

5. Control System

5.1 Introduction

The control system covers operations of all accelerator facilities (Linac, 3-GeV RCS and 50-GeV MR) and beam transports (L3BT, 3NBT and 3-50BT). The control and operation of user facilities (Material and Life Science Facility and Nuclear and Particle Physics Facility) will be carried out primarily by members of each facility. However, since the operation of the accelerator is very much related to the conditions of user facilities, information exchange between the accelerator control and users' facilities must be intensively made. All important information in the users' facility should be seen in the Central Control Room (CCR) at any time. Moreover, the control system should be capable to control any parameters in the users' facility in some occasions.

The accelerator is a high-intensity proton machine, and therefore, extreme care must be taken in order to keep the radiation loss be as low as possible. Conditions and status of important devices must be taken and checked in all macro beam bunches (25Hz or 50Hz when the ADS facility becomes available) so that it is possible to stop the beam immediately when any of the devices malfunctions. Of course, such an immediate beam stop is carried out primarily via hardwired logic, the monitoring and logging of the important device is indispensable for troubleshooting.

We think that the following points are important for designing an accelerator control system in general, and we should keep in mind all the time when designing.

- Easy for maintenance — in order to avoid unnecessary effort and extra cost in both manpower and money, maintainability is very important. To accomplish it, we use commercially available products in as many areas as possible and we also keep watching the market trends.
- Easy for upgrade — since the operation of an accelerator usually lasts for a very long period, upgrades of the system often happen. It is ridiculous if we have to replace all parts of the system at the upgrade time. Therefore the system must be designed including the concept of layers or hierarchy, so that the replacement of limited layers would be enough for any upgrade.
- Common use — we should use the same products in networking, hardware and software in as many places as possible in order to reduce the number of different kind of parts so that the operation cost is significantly reduced.

One of the outcomes from the principles mentioned above is about field-busses. There are so many different field-busses are being used in existing accelerators. Keeping different parts and cables for different field-busses in stockroom costs a lot. Instead, we have decided to use the Ethernet as a field-bus. Recent developments of commercial network technology

make it possible to unify communication links. The use of any other field-bus must be limited in a case that there is no alternative solution with the Ethernet.

As a software system framework, we decided to use the Experimental Physics and Industrial Control System (EPICS), because;

- It is widely used in the field of accelerator control, and therefore many of the sharable software resources are available.
- It is scalable and also easy to integrate. For example, once we develop an EPICS based control system in a development stage of some device such as a magnet system, the system can be easily integrated into the total control system if we design it appropriately.

Under the EPICS environment, we are developing three Ethernet/IP network controllers; FA-M3 PLC's, WE7000 measurement stations which are used mainly as a digital oscilloscope (waveform digitizer), and general-purpose Ethernet board which are designed primarily for the power supply of the DTL Q pulsed magnets.

Detailed descriptions on the EPICS (5.2), the network (5.3), interface to user applications (5.4), database (5.5) and personal protection system (5.6) are in the following sections.

5.2 EPICS

5.2.1 Basic architecture of the control system

The most of modern control accelerator control systems shares several common features in their architecture.

- intelligent hardware controllers distributed for local controls
- host computers serve as operator interface and runs overall control programs,
- a high-speed network connecting these intelligent controllers and host computers.

Lots of efforts in the various laboratories were used to develop the control systems. These products have many common functionalities and unique features. Unfortunately these products are not interoperable each other.

EPICS was developed as one of these control system. However, it was designed as a toolkit for an accelerator control system and the accelerator control system were constructed on a top of this toolkit. This approach allows different control systems to share applications based on EPICS framework.

The importance of sharing of software for accelerator operation is considered as one of key issues in the accelerator community. EPICS is recognized as one of, if not only one, basis for this efforts of software sharing. Many recently constructed accelerators and some experimental facilities, including KEKB and PF-AR, adopted EPICS as an infrastructure of its control system. In other words, EPICS is a simplest way to take benefit of shared software for accelerator controls.

5.2.2 What is EPICS

Experimental Physics and Industrial Control System (EPICS) is a collection of software tools developed by EPICS collaboration. EPICS uses a system architecture common to modern accelerator control systems. A control system based on this architecture consists of:

- Distributed intelligent Input/Output Controllers(IOCs),
- High-speed network based on TCP/IP and ,
- Unix, including Linux, and/or Windows NT host computers for various high level control applications.

The core software and the general purpose applications are built upon this. A VME single board computer running VxWorks real-time operating system is used as an IOC in EPICS. The IOC's are distributed along the accelerator. EPICS run-time database on the IOC's and CA (Channel Access protocol) constitute the core of the EPICS software. An EPICS client software accesses the record in this run-time database using the logical name of the record. The protocol to access data in the distributed run-time data base is called "Channel Access (CA)". Read and write accesses to the EPICS run-time database from the EPICS client software triggers the access to the hardware from the IOC. User of EPICS only needs to supply hardware specific routines, hardware driver and device support routines.

EPICS core software also includes programs such as,

1. A periodic/event scanner to scan the status of hardware in the way specified by the user,
2. CA server to handle the database access request from the client program.

Configuration files prepared by the user define the actual behaviors of these programs.

5.2.3 Usable Modules for Device control

In EPICS, all device controls are carried out through input/output controllers (IOC's). At present, only VME under the vxWorks operating system can be used as an EPICS IOC. In near future, a PC under the Linux or other real-time OS will be available as an IOC.

Many VME modules are commercially available for processing normal digital and analogue signals. EPICS drivers are already available for most of those modules. A VME module to handle a stepping motor is now being evaluated whether it is suitable to our applications.

Programmable Logic Controller (PLC's) are cheap and reliable in a sense that they keep running under any trouble in computers or networking, and therefore it is preferable to use PLC's for some critical devices such as an ion-source. How PLC's communicate with IOC's is an important issue. Our solution is as follows;

- Use Ethernet TCP/IP. Among PLC's commercially available, presently only

FA-M3 PLC by Yokogawa support data transfers protocols we required.

- Assign an identification number (ID) to each PLC. It is dangerous to rely only on the IP address. Before any communication with a PLC and at any data (command) transfer to a PLC, check the ID to make sure you are communicating with an appropriate PLC.
- No individual commands for operation. Only data transfer from/to PLC memory is supported. Any device operation should be done through contents of memory in a restricted address range.
- No direct write to PLC memory. An IOC sends 3-word data (an ID, a memory address and content) to a communication area in the PLC memory. Then, a PLC ladder program moves the content to an appropriate address after checking its ID.

A prototype of the PLC EPICS driver has been written and successfully used for the ion-source operation, although all the rules mentioned above are not fully implemented yet in the prototype driver.

Choice of waveform digitizers is another important issue we have to consider for device control. A measurement station called WE7000 from Yokogawa Co. seems to be promising when cost performance and electromagnetic noise elimination are taken into consideration. Its EPICS driver has been partially completed and tested. For this station, the same TCP/IP Ethernet communication method is used as that for the PLC's.

For precise current control of power supplies, we should avoid extending an analogue signal in a long distance, and instead, should use digital data links. Since Ethernet network runs all over the area, we chose Ethernet for the digital data links avoiding another type of field bus so that all of the data communication is unified. By doing so, we can trace back all data through the network which will significantly help us for operation diagnostics. To achieve the unified Ethernet links, we are developing an Ethernet interface board which will be used primarily in the power supplies for the pulsed quadrupole magnets at the DTL. The board is designed considering more general uses and may be embedded in other devices.

Some devices required for some equipment may communicate with our control system only via a method other than Ethernet. For example, most of low-price power supplies have a GPIB or RS232c interface for remote access. In such cases, we will use Ethernet interface such as a GPIB LAN gateway for GPIB and a terminal server for RS232c to minimize the area covered by field busses.

5.3 Network

5.3.1 Functional Requirements

Network is one of the most important components in the control system and should be very

reliable for the stable operation of the accelerator. The followings are the requirements and design criteria for the control network;

- The network backbone is a gigabit Ethernet with redundant (double cabling) fiber optics.
- Most of the network devices are linked via 100baseTX. Some of the devices which are located in noisy areas should use 100baseFX.
- The network is suitably divided into several subnets. (1) EPICS subnet; IOC's, network devices controlled by an IOC and operator terminals are in the EPICS subnet. All network packets in the EPICS subnets should be logged and kept for a reasonable time period for maintenance and troubleshooting. When any accident is encountered, all packets are back traced to find causes of the trouble. (2) a subnet for maintenance; IOC console is connected via a terminal server which is in a subnet different from the EPICS subnet. (3) PLC subnet; PLC's those communicate with an IOC are in the EPICS subnet. PLC's those do not communicate with an IOC are in a subnet different from the EPICS subnet.
- All network hubs should be fully switched.
- All network devices should be powered from UPS.
- So called virtual-LAN should be utilized in order to reduce the number of switching hubs and cablings.
- Network configuration should be in a database, and all network reconfiguration must be carried out through the database. All network switches should be remotely controlled.
- Access to the control network must be restricted. All access to the control network from outside LAN must be through authorized gateway machines only. Installation of an unofficial router to outside LAN is strongly prohibited.

5.3.2 Preliminary design of the control network

Redundant gigabit Ethernet with fiber optics linked as a "star" starting from the central control building to each accelerator and experimental facilities is the backbone of the control network. Fig. 5.1 shows the schematic drawing of the network backbone.

From each backbone switch, star-like optical fiber cables (100baseFX) extend to network switching hubs over the all facilities. Most of the network end-nodes such as IOC's are 100baseTX. Some nodes in a high EMI noise levels such as near klystrons or high-powered pulsed power supplies should be 100baseFX.

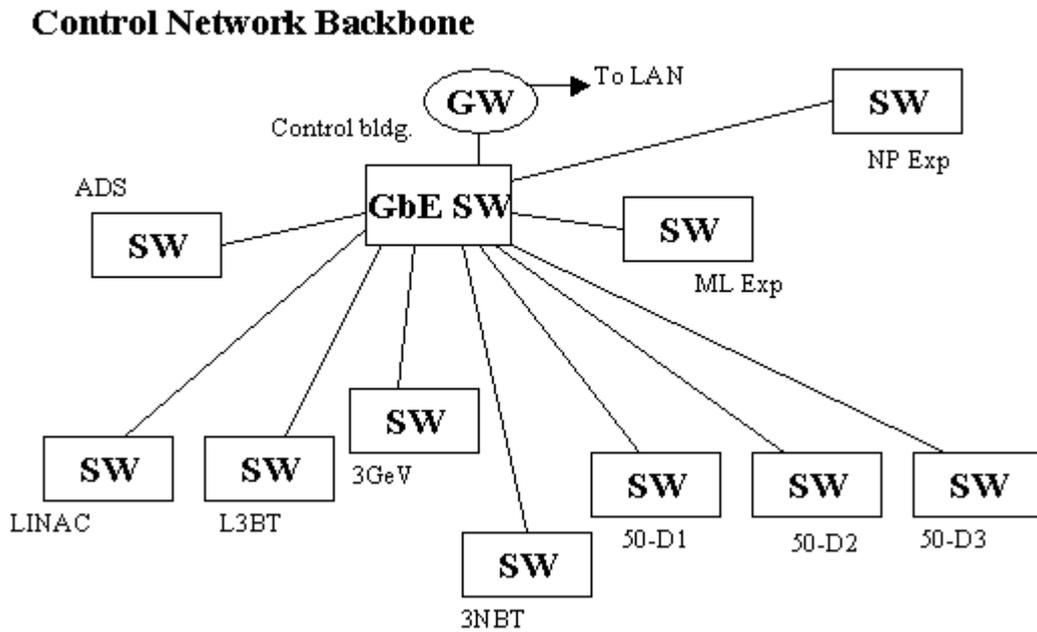


Figure 5.1 Schematic drawing of the Network Backbone

Since the number of global IP addresses available is not enough to cover all network devices, which might be over 1000, a Class B private IP address space will be used. In order to make the maintenance be easier and to set the highest priority to the EPICS communication, the network is divided into several subnets. The EPICS channel access (CA) protocol requires the network broadcast, which means all of the EPICS devices including operator terminals should be in a same subnet. However, we may subdivide the EPICS subnet into 3 or 4 if the network traffic in the subnet becomes so high. In this case, an intelligent gateway is installed to handle the EPICS broadcast protocol. In order to reduce cabling and number of network switches, so-called virtual LAN technique is employed. The following shows the list of subnets.

1. EPICS subnet: all IOC's and operator terminals are in this subnet. Network devices such as WE7000 measurement stations and PLC's which communicate directly with an IOC are also in the subnet. This subnet has a highest priority because EPICS channel access communication is the most critical for stable operation. As mentioned above, we may subdivide the subnet into 3 or 4.
2. Maintenance subnet: Remote access to programming ports of programmable network devices is connected in this subnet. Those include; IOC's CPU console (RS232c through a terminal server), network switches for configuration settings and maintenance, and the packet monitoring machines.
3. PLC subnet: PLC's which don't communicate directly with an IOC are in another subnet.
4. Video subnet: Recently net cameras become commercially available. We will use some of them where high-quality video picture is not required.
5. a subnet for software and hardware development.

Since the detailed method to control equipment is not decided yet, total number of IP addresses in each subnet is not counted yet.

5.4 Higher Level Applications and Operator Interface

In this section, application software in the control system is described from several different view points.

5.4.1 Application Software on IOC

Application software on an IOC (I/O controller) may be developed using these facilities.

- (a) Linked records
- (b) State Notation Language (SNL or Sequencer)
- (c) Writing an application with C/C++ language
- (d) Writing a new record

(b) and (c) may be developed at the client side as well, while it is preferable in performances to develop at the IOC side since local records can be accessed without network intervention. It may also access remote records via the channel access, if it is necessary.

(a) is a basic EPICS programming technique to describe a procedure without writing a code. A group of records are designed to behave properly when a record changes, when a record is accessed, etc. One may simply fill the fields of EPICS database to describe the behavior.

(b) may be used to write a more complicated procedure. Since SNL is designed to describe event-driven sequences, it is adequate to write most control procedures. If it is necessary, one may write (c).

(d) may be used to describe a behavior of complicated accelerator equipment. For a complicated system, a lot of records may have to be used and much memory can be consumed. In order to simplify the database and to reduce the memory consumption, it is sometimes better to write a new records.

Examples of (a) and (b) can be found in many EPICS documents. Examples of (c) and (d) should be provided by the controls group.

5.4.2 Application on Client

Application software at the client side (OPI) can be developed in many different ways. Many kinds of software interfaces are provided in EPICS community. Any software environments which can use the channel access library routines may be used to develop application software. (For performance reasons, it is preferable to utilize the monitor functionality of the channel access.)

Since it is sometimes necessary to reboot an IOC to develop application software at the IOC side, it may be easier to write software at the client side for a rapid development. If the software is stabilized, it may be transferred to the IOC side for the better performance.

These are examples of software environments at client side.

- (a) EPICS Display Manager (EDM, MEDM, DM2K, etc)
- (b) EPICS applications (Archiver, Alarm-handler, Strip-chart, etc)
- (c) General scripting languages (Python/Tk, Tcl/Tk, etc.)
- (d) Scripting environment for accelerator operation (SADscript/Tk, SDDS, etc)
- (e) State Notation Language
- (d) Compiler languages (C/C++, Java, Fortran, etc)

(a) is used to display EPICS records. If this and (a) of 1.1 are combined, one may build a simple application without writing any codes. (That may correspond to a simple SCADA (Supervisory Control and Data Acquisition) system.) Although the formats of description files (adl) between display managers are mostly interchangeable, we should concentrate on a display manager in order to avoid a mixed environment. Since EDM can handle simple scripts, we may employ EDM.

(b) can be utilized in many applications. Since many control systems have the same requirements, these special-purpose applications may have features which meet our requirements. If they meet most of our needs, we should utilize them as much as possible and improve them instead of writing ones since they save our human resources.

(c) may be used in many applications since it is suitable to develop software rapidly. Common library routines should be provided by the controls group in order to facilitate the same environment at the operators' console. If possible, we should concentrate on one language. In order to choose a language, the items described in the next section should be considered.

(d) is necessary to operate on beams. It would be used heavily during the commissioning phase. In KEKB SADscript has been used by the commissioning group, and more than half of the operation panels have been built with SADscript. It was often used even as a general scripting language since it covers most of features in the next section. Some of other laboratories use a combination of SDDS and Tcl/Tk. At least those two environment should be prepared for the commissioning. Other software may be built using (d) of 1.3.

(e) may enable the rapid development of sequence procedures on client computers. They can be eventually transferred on to IOC's.

(f) may be used to replace a part of (c) in order to improve the performance. The on-memory processing speed of (f) can be 10-times faster than that of (c). In order to utilize some software environment like MAD etc. one may have to use (f). Java is quite interesting to make the application be shared between multi-platform and to adopt technologies developed for internet/intranet.

5.4.3 Features of Application Development Environment (ADE)

In order to develop software for the accelerator operation these features should be covered.

- (a) EPICS channel access capability
- (b) graphical user interface
- (c) 2-dimensional (and 3-dimensional) data visualization
- (d) interface to other software
- (e) interface to relational database
- (f) object oriented programming and other software engineering support
- (g) data reduction/analysis facilities
 - . data modelling (data fitting)
 - . Fourier and other data transformation
- (h) accelerator design facilities
 - . beam line geometry management
 - . lattice designing
 - . beam particle tracking
 - . optics matching
- (i) multi-platform (POSIX/X11 and Win32) environment

Since one environment cannot cover all the features, a few development environments should be prepared. SADscript/Tk will be included as it may cover most of the items above.

Scripting environments which are considered beside SADscript/Tk are Python/Tk, Tcl/Tk, and Ruby/Tk.

Accelerator design codes which may be employed beside SAD are

- MAD, Parmila, Trace-3D, Transport, etc.
- Mafia, HFSS, Opera, Superfish, etc.

They may be used mostly off-line. In order to utilize them in operation some scripting interface should be developed.

5.4.4 Basic Operational Applications

Beside specific applications, these basic applications should be provided for the commissioning.

- (a) Parameter displays for each equipment group
- (b) Parameter displays for beam operators

- (c) Machine status displays
- (d) Beam characteristic displays
- (e) Archiver
- (g) Archive viewer
- (h) Alarm handler/logger
- (i) Data-set save/restore/compare
- (j) General feedback facility
- (k) Active and passive correlation plot
- (l) Error logger
- (m) Application launcher
- (n) Application window management
- (o) EPICS management
- (p) IOC console management
- (q) channel save/restore

Application software developed in the EPICS community can be used for some of those. They have to be evaluated whether they meet the requirements in this project. Some others have to be developed before the commissioning.

5.5 Database.

5.5.1 General Requirements

In general, there are four different 'databases' in accelerator controls.

1) Static database

The static database has information on the relationships between the control signals and the associated properties, such as physical addresses and calibration coefficients, etc. For example, this database has information of a magnet power-supply 'QM-12A', which is linked to the channel 2 of the second I/O card in the 16th VME-bus computer. This database may not be changed during the normal accelerator operation. However, small corrections should be possible even during the operation to follow troublesome problems.

It is apparent that some ready-to-use database management system (DBMS) is preferable to maintain the database. However, the DBMS is too slow for run-time use by server-level processes. Instead, local files or on-memory caches are generated from DBMS, then used for this run-time purpose.

2) Run-time dynamic database

The run-time dynamic database reflects the status of real accelerator devices. The signal values in the database change in real-time (typically 1 Hz). The database resides at a middle layer between the operator interfaces and the front-end control devices. The bare control functions use the values in the database rather than communicating to the front-end devices. This policy decreases total CPU consumption rates and network

traffics.

3) Persistent dynamic database

In the real accelerator operation, a collection of run-time parameters at the same moment has special significances. For example, an injector may have operation modes, such as 'Ring-1 3GeV injection #1', 'Injector stand-alone tuning', and so on. Each mode has groups of initial setting values of control devices to start the specified operation mode. The most of this database has been kept unchanged, but partly modified over day-by-day operation. Thus, this type of database has both characteristics of static database (persistent) and run-time database (dynamic).

4) History archive

The history archive is a collection of large records which contain histories of control signals. The signal values are logged every 1 sec.-1 min., or each time the value has changed. The history archive requires a sophisticated data-size reduction technique and ideas to enable quick and efficient retrieve from a large disk volume. Public tools, including commercial DBMS, would be expected for easy management of the history archive.

5.5.2 Use of EPICS database and DBMS in the Joint Project

In the Joint Project, we will use EPICS toolkit. The possible candidates for each database are given in Table 5.1.

static database for management for run-time	commercial/public DBMS (Oracle, Postgres, etc.) use EPICS-style files (*.dbd, *.db)
run-time dynamic database	use EPICS run-time database
persistent dynamic database for management for run-time	commercial/public DBMS (Oracle, Postgres, etc.) [not yet decided]
history archive	use EPICS tools (channel archiver, ALH, etc.)

Table 5.1 Summary of Database

5.6 Personnel Protection System

The purpose of the personnel protection system (PPS) is to protect personnel from radiation and other hazards accompanying accelerator operations. The most important requirement for the PPS is reliability. Therefore, two redundant systems are installed, and the beam operation is allowed only when permitted by both systems. Each system consists of a supervisory programmable logic controller (PLC) in the central control building and several local PLCs located around the accelerators. The redundancy of signals is also required for important PPS devices such as emergency switches and door switches. Signals of devices are led to a local PLC via metal cables and then transferred to the supervisory PLC through optical cables. Some important signals will be transferred redundantly by metal cables, too. The operator console of the PPS is placed in the CCR, with which the operator selects the operation mode and carries out the access control.

For the convenience of the beam operation and the access control, the accelerator region is divided into three areas: Linac area, 3GeV RCS area, and 50GeV MR area. Each area takes one of the following three access states.

Limited Access This is the state where the beam operation is not intended and all the high power components are turned off. The access to the area is, however, limited even in this state because the level of residual radiation is supposed considerably high. Only the trained radiation workers are allowed to enter the beam line area, and they have to carry alarm dose meters.

Controlled Access In this state, access is allowed under operator control only. Brief accesses will be frequently necessary for checking or repairing accelerator components during the operation especially in the commissioning phase. The rigorous access control makes it possible to restart the beam operation without requiring another search. It makes the downtime as short as possible, and increases the operation efficiency.

No Access No access is allowed in this state. Release of safety keys and electromagnetic locks of entrance doors are disabled. Beam operation is permitted in this state only.

When state of an area is changed from Limited Access to Controlled Access, a search of the area must be carried out to ensure that no workers are left in the area. After that, the access to the area should be controlled by the operator in the CCR. To make this remote control possible, each entry point is equipped with an access control booth, which has a key bank, outer door, inner door, door control boxes, interphones, and TV cameras. The access procedure in the Controlled Access state is as follows:

1. Workers intending the access have to obtain the permission by the chief operator in duty.
2. When they arrived at the entry point, the operator enable the key release and unlock of the electromagnetic lock of the outer door.
3. The workers take safety keys, open the outer door with a safety key, enter the booth, and

close the outer door behind.

4. Ensuring that every worker in the booth has a safety key, the operator enables to unlock the inner door so that the workers can enter the accelerator area.

When workers exit, they contact the operator with interphone. Then, the operator watches the booth by TV monitor so that no other people enter the area through the opened door.

For keeping the area safe, it is most important to prevent the beam from being injected into the area. Therefore, when the 3GeV RCS area (50GeV MR area) is in Limited Access state or Controlled Access state, at least two dipole magnets in the L3BT (3-50BT) are interlocked off and a beam plug is inserted. In case of the Linac area, beam stoppers are inserted into the LEBT and MEFT. These devices are monitored redundantly, as mentioned before. If any failure occurs, the ion source is interlocked to be off.

In addition to the experimental targets, several beam dumps are installed for beam tuning. Their capacities (600W – 10kW) are much less than the full beam power (1MW at 3GeV or 750kW at 50GeV). When the beam is conducted to one of these dumps, therefore, beam power should be restricted within the capacity of the dump. This is accomplished by interlocking the beam operation if the average beam current exceeds the threshold, which depends on the operation mode. The averaging will be carried out by a computer or a circuit module.

So far we have described the part of PPS in the accelerator facilities. However, the rest of PPS is in the user facilities. The construction of this part should be performed under close collaboration between both facilities. Although the PPS areas in the user facilities are small, they must be constructed with great care because there are targets where the beam power as high as 0.75 – 1 MW is dissipated.

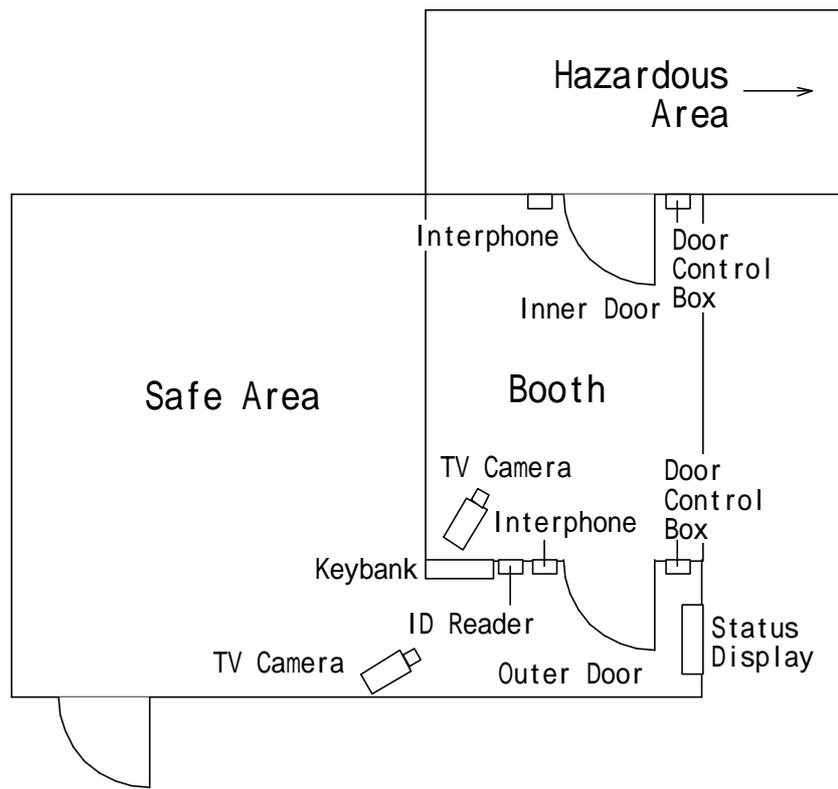


Figure 5.6.1 Conceptual drawing of the access booth