DEVELOPMENT OF AN ION THRUSTER CONTROL UNIT FOR THE MUSES-C MISSION

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Abstract

The architecture of the Ion Engine System (IES) of the MUSES-C (Mu Space Engineering Satellite - C) spacecraft features four ion thrusters, four microwave power amplifiers (MPA), three IES power processing units (IPPU), a propellant management unit, an IES thruster control unit (ITCU). The ITCU and Data Handling Unit (DHU) cooperatively provide for initiation of thruster operation, throttling by xenon flow control, data, and recovery from fault conditions. The prototype model of IES components will be fabricated and tested in the near future. This paper describes the concept and design of IES control system.

Nomenclature

AOCS	Attitude and Orbit Control Subsystem
AOCU	Attitude and Orbit Control Unit
AQM	Accumulater (plenum sub-tank)
ATMC	Autonomous Macro Command
CCSDS	Consultative Committee for Space Data Systems
CPBX	CouPler BoX
DHU	Data Handling Unit
EPS	Electrical Power Subsystem
FRES	Flow Restrictor
HCE	Heater Control Electronics
HK	Housekeeping
HLV	High pressure Latching Valve
HPRE	High PREssure transducer
IES	Ion Engine (Sub)system
IPM	IES Pointing Mechanism (IES gimbal)
IPPU	IES Power Processing Unit
IPSU	Itcu Power Supply Unit
ITA	Ion Thruster Assembly
ITCU	IES (Ion) Thruster Control Unit
ITH	Ion Thruster Head (ion source)
ITHV	Ion THruster Valve
ITR	Ion ThrusteR
LPRE	Low PREssure transducer
MPA	Microwave Power Amplifier
MUSES-C	Mu Spacecraft Engineering Satellite - C
NEUT	Neutralizer
PCU	Power Control Unit
PIM	Peripheral Interface Module
PMU	Propellant Management Unit
RLBX	ReLay BoX
TCIU	Telemetry and Command Interface Unit

Introduction

The xenon ion engine system (IES) driven by microwave discharge is under development in the Institute of Space and Astronautical Science (ISAS) for the application to MUSES-C (Mu Space Engineering Satellite - C) mission which is scheduled for launch from Kagoshima Space Center, Japan on a Japanese M-5 rocket in July 2002. The target for the space mission is the asteroid 1989 ML. The asteroid comes to within about 2.5 astronomical unit of Earth. The space vehicle will arrive at the asteroid in October 2003, alight on the surface up to three times and collect surface samples for return to Earth in June 2006. MUSES-C is the second next to NASA's Deep Space 1[1] as a deep space probe driven by electric propulsion, but the first sample return mission.

The IES will consist of four 10 cm xenon ion thruster heads including one redundancy. Each of

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them has a microwave power amplifier (MPA) per thruster, while three acceleration power supply units are available as the ion engine system and are switched according to the operational duty.

The engineering model (EM) of the thruster was assembled in the endurance test system, and has been tested for its life time since February 1997[2]. The total operational time achieved 18,000 hours without any fatal problems at the end of July 1999, and the test was completed[3]. The prototype model (PM) is under preparation for the next endurance test starting in November 1999.

Based on the experience gained in the EM ground test program, the design of IES control logic is derived from the software running on the Hewlett–Packard workstation which was used in the EM test. The number of watched properties of IES was decreased so that the simple hardware logic can drive at most four thrusters at the same time.

The ITCU is the central data acquisition and control system for the IES. According to the feature requirements from ISAS, NEC Corp., the ISAS's prime contractor for the MUSES–C mission, has started designing the ITCU. A prototype model of the ITCU is under development and to be fabricated by the end of November 1999.

The flight hardware development program also included many development and engineering tests of prototype and flight hardware prior to the qualification test program, which will not be discussed here. This paper focuses on the design and fabrication of the ITCU, describing the general box specifications, architecture, design, and fabrication. Function sharing with spacecraft's DHU will also be presented. Mechanical or electrical details of the ion sources, neutralizers, MPA and beam acceleration power supplies (IPPU) will not covered herein. The overall system design and the development status are summarized elsewhere[4,5].

Ion Engine System Overview

The Ion Engine System (IES) on MUSES–C has four thruster assemblies (ITA), four microwave power amplifiers (MPA) and three acceleration power supplies (IPPU) as seen in Fig. 1. An ITA includes four ion thrusters (ITR) consisting of a pair of ion thruster head (ITH) and neutralizer (NEUT). Four sets of ITA are mounted on a plate, which can be gimbaled by a pointing mechanism so as to pass the combined thrust vector of two or three ITRs simultaneously operated through the center of gravity of the spacecraft. A single MPA is connected to each ITA and feeds the C–band microwave power to both the ion source and the neutralizer with a fixed division ratio. Three IPPUs are linked to four ITAs through a relay switch mechanism so that three of four ITAs can be operated simultaneously. The Propellant Management Unit (PMU) stores and feeds xenon gas to four ITAs through flow restrictors. The ITCU and DHU cooperatively provide for initiation of thruster operation, throttling by xenon flow control, data, and recovery from fault conditions.

ITCU Functions

The primary ITCU functions are:

- Execute stored operation sequences in response to ground commands or onboard commands
- Provide a command and telemetry interface via a data bus
- Control PMU solenoid and latching valves and regulate thruster xenon flow to one of four stored operating points according to the required IES throttling level
- Control IPPU power supplies
- Control MSU power supplies and an oscillator
- Detect and respond to a limited number of thruster fault types
- Anomaly of the temperatures of IES components and bus voltages are detected by other subsystems. ITCU responds to these faults in cooperation with DHU.

These functions are performed via ITCU hardware and DHU software capability. Table 1 lists the design resource allocations for the ITCU with regard to physical size, power and electrical interfaces.

Table 1. ITCU specifications.

Mass	4.24 kg
Volume	220 × 202 × 141.6 mm
Input Power	30.0 to 52.0 V
Efficiency	< 30 W input 80 W at transient peak)
Operating Temperature	−30 to 40 °C
Valve Drivers	8
Relay Drivers	26
FET Drivers	12
Heater Drivers	2
Active Analog Inputs	35
Active or Passive Bi–Level Inputs	25
Data Interface	Serial Data Bus with PIM (ITCU–S/C)

ITCU Design

The ITCU consists of seven circuit boards, each sandwiched between two flames. The stacked magnesium flames and panels form the casing. A block diagram of the ITCU appears in Fig. 2. The seven boards used are a PIM I/F board, two data acquisition boards, an IPSU, a sequential control board, a IPPU/MPA driver board, and a valve and relay driver board. All the boards utilize Field Programmable Gate Arrays (FPGA), allowing flexibility in the ITCU design. Twelve FPGAs with 8,000 gates are used in total.

The PIM I/F board provides a serial data bus interface so that the ITCU can communicate with DHU. On this board several ITCU functions such as auto AQM pressure control, IPPU power management control, time counter and RV open/close counter are also implemented.

The valve and relay driver board contains 8 valve drivers for 2 RVs (solenoid valves), 4 ITHVs (solenoid valves) and 2 HLVs. This board is also equipped with 2 drivers for IPM launch-lock release heaters, and 6 RLBX drivers because 2 relays are necessary for each relay direction.

In the IPSU, a ± 5 VDC, ± 12 VDC and + 29 VDC output DC/DC converter is present to provide internal ITCU housekeeping power. As shown in Fig. 1, LPRE power is also routed through the ITCU and counted in the ITCU power budget, while HPRE power is provided by TCIU. Thus xenon tank pressure can be monitored even if IES including ITCU is completely off.

A data acquisition board provides for up to 35 multiplexed analog inputs with 8 bit analog to digital conversion resolution. Another board houses 25 active or passive bi-level inputs for obtaining the statuses of IES components.

ITCU Control Logic

The control logic of ITCU handles up to four ITRs though the maximum operating thrusters is limited to three by the thermal design of MUSES-C. Even if one of the three ITRs suddenly stops, the others can continue to thrust and another backup one will start. There has been several satellites having one or more ion thrusters. In most of the north-south stationkeeping (NSSK) applications[6], four thrusters are prepared including redundancy, but only one or two of four are operated at a time. The simultaneous burning of three ion thrusters will be the first time in the world. The details of the control algorithm of ITCU will be discussed below.

MPA Control Algorithm

The forward and backward microwave powers of ITRs and NEUTs are monitored and used as plasma discharge status. If an abnormal large backward power is detected, the ITCU stops beam acceleration for a while and restart thrusting, or stops microwave discharge. The MPA health check is also done by using MPA helix current telemetry whose anomaly leads to the ITR shutdown by ITCU.

PMU Control Algorithm

The PMU stores the xenon propellant at gaseous state and supply it to the four ITRs as needed. By maintaining the sub-tank (AQM) pressure at the preset level, gas flow rate can be controlled by using FRES, and all the ITRs have the same propellant flow rate. All the valves in PMU are operated by ITCU. The valve-driving power and LPRE power are supplied by ITCU. The ITCU monitors LPRE output and open/close a RV so as to keep the AQM pressure in a preset range determined by an IES throttling level. In addition to the propellant regulation, ITCU watches the AQM pressure to detect some kind of anomaly such as valve malfunction or gas leakage. When the upper or lower pressure limit is detected, ITCU closes all the valves and stops IPPUs and MPAs, then sends an error report packet to DHU. For fear of LPRE failure, the function of RV's timed close capability (64 minutes at maximum) is optionally provided by ITCU.

IPPU Control Algorithm

An IPPU contains three power supplies for screen grid, accelerator grid, and neutralizer. The ITCU provides an out of tolerance limit checking algorithm which watches voltages, currents and microwave powers. The high-speed control for the protection of the IPPU circuits and ITR critical parts in case of high voltage breakdown in beam optics is the major function. The limited number of thrusting retries are included to cope with possible frequent breakdowns at the beginning after launch.

Because IES thrust throttling can be done by adjusting propellant flow rate only, the screen/accelerator voltage are kept constant generally. But in order to suppress the fluctuation of IES power consumption caused by AQM pressure change, accompanying beam current's ripple, the screen voltage can be selected to 1525 V at low pressures or 1475 V at high pressures. The accelerator voltage is automatically changed by IPPU so that the voltage ratio of screen and accelerator remains constant. The voltage switch is triggered by ITCU according to a preset AQM pressure.

Error Report Packet to DHU

If some kind of error occurs, the ITCU stops an ITR or IES overall and send a report packet with an error code and an absolute time stamp obtained from the spacecraft's clock to the DHU. Then the DHU stores the packet to data recorder which will be played back and downloaded with highest priority over other telemetry data at the beginning of each ground operation.

DHU Service for IES

The DHU provides computation, telemetry generation, command storage and execution, and payload data handling. Command is based on CCSDS telecommand recommendation. Telemetry is based on CCSDS AOS (Advanced Orbiting System) recommendation.

The command signal from the ground system is received and PM/PSK–demodulated by an X–band receiver, BCH–decoded and delivered to each component, including ITCU, AOCU, HCE and so on, by DHU through Peripheral Interface Modules (PIM). Up link bit rate changes from 15.625 to 1000 bps according to the distance between the spacecraft and the Earth. Down link bit rate also changes from 8 to 8192 bps.

The IES utilize the DHU functions of automatic control and onboard trigger command.

Automatic Control

The DHU provides two types of commands, "Time Line" as an absolute time sequencer, and "Macro Command (MC)" as a relative time interval sequencer. The IES will start and stop with this function in addition to the real time commands from the ground system. The number of ion thrusters operated can also be changed without ground support.

Grid clearing, in the event a flake temporarily shorts the grids, is accomplished by an MC which switches the output of the IPPU on without ITR connection and, after high voltage charging, reconnects relays to the ITR with grid short.

Onboard Trigger Command

The DHU has the function of Onboard Trigger Command (OTC). The OTC is the command, which is generated onboard without any requirement from the ground system and delivered to the specified component. For each OTC, one of the two statuses ("ENABLE" or "DISABLE") can be selected.

The DHU gathers HK data periodically and judges the spacecraft status and , if necessary, executes the specified Autonomous Macro Command (ATMC). The period of comparison with the threshold is 10 s. This function is called spacecraft autonomous housekeeping. The ITCU outputs all telemetry as a fixed format of HK data whose size is about 500 bits. The telemetry list is too extensive for incolusion herein, but contains all power supply outputs, pressures, digital status words, and ITCU control logic flags.

Another OTC is issued by components other than DHU. DHU executes the specified ReQuest Macro Command (RQMC) according to the request code. The IES utilize the DHU's OTC described below.

IES Temperature Monitor

The temperatures of the IES are monitored and controlled by the HCE. The DHU watches the HK telemetry from the HCE. If the temperature of any part of IES exceeds its threshold, ATMC, which will do the reconfiguration of IES (Used IES thruster heads will be changed or decreased), will be issued.

Intercession to AOCS for IES

The DHU watches the "IES operating flag" bit in the HK telemetry of ITCU, which indicates any of four ion thrusters burning. The status change triggers one of two ATMCs which informs Attitude and Orbit Control Unit (AOCU) of the IES turning on (or off). The AOCS uses this command so that the unloading of the spacecraft momentum wheels can be properly carried out by controling the IES gimbal.

Intercession to EPS for IES

The output of Solar Cell Panel (SCP) is distributed to IPPUs without DC/DC conversion. This non–regulated primary bus is called SCP bus. The bus power line may be turned off by Power Control Unit (PCU) in Electrical Power Subsystem (EPS) in order to prevent overload. The DHU monitors the power consumption of the spacecraft and, if necessary, decreases the acceleration voltage of the IES, stops thrusting, or completely shuts off IES, avoiding brutal stop of IPPUs. After an inevitable SCP bus power cut, the DHU send a "IES SHUTOFF" command to the ITCU as soon as possible.

Fault Recovery

When a thruster malfunction occurs, the proper RQMC which starts up a backup thruster will be requested by ITCU, according to the ITR out of order. This function keeps the number of ITRs operating automatically, but only after the first fault: the second backup is not prepared.

Xenon Tank Pressure Monitor

The DHU obtains the xenon tank pressure through the TCIU and generate HK telemetry packets.

IES Operation

An example of IES operation procedure is shown in Fig. 3. This example illustrates a case of three ITR operations. Prior to thruster start, the operational parameters such as limit values of health–check, RV open/close pressures, a pressure threshold of power management control, maximum number of thrusting retries, and enable/disable of particular functions. After the start of propellant regulation, microwave plasma discharge procedures are initiated by the programmable DHU software sequence. In order to avoid the power peak by in–rush currents, relay and valve driving, and IPPU's turning on is carried out in sequence. Next, the plasma ignition check functions of ITCU are called one after another, and the confirmation of successful discharge is followed by start of beam acceleration. In ITCU hardware sequences, several breakpoints are available for troubleshooting. During thrusting, several background monitors are activated and, if necessary, stop ITRs and request starting a backup ITR to DHU.

Finally, the operation is normally terminated by DHU commands.

Development Testing

A number of development tests involving the PM of ITCU, ITR, NEUT, IPPU, MPA and MPU are planned from December 1999 to March 2000. Such tests include:

- Integration test of ITCU and MPU.
- Compatibility test of the IES and MUSES-C X-band receiver.
- IES total performance test.
- Integration test of ITCU and DHU.

Conclusions

The Ion Engine System (IES) for MUSES-C is under development successfully. Now that the design of the control system of the IES is completed, prototype model of ITCU is under fabrication and to be tested soon.

References

1. Sovey, J., et al., "Development of an Ion Thruster and Power Processor For New Millennium's Deep Space 1 Mission," AIAA Paper 97-2778, July 1997.
2. Kuninaka,H. , Funaki, I. and Toki, K., "Life test of microwave discharge ion thrusters for MUSES-C in engineering model phase," AIAA Paper 99-2439, June 1999.
3. Funaki, I., Kuninaka, H., Shimizu, Y., Toki, K. and Satori, S., "Verification Tests of 10-cm-diam. Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster," IEPC 99-164, 17-21 October 1999, Kitakyusyu, Japan.
4. Horiuchi, Y., Iida, H.,Kuninaka, H. and Toki, K., "Microwave Ion Engine System for MUSES-C," IEPC 99-052, 17-21 October 1999, Kitakyusyu, Japan.
5. Toki, K., Kuninaka, H., Funaki, I., Nishiyama, K., Shimizu, Y. and Kuriki, K., "Development Status of a Microwave Ion Engine System for the MUSES-C Mission," IEPC 99-139, 17-21 October 1999, Kitakyusyu, Japan.

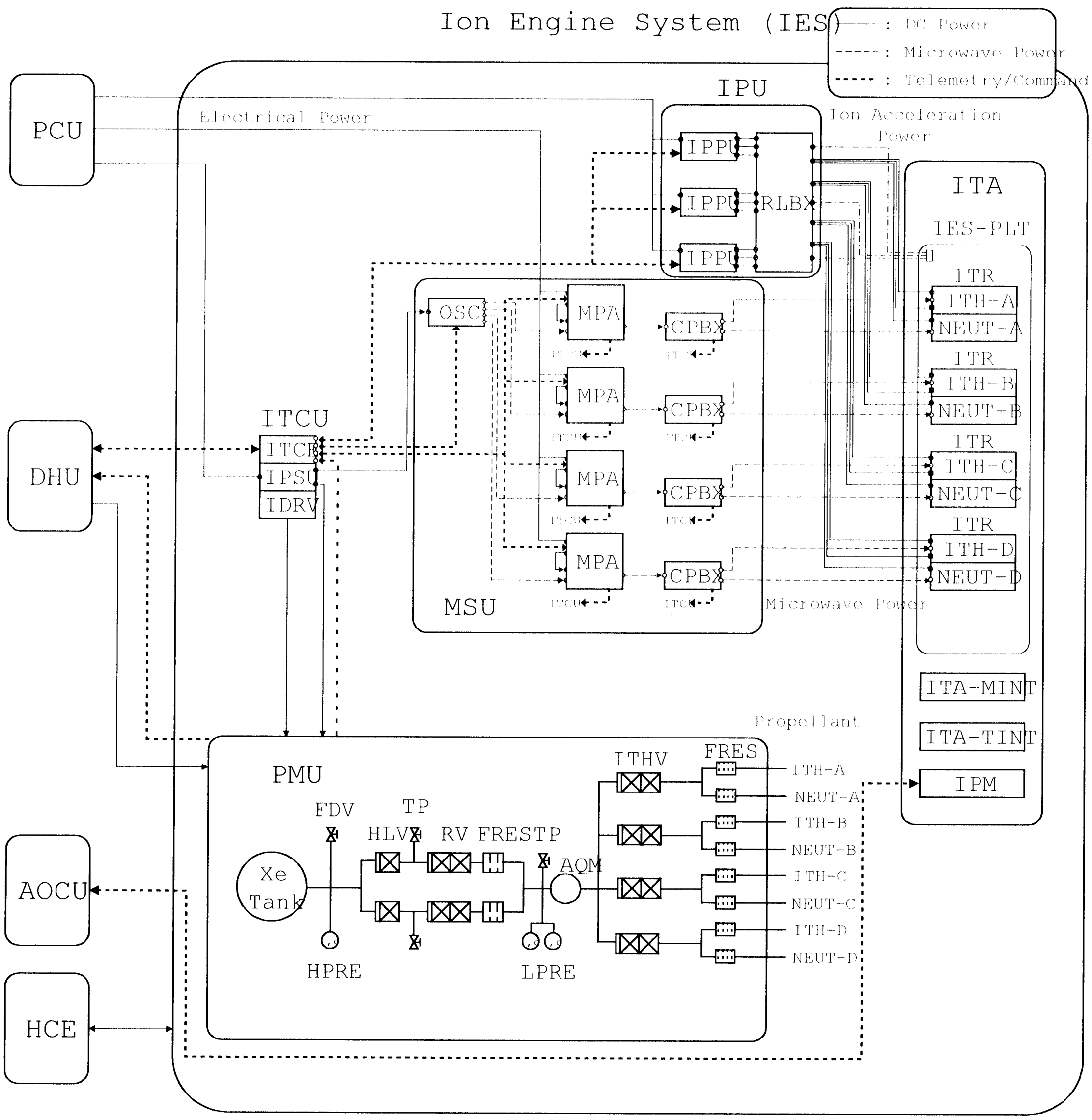

Fig. 1. Ion Engine System Block Diagram.

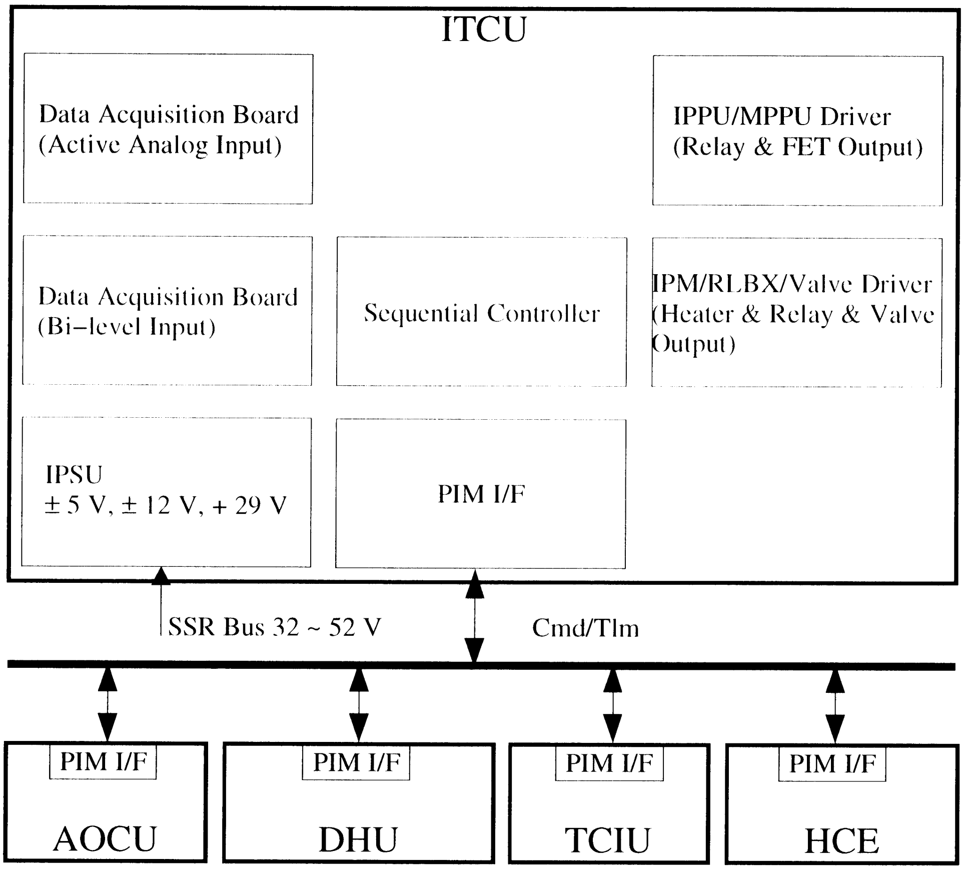

Fig. 2. ITCU Block Diagram and Related Other Subsystem Components.

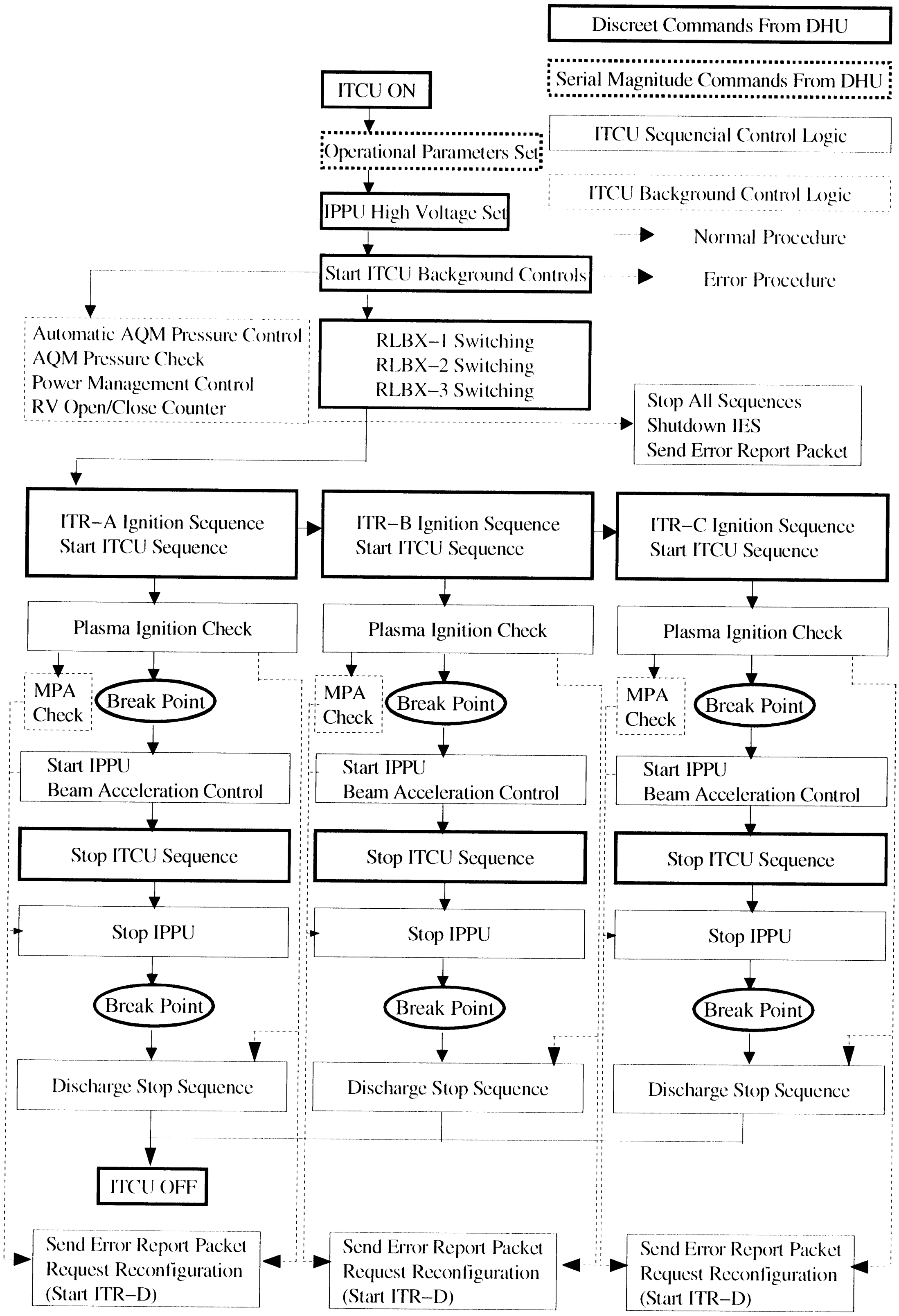

Fig. 3. IES Operation Command Sequence and Hardware Logic.