

Robotic Radionuclide Inspection and Mapping of Surface Contamination On Building Surfaces

Georg F. Mauer, Chris Kawa
Department of Mechanical Engineering
University of Nevada, Las Vegas
Las Vegas, NV 89154-4027
USA

ABSTRACT

The mapping of localized regions of radionuclide contamination in a building can be a time consuming and costly task. Humans moving hand-held radiation detectors over the target areas are subject to fatigue. A contamination map based on manual surveys can contain significant operator-induced inaccuracies.

A Fanuc M16i light industrial robot has been configured for installation on a mobile aerial work platform, such as a tall forklift. When positioned in front of a surface, the robot can map the radiation levels over a surface area of up to 2m by 2m. The robot's end effector is a commercial alpha-beta radiation sensor, augmented with range and collision avoidance sensors to ensure operational safety as well as to maintain a constant gap between surface and radiation sensors. A graphical user interface guides the robot operator to position the robot at the desired wall segments, and to select an area for surveying. After the operator has entered the required parameters, the custom surveying software plans the scan sequence, alerts of any potential problems, such as unreachable singularities, and creates a contamination map of the surveyed region. Maps of multiple regions can be combined into a single map of the entire region. The survey data are stored in a data base file. In addition to automated surface scans, operators can manually select regions for further inspection, as well as control the end effector motion manually. In comparison to manual contamination surveys, the robotic approach is more accurate, reliable, and faster.

INTRODUCTION

The US Department of Energy (DOE) is charged with cleaning up contaminated areas at the Nevada test site (NTS). Contaminants are mostly radionuclides, especially plutonium. In former laboratory buildings contamination is found on isolated spots on wall surfaces. In order to minimize waste quantities, these contamination 'hot spots' must be located, quantified, and mapped.

Radiation contamination surveys of large areas are often time-consuming, and it can be difficult to correlate contamination readings with the sample's location when manual surveying and data logging methods are employed. Among products addressing the need for more efficient surveys are the Surface Contamination Monitor / Survey Information Management System (SCM/SIMS)

by Millenium Services, Inc, and related designs by Shonka Research Associates, Inc., [1,2]. Here, the radiation sensors are mounted on a vehicle and moved over the contaminated terrain by an operator. Data are stored by a data logger. A description of the inspection robot design and path planning is given in Mauer and Kawa [3]. Robot documentation is contained in [4].

The project objectives were two-fold:

- (1) Non-contact inspections of surface contamination of walls in order to reduce the need for decontamination.
- (2) Fully automated radiation survey of the target area.

The Contamination Survey Machine (CSM) was designed and built to automate radiation measurements. It is intended to measure contamination levels on walls in buildings previously used to process radioactive material

CONTAMINATION SURVEY MACHINE

The Contamination Survey Machine (CSM) consists of a computer controlled robot mounted on a steel pallet. A forklift positions the robot vertically and laterally in front of large wall surfaces. Custom software applications control the robot and store, manage, and display the measured radiation data.

The CSM uses an alpha-beta scintillation probe to carry out both ratemeter and scaler surveys. For ratemeter surveys, the robot arm scans the probe in a serpentine path over the wall, gathering ratemeter measurements every few inches. The user specifies the scan speed and survey gap.

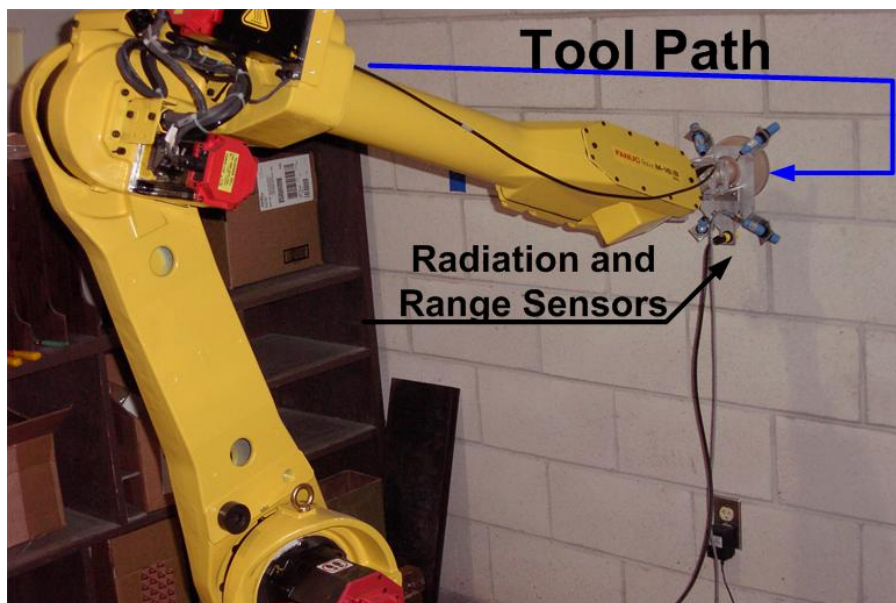


Figure 1 Inspection for Radionuclide Contamination with Fanuc M16i Robot

The CSM can scan a rectangular area up to about 2m by 2m (6ft by 6ft). Multiple area scans map larger surface areas. The CSM software manages the collection, storage, merging, and display of these area-survey datasets. For scaler counts, the robot positions the radiation probe

over a selected point. The user specifies the location, gap between surface and scintillation probe, and scaler-count duration. Upon completion, the counts are stored in a data file, along with the date, time, and location information.

Position and radiation data are collected and stored in real time during the scan. After the completion of the survey, a spatially accurate map of the contamination distribution can be created for D&D purposes. The robot end effector is equipped with the radiation probe and with non-contact sensors for collision-avoidance and for control of the gap between the radiation probe and the wall. Flat wall surfaces in many laboratory buildings are interspersed with protruding columns as well as recesses. The robot controller can follow continuous changes of wall curvature, but not steep changes of slope that would occur for instance when encountering protruding columns or conduits. In those cases, the operator should conduct inspections of regions having different depths in separate scan segments.

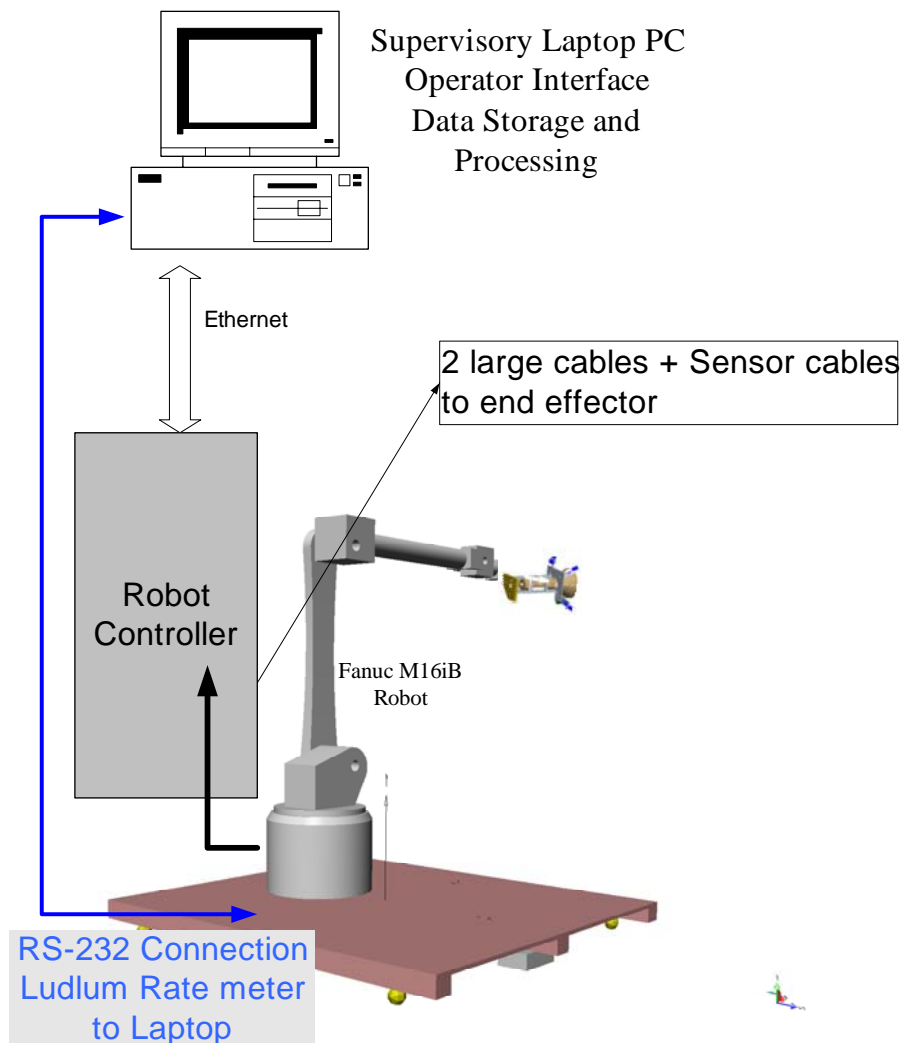


Fig. 2 Configuration of Contamination Survey Machine

Figure 1 shows the conceptual CSM design: The robot is mounted on a mobile platform such as a forklift, and positioned at regular intervals in front of the target surface. At each platform position, the robot can automatically survey an area of up to 2m by 2m. In order to ensure

consistent data and safe, collision-free operation, the robot end effector is equipped with range sensors in the direction of the wall as well around all sides. The sensors ensure that the robot controller can automatically maintain the end effector trajectory at a constant gap distance of 1 cm normal to the wall surface, as well as prevent collisions with possible unmapped obstacles, such as ducts or columns protruding from the wall. The sensors provide real time position feedback to the robot controller. The end effector trajectory normally moves along a horizontal meandering pattern as seen in Fig. 1.

Fig. 2 shows the complete CSM system. A laptop PC plans the robot motion patterns, collects process and contamination data, and supervises the robot during the contamination survey. In those cases where multiple scans of an area have been performed, a post processor computes a contamination map of the entire surface. The robot is mounted onto a steel pallet which is designed for rapid attachment to a forklift. The forklift should be selected to reach the required vertical elevation and have a minimum lift capacity of about 450 kg.

SOFTWARE FOR PATH PLANNING, ROBOT CONTROL AND DATA ACQUISITION

The CSM control software is written in two languages: Visual Basic (VB) and the Teach Pendant (TP) programming language. Visual Basic runs on the laptop PC, while TP is embedded in the R-J3 robot controller.

VB is an object-oriented, event driven language. Fanuc provides access to robot control via their PC Developer's Kit (PCDK) through a purchasable option. TP is an interpreter language used to write robot control programs.

In the CSM, the user interface, the data display and the supervisory control over the robot are encoded in Visual Basic. The VB controller routines in the PCDK convey commands to the TP routines in a master-slave configuration. All path planning and gap control calculations are carried out in VB. Small TP programs carry out motion segments as computed by VB. The robot controller contains over 8000 lines of VB source code, about half devoted to robot control. In contrast, there are 8 TP programs called by VB, most less than 10 lines long.

Visual Basic software

The CSM user interface is a Visual Basic Windows GUI application providing point and click control over radiation surveys. The functions coded in VB fall into three categories: User Interface, Radiation Display, and Robot Control. The VB source is divided into forms, modules, and a single class as follows:

- 20 forms for the user interface
- 2 code modules for utility functions
- 1 class module to encapsulate the robot control algorithms.

Robot Control algorithms

The robot control algorithms fall into 4 categories:

- 1) wall acquisition
- 2) area scan ratemeter survey
- 3) point scaler survey
- 4) collision avoidance

Wall Acquisition

Wall Acquisition refers to the process of accurately computing the robot's location relative to the wall being scanned. There are two parts to this calculation: user inputs and robot measurements. This calculation includes compensation for the uncertainty of robot orientation that results from the manual positioning in front of the wall by a forklift. It suffices to position the robot visually approximately normal to the wall. The wall acquisition software then computes the true spatial orientation and plans the scan patterns accordingly.

Before each area scan, the program asks the user to enter the Cartesian x- and y-position coordinates of the robot base relative to the surface region being scanned. The reference points are the lower left corner of the wall and a reference corner marked on the pallet. The user also specifies the row spacing to be used for the area scans. During the wall acquisition process, the robot controller measures 3 parameters with high accuracy:

- a) the range (distance) between the robot's origin and the wall surface
- b) the pitch angle of the robot relative to the wall surface
- c) the yaw angle of the robot relative to the wall surface

These measurements are carried out through the following robot motions:

- a) the robot arm moves forward until the laser range sensor detects the wall
- b) the robot arm scans vertically to measure the pitch angle
- c) the robot arm scans horizontally to measure the yaw angle.

During the pitch scan, the arm moves vertically over a distance of 300mm, collecting approximately hundred range measurements. The range measurements are then processed using a least-squares algorithm to yield a raw pitch measurement. The yaw scan is analogous to the pitch scan, with the end effector moving parallel to the wall surface in the horizontal plane. When both scans are completed, an estimate of the range (distance between robot and wall), and of the pitch and yaw angles is computed and used for robot path planning. Our tests show that the angular estimation error in any direction is generally less than 0.5 degrees. This level of accuracy is sufficient to orient the radiation probe approximately normal to the wall.

The robot measurements are then combined with the pallet measurements and the known offsets between the robot origin and the pallet reference corner. This calculation yields a final estimate of the location of the robot's origin relative to the wall's lower left corner. This location, along

with the robot's orientation, is used to convert robot arm locations during a scan to positions on the wall.

The completed estimates for pitch and yaw also allow the calculation of some robot-to-wall coordinate transforms. These transforms map the unit vectors from the robot frame into the local wall frame, and vice-versa. These unit vectors are used in the area scan and point surveys.

Area Scan Ratemeter Survey

During an area scan ratemeter survey, the robot scans the radiation probe over the wall using a serpentine path. The rectangular area scanned is called a "patch". The limits of the area are graphically specified by the user using the "patch planner" form. The patch planner calls the robot class's path planning function. The path planner creates a path that avoids the robot's singularities (i.e. unreachable destinations). The data from each scan are stored in a "patch file". The user specifies the name of the patch file.

While scanning, the ratemeter and robot are periodically queried. These simultaneous measurements associate the radiation measurements with a position in robot coordinates. The robot coordinates are then transformed using the acquisition data to yield positions on the wall. The survey gap and speed are user inputs.

The gap commands are limited to numbers between .4 and 3.3 inches. The lower limit is to avoid collisions. The higher limit is derived from the maximum range of the sensor, plus some margin to avoid saturation. The speed commands are limited to numbers between 0.4 and 2 inches/second.

As the robot scans a row, laser range measurements of the next row are gathered. By knowing: a) the laser range, b) the row spacing, c) the robot's position associated with each laser range measurement, and d) the orientation of the robot relative to the wall, compensated motion control points can be computed. The compensated motion control points are found using the local-wall unit vectors mapped into the robot's own coordinate frame.

The ratemeter signals (alpha and beta counts) exhibit some rise and decay lag. These lags result in a "smearing" of the radiation data. Faster scan speeds result in more smearing, lower speeds in less, at the expense of longer measurement times. For example, a scan of a 6ftx6ft area at 1 in/sec takes about 45 minutes.

Point Scaler Survey

During a point survey, the robot is commanded to hover over a point on the wall and engage the scaler count feature of the Ludlum 2360 scaler/ratemeter. The user specifies the survey gap, survey location, and the duration of the scaler count.

Collision Avoidance

During most robot motion segments several distinct threshold conditions are monitored in the background:

- 1) the state of the proximity sensors
- 2) power supply to the sensors
- 3) the laser range signal dropping below 3mm.

If any of these conditions are violated during a scan, the robot will stop. When a scan is aborted, the following events take place:

- 1) the robot motion stops,
- 2) the robot backs up 1 inch, reversing it's direction of travel,
- 3) the robot retracts to it's home position,
- 4) a message flashes on the user's screen indicating the cause of the abort,
- 5) any data gathered up to that point is erased.

Visual Basic Forms and Modules

The VB software is organized in 23 code modules. Several forms are described in the appendix at the end of this paper.

Robot_Algorithms Class

This class module encapsulates all of the VB robot control algorithms. During execution, the CSM software creates a single instance of this class. All algorithms are accessed via user interface functions.

The robot algorithms object consists of both public and private methods. The public methods form the robot's interface. The private routines are for internal calculations.

The robot class contains 31 functions and subroutines.

Frames of Reference

The robot's world frame (abbreviated as the "bot" frame in code) is specified by the manufacturer (Fanuc). The origin of the bot frame is located at the intersection of the Joint-1 axis and a plane, normal to J1, that passes through Joint-1. This is a fixed point, relative to the robot, 525mm above it's base, along the J1 axis. All commands to the robot are referenced to this frame. The axes are: X-forward, Y-Left, and Z-up. When a forklift elevates the robot, there will be random element to the orientation of the robot and its frame of reference. The wall acquisition process estimates those random elements.

The robot class uses four distinct frames of reference as follows:

- 1) The UserWall frame
- 2) The robot's "world" frame (the "bot" frame)
- 3) The local-wall frame

4) The coincident frame.

The UserWall frame has its origin at the lower left corner of the wall being surveyed. Its x axis is horizontal and positive to the right. Its Y axis is vertical and positive up.

TP (Teach Pendant) software

The TP language offers several options for robot control. Some capabilities used by the CSM are:

- storing positions for re-use
- commanding joint motions
- commanding linear motions
- multi-thread execution
- control over joint + linear speed
- control over start and stop acceleration
- absolute and incremental movements
- direct access to both digital and analog sensor signals
- background condition monitoring to trigger sensor-driven interrupts
- logic for conditional branching and looping.

Some limitations of the TP language include:

- no variable names
- limited arithmetic logic (e.g. no trig).
- code entry via the Teach Pendant.

VB-TP Handshaking and Communications

The VB robot algorithms call TP programs in the robot controller. VB communicates with the TP programs by both direct calls for execution and through registers to exchange data.

Two types of registers reside in the RJ3 controller: numeric registers and position registers. Numeric registers hold a single number, and can be thought of as variables. Position registers contain 6 or 7 data items to completely specify a robot position. In joint coordinates, these are the 6 joint angles. In linear coordinates, these would be x, y, and z coordinates, roll, pitch, and yaw angles, and a configuration string. The configuration string resolves kinematic ambiguity.

WALL CONTAMINATION SURVEYS



Fig. 3 The Wall with Lantern Mantles (Alpha and Beta Emitters) attached.

Much of the software described above is devoted to operational safety, and to guiding the user consistently through the data acquisition and survey process. The user selects the wall area to be scanned using either the VB GUI, or by manually moving the robot to two corner locations (upper left and bottom right corners of the area to be mapped). The user should verify through visual inspection that the selected region is reasonably flat. Regions containing sharp protrusions or cavities should be scanned separately or manually. After the region has been selected and the controller has verified that it can reach all targeted locations, the scan proceeds automatically. The laptop PC reads the alpha and beta records from the ratemeter and stores them together with the pertinent location information.

Figures 3 and 4 show an experiment in which four gas camping lantern mantles (Alpha and Beta Emitters) were attached a cinderblock wall segment. The total scanned area is 6ft wide by 18 feet tall. The wall area was scanned at three vertical robot positions. All three datasets were merged

into two comprehensive maps of radiation sources. Fig. 4 shows the resulting composite Beta contamination map, which corresponds well with the locations of the mantles on the wall.

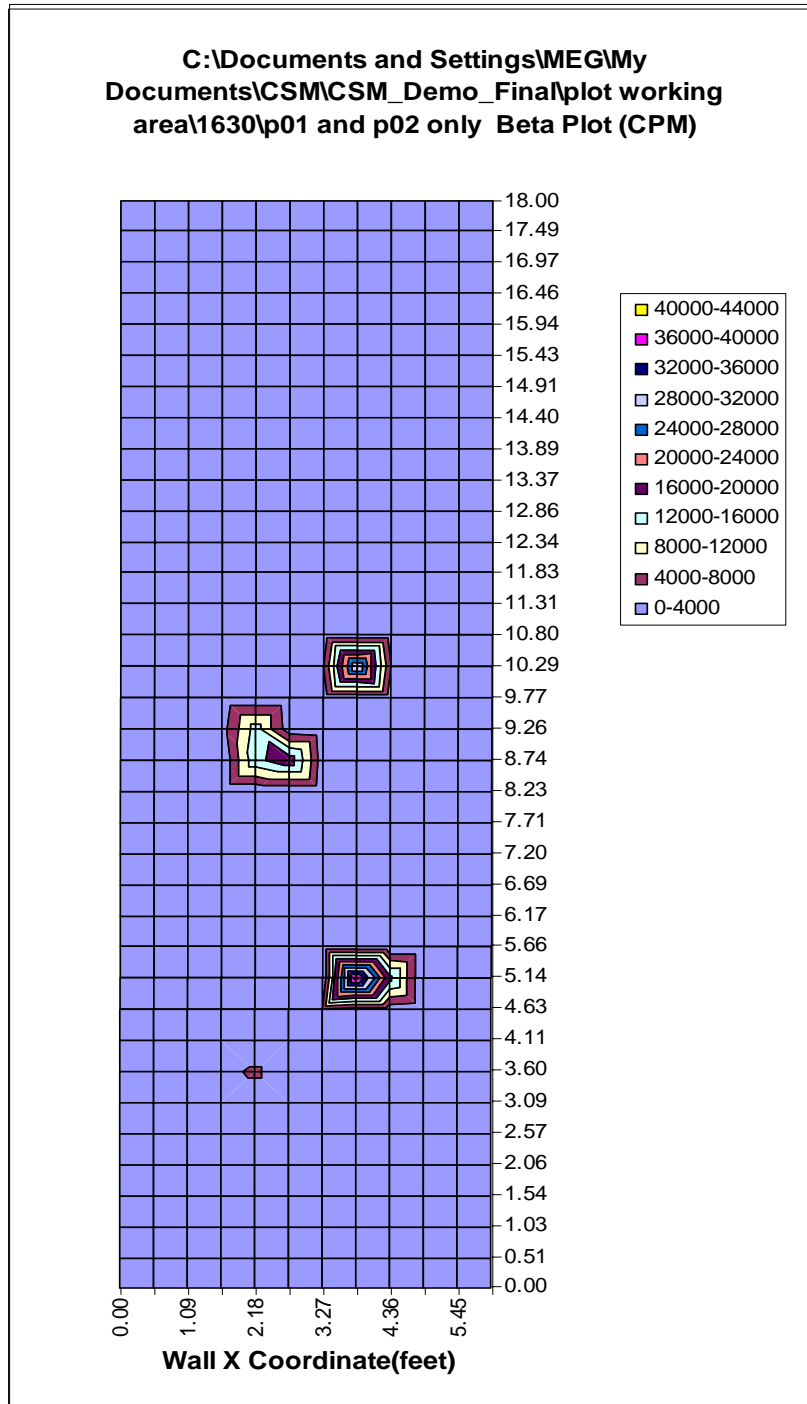


Figure 4. Composite Beta ratemeter plot for the wall of Fig. 3

CONCLUSION

A robotic contamination survey machine was developed and demonstrated. The contamination survey machine automatically surveys and maps the contamination of smooth surface areas up to 2m by 2m, while maintaining a constant gap between contamination sensor and the surface being inspected. The post processing software automatically generates maps of larger surface regions from individual area scans.

ACKNOWLEDGMENT

The authors gratefully acknowledge the project funding by the DOE- Nevada test Site, and by Bechtel, Inc. scientists and engineers, who participated actively in the project and provided many useful suggestions during the development of the contamination survey machine.

REFERENCES

1. Shonka Research Associates, Inc. "Surface Contamination Monitor (SCM)," <http://www.shonka.com/scm.htm>
2. Millenium Services, Inc. "Radiological Services/D&D," <http://www.millenniumservicesinc.com/rdd.html>
3. Mauer, G. F. and Chris Kawa (2005) "Automated Inspection And Mapping Of Radionuclide Contamination On Building Surfaces," Proc. WM'05 Conference, February 27- March 3, 2005, Tucson, AZ Paper# WM-5360.
4. Fanuc, Inc. "V6.31 R-J3iB Documentation", Robot User Manual, 2003 (on CD-ROM)

APPENDIX SELECTED VISUAL BASIC FORMS

frm 0 Splash

This form simply announces the start of execution.

frm 1 CSM Choice

This form displays the 7 command buttons for controlling the CSM.

frm 2 Wall Select

CSM uses a separate folder for each wall to be surveyed. This form lets the user select the folder.

By using a separate folder for each wall, a hierarchical folder tree can be used to mirror the natural hierarchy of walls in rooms, rooms on floors, floors in buildings, building on sites, etc.

frm 2a Pallet Locator

This form is used for the Pallet Positioning command. When a wall is being surveyed, multiple scans are used to cover the whole wall. Each scan is referred to as a “patch”. This form displays the limits of previous scans, and, circles representing the robot reach. When the user positions the circles where the next scan will be made, a button is pressed which computes + displays a numerical estimate of where the pallet should be positioned.

frm 2b Hint

This form explains that while the numbers given by the Pallet Locator are guides, the actual measurements of the pallet reference corner must be entered into the Wall_Aquire form.

frm 3 Acquire Wall

This form prepares for and initiates wall acquisition. The term “wall acquisition” refers to the process locating the robot relative to the wall being surveyed. This process consists of: a) entering the coordinates of the pallet’s reference corner into the user interface, and b) the robot measuring its own range and pose relative to the wall. The acquisition process allows both accurate scanning and the conversion of radiation data positions from robot coordinates to wall coordinates.

In this form, the user also inputs the row spacing. For accurate surveys, this numerical entry must agree with the position of the laser on the end-effector laser slide.

frm 3a Pallet Coords

This is the form where the user enters the location of the pallet’s reference corner. The user also enters the size of the wall. The size data is used to scale various graphical displays and provide some collision avoidance.

frm 3b Acquisition Sim

This form simulates the acquisition process. It gives simulated displays of the range, pitch, and yaw phases of acquisition.

frm 4 Area Scan

This form is used to carry out an area scan. The user inputs a filename and specifies the survey gap and scan speed. The user also uses the Patch_Planner form to set the limits of the patch area. This form also uses a VB comm control to connect to the Ludlum scaler/ratemeter via the RS232 serial port.

Since an area scan can easily take 30 minutes to complete, this form also includes some progress displays. Estimates for scan start time, duration, and completion time are displayed. Also, while the scan is underway, there is a display of the number of total rows in the patch and the number of rows that have been completed.

frm 4a Patch Planner

The patch planner is used to set the limits of the patch area to be scanned. This form displays: a) the limits of previously scanned patches, b) the reach of the robot, and c) safety margins for the walls, ceiling, and floor. The user uses a click-and-drag "rubber-band" to select the limits for a new scan.

When the user has selected new limits, there is a button to check the limits for validity. During this check, the actual path of the robot is displayed on the screen. Since the pattern may be shifted slightly to avoid the robot's singularity, the user should check the resulting pattern to make sure it overlaps the existing patches. If it doesn't the user should try again, clicking slightly different limits.

frm 4b Area Sim

This form gives a simulated display of the area scan process.

frm 5 Point Survey

This form is used to carry out a point-survey scaler count. The user specifies the location, the survey gap, and the scaler count duration. This form also uses a VB comm control to connect to the Ludlum scaler/ratemeter via the RS232 serial port.

frm 5a Point Planner

This form displays the robot reach circle and the robot's singularity. When a user enters survey coordinates, the location is shown on the screen. There are software checks to make sure that the selected point is within the reach circle and sufficiently removed from the robot's singularity.

frm 5b Point Result

This form displays the point survey results. It includes the alpha and beta counts as well as the date, time, location, gap, and scaler count duration.

frm 5d Point Sim

This form displays simulated point results.

frm 6 Rad Display

This form allows the display of ratemeter area surveys. The displays are given as color contour plots, with legends for quantitative scaling. Since the radiation data stored in a patch file is

irregularly spaced, the radiation data is sorted into square “bins” or “pixels”. For each bin, this highest radiation reading is used for display. The user specifies the bin size. Smaller bin sizes give better resolution, but take more time to render.

Since the surveys are stored in individual patch files, this form allows the user to select between displaying individual patches or multiple patches at once. The multi-patch option lets the user set the limits 3 different ways: a) manual entry of the limits, b) show the whole wall, c) use the aggregate limits of the existing patches.

This form uses Microsoft Excel for the contour display. The results are automatically stored in an Excel file with the same name as the patch file. For multi-patch plots, the data is stored in a file called “Multi.xls”. Once this file is opened, the entire range of Excel user controls can be used to tailor the plot for a users needs.

In addition to storing the sorted radiation data, the resulting Excel file also includes the survey gap data. A macro is included in the Excel file to allow a display of the actual survey gap data for the displayed patch. This allows a check of the survey gap accuracy.

Public Methods for Pallet Positioning

```
Public Sub Get_Reach_Limits_ft( _  
    Min_Reach_ft As Single, _  
    Max_Reach_ft As Single _  
)
```

This sub is called by frm_2a_Pallet_Locator. It has no inputs and simply returns the robot’s min and max reach radius. The true robot reach cannot be shown until the wall has been acquired and the true range to the wall is known. The max and min correspond to the front edge of the pallet being between 3 and 6 feet from the wall, the larger reach corresponding to being closer to the wall.

```
Public Sub Get_Pallet_Offsets_ft( _  
    Pallet_offset_X_UserWall_ft As Single, _  
    Pallet_offset_Y_UserWall_ft As Single _  
)
```

This sub is called by frm_2a_Pallet_Locator. It has no inputs and simply returns the pallet offsets from the robot class. Theses offsets are used to compute the location of the pallet’s reference corner, based on a click-selected robot reach circle center location.