

HISTORY OF VISUAL SYSTEMS
IN THE SYSTEMS ENGINEERING SIMULATOR

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ABSTRACT

The Systems Engineering Simulator (SES) houses a variety of real-time computer generated visual systems. The earliest machine dates from the mid-1960's and is one of the first real-time graphics systems in the world. The latest acquisition is the state-of-the-art Evans and Sutherland CT6. Between the span of time from the mid-1960's to the late 1980's, tremendous strides have been made in the real-time graphics world. These strides include advances in both software and hardware engineering.

The purpose of this paper is to explore the history of the development of these real-time computer generated image systems from the first machine to the present. Hardware advances as well as software algorithm changes are presented. This history is not only quite interesting but also provides us with a perspective with which we can look backward and forward.

ACRONYMS AND ABBREVIATIONS

CIG --- Computer Image Generator
CT3 --- Continuous Tone Computer Image Generator - third generation
CT6 --- Continuous Tone Computer Image Generator - sixth generation
EPU --- Edge Processing Unit
ESG --- Electronic Scene Generator
JSC --- Johnson Space Center
MMU --- Manned Maneuvering Unit
NASA --- National Aeronautics and Space Administration
OGU --- Object Generating Unit
OMV --- Orbital Maneuvering Vehicle
R520 --- Raytheon 520
SAIL --- Shuttle Avionics Integration Laboratory
SEL --- Systems Engineering Laboratories
SES --- Systems Engineering Simulator
SGS --- Surface Generator Subsystem
TOU --- Timing and Output Unit
VCU --- Vector Calculating Unit

INTRODUCTION

In the twenty odd years between the first real-time computer image generator to the present, many strides have taken place to provide realistic, full color, three-dimensional displays for use in many areas in the simulation community. NASA/JSC is rare in that it contains a snap-shot of this development approximately every ten years.

From the first of its kind to the current, real-time computer image generators provide the necessary visual displays to support the increasingly heavy demands placed on the Systems Engineering Simulator (SES). This paper explores the history of the scene generators which existed and still exist in the SES.

The hardware configuration and new technology of each graphics system is explained. The salient features and innovations of each system as they were introduced to the SES is explored. Several advances in the theory of database modeling have evolved throughout the years and real-time programming has changed from minimal to extensive.

Due to historical carryover, the terms Electronic Scene Generator (ESG) and Computer Image Generator (CIG) will be used interchangeably.

SES -- SYSTEMS ENGINEERING SIMULATOR

The Systems Engineering Simulator (SES), formerly the Shuttle Engineering Simulator, has been in continuous operation since the programs conception in 1968. The SES supports real-time man-in-the-loop computerized engineering simulation for the Shuttle, space station, and other space related programs and projects.

The two main areas of operation utilizing Electronic Scene Generators (ESG) are entry and on-orbit.

The entry simulation is hosted by a Cyber 840. The orbiter forward cockpit mockup is located in the East High Bay of Building 16.

On-orbit simulation is accomplished with the use of five SEL 32/8780 supermini digital computers and four SEL 32/75 digital computers. Mockups include an orbiter aft station, MMU station, and a cupola station. The cupola is the operations station for the space station. All of these mockups reside in Building 16. On-orbit operations which are supported include space station docking/berthing, payload handling/deployment, MMU operations, and OMV studies to mention a few.

NASA I -- THE ORIGINAL SCENE GENERATOR

"And, in the beginning, there was texture."

NASA/JSC was instrumental in bringing to fruition the concept of real-time computer generated images. In the time before the mid-1960's, the out-the-window visual images were generated by model boards: large, scaled replicas of the simulation terrain over which a closed circuit television camera traversed. These model boards were built specifically for the purpose at hand and not easily modifiable.

A new concept emerged in the early 1960's. Although rather idealized, the scenes produced by computers could be generated in real time to satisfy the requirements to provide scenes for out-the-window displays. In August, 1964, NASA at the Manned Space Center installed the first such computer device. The dawn of real-time computer generated images began with the "Visual Contact Analog: Three-View Interim Space-Flight Simulator" built by General Electric.

As intimated above, this computer system produced three views. These views consisted of an unbounded textured planar surface for the ground. This special purpose computer, the Surface Generator System, calculated the perspective transformation of a surface texture. The optical system displayed the resulting pictures so that the environment appeared distant to the observer.

There were a few interesting details to be discovered about this system. Due to the state of the digital art at that time, several problems were solved with analog methods. The textured surface

was computed in digital form without a roll angle. This made the algorithm simpler and roll was accomplished in the circular television monitor by electronically rolling the raster. Precise nonlinear sweeps were generated by the display unit to compensate for optical distortions. To avoid disturbing moire patterns, fine detail was gradually faded out of the picture with analog circuitry.

The entire computer system consisted of six pipelined processors built with pre-TTL equipment: Computer Control Corporation (3C) circuitry cards containing discrete components.

Screaming along at 5 MHz, the displays were generated at 30 frames a second. This corresponds to the current American commercial standard.

As in all computer image generators, the first processor unit is the unit with the highest programmability. The first unit of the Surface Generator System, the Program Control Unit, contained 512 48-bit words and had a memory access time of 5 microseconds.

This machine served the Guidance and Control Division for several years.

NASA II -- THREE DIMENSIONAL CAPABILITY

In February, 1968, modifications were made to the Interim Visual Space Flight Simulator and a large complement of equipment was added.

An innovation occurred in the field of computer generated images. Three-dimensional objects were added to the textured surface. In this time frame, the Manned Space Center was heavily involved with moon landings. The additional capability provided the simulation with idealized forms of lunar mountains and craters as well as the traditional realistic landing fields.

The new system consisted of the following components:

1. A Raytheon 520 (R520) general purpose computer. Flexibility was introduced by linking a general purpose computer to a set of special purpose computers. Although minimal by modern standards, the memory capacity was 8096 24-bit words core memory and 256 24-bit words of high speed memory. This concept formed the basis of flexibility in the succeeding generations of real-time visual systems.

2. A Vector Calculating Unit (VCU). This special purpose computer deviated from the classical Von Neumann computer architecture. It contained a 4096

24-bit word program memory unit and three sets of 2048 30-bit word data memory units corresponding to the X, Y, and Z components of the Cartesian coordinate system. The data memory units can be accessed in parallel, enabling dot and cross product calculations to be made quickly.

3. A set to two Object Generating Units (OGU). Each unit was capable of working on twenty objects made up of eighty faces and described by a maximum of 120 edges. For each edge of the environment, one circuit board was required.

4. A Timing and Output Unit (TOU). This unit performed three functions. It generated the master timing signals for the entire system. The TOU served as a mixing and distribution point for the video outputs from the two OGU's and routed data from the VCU to the OGU's, SGS, and displays. Test patterns were generated in the TOU for aligning and trouble shooting the system.

The Surface Generating Subsystem (which was the Visual Three-View Space-Flight Simulator) was modified to allow its operations at 20 frames a second. The NASA II system operated at a slower rate due to the constraints imposed on it by the R520 and VCU.

Of interest here is the fact that the objects which were generated came from a catalog of two-dimensional polygons and three-dimensional objects. Each OGU had the capability of generating one decahedron, one octahedron, two hexahedrons, and four tetrahedrons as well as two dodecagons, three octagons, four hexagons, three quadrilaterals, and two triangles. The maximum capability of 120 edges per OGU could not be exceeded. The combined capacity of the two OGU's was 240 edges.

The database designer had to create a scene choosing objects and polygons from a catalog of available objects and polygons. The specification of vertices for the objects and polygons followed stringent rules. The concepts of planarity and convexity were required for each planar surface. Because object topology was predefined, vertex selection required a lot of precalculation for irregular objects. Selection of the objects and polygons amounted to filling specific absolute locations in the R520 memory. Color selection followed a similar procedure.

The designer also had the choice of one quadrilateral shadow polygon and one beacon. The shadow polygon emulated the shadow created by ones ownship. It changed configuration in response of the vehicles attitude with respect to the

surface and an imaginary sun. The one beacon was a two element by one line pair dot. It had the capability of flashing and the period was programmable.

The real-time programming consisted mainly of calling the subroutines which transformed objects and polygons in the correct order. At this point in time, there was not a clear distinction between database design and real-time programming. The two concepts were closely intertwined.

The NASA II system, therefore, presented an environment consisting of three-dimensional objects on a two dimensional textured surface.

NASA III -- A BETTER WAY

In November, 1971, a major innovation was incorporated into the then current visual system. The two OGU's with its combined capacity of 240 edges was replaced with an Edge Processing Unit (EPU) which increased the edge capability to 320 edges. The theory of a fixed set of objects and polygons was superseded with a more general approach of just polygons. Groups of polygons were gathered to form three-dimensional objects.

A new concept was also introduced. Edges could now be shared between an object or among objects which did not move relative to each other. This provided an addition edge capacity capability. For example, a cube has six sides and each side has four edges. With this method, a cube could be described as six sides with twelve shared edges rather than six sides with four edges each for a total of 24.

With the added flexibility that this new system brought, a need for programs to generate databases was required. The first database compiler was written by Lockheed at the NASA Manned Spacecraft Center. Because the program was written in an early version of Fortran, the syntax was necessarily field sensitive. Things had to be in the right column.

The database designer specified clusters by grouping polygons. He specified polygons by grouping vertices. Clusters had to follow some rigid constraints. NASA III used the idea of separating planes. Clusters were separated from each other by invisible, infinite planes called nodes. Modules were groups of clusters which did not move relative to each other. Each polygon was given an attribute such as color, back-face generation, and shadow or beacon generation. Given the capacity of the machine, the number of edges per polygon was completely arbitrary. One of the

test patterns which existed on the machine has sixteen polygons of twenty edges each.

The real-time program, which resided in the R520 and the VCU, was written by General Electric. It was an upgraded version of the one which resided in the R520 in NASA II but the new algorithm made the program much less complex and easier to manage.

Programming of the real-time software was rather trivial. The program was mainly driven by the database environment. It required little modification for each new environment. The environment consisted mainly of two independent coordinate systems which could contain an eyepoint or modules, one coordinate system which could contain only an eyepoint, and the ever present textured surface.

With the advent of the CT3, described below, the NASA III system was renamed the Electronic Scene Generator #1 (ESG #1).

CT3 -- A MAJOR STEP

A major step in the evolution of real-time computer generated image systems was made in November, 1976. The CT3 made by Evans and Sutherland was introduced to the SES. This system had many new attributes which deserve mentioning. This system is currently employed to a great extent in the SES laboratory.

The CT3 consists of three general purpose computers of the PDP-11 series, a visual pipeline, and a collision detection pipeline.

A central PDP-11/40, called the HOST, is interfaced to the simulation laboratory. The HOST interfaces to the visual system and the collision detection system. The main purpose of this machine is to gather the data from the simulation, format the data, and send the results to the other subsystems.

The visual subsystem is driven by a PDP-11/40. It is connected to a visual pipeline containing 10 programmable special purpose processors. Two independent channels of visual images are produced. The total capacity of the visual system is 900 polygons.

A separate collision detection system allowed the simulation to detect the intersection of impenetrable objects. This system consisted of a PDP-11/45 as well as a collision detection pipeline containing two programmable special purpose processors.

The frame rate of this system was 25 Hz.

This corresponds to the European commercial standard. Although ESG #1 was operating at 20 Hz, no problem was presented. CT3 was used for on-orbit studies and ESG #1 was not.

The visual system included many new features which are described below.

Anti-aliasing and edge smoothing were added to improve picture quality. Spatial filtering was used as the algorithm.

Directional illumination was introduced to provide an illusion of sun direction, intensity, and environmental depth.

Smooth-shaded polygons simulated round or complex shaped objects. The Gouraud shading algorithm was implemented in hardware using extremely fast ECL circuitry.

Hidden surface removal by range priority was done in hardware as well. This eliminated the necessity for separating planes.

A separate modeling system was delivered which was used to create and analyze databases. This system consists of a calligraphic display system and a general purpose computer, PDP-11/40. Software packages aid the designer in producing new databases. The databases are viewed in wireframe on the display system.

This is the first time that the database modeling was implemented on a system other than the visual system. Due to the extremely heavy usage of the CT3 in the simulation laboratory, a separate modeling station is necessary.

A new language was developed for database modeling. The new compiler set, MEDUSA for the visual system and COLIDE for the collision detection system, offers the designer a capability and flexibility heretofore unknown. In the process of constructing an environment, the designer defines and names points. Subsequently, he defines polygons in terms of these points and adds attributes such as color and reflectivity. With this innovation, the database design becomes much more like programming rather than filling out specification requirements.

Another language set, VIS for the visual system, CDS for the collision detection system, and HOST for the host machine, was developed for the real-time programmer. Symbolic parameter areas are defined by the programmer and transformation sequences are specified to meet the simulation requirements. Again, the real-time programmer is more of a programmer rather than someone who

allows the data to dictate the real-time configuration. Currently, two versions of the HOST software exists. HSTSES interfaces to SES and HSTSTS interfaces to SAIL. At the present time, CT3 is in use at least 16 hours a day supporting on-orbit studies in the SES.

ESG #1 -- A NEW LEASE ON LIFE

Returning to ESG #1 (alias NASA III), the Raytheon 520 was more and more difficult to maintain and the SGS was even more difficult to maintain. During the early 1980's, this author's project was to replace the R520 with a more modern Systems Electronic Laboratory (SEL) 32/55. During this project, the SGS was removed from the system as well as some other parts of old ESG #1. The remaining units are the VCU, TOU, and EPU. The display systems were reworked. This effectively removed the texture capability from the system.

The frame update rate of ESG #1 was not changed. To have done so would have required major hardware modifications. Therefore, the frame update rate was retained at 20 Hz.

Along with the hardware changes, a new set of software packages had to be written. Rather than follow the original design for database modeling and real-time application software, it was desirable to model the software after CT3. In this effort, the database modeling software closely approximates that of CT3, given the different hardware algorithms between the two machines. In addition, the real-time software approximates the real-time software of CT3. The desired effect was the capability of a database designer or real-time programmer to move between the two machines with very little effort.

The database modeling software, ENCOM, was designed to emulate the database modeling software which exists on CT3. A complete rework was undertaken so that a programmer on CT3 could move to ESG #1 with minimal effort. The established procedure of defining and naming points followed by defining polygons in terms of these points was introduced to ESG #1.

The real-time software followed a similar theory and procedure. The real-time software on CT3 was deemed a standard and the real-time software on ESG #1 was designed to match as closely as possible. Currently, three versions exist. VISUAL interfaces to the SES, VISSTS interfaces to SAIL, and VIS is a standalone version used for local applications and development.

As of this writing, ESG #1 is actively supporting entry simulation. A set of

13 entry scenes are available. Due to its age, it is difficult to maintain and some of the electronic components are not obtainable. There is a project underway to retire it and replace it with a more modern computer image generator.

POLY 2000 -- A MEDIUM RESOLUTION, LOW COST APPROACH

A POLY 2000 built by GTI, Incorporated (GTI) was purchased in October, 1985. It was planned to add three low resolution channels to the complement which existed in SES at that time. However, the software and hardware theory was radically different.

The digital technology had advanced so greatly during this period in time that the POLY 2000 could accomplish real-time computer generated images using micro-coded, high-speed bit slice processors.

The POLY 2000 at that time was in its infancy. It did not have anti-aliasing or smooth shading. It did have diffuse reflectivity which gave the impression of a sun direction. Alphanumeric characters could be overlaid on the scene.

The POLY 2000 consisted of a general purpose computer and a set of special purpose bit-slice processors. The general purpose computer, the Alcyon, was used in database development as well as generating load modules for the POLY 2000 proper. The first major processor was the System Control Module (SCM). When the system was connected to the simulation, data was sent directly to the SCM and the Alcyon was not used. This left the Alcyon free to be used in other capacities.

Special requirements were insisted upon. The frame update rate was set at 25 Hz to match that of CT3. Multiple channels were required. The vendor produced a system with three independent channels.

Database modeling was done on the Alcyon and the binary object files were stored on its disk. When needed, the object modules were downloaded to the SCM. The database compilers, polyi2I and polyd2D, were not compatible with any of the database modeling software which existed in the SES.

The real-time programs were written in C on the Alcyon and, also, downloaded when required. No special language was implemented; all special functions were included in a library.

These concepts were radically different than the ones established on ESG #1 and CT3. Lockheed personnel undertook the

effort to write a set of software packages which would more closely emulate the concepts of the other graphics systems. These included the database compiler (POLYS) and the real-time support software packages known as the linker (LOADER), and the loader (LOAD). The syntax of the language was modeled after those commands found in the software of the other systems.

POLY 2000e -- AN ENHANCED VERSION

Given a few years, GTI enhanced the POLY 2000 to include additional features. Their new POLY 2000e provided the following enhancements:

1. Smooth-shading - Gouraud shading was added to the flat shaded and fixed shaded polygons already in the system.

2. Anti-aliasing - Sub-pixel averaging was used as the algorithm for curing the jaggies.

3. Transparency - Eight levels of polygon transparency was incorporated into the system.

4. Depth fogging - Gradual dissolution to the background provided for fog and haze.

Essentially, the enhanced system was an entirely new system. New algorithms and hardware were exchanged for the older system. The three channels operating at 25 Hz were retained. The general purpose computer, the Alcyon, was also retained.

Because the hardware and software theories were changed, the custom-made compilers had to be changed. Extensive effort was employed to upgrade the compilers to match the new system without having to rework all the previous database and applications software.

The three channels of the POLY 2000e are currently supporting on-orbit studies in the SES.

CT6 -- A PRIDE AND JOY

As of this writing, an Evans and Sutherland CT6 is in the process of being integrated into the SES laboratory. As with the advent of CT3, major steps in computer graphics were introduced to the SES.

The general purpose computer of the CT6 is a Gould Concept 32/67. The special purpose computers are still arranged in a pipeline fashion but there are fewer major components doing much more. The configuration of the pipeline allows

channelization to be performed early in the processing.

The current system has six independent channels of high resolution, high quality images. The system is capable of processing thousands of polygons and each channel can display up to 1500 polygons. Compared to the hundreds in the other systems, the increased capacity is impressive.

Not all the database need reside in active memory. Parts of the database which are potentially visible reside in memory while the rest resides on disk. When those objects not in memory become potentially visible, they are paged in from disk to memory. This provides a mechanism which essentially expands the potentially visible database many fold.

Texture returns. Not only ground texture but polygonal texture is made available. Any polygon regardless of orientation can have texture. Many texture patterns are available in the system. Texture can be produced by closed form equations or photographically derived.

Database development is now necessarily more complex. Database modeling is done on a MicroVax II. Not just one software package is enough. Several database modeling software packages are provided not only to develop databases but also to display the resulting databases on a color calligraphic display device, the PS330. Database development includes object and surface production capability. The main database compiler, DBC, deals with objects, polygons, and points. A separate linker, LNK, is used to join the intermediate binary object files. The surface feature editor, SFE, assists in creating large terrains principally used in landing scenarios. Several display packages are included such as the CT simulator, CTS, and the graphics editor, GRE.

Complexity also manifests itself in the real-time software. The increased memory and speed provided by the Gould Concept 32/67 also provides a wealth of capabilities for the real-time system. Because the Gould Concept 32/67 is a dual CPU system, the real-time tasks have been divided to optimize this feature. The user interface to the real-time process, RTS, allows the user a wide variety of commands and capability to control and configure the system.

As of this writing, the CT6 is in the last stages of integration into the SES. The database designers are working hard to supplement the databases already delivered by Evans and Sutherland. The SES is looking forward to the time when

the CT6 will be brought on-line and support the simulation studies.

CONCLUSION

This paper has explored the history of the computer image generator as they existed and still exist in the SES.

Many advances have been made in the hardware, taking advantage of the current state-of-the-art circuitry available at the time. From the discrete components to the first integrated circuits to the very large scale integrated devices, the real-time graphics industry has tried to use everything at its disposal to create the best images available. The theory on how to best utilize the hardware advances has also changed toward flexibility, programmability, and manageability.

Database design has grown from data specifications to large and complex programs. As the complexity in databases increased, the complexity in the database software increased.

Real-time software has changed radically over the duration of the real-time computer image generator. In the early stages, the simulation visual system was driven mainly by the data which it received. As more and more powerful front-end general purpose computers were available, the real-time programmer was able to enjoy more and more flexibility in the control of the visual system.

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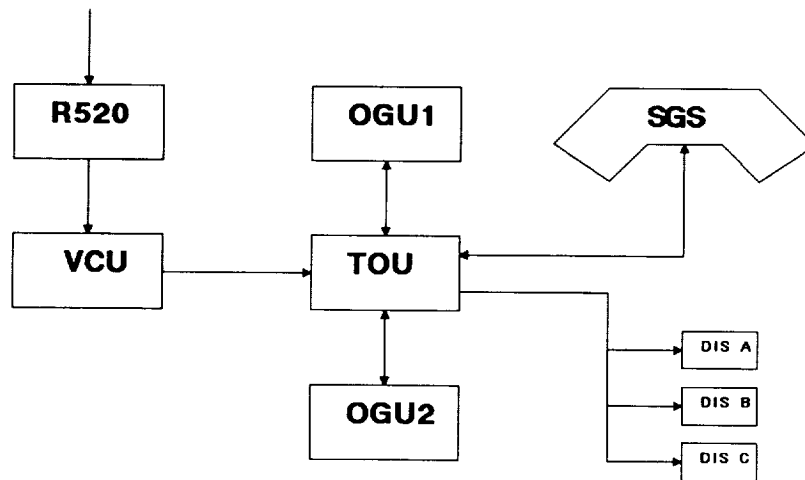


FIGURE 1: BLOCK DIAGRAM OF NASA II

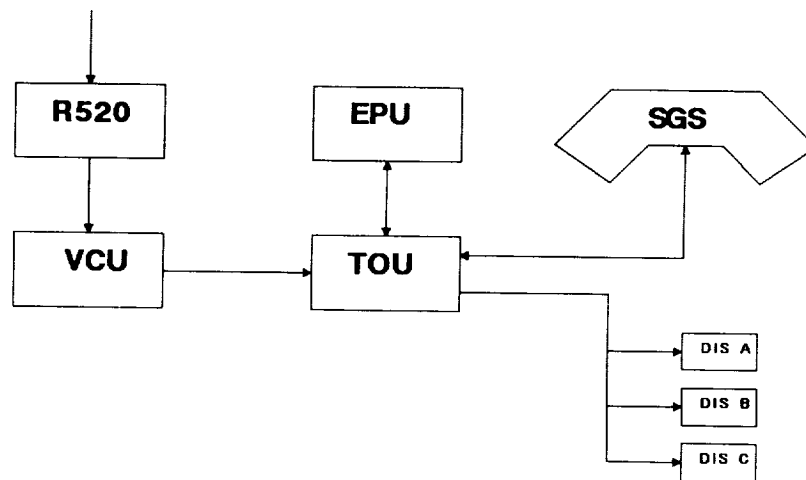


FIGURE 2: BLOCK DIAGRAM OF NASA III

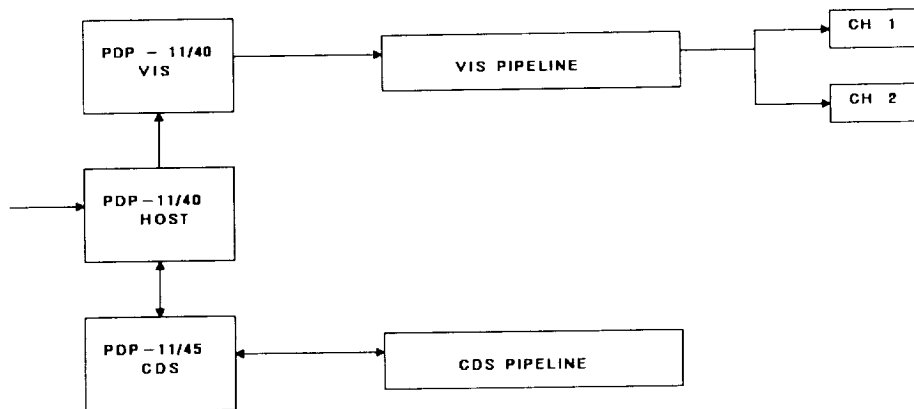


FIGURE 3: BLOCK DIAGRAM OF CT3

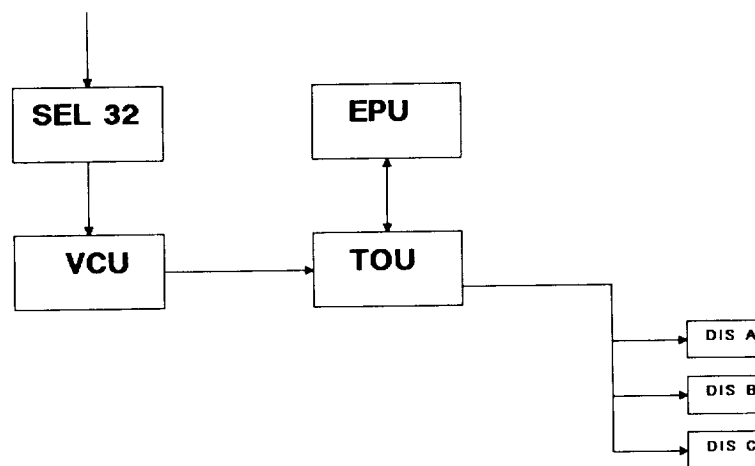


FIGURE 4: BLOCK DIAGRAM OF NASA III, UPGRADE

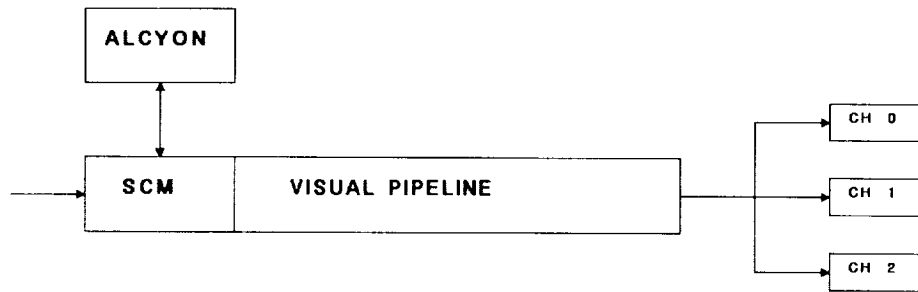


FIGURE 5: BLOCK DIAGRAM FOR POLY 2000 AND POLY 2000e

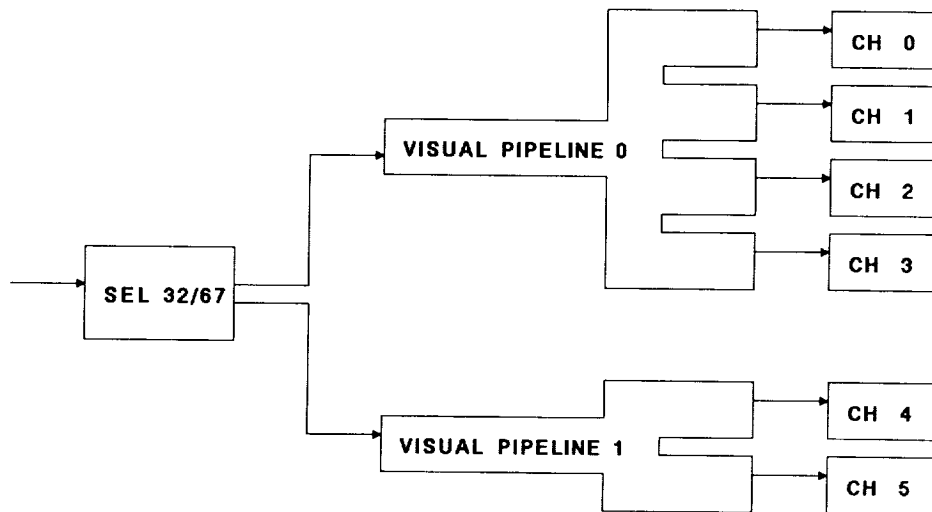


FIGURE 6: BLOCK DIAGRAM FOR CT6