CONF- 950232--10

REQUIREMENTS AND DESIGN CONCEPT FOR A FACILITY MAPPING SYSTEM*

R. E. Barry and B. L. Burks
Robotics & Process Systems Division
Oak Ridge National Laboratory
Post Office Box 2008
Oak Ridge, Tennessee 37831-6304

C. Q. Little
Intelligent Systems Department
Sandia National Laboratory
Post Office Box 5800
Albuquerque, New Mexico 87185

To be presented at the
American Nuclear Society Sixth Topical Meeting
on Robotics & Remote Systems
Monterey, California
February 5-10, 1995

*Research sponsored by the Office of Technology Development, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

RWR

DISCLAIMER

REQUIREMENTS AND DESIGN CONCEPT FOR A FACILITY MAPPING SYSTEM*

R. E. Barry
Robotics & Process Systems Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6304
Telephone: (615) 574-7027
Facsimile: (615) 576-2081
E-mail: barryre@ornl.gov

C. Q. Little
Intelligent Systems Department
Sandia National Laboratory
P.O. Box 5800
Albuquerque, NM 87185
Telephone: (505) 844-8366
Facsimile: (505) 844-6161
E-mail: clittle@isrc.sandia.gov

B. L. Burks
Robotics & Process Systems Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6 304
Telephone: (615) 576-7350
Facsimile: (615) 576-2081
E-mail: burksbl@ornl.gov

I. ABSTRACT

The Department of Energy (DOE) has for some time been considering the Decontamination and Dismantlement (D&D) of facilities which are no longer in use, but which are highly contaminated with radioactive wastes.[1] One of the holdups in performing the D&D task is the accumulation of accurate facility characterizations that can enable a safe and orderly cleanup process. According to the Technical Strategic Plan for the Decontamination and Decommissioning Integrated Demonstration, "the cost of characterization using current baseline technologies for approximately 100 acres of gaseous diffusion plant at Oak Ridge alone is, for the most part incalculable."[2] Automated, robotic techniques will be necessary for initial characterization and continued surveillance of these types of sites. Robotic systems are being designed and constructed to accomplish these tasks. This paper describes requirements and design concepts for a system to accurately map a facility contaminated with hazardous wastes. Some of the technologies involved in the Facility Mapping System are: remote characterization with teleoperated, sensor-based systems, fusion of data sets from multiple characterization systems, and object recognition from 3D data models. This Facility Mapping System is being assembled by Oak Ridge National Laboratory for the DOE Office of Technology Development Robotics Technology Development Program.

*Research sponsored by the Office of Technology Development, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

II. REQUIREMENTS DERIVATION

The Department of Energy (DOE) Morgantown Energy Technology Center (METC) along with the Environmental Management (EM) Office of Technology Development (OTD), has funded many research and development efforts to address the problems of characterization and removal of hazardous waste from DOE sites. The areas of research and development span the spectrum from remote characterization using Coherent Laser Radar, Mass Spectrometry, Molecular Vibration Spectrometry, and Automated Chemical Analysis to Robotic Manipulation of hazardous wastes, Robotic Inspection Systems for stored waste, and more. This paper will define the requirements for a Facility Mapping System (FMS) which is capable of accepting input from a variety of sensor systems, storing and processing that input so that users can access it conveniently, and providing copies of the data accumulated to external systems. Because an FMS could have interfaces with many external systems, it is necessary to define these interfaces at some level so that systems developers can proceed with design and implementation on both sides of the interface. The intent is to define interfaces so that specific components can be replaced with other task-specific tools and thus provide a flexible, reconfigurable, mapping system. In order to support this discussion, several terms are defined as follows:

Mapping Session - A period of time during which characterization data for a specified volume of space within a facility are collected.

World Model - The composite data set for a facility. The world model shall contain a 3D geometric representation of the facility and all other collected data.

Task Space Model - A subset of a World Model. The task space model is used to define a facility volume within which a Decontamination and Dismantlement (D&D) operation is desired.

Specified Characterization Volume - A well-defined subset of a facility for which characterization data are desired.

Characterization Capability Definition - A definition of the capability of a sensor to characterize a volume of space. This definition shall include a specification of the volume that a sensor system is capable of mapping, estimated time, and data provided (e.g., spatial, radiometric, chemical or physical property, etc.).

A. General Facility Mapping Requirements

The FMS is a set of software processes with interfaces to one or more Robotic/Telerobotic Sensor Subsystems (R/TSS), a site specific Data Base Management System (DBMS), external image and data processing functions, a D&D planning and assessment module, as well as one or more Robotic/Telerobotic Manipulator Systems (R/TMS). The objective of the FMS project is twofold: (1) to define a system level architecture/approach for integration of a variety of sensors, data management tools and manipulation systems for D&D facility mapping and (2) to assemble a functional FMS using the products of the several DOE Program Research and Development Agreement (PRDA) contracts. Oak Ridge National Laboratory and Sandia National Laboratory are currently working on the integration of data from several different systems[a] developed under DOE PRDAs as well as systems from other DOE National Laboratories.[b] Figure 1 illustrates the proposed relationships between the FMS and other subsystems.

The FMS shall accept characterization data from and provide Specified Characterization Volume definitions to one or more R/TSS which are capable of independent navigation and of collecting data about internal facility structures and/or hazards.

The FMS shall consist of one or more computer subsystems which are capable of collecting, processing, storing, displaying, and outputting characterization data collected by one or more R/TSS.

The FMS shall contain interfaces to one or more R/TMS which allow for exchange of subsets of the World Model for a specific facility.

B. Robotic/Telerobotic Sensor Subsystems Interface Requirements

The FMS interfaces with a set of R/TSS which are controlled either autonomously or via teleoperation. Each R/TSS is capable of navigation and of collecting data about internal facility structures and/or hazards. There are currently four types of R/TSS deployment methods under consideration: gantry crane deployment, floor traversal, pipe crawling, and duct crawling. Of these deployment methods, the gantry crane, where it is available, provides the largest workspace. Floor traversal systems provide the next largest workspace, and may have manipulators that are capable of positioning sensor devices in hard to reach areas. The workspace of currently planned pipe and duct crawlers is limited to the structures they are deployed within although the capability of their sensors is not necessarily so limited. Each R/TSS will have one or more sensors capable of characterizing the facility in a domain of interest. The primary domains of interest are: spatial, chemical, radiological, material property, and video graphic, although other domains are also of interest.

---

a Coleman Research Corp., Springfield, VA, is developing the 3D-ICAS, Integrated Characterization and Archiving System; Mechanical Technology Inc., Latham, NY, is developing the Interactive Computer Enhanced Remote Viewing System.

b Idaho National Engineering Laboratory is developing both pipe and duct crawling systems for radiometric and visual inspection of internal pipes and ducts; Sandia National Laboratory has developed MINILAB, a multisensor system for hazardous waste characterization; Oak Ridge National Laboratory and Savannah River Technology Center are developing the Modular Autonomous Characterization System for radiometric characterization of floors.

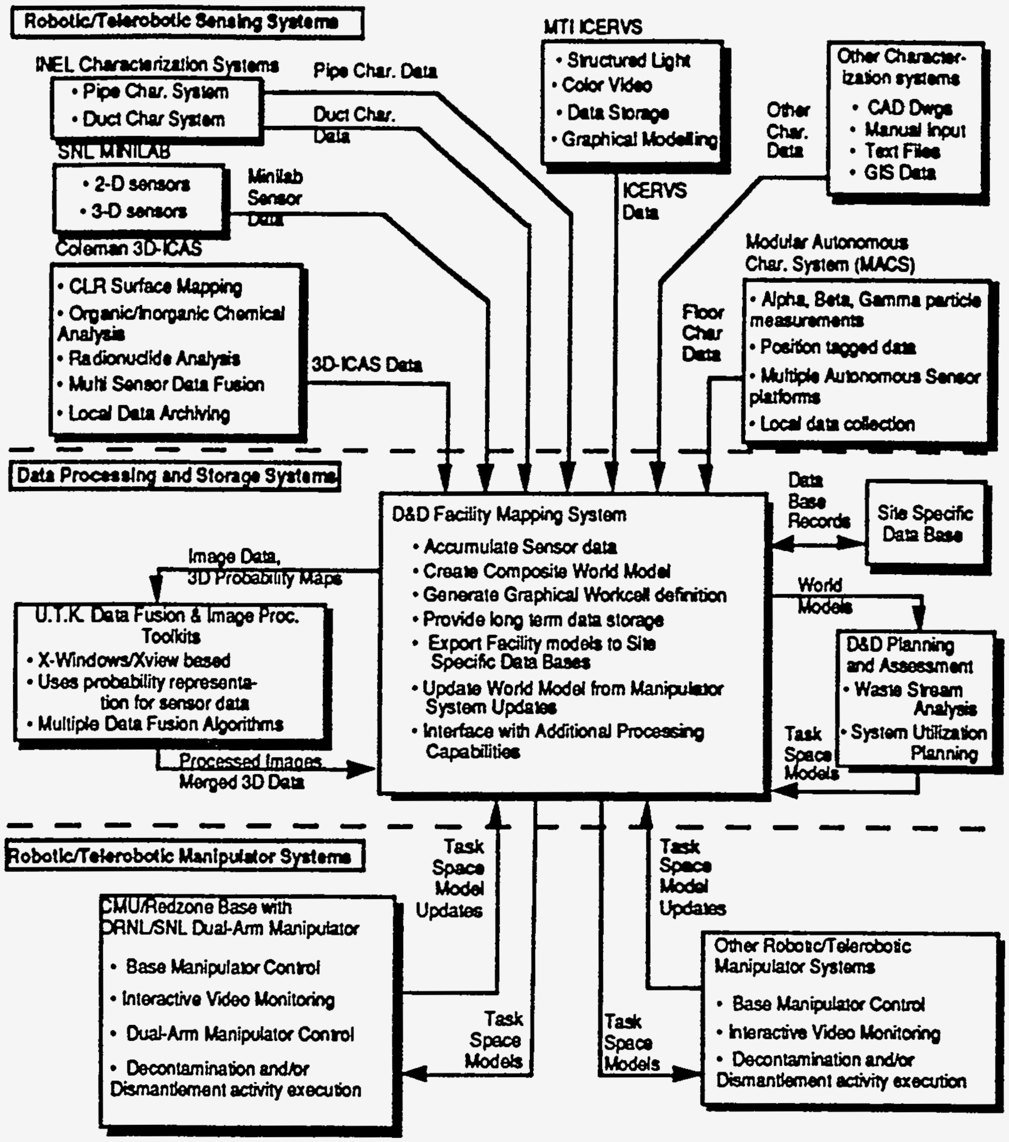

Figure 1 - Facility Mapping System Interface Diagram

Requirements for the R/TSS are further subdivided in this section as general, mobility, and sensor-related.

1. General R/TSS Interface Requirements

The FMS will construct a composite view of the facility being mapped from the individual sensor data sets, CAD drawings, and other inputs. In order to simplify the FMS implementation each sensor subsystem is required to present its data to the FMS in the form of a surface model and as a "raw" data set. The "raw" data set is envisioned as being the positional data combined with the sensor data values for each point evaluated by a sensor.

1.1. Raw-sensor data sets shall contain a header record with data acquisition start time, a unique sensor ID, operator ID, the facility name, calibration data, specified characterization volume and any other sensor specific data that may be required for post-processing of the data.

1.2 Surface model data sets shall contain a header record with data acquisition start time, a unique sensor ID, operator ID, and the facility name.

1.3 Each sensor data set shall be referenced to a detectable, primary "landmark" or "fiduciary" point, for which the position is defined as (0,0,0) in Cartesian space, and for which the orientation of the X and Y axes are defined by at least one additional "landmark" point. The Z axis defined as orthogonal to the X-Y plane. The X and Y axes will always be planar to the floor, and the Z axis positive range will always indicate an increase in altitude.

Facilities may have additional "landmark" points other than the primary landmark. If additional "landmark" points are used they should be placed at well-known offsets from the primary landmark. R/TSS are not required to register to all the landmarks, although multiple registration should provide additional navigational accuracy.

1.4 Each R/TSS shall provide a graphical, surface model representation of its raw data set, if possible, to the FMS server process in the format defined in the D&D FMS Graphical File Format specification.

1.5 Surface mapping sensors shall provide a confidence factor for each data point represented in a scanned volume. The confidence factor shall indicate the probability that a data value is accurate and shall range from 0 = no confidence to 1 = certainty.

1.6 Each R/TSS shall provide a characterizaton capability definition when requested by the FMS.

C. Data Storage and Display Subsystems

The Facility Mapping Data Collection and Processing subsystem is a system of computers dedicated to the tasks of storing, processing, and displaying data collected from the R/TSS so that a composite view of the facility being mapped can be obtained. The Display portion of this subsystem provides viewing of both the graphical and video representations of the entire facility and allows for user-defined filtering of the data to be displayed. The Processing portion of this subsystem provides functions such as user-interactive object identification, world model export to other systems, import of world model subsets from other systems, export of raw sensor data to other processing systems, and import of processed sensor data from other processing systems. The Data Collection portion of this subsystem provides the mechanisms for collecting data from the various R/TSS for which an interface has been developed.

1. **Data Collection.** The data collection phase of facility mapping will be driven by the R/TSS. When an R/TSS has collected data and completed local processing it will initiate a data transfer to the FMS.

1.1 Collection of data from the R/TSS by the FMS shall be accomplished using a client/server paradigm where the FMS is considered the server and the R/TSS are considered clients.

1.2 Each R/TSS shall define a unique External Data Representation (XDR) for each sensor data set and each graphical data set to be transmitted to the FMS. When an R/TSS merges or "fuses" data from multiple sensors, it shall pass the merged data set but may also pass the individual, "raw" data sets to the FMS.

1.3 The FMS shall provide a server process based on the XDR for that data set, for each raw and graphical data set defined for each R/TSS.

1.4 Each FMS server process shall be capable of receiving and storing the sensor data passed to it by an R/TSS client process.

1.5 The FMS shall be capable of collecting data directly from network resources without providing an explicit client/server interface. This type of data collection is envisioned for data such as CAD models, manually entered text data, and data which cannot be provided through the client/server, XDR-based interface.

2. **Display Requirements.** The FMS will generally display data through a 3D graphical world modeling format, using surface modeling techniques, with a high-speed graphics engine for display. The inputs into this world model include the various sensor determined data as well as physical layout of the facility, most likely generated from engineering drawings and floor plans but also from object modeling of sensor data. The world model will be enhanced by additional, pre-defined models of known equipment within the facility. Tools will be incorporated to provide interactive model modification. and techniques such as object modeling from stored, remote system video images will be added. Once data have been incorporated into the FMS, a user interface will aid the user in exploring the mapped facility.

2.1 During the data collection phase of facility mapping, the Data Collection and Processing subsystem shall be capable of decompressing and displaying mpeg video streams at 15 frames/s from any R/TSS that has transmitted such video. An initial implementation should support switching of video input from the various R/TSS that supply a video signal while in operation.

2.2 To support the display of data, this subsystem shall contain a user interface that allows users to select any available data type (e.g., radiometric, chemical, or physical property data) for display either by itself, or with other data types. This subsystem shall also be capable of displaying data by individual data set.

2.3 All data displayed by the Data Collection and Processing subsystem shall be represented by a surface model which indicates the actual data sampling point(s) in the facility being mapped.

2.4 Data that is too complex to display as a surface model, such as gas chromatography data, shall be indicated by a surface modeled "data indicator" such as a small sphere or box, which when selected from the user interface will cause an additional display window to be opened.

2.5 The display window opened by a user reference to a "data indicator" shall display the detailed, raw, sensor-data set in a graphical manner where possible, otherwise, in a tabular manner with appropriate textual headers.

2.6 The Data Collection and Processing subsystem shall be capable of outputting an ASCII data file that contains the actual sensor measurements for a data set or subset that is being viewed by the user. The ASCII output shall be formatted with textual headers indicating the meaning of the data.

2.7 The user interface shall allow the user to "navigate" the facility map quickly, so that a complete facility surface map representation can be "walked through" at user determined speeds.

2.8 The Data Collection and Processing subsystem shall be capable of displaying image information overlaid on graphical object surface models as a texture map.

2.9. The user interface shall provide the ability to select a specific data type, such as "alpha particle count" and then display all facility areas with levels of concentration or intensity that exceed a user-defined threshold.

2.10 The facility map shall be displayable showing all sensed contaminants, in a color-coded manner, for a volume of the facility identified by the user.

2.11 The user interface shall provide a zoom capability that allows the user to enlarge a facility volume display so that a single sample point fills the entire display window, and to reduce the displayed data so that an entire facility can be displayed within one window.

3. Processing Requirements

3.1 The Data Collection and Processing subsystem shall be capable of accepting input from any R/TSS subsystem, and of displaying the sensor data with other sensor data in order to provide a composite data view.

3.2 The Data Collection and Processing subsystem shall be capable of exporting raw data sets from multiple inputs to an external process.

3.3 Data from each separate sensor shall be stored so that it is accessible separately, or in combination with, other sensor data

3.4 The Data Collection and Processing subsystem shall be capable of segmenting and classifying objects from the surface modeled data.

3.5 The Data Collection and Processing subsystem shall be capable of registering multiple data sets to the FCS.

4. Data Storage Requirements

4.1. The Data Collection and Processing subsystem shall be capable of storing raw and surface modeled sensor data for all R/TSS subsystems for as long as the data are considered useful.

4.2. Data storage shall consist of "on-line fast" data, which can be accessed in < 15 ms. (e.g., memory or hard disk), "on-line slow" data which can be accessed in < 500 ms (e.g., CD-ROM), "near on-line" data which can be accessed in < 1 h (e.g., local tapes, CD-ROMs) that are unmounted, and off-line data which can take > 2 h to access (e.g., remote tapes, CD-ROMs). Initial estimates of required storage amounts for each of these types of data are indicated below:

Table I. Required Data Storage Amounts by type of data

on-line fast	~10 GB.
on-line slow	~20 GB
near on-line	~40 GB
off-line	~50 GB

4.3 At the very least, the FMS shall be capable of storing all data from a single facility mapping exercise in on-line fast storage.

D. R/TMS Interface

As part of the overall D&D activity, facility mapping must output usable data to remote manipulator systems and to external viewing systems so that the characterization data collected can be reviewed or used for simulation or actuation of manipulator activity. The manipulator systems that will be used for D&D activities may vary from operation to operation. Because of this fact, it is desired that a standard method of supplying facility data to manipulator systems and other external systems be defined. Use of the IGRIP program from Deneb Robotics, as the main robotic simulation package within the DOE Robotics community, allows the facility mapping system to standardize on an IGRIP data model for graphical representation of collected data. The FMS shall provide an IGRIP model of all geometry mapped to any external system requesting it. Additional characterization data not suitable for representation within IGRIP shall be provided in an Standard Query Language (SQL) based DBMS.

E. Site Specific DBMS Interface

As the facility world model is created, it will be necessary to organize hazard data by other than volumetric index. Initially, all material, property, radiological, and any other sensor data will be indexed by its location in the volume space that has been sampled by the R/TSS. Once the data collection is complete it will be beneficial to export the hazard information to a relational DBMS so that searches can be accomplished using a SQL. For this reason, it is required that the FMS provide an export capability to an external DBMS. Data table definitions will be given to the DBMS system in advance, so that this interface will consist of the actual data transfer only.

F. Planning and Assessment Module Interface

The FMS shall be capable of exporting complete World Models of a facility to an external Planning and Assessment Module. This export shall be accomplished by transferring the surface model representation of a facility, along with all material and property data.

III. DESIGN CONCEPT

The design of the FMS will be a dynamic process that will need several iterations before successful implementation can occur. Additionally, construction of the various subsystems will not be performed by the same organization. A flexible, yet powerful mechanism is needed in the FMS design that will allow components from multiple developers to be integrated successfully. The basis of the FMS design will center on a modular architecture, network-based communications, and object-oriented software development. Conceptual system components are shown in Fig. 2.

Since one of the main goals of the FMS is to convert sensor data into 3D geometric models, a large part of the FMS system is dedicated to visualization and geometric object modeling. Geometric object modeling is necessary so that the expected large volume of sensor data can be compactly stored and viewed. While the bulk of the FMS processing in this area is planned to be user interactive, it is realized that some of the geometric object modeling could and should be automated. The Autonomous section of Fig. 2. indicates that sensor data processing and geometric object modeling could have autonomous process paths that run parallel to the interactive paths. This feature allows for as much automation of the mapping process as is feasible.

In actuality, the bulk of the FMS is contained within the capability to import data from multiple sensor systems, process and display the data, and export 3D geometric models based on the sensed data. A high level object oriented design of the FMS is shown in Fig. 3. Several data stores are shown outside of the objects which would serve them so that the reader may get a better concept of information flow.

A. Robotic/Telerobotic Sensor Systems

The sensor systems that make up the front end of the FMS will vary according to the type of facility and type of contamination expected. The intent of this document is not to design individual sensor systems but to define a framework within which a given sensor system may interface to the FMS. The requirements portion of this paper define various interface requirements for all types of sensors. This section will only attempt to describe some of the common functionality needed as well as a fairly generic data collection and transfer protocol that can be used to communicate an area to be sensed by a particular sensor, as well as a mechanism by which the sensed data can be transferred to the FMS for processing.

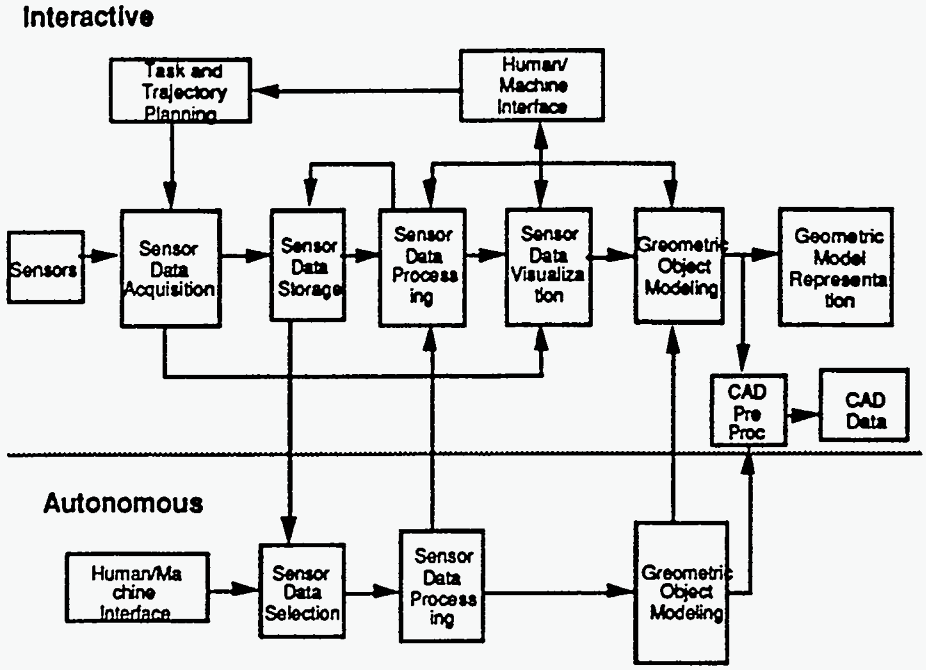

Figure 2. Conceptual Components of the Facility Mapping System

One of the main concerns with handling multiple sensor data input is registration of the data sets to one another. Without a workable method for referencing data sets among and within the various sensor data collection sessions, it will be extremely difficult to make good use of the resulting data. The FMS will provide enough direction to individual sensor systems so that the data sets collected are usable and integrateable as a whole. The form of this direction will be to specify a set of reference points which bound a volume to be mapped. A resolution factor will also be given which indicates the level of detail needed by the FMS. Each sensor system will be responsible for collecting data sets that are of good quality, have consistent resolution, and are locatable relative to the Facility Coordinate System (FCS). The design of this portion of the FMS will be client-server based with the FMS application acting as the client to a Sensor Interface Subsystem. The Sensor Interface Subsystem will receive all commands destined for sensor systems and route them to the appropriate sensor control system. Individual sensor interface modules will act as servers for specific sensor functions, such as queuing up data collection requests and translating raw sensor data into standard format.

A set of fairly common capabilities can be anticipated from the above requirements. First is a common capability to detect some sort of fiducial point and calculate relative sensor system position. Although the type of fiducial points to be used is not yet determined, it can be assumed that each point will at least have an associated ID number. Ideally, each fiducial point would also contain its offset from the FCS encoded in a machine readable format.

B. Data Storage, Processing, and Display

The data storage, processing, and display portion of the FMS represents the bulk of the system functionality. This portion of the FMS deals with image processing of the raw sensor data sets, fusion of multiple data sets into unified 3D views, surface modeling, object modeling, feature annotation, visualization of the data, and conversion of the data into CAD format as needed by Manipulator Systems. The main agents of these functions are the Image Processing subsystem, the Volumetric DBMS, the Surface Modueler Subsystem, the Object Modeler Subsystem, the Feature DBMS, and the Model Conversion Subsystem. Each of these subsystems will be discussed separately below.

1. Volumetric DBMS. The heart of the Data Storage, Processing, and Display system is a commercial, volumetric DBMS which supports multiple data set storage, display, and manipulation. The DBMS provides union and difference functions between data sets, geometric data representations, and attribute data storage

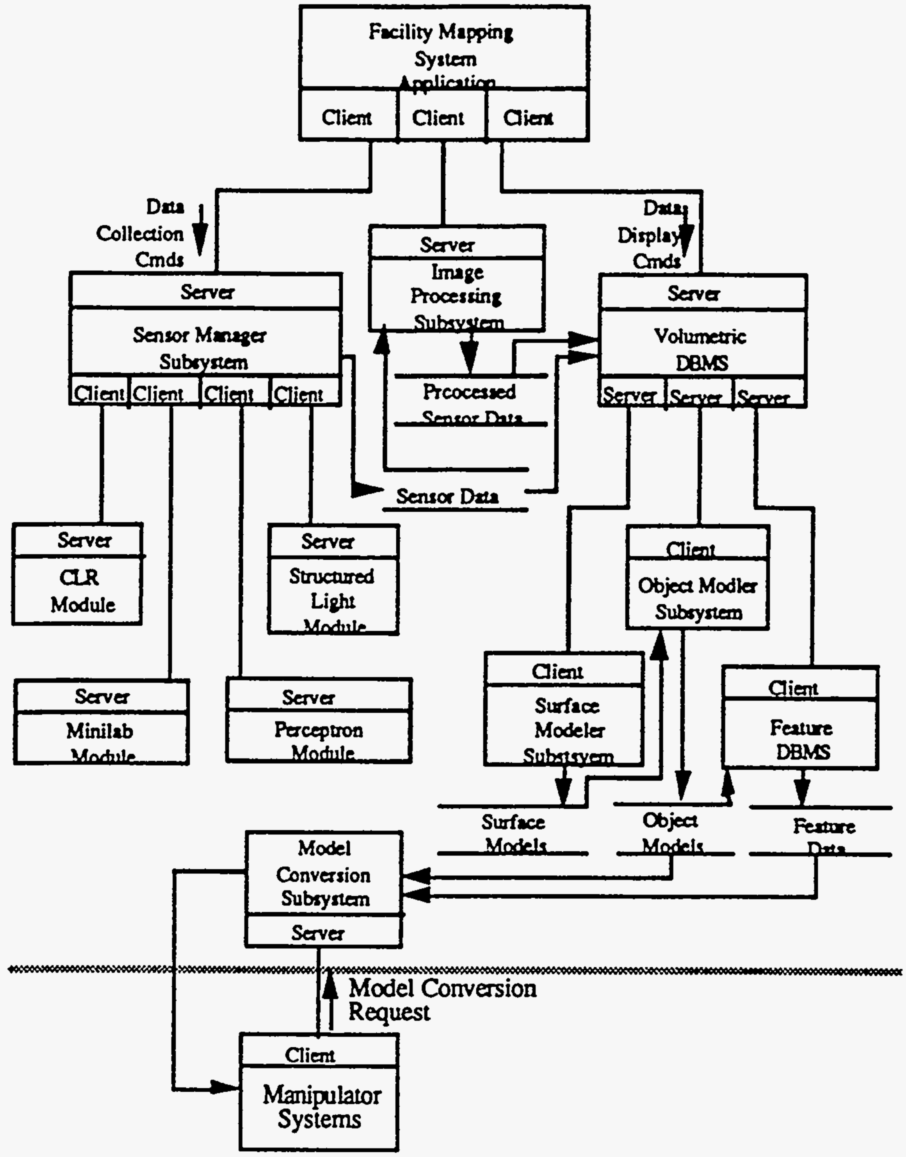

Figure 3. Facility Mapping System Top Level OOD

for each data point. The Volumetric DBMS is an octree based DBMS named TrueSolid, produced by OCTREE Corp. Octree-based storage of volumetric data collected by the Sensor Interface Subsystem allows each data set to be represented independently, but also supports the merging of multiple data sets under user commanded interaction. Processed sensor data sets may represent "virtual sensors" in that they are created from "raw" data sets by a well-known transform function, or by a fusion of multiple "raw" and/or "processed" data sets. Client modules can request specific volume data from the volumetric DBMS by individual sensor type, individual data set, or by virtual sensor type for further processing or modeling. Client modules may also request the display of data sets from various perspectives by the volumetric DBMS. See the following section on Data Display commands for details of the display capabilities of the volumetric DBMS.

2. Image Processing. The Image Processing subsystem consists of a collection of image processing and data fusion programs which are capable of operating on "raw" sensor data sets. Example of functionality to be implemented within this module include: edge detection, line detection, range image segmentation, range image histogramming, image morphology, and multiple image fusion. This module is capable of generating new "virtual sensors" by modifying or creating new data sets from existing "raw" sensor data. These "virtual sensor " data sets can then be added to the Volumetric DBMS to support surface modeling and object modeling.

3. Surface Modeling. The Surface Modeling subsystem is used to generate surface contours from the collection of volumetric data sets. This subsystem provides the FMS user with several different surface modeling techniques such as triangular mesh, rectangular mesh, octahedral mesh, marching cubes, and union of spheres. The FMS user will select the technique that generates the best results for object modeling.

4. Object Modeling. The Object Modeling subsystem is a highly user-interactive program which supports the definition of a geometric Object Model of the facility, based on collected sensor data. The Object Modeling subsystem is served volumetric data by the Volumetric DBMS and has visibility into Surface Models created by the Surface Modeling subsystem. The Object Modeling subsystem assists the FMS user in defining the separate geometric objects within the facility, to the level of detail needed by the user for D&D planning. This subsystem is supported by a set of predefined, site-specific object definitions which can be quickly added to the facility Object Model by identification of common points in the volumetric data and the geometric representation.

5. Feature DBMS. The Feature DBMS will hold the detailed feature data ascribed to geometric objects once they are defined. Sources of feature data are sensor data files, predefined object definitions, user entered characteristics, and attribute data in the Volumetric DBMS. Since the Volumetric DBMS has the capacity to store attribute data associated only with precise 3D points, this data needs to be related to geometric objects generated by the Object Modeling subsystem. The Feature DBMS will be a commercial DBMS that can support multi-user access, SQL queries, and time dependent data display. The users of the Feature DBMS will want to monitor how contamination data (an attribute of a specific 3D point or object) has changed over time due to various decontamination activities. The Manipulation system may want to know the weight and center of gravity of an object before attempting to relocate it.

6. Data Display Commands. Data Display commands that will be processed by the Volumetric DBMS are as follows:

1. Select data set for display.
2. Rotate data set in X, Y, or Z axis direction.
3. Translate data set in X, Y, or Z axis direction.
4. Display union of two data sets.
5. Display differences between two data sets.
6. Display differences between data set and geometric object.

7. Model Conversion Subsystem. The Model Conversion subsystem is a simple module that provides a conversion service to client modules. This module is able to convert the FMS internal representation into various CAD type models for use by other systems. Expected CAD output types are IGRIP Workcell, AUTOCAD 3D Render, and ProEngineer Render. The conversion process is accomplished by a call with parameters indicating output type desired and the facility model to be converted.

C. Manipulator System Interface

Manipulator systems for D&D applications will typically require some information about the environment within which they will operate. The intent of the FMS to Manipulator systems interface is to provide a two-way path for communication of facility model data. The FMS will generate "coarse" facility models with sparse attribute data. The manipulator systems will use these data as well as local sensor data to construct a high-resolution "task space model" of the work area. Once a D&D activity has been completed the Manipulator system will provide the high-resolution "task space model" representing the final state of the workspace to the FMS. This will ensure that the FMS data bases are always kept current.

IV. SUMMARY

We have described a set of requirements for a FMS that has the capability to accumulate both raw and processed data from a variety of sensor systems, generate 3D geometric models of the raw data, archive pertinent characteristics to an external data base, and export World Models to both manipulator systems and planning modules. The system described is being constructed at ORNL under funding from the DOE OTD to demonstrate solutions to specific Mapping, Characterization, and Inspection problems inherent within the D&D domain.

V. REFERENCES

1. Oak Ridge K-25 Site Technology Logic Diagram, Volumes 1, 2, 3A, 3B. Martin Marietta Energy Systems document K-2073, February 26, 1993.

2. Technical Strategic Plan for the Decontamination and Decommissioning Integrated Demonstration, Los Alamos National Laboratory Document number LA-UR 93-2758, October 29, 1993.