEAR-unique command bit formats. Telemetry data use the CCSDS transfer frame and packet structures. CCSDS headers provide virtual channel (VC) designations for telemetry frames. Assignment of VCs is mission dependent. NEAR uses four VCs, referred to as VC0, VC1, VC2, and VC3. These four channels have specific meanings, as defined in Table 2. Within a telemetry frame are telemetry packets that contain data from one source, such as a subsystem or subprocess. Table 2 lists the packets defined for NEAR. A telemetry packet is designated by its application process identifier, a number from 0 to 13.

Table 1. Telemetry downlink data rates.

Multiplier	Bit rate (kilobits/s)	Transfer frame (TF) rate (TF/s)
24	26.496	3
16	17.664	2
8	8.832	1
4	4.416	1/2
2-2/3	2.944	1/3
1	1.104	1/8
1/28	0.0394	1/224
1/112	0.0099	1/896

The C&DH 1553B data bus is a time multiplexed, bidirectional data interface<sup>5</sup> for communication between bus controller and remote terminals. It is useful for all intraspacecraft messages except those that would

Table 2. CCSDS virtual channel and application process identifier assignments.

Virtual channel or application process identifier <sup>a</sup>	Description
<b>Telemetry transfer frames (virtual channel)</b>	
VC0	Recorder input science and engineering data packets, used for recorder input only
VC1	Recorder output data stream
VC2	Recorder input Multispectral Imager data, nonpacketized image data
VC3	Real-time data packets, used for down-linking only
<b>Telemetry packets (application process identifier)</b>	
0	CTP 1 packets
1	CTP 2 packets
2	Attitude Interface Unit 1 packets
3	Attitude Interface Unit 2 packets
4	Multispectral Imager DPU packets
5	X-Ray/Gamma-Ray Spectrometer DPU packets
6	Near-Infrared Magnetometer DPU packets
7	NEAR Laser Rangefinder packets
8	X-Ray Spectrometer packets
9	Gamma-Ray Spectrometer packets
10	Near-Infrared Spectrometer packets
11	Magnetometer packets
12	Flight computer 1 packets
13	Flight computer 2 packets
<b>Telecommand transfer frames (virtual channel)</b>	
VC1	Transfer frame addressed to CTP 1
VC2	Transfer frame addressed to CTP 2

Note: CCSDS = Consultative Committee for Space Data Systems, VC = virtual channel, CTP = command and telemetry processor, DPU = data processing unit.

<sup>a</sup>The application process identifier was not used for telecommand packets.

overload its 1-megabit per second data rate. Dedicated high-speed serial circuits are provided for the multispectral imagers that must transfer images at 2 megabits per second to the solid-state data recorders (SSDRs).

Power switching merits a special dedicated control and status interface to the CTPs, because the capability for switching relay contacts under fault conditions is critical. Relay contacts from power switching are used to turn spacecraft +28-V bus power on and off to other packages and in some cases to control discrete functions.

Discrete interface lines, i.e., single wires, are used for distributing the 1-Hz synchronization pulse (time tick) to spacecraft subsystems. A set of discrete line interfaces is also provided for fault protection between the CTPs and the attitude interface units.

### Redundancy and Cross Strapping

System reliability concerns dictated that the NEAR C&DH system have no credible single point of failure that could compromise the mission. Figure 1 shows the configuration in which full hardware redundancy is provided for C&DH components. Cross strapping at critical points makes use of the redundancy. Both CTP 1 and CTP 2 are powered and operational for the entire mission. The command function is actively redundant, which means that both CTPs accept and decode all uplink signals from both sides of the RF system. Control bits in the command message headers prevent any command from being executed more than once. Only one CTP at a time can be in control of telemetry generation, the data recorders, and the 1553B data bus. The position of a relay in the power switching unit is used to select the CTP used for active telemetry and 1553B bus control. Thus, where spacecraft systems are redundant in a stand-by sense, the active side is selected by command. Finally, the 1553B data bus is a fully redundant system in itself. It features redundant cable harnessing, drivers, and receivers,

as well as a message parity error detection scheme with automatic retry for failed messages.

### Stored Command and Autonomous Fault Protection Capabilities

Commands from the ground station can be executed as they are received or can be stored for later execution. Up to 10,000 commands can be stored per CTP. Stored commands can be time tagged for execution at a specific value of mission elapsed time (MET), or they can

be organized into a macro that is called by another command. More details on stored commanding are described in the section on C&DH software.

Autonomous fault protection is based on autonomy rules that are uploaded and stored in special locations in the CTP memory. Each rule can sense up to two telemetry points, test them separately for limits, and logically combine the test results. When a rule “fires,” it causes a specific command to be executed.

Within each CTP are four levels of hardware watchdog timers to protect against processor failures. In order of time-out period, they are the RTX2010 microprocessor wait-state time-out (10.6  $\mu$ s), the 1-s polling loop time-out (1.001 s), the 1553B bus initializer time-out (4.0 s), and the “last resort timer,” which fires if no command is received from the ground for 12 days. The occurrence of any of these events will result in a processor hard reset. Such a reset reloads computer software and default autonomy rules from electrically erasable programmable read-only memory (EEPROM) devices on the computer board and resets all hardware.

### Management of Stored Data

NEAR mission scenarios require science and engineering data to be stored onboard for later transmission to the ground station. As shown in Fig. 1, two SSDRs provide this function. They have capacities of 1024 and 512 megabits. Recorder input-output circuits are fully cross strapped between the two CTPs. Either or both of the SSDRs can be operated at any time, according to mission needs. Data recording rates are driven by the availability of science data packets. This scheme gives maximum flexibility for allocating recorder capacity. For NEAR, the quantity of science data delivered to the ground station is limited by the bandwidth of the X-band RF downlink, not by the capacity of the recorders. NEAR is the first APL spacecraft to use solid-state devices for spaceborne mass storage.

### Timing and Synchronization

Timing for the NEAR C&DH system is driven by a crystal oscillator and fixed-hardware divide chain in the active (bus controller) CTP. All of the frequencies for bit rates, 8-Hz 1553B bus minor frames, 1-Hz time tick, etc., come from this chain; thus, all C&DH events are synchronized. Given the downlink telemetry frame length of 8832 bits (from CCSDS), the

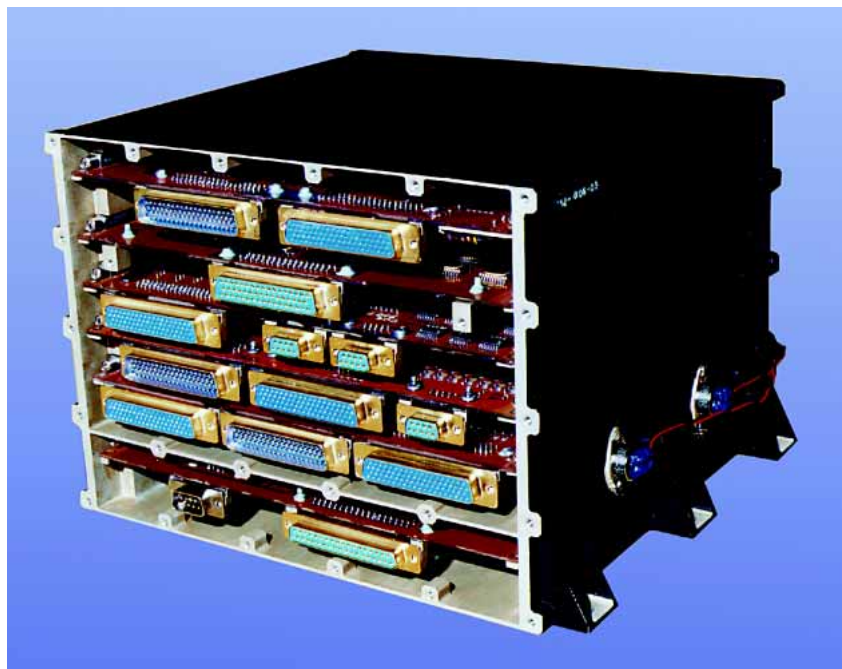
oscillator frequency and downlink bit rates were chosen so that all frame rates are multiples or even divisions of the 1-Hz time tick. The MET is a count kept in CTP software of the 1-Hz time ticks. A length of 32 bits allows MET to run continuously throughout the mission without rolling over. MET, which was set to zero at launch, is used to time tag all downlink telemetry frames and packets.

The value of MET is distributed once per second by messages on the C&DH 1553B bus to each remote terminal. The remote terminal can get a 1-s time marker to an accuracy of several milliseconds by detecting an event on the 1553B bus. Three of the science digital processor units require more accuracy, and, as shown in Fig. 1, receive a hardware 1-Hz time tick pulse from the CTP.

The MET and Coordinated Universal Time (UTC) are correlated on the ground. Correlation is based on the measured UTC of receipt of a transfer frame, the value of MET in that frame, and the known distance from spacecraft to ground station.

## COMMAND AND TELEMETRY PROCESSOR FLIGHT HARDWARE

The CTP flight hardware processes uplink command messages, formats downlink telemetry data, and keeps spacecraft time. It is fully redundant and consists of two mechanical assemblies, each housing six electronics boards. Figure 2 is a photograph of one of the two processor assemblies before final installation of the flight cover. The following paragraphs describe CTP



**Figure 2.** The command and telemetry processor with front cover plate removed.

functionality, as well as some of the processor's significant design features.

### Functional Description

Figure 3 is a functional diagram of one of the CTP assemblies. The processor performs the following spacecraft functions:

1. Processes real-time and time-tagged uplink command messages and outputs the appropriate command data over the 1553B data bus or one of several dedicated command interfaces
2. Gathers and formats real-time and recorded science and housekeeping data and downlinks the data at one of eight selectable downlink data rates
3. Encodes downlink data in accordance with the commanded operating mode using Reed–Solomon and convolutional techniques
4. Formats and stores real-time science and housekeeping data on the onboard SSSDR for subsequent playback and reformatting of the data for transmission on the downlink
5. Detects anomalous spacecraft conditions, including power bus undervoltage conditions, attitude control system safing flags, and out-of-limit housekeeping data, and reconfigures the spacecraft in accordance with uploaded and stored control sequences

6. Maintains spacecraft time, distributes time data over the 1553B data bus, and embeds time data in all formatted data outputs

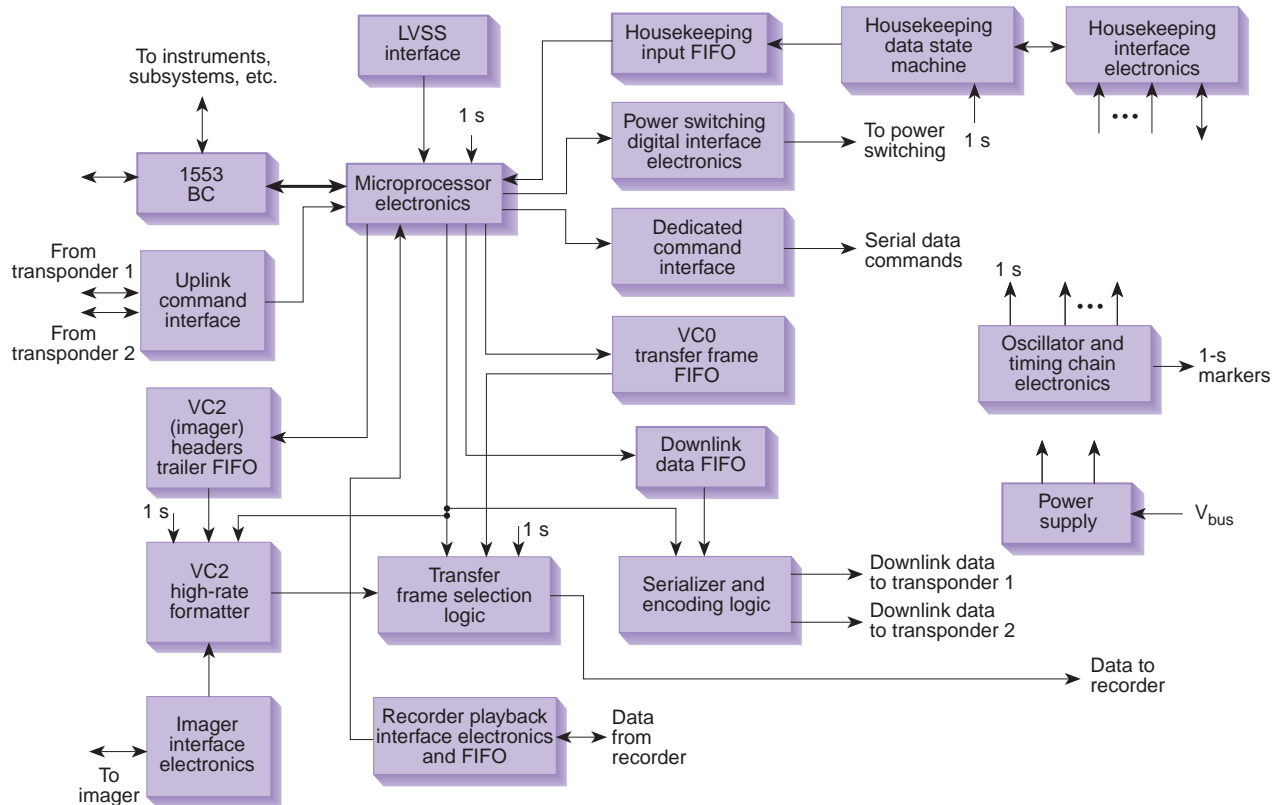
Both CTPs are always powered, one serving as the 1553B bus controller and the other as a 1553B bus remote terminal. Each processor requires approximately 230 mA at +28 V in its normal operating mode.

### Board Descriptions

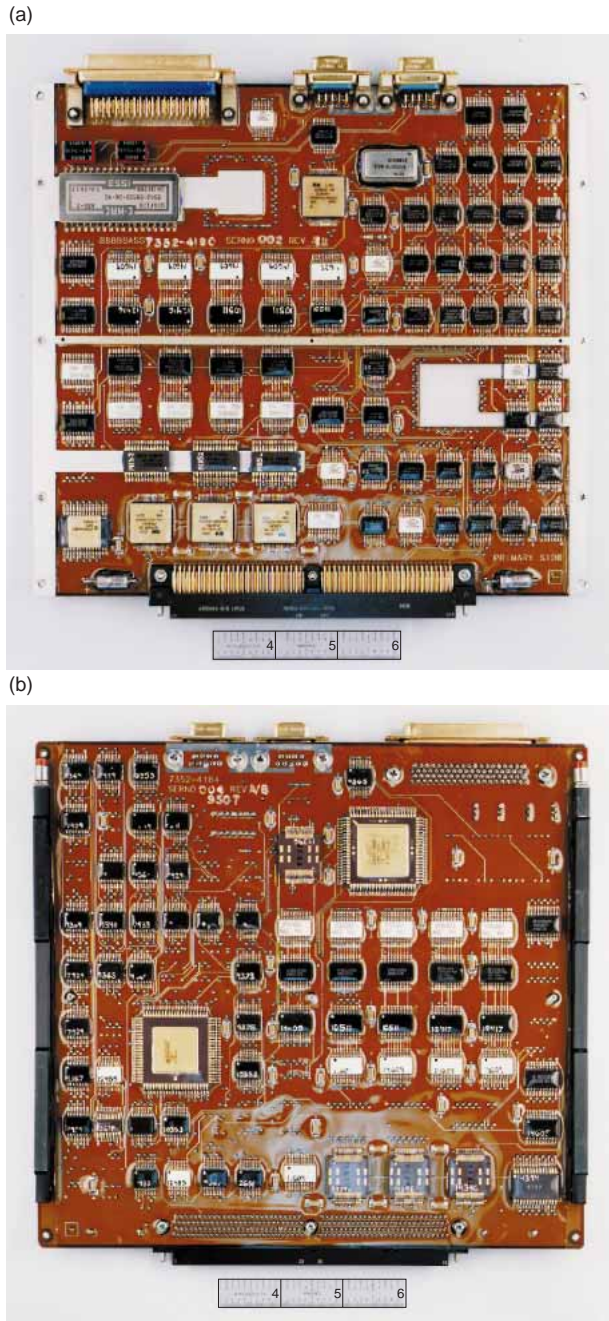
Figure 4 shows the processor board, one of the six printed-wiring electronics boards. All boards but the flight direct current (DC)/DC converter board are 22 × 20 cm. Each board performs specific processor functions.

#### Processor Board

The processor board design is based on the RTX2010 microprocessor and the United Technologies Microelectronics Center Summit MIL-STD-1553B bus controller. Fault tolerance features added to the design include memory error detection and correction electronics, as well as memory write protection. The processor provides 32,000 words of EEPROM, which is used to hold program, constants, and autonomy rules, and 64,000 words of random access memory.



**Figure 3.** Functional block diagram of one command and telemetry processor. (BC = bus controller; FIFO = first in, first out; LVSS = low-voltage sense switch; VC = virtual channel.)



**Figure 4.** (a) Top and (b) bottom views of the RTX2010 processor board removed from the command and telemetry processor chassis (scale is in inches).

### Housekeeping Board

The housekeeping board contains the state machine logic and interface electronics necessary to gather and condition 31 single-ended analog voltage channels, 31 differential analog voltage channels, 31 AD590 temperature transducer output channels, 31 platinum wire temperature sensor channels, 24 digital telltale channels, and 8 serial digital channels once every second and to transfer the data to the processor board.

Each housekeeping board contains two separate state machine programs—one for when the processor is functioning as the bus controller, and one for when the processor is functioning as a remote terminal on the 1553B data bus.

### Encoder Board

The main purpose of the encoder board is to encode telemetry data received from the processor board using Reed–Solomon and convolutional coding standards and to serially transmit the encoded data to the telemetry conditioning unit. The convolutional encoding is rate 1/2, constraint length 7, or else rate 1/6, constraint length 15. The encoding is done according to CCSDS recommendations and is a means of keeping downlink transmissions from corrupting data. The encoder board also contains redundant interfaces to the command detector units to collect telemetry data and to control the uplink data rate.

### Common Interface Board

Dedicated serial digital data command outputs and power switching matrix control signals are generated on the common interface board. Innovative design features include rise-time control on all serial data outputs to minimize interference with other signals and interface overvoltage protection circuitry to ensure C&DH subsystem functionality should a converter fail in one processor. In addition, the common interface board includes uplink command interface logic and circuitry to control playback of the SSTR.

### Transfer Frame Generator Board

The transfer frame generator board contains a precision temperature-compensated crystal oscillator and the timing chain logic necessary to maintain accurate mission time and to generate all of the internal C&DH clock signals. Additional processor functions performed on this board include gathering high-speed science data from the Multispectral Imager, formatting Imager data into transfer frames stored on the SSTR, and processing spacecraft bus voltage and attitude anomaly flags.

### DC/DC Converter Board

The CTP power converter uses two modules produced by Interpoint to convert the +28-V direct current power from the spacecraft into  $\pm 15$ -V and +5-V regulated DC power for use by the C&DH electronics. Another Interpoint module is used to filter the input power to meet electromagnetic interference requirements. The converter contains custom circuitry to provide output overvoltage and low-input voltage turn-on protection.

## PACKAGE DESIGN

Each CTP flight unit consists of six multilayer electronics boards and a motherboard, with overall dimensions of  $24 \times 24 \times 17$  cm and a weight of 5 kg. The chassis of the C&DH is machined magnesium ZK 60A-75 with a minimum thickness of 1.5 mm. The design uses an integral housing for improved thermal control and includes separate compartments for the power converter and the digital electronics to eliminate potential cross talk.

The CTP board assemblies consist primarily of surface-mounted components populated on both sides to minimize board area. The printed wiring board designs use polyimide glass material with a high glass-transition temperature. To meet the requirements imposed by the launch environment, each board is supported by a set of wedge lock card guides and a stiffener.

The CTP was designed for only conductive cooling to ensure that junction temperatures are held within operational limits. For highly dissipative devices, an additional aluminum heat sink was bonded to the board to improve the heat path between the devices and the chassis.

## C&DH SOFTWARE

### Background

The most pressing requirements that had to be addressed during the C&DH software development effort were programmatic constraints. To meet the NEAR launch date, C&DH software had to be ready for installation on the spacecraft at the outset of the integration and test phase; other spacecraft components could not be operated by the integration and test ground system without a functioning C&DH. An early program decision was made that C&DH software could not be changed via upload commands after launch. This placed added emphasis on early requirements definition and exhaustive testing of the implementation, as well as mandating a software design that could be flexibly configured by mode commands and parameter uploads. In addition, NEAR development began when the costly and very public failures of the Clementine and Mars Observer missions were fresh reminders to NASA and the aerospace community of the importance of autonomous fault detection and correction capabilities. Thus, early delivery, an inflexible launch date, the need for configurable yet robust software, and the need for extensive autonomous capabilities for health and safety were the biggest design challenges.

### C&DH Software Overview

The NEAR C&DH software is implemented as compiled FORTH code resident in 64 kilobytes of main

memory of the CTP RTX2010 microprocessor board. The FORTH language was selected because the RTX2010 processor design uses a native instruction set modeled after FORTH for optimum processor efficiency. FORTH on the RTX2010 also offers the advantage of supporting both interactive and compiled software modes.

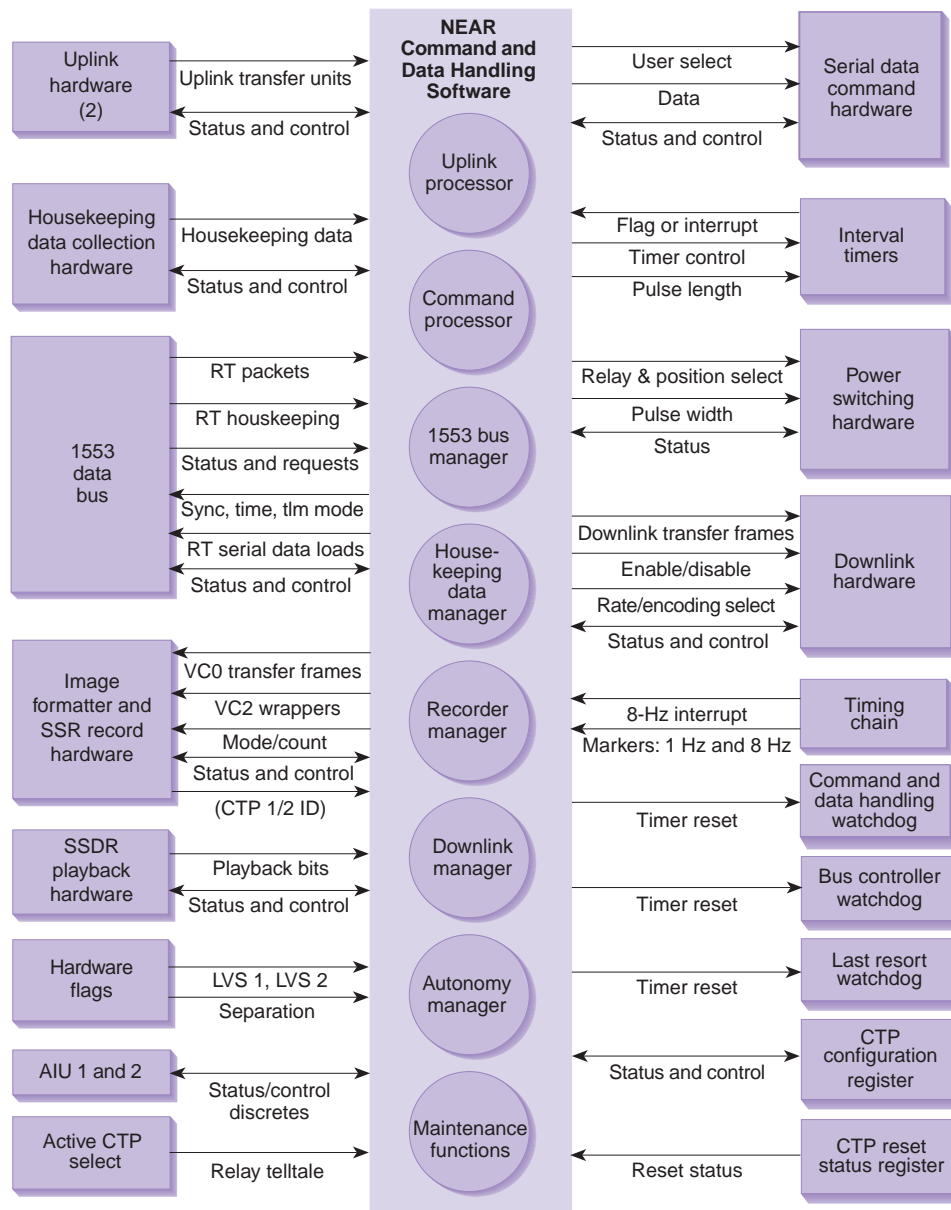
The context diagram of Fig. 5 depicts the C&DH software environment and external interfaces. The software is structured as an executive that is defined by a 1-s major frame subdivided into eight 125-ms minor frames. The top-level software functions controlled by the executive include the following: uplink processor, command processor, 1553B bus manager, housekeeping data manager, SDR manager, downlink manager, autonomy functions, and maintenance functions. Highlights of these software processes are described in the following paragraphs. Functional differences between the active (1553B bus controller) and backup (1553B bus remote terminal) CTPs are described in the section on the bus manager.

### Executive

All C&DH software functions are scheduled with respect to the eight minor frames, each driven by an 8-Hz hardware interrupt that also provides a marker to define the 1-s major frame boundary. The executive is an interrupt service routine that responds to every 8-Hz interrupt, increments minor frame count, and maintains MET in seconds. All subordinate software routines are scheduled with respect to minor frames 0 through 7. This scheduled polling approach for C&DH functions eliminates the need for multitasking and additional interrupts, and it also results in a simple deterministic design that can be readily tested. Functions are allocated by minor frame to ensure that processor use is distributed among tasks; stress testing under maximum load conditions verified that peak processor use within any single 125-ms minor frame is 73 ms. Upon initial power-up or reset of the CTP, the executive executes a number of self-test and initialization functions before enabling the interrupt to start the minor frame schedule.

### Uplink Processor

CTP uplink hardware decodes received telecommand transfer frames and buffers the binary data in first-in, first-out memory. The uplink manager controls that interface and reads up to four buffered data bytes in each minor frame, performs additional decoding, and detects when a full transfer frame has been received from either of the redundant uplink decoders. Any transmission error detected by the above logic is signaled to ground via the CCSDS status word reported in downlink telemetry frames. If the received data have no transmission



**Figure 5.** Diagram of the NEAR command and data handling software context. (AIU = attitude interface unit, ID = identifier, LVS = low-voltage sensor, RT = remote terminal, SSSDR = solid-state data recorder, VC = virtual channel, CTP = command and telemetry processor.)

errors, and if the frame has the expected sequence number and contains commands that meet validity checks, the commands are extracted from the frame and passed to the command processing task. Upon receipt of each valid command, the uplink manager also resets a software-controlled CTP RF watchdog timer that will time out if not reset within a commandable time interval (from 1 h to 12 days), thereby triggering a stored command sequence that autonomously switches the uplink hardware to the redundant side.

### Command Processor

Command processing entails handling real-time commands received from the uplink, managing storage

of command sequences in C&DH memory, and dispatching pending commands based on a priority scheme. Real-time command packets containing an operation code targeting one of the NEAR instruments or the attitude interface unit are routed to the 1553B bus manager for delivery to that subsystem. Commands destined for the C&DH software are processed directly by the command processor; such commands include control and mode options associated with the various C&DH functions. Some C&DH commands support definition of autonomy rules and upload of command sequences (macros) to be stored in memory for later execution. The command processor also accepts a data load command and, via a hardware serial data interface, delivers control bits to the SSSDRs, command detector



units, and telemetry conditioning units (none of which is accessible via the 1553B data bus). Last, relay commands are dispatched by controlling a hardware interface with the power switching unit. Command manager software prepares a command history and error status that is stored in memory for diagnostic use.

Once per minor frame, the queue of pending commands is examined and the command with the highest source priority is executed. The source priority, in high-to-low order, is real-time command, spacecraft separation sequence, macro triggered by safing autonomy rule, macro triggered by housekeeping autonomy rule, a command sent from the attitude interface unit, and a time-tagged macro scheduled to execute at the current MET. A macro queued for execution is processed to completion unless a command from a higher priority source is received, at which point the macro is suspended; it resumes once the intervening command is completed.

### 1553B Bus Manager

A 1553B data bus is the means by which the C&DH software communicates with the four NEAR instruments, the two redundant attitude interface units, and the backup CTP. The primary CTP, which serves as bus controller, knows each of these systems as a remote terminal identified by an assigned index. Each subsystem contains a 1553B controller chip that arbitrates exchange of data via shared memory subdivided into receive subaddresses and transmit subaddresses. Bus manager software schedules and controls all of these data exchanges; it also manages various internal self tests and retry strategies associated with the redundant bus architecture. Software interaction with the bus controller chip is managed by delivering control blocks that direct bus activities as delineated in a schedule that assigns transactions by minor frame.

Once per major frame, the bus manager picks up housekeeping data provided by each of the remote terminals and provides these data to the housekeeping data manager. The bus manager also supports pickup of science or engineering data packets from designated subsystems, which are provided to the SDR manager (VC0) or the downlink manager (VC3). Each remote terminal can deliver up to two VC0 packets per second. Other bus manager functions include distribution of MET and a time synchronization message to all remote terminals, as well as preparation of bus status statistics maintained for diagnostic use.

One of the two CTPs is always designated as the backup CTP, which means it actually appears to the active CTP as a remote terminal. The C&DH software on the backup CTP senses that it is not "active," and its bus manager software reverts to a different status, in which it receives commands from the active CTP,

provides housekeeping and a status message to the active CTP, and receives MET from the active CTP. The backup CTP can dispatch commands, but it collects only a subset of the housekeeping data and does not collect or provide packets to the SDR or the downlink VCs.

### Housekeeping Data Manager

Once per major frame, housekeeping software concatenates housekeeping data collected from all NEAR subsystems and the CTP housekeeping board to create the spacecraft housekeeping packet on which autonomy rules operate and which is downlinked at a period dependent on telemetry rate and mode. The software also prepares the part of the housekeeping packet that contains internal C&DH status information. Other data inserted into the housekeeping packet are computed telemetry points, which comprise an arithmetic combination of two or more collected data elements. Upon receipt of a command to do so, the data manager delivers to the SDR manager a copy of the current housekeeping packet for storage on the recorder.

Several bookkeeping functions are provided by data manager software: a stored table retains a history of high and low values for all telemetry points; snapshots of the housekeeping packets are stored in memory when an error is autonomously detected; and various one-bit telltales are maintained to serve as indicators of problem conditions. Some of these telltales are "sticky," in that they signal an error, and a ground command is required to clear them.

### Solid-State Data Recorder Manager

The recorder manager controls the SDR hardware interface that accepts data to be recorded. Once per second, the buffer of accumulated VC0 packets is examined. Sets of three packets are extracted, packaged into a VC0 transfer frame, and delivered to the recorder interface. As many as five VC0 transfer frames per second are written to the recorder, depending on how ground commands have configured remote terminals to deliver packets. To record images, a hardware formatter (Fig. 5) interfaces with the Multispectral Imager to read image data from a high-speed serial line. Because the image bits must be packaged into VC2 transfer frames, the SDR manager task is notified (via the 1553B bus) when an image is to be collected; the task then prepares the 184 transfer frame wrappers needed by the formatter to encapsulate one image as it is delivered to the recorder.

### Downlink Manager

The downlink manager can be commanded to configure the downlink in any of eight transmission rates

and five different modes that designate recording mode and interleaving of real time (VC3) and SSSDR playback (VC1) telemetry frames. This flexibility was mandated by mission requirements that vary dramatically, depending on mission phase (launch mode, cruise phase, at-asteroid operations) and state (safe holds vs. normal operations). The downlink manager keeps track of the current transmission rate and builds a telemetry transfer frame when the downlink hardware has finished transmitting the previous frame. When directed to transmit a frame, the software manages a downlink interface that alternates between two buffers at the occurrence of a major frame marker. The same interface controls downlink hardware frequency and encoding options, as set by ground command sent to the CTP. The downlink manager mediates changes to these parameters so that they take effect only on telemetry frame boundaries. At the slowest downlink rate, a frame is transmitted every 896 s; at the fastest rate, three frames are transmitted per second. Because of the variable frame transmit rate and various interleave modes, downlink software incorporates the handshaking necessary for the bus manager to notify remote terminals when VC3 packets will go in the downlink in the following major frame.

The C&DH telemetry mode specifies (via command) the interleaving of VC3 and VC1 frames. In a second in which a VC3 frame is to be prepared, the current housekeeping packet is inserted into slot 1 in the frame. Slots 2 and 3 are filled with packets collected from designated remote terminals. Slots 2 and 3 can also be assigned as memory dump packets, in which case the downlink manager prepares packets that contain data words read from designated C&DH memory locations. The CCSDS frame header and trailer (including the status word that alternates between reporting the uplink status for the two CTPs) are added to the three packets, and the frame is written to the downlink buffer. At the higher downlink rates, when more than one VC3 frame is transmitted per second, the second and third VC3 frames are fill frames to avoid reporting of duplicate data.

Similarly, for a 1-s period in which the telemetry mode calls for a VC1 frame to be transmitted, downlink software manages the SSSDR playback interface to read data bytes played from the recorder. One thousand seventy four bytes of recorder data are encapsulated in VC1 frame wrappers, and the appropriate number of frames is delivered to the downlink buffer.

### Autonomy Functions

Autonomous fault detection and correction functions are implemented in the form of uploadable monitor rules. The autonomy manager maintains 165 rules. Each rule identifies one or two telemetry points in the

housekeeping packet, optional arithmetic or masking operations to be performed on those data, and a logical compare operation that results in a Boolean flag that is "true" if the criterion is met for the designated number of consecutive housekeeping packets. When evaluated as true, a rule causes the specified stored command macro to be queued for execution. Rules are evaluated in priority order, so high-priority safing functions take precedence. Commands to the autonomy manager can load or clear rules, turn individual rules or sets of rules on or off, or disable checking of all rules in either of two subsets: safing rules that are stored by default upon CTP power-up, or housekeeping rules that are used for less critical monitoring functions. The safing rules are the means by which mission safing modes are implemented. The spacecraft separation sequence, Sun-safe mode, Earth-safe mode, power system monitor functions, and attitude interface unit monitor functions are all implemented as stored command macros triggered by autonomy rules.

This rule-based approach to meeting autonomy requirements allowed C&DH design to proceed, even when autonomy modes and actions had not been fully specified at the mission level. The autonomy manager is basically a housekeeping checker and rule evaluation engine that queues stored commands. This software was thoroughly tested under maximum stress conditions before delivery to the spacecraft. Later in the integration phase, the actual mission rules and macros were installed. What seemed at first to be a simple rule-based design actually became quite complex when it came to defining the checks and command responses needed to coordinate safing for all spacecraft subsystems. For example, a rule may trigger a command sequence that in turn disables sets of rules and enables others. Mission rule and macro definition was done by the systems engineering team, which coordinated all subsystems and defined cross-subsystem tests.

The autonomy manager performs several bookkeeping functions to provide data that summarize rule-checking status. An autonomy history table is maintained, and a handshake to the data manager and command processor ensures that triggered macro commands and housekeeping packet snapshots are stored in memory.

### Maintenance Functions

Software maintenance functions are distributed among the minor frame schedule as small tasks requiring little processing time. Such functions include resetting a watchdog timer that times out if a software error occurs, thereby causing a processor reset; stepwise reading of all electronically correctable memory to cause the hardware to correct any single-bit errors that may have occurred; and computing checksums over blocks

of memory so the checksum table can be dumped by command to verify that current memory contents match the image model maintained by the mission operations team.

## POWER SWITCHING UNIT

Power switching for the NEAR spacecraft is a single unit that provides switched power and signals for the operation of the spacecraft. The unit is capable of 64 on/off relay commands. Design of the unit was adapted from similar units used on the Midcourse Space Experiment spacecraft.

### Functional Description

The unit contains a motherboard and six  $18 \times 18$  cm plug-in cards, two driver/telemetry boards, and four relay boards. The boards are mounted in a  $23 \times 23 \times 25$  cm chassis. Two types of latching relays provide the various switching functions, with each relay selected according to the power requirements of the users. Relay contact ratings are 2 and 10 A. In addition, 2-A nonlatching relays generate high-level pulse commands. The interface between the spacecraft power bus and the subsystems is through the two 50-pin "D" connectors mounted on each relay board, one for power in and the other for switched power out. Table 3 lists the characteristics of the power switching unit assembly; Table 4 shows the types, contact ratings, and quantities of relays.

Table 3. Characteristics of the power switching unit.

Characteristic	Range or value
Power	+20 to +34 V, 12–200 mA +5 to +0.5 V, 1–8 mA
Size	$23 \times 23 \times 24$ cm
Operating temperature	–30 to +70°C
Weight	5.9 kg

Table 4. Power switching relay types.

Relay type	Contact rating	Number
3PDT	10A	24
4PDT	2A	28
2PDT-NL	2A	72

Note: 3PDT = 3-pole double throw, 4PDT = 4-pole double throw, 2 PDT-NL = 2-pole double throw, nonlatching.

## Circuit Description

The two driver/telemetry boards provide redundant relay coil drive and relay contact position telemetry. Relay drive circuits are configured in an  $8 \times 8$  matrix. Each driver/telemetry board accepts an 8-bit parallel command word from one of the two command processors and decodes the command into the appropriate signal to operate the relays. The driver/telemetry boards also contain parallel-to-serial shift registers with output interfaces for telemetering the relay contact positions. All latching relays are monitored. The telemetry data stream, one from each driver/telemetry board, supplies data to one of the redundant CTPs. All command decoding and telemetry logic is implemented with CD4000B series integrated circuits. Relay coil drive circuits use discrete transistors.

### Power Requirements

The unit operates with a nominal +28-V and a +5-V input to each driver/telemetry board. The +28-V power, supplied by the spacecraft battery, operates the command decoding and relay coil drive circuitry. The +5-V power operates the telemetry circuits.

## FLIGHT COMPUTER

The NEAR flight computer is a Honeywell model HSC-E, which is a three-slice assembly consisting of two independent processor slices and a dual-power converter as the middle slice. Figure 6 is a composite photograph of the flight hardware chassis and circuit boards, with a summary of attributes. The HSC-E occupies less than  $3770 \text{ cm}^3$  and weighs 5 kg. One processor and one-half of the dual-power converter constitute a computer element called a string. The two strings can be operated simultaneously, or one can be active and one can be in standby (hot or cold) mode. Each string operates from a +28-V source, drawing, nominally, 8 W. Each processor slice contains a generic very-high-speed integrated circuit spaceborne computer (GVSC), 512,000 words of static random access memory, 16,000 words of start-up read-only memory, 256,000 words of EEPROM, and input/output (I/O).

The central processing unit function consists of a GVSC chip set and associated processor support logic. The GVSC chip set implements the MIL-STD-1750A<sup>6</sup> instruction set. Processor support logic is implemented in a gate array with the I/O control functions. All memory access goes through the GVSC memory management unit and block protect unit. The memory management unit maps logical addresses to physical addresses in 4000 pages via 16 sets of page registers and provides lock and key protection for 4000 blocks of memory to prevent unauthorized accesses. The

HSC-E processor supports four I/O interfaces: 1553B, serial I/O, parallel I/O, and a test port.

## PRE-INTEGRATION TESTING AND TESTBED SIMULATOR

The NEAR C&DH system consists of five chassis assemblies that are structurally and thermally attached to spacecraft honeycomb panels and powered by the +28-V bus. Each item received comprehensive stand-alone testing and a formal pre-integration review of test results before it was installed on the spacecraft. These tests included

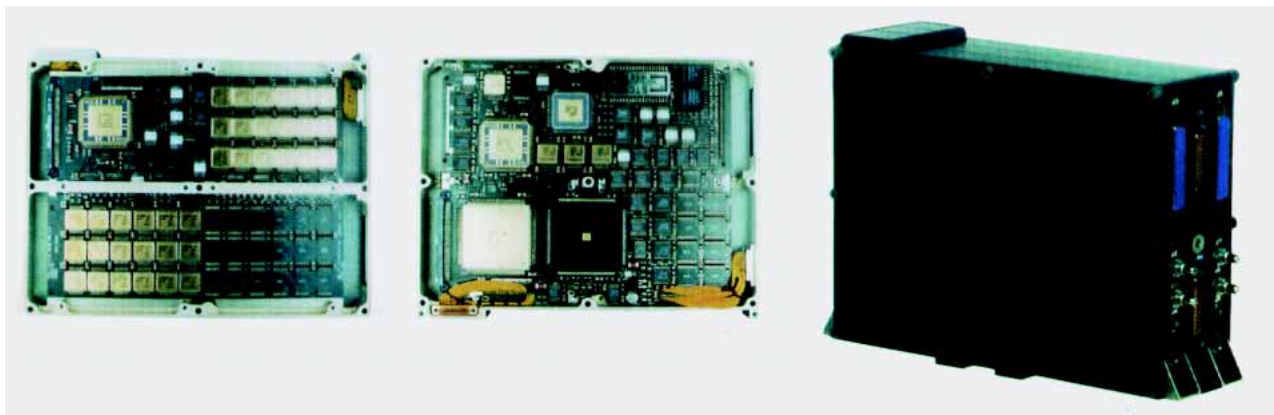
- Full functional test at ambient conditions
- Hot and cold temperature tests in air
- Powered 3-axis sinusoidal and random vibration tests
- Hot and cold soaks and temperature cycles in thermal vacuum

Additional compatibility tests were performed to verify all of the interfaces shown in Fig. 1. These tests involved connecting the breadboard CTP to prototypes of the other units one at a time. To prove the interfaces, commands were sent, telemetry verified, 1553B bus traffic analyzed, waveforms confirmed, etc. This effort led to well-understood interfaces and exceptionally trouble-free spacecraft integration.

Software testing of the RTX2010 microprocessor code in the CTP was initially performed by the development team. Additional independent validation and verification testing was done by an outside contractor.

Finally, a testbed simulator for the ground station evolved from an early command and telemetry test between the CTP and the spacecraft electrical ground support equipment. The breadboards and CTP bench test equipment were preserved for use by the NEAR mission operations team. The team uses this local testbed to try out operational commands and memory loads and to connect various exercises with prototype instruments and the SDR.

Test sets were developed specifically for each of the flight units previously discussed. The most elaborate of the test sets was the CTP bench test equipment. This equipment was custom designed for the NEAR CTP by Telenetics, Inc., in Columbia, Maryland. Its scope was established by the need to drive every CTP input and to monitor every CTP output under closed-loop control by a computer. Telenetics implemented this bench test equipment with off-the-shelf VME-based modules augmented by custom-designed interface boards where necessary. The control software was written in C language and runs on a 486 PC under the OS2 operating system. Originally planned as a hardware tester, the flexibility of the design lent itself to expanding requirements during CTP development. This bench test equipment became the platform for independent validation and verification testing of the CTP software. Its capability for negative testing, such as sending a deliberately bad command message and seeing that it is rejected, was used extensively during these tests. The bench test equipment is now incorporated into the testbed simulator that is used routinely by the NEAR mission operations team.



**Figure 6.** The Honeywell HSC-E flight computer showing the fully assembled chassis and front and back sides of one processor module. The module has two printed wiring boards laminated to the front and back of an aluminum heat sink plate. Hardware attributes: RH1750 processor; 1.6 million instructions per second at MHz Defense Avionics Instruction Set (DAIS); 512 K words static random access memory, single error correcting double error detecting (SECCDED), error logging; 16 K total startup read-only memory; 256 K words electrically erasable, programmable read-only memory (EEPROM), SECCDED, error logging; 1553B port; serial input/output port; 12 user interrupts; probability of success  $P_s = 0.998$  for the dual-string computer of the NEAR mission; size,  $26.2 \times 7.2 \times 20.3$  cm; weight, 5 kg (dual string); power, 8 W nominal (single string), 16 W with programmable read-only memories (PROMs) on.

## CONCLUSION

The NEAR CTPs and power switching unit were designed, fabricated, and tested at APL. Schedule and cost constraints from the NASA Discovery program dictated a “keep it simple” approach and the use of design heritage as much as possible. The outside contracts with SEAKR Engineering and Honeywell were closely monitored by APL staff with many years of technical and contract management experience. The C&DH software was developed by a three-person team that defined unit tests and an acceptance test procedure using bench test equipment that could simulate spacecraft subsystems. The preliminary build of C&DH software was delivered to the spacecraft for integration in June 1995, 9 months after the software requirements were signed off (Artis<sup>7</sup>). The CTPs were loaded with new C&DH software a total of 22 times during integration and test and prior to launch. Eight of these revisions incorporated a minor code change; all other revisions incorporated an updated set of default mission autonomy rules and stored macros. After a full year in cruise mode and a flyby of the asteroid Mathilde, NEAR operations experience has shown the success of the C&DH implementation.

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