NuMI-B-546

Robotic Repair for NuMI Hadronic Hose

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abstract

The NuMI Hadronic Hose (NuMI-B-542, J. Hylen, et.al.) is designed to significantly reduce differences in shape of the neutrino spectra at the MINOS far and near detectors, and hence considerably reduce uncertainties in the neutrino oscillation measurements. The hose consists of segments of wire down the center of the decay pipe, which are pulsed with a current of about 1000 Amps to produce the focusing magnetic field.

A serious concern for the Hadronic Hose is that after a period of beam operation, the NuMI decay pipe will become too radioactive for human access to fix any problem with the system during a data run. Coupled with the potential fragility of a thin wire pulsed for years with large currents, and the experiment dependence on system reliability once committed to using it, we consider a viable repair capability to be essential.

A proposal for a robotic capability to install and repair the Hadronic Hose is presented here.

Contents

1 Overview

The need for a potential means of repair for segments of the NuMI Hadronic Hose[1], in the very radioactive environment of the decay pipe, is an essential consideration in the determination of the viability of this innovative design. This need has been addressed by the design development of a robotic manipulator system, which can be used both in the installation and repair of segments of the Hadronic Hose.

Concept and system components of this design are presented here, along with an M&S cost projection. Prototyping and testing plans are projected.

2 Design Criteria

Key design criteria for the robotic manipulator system are to establish a repair capability for the NuMI Hadronic Hose using hardware which has a high degree of reliability, a "fail-safe" mode for problems which may arise, uses established commercial components when feasible, and is cost effective. These criteria include:

- A parallel capability for initial installation of the Hadronic Hose wire segments. The repair process, when human access is not feasible, should duplicate initial installation steps when human intervention is readily possible.
- Accomplishing the wire alignment requirements by combination of an initial installation wire support alignment, and the use of common length spider supports.
- A fail-safe "sleep" position for the robotic manipulator arms, along with control prevention of potentially damaging arm motions.
- RF wireless control of the manipulator functions.
- Continuous video monitoring of all transport cart and manipulator operation.
- External maintenance capability for drive system components.
- Advance prototyping of all transport and manipulator functions.

3 Hardware and Function

The following WBS items have been identified as the major sub-components necessary to construct an installation and repair robot for the NuMI Hadronic Hose. The research performed at this time has been to evaluate the feasibility of such a device and to formulate an overall M & S cost estimate.

.1 RX-90 Robotic Manipulators (Torso Robot)

The repair robot would utilize two industry standard robotic manipulators mounted on a rotating base. Staubli Corporation manufactures the specified robotic manipulators, model RX-90. The manipulators have 6 axes of motion, a reach of 985mm, and are capable of lifting up to 12kg. The costs include a complete turnkey motion control system with repeatable accuracy of +/- 0.02mm.

When combined with the transport cart there are 8 axis of movement for each arm. Each member of the arms is connected to another, much like a human arm and torso. Through each joint passes one or more axes around which the members

[1] Proposal to Include Hadronic Hose in the NuMI Beam Line, J. Hylen et.al., NuMI-B-542

rotate. The members of the arm consists of a base, trunk, shoulder, upper arm, forearm, wrist and gripper. To achieve maximum strength with a minimum weight, the upper arm and forearm are of monocoque construction. Monocoque is a method of construction that uses the covering plates or “skins” of an assembly to carry all or part of the stresses.

Each member of the manipulator assembly is driven by a permanent magnet DC servomotor. Each motor contains an incremental encoder and a potentiometer. The incremental encoders are mounted on the shaft of each motor and provide both position and velocity signals for the servo system. Each major axis is equipped with electromagnetic brakes.

.2 Control Computer

The control computer will be an industry standard PC providing the interface between the user and the RF control system.

.3 RF Control System

The RF control system consists of three 2.4 GHz industrial RF modems. The RF modems will transmit commands from the control computer to each robotic manipulator motion control computer. In this fashion motion commands are input into the control computer, then transmitted via the RF modems to the robotic manipulator motion control system. The robotic manipulator motion control system is responsible for moving the manipulator and monitoring the position of the manipulator. The use of a RF system to send motion commands to the repair robot and status information to the control computer eliminates the need for a cabled umbilical to the robot.

.4 Gripper

It is expected that two pneumatically controlled grippers or robotic hands will be used on the two manipulators. These will hold tools, tighten components, and function much like the human hand. The pneumatic system for the grippers will use a cylinder of liquid CO2 and a phase separator to generate the necessary air pressure for the gripper operations.

.5 Wire Feed System

An in house designed wire feed system will be needed to install and replace wire segments. This system will be a constant tension wire feed to eliminate any additional stresses being placed on the wire segments during the installation process.

The wire feed will store the spool of Hadronic Hose wire. As the wire is fed out, it will be passed through a series of rollers to eliminate any coiled memory from the storage spool. A constant torque will be placed on the wire at all times to eliminate concerns of excess slack or breakage.

.6 Transport Cart

The transport cart will transport the two robotic arms, power supply, cameras, wire feed and all the necessary controls. Large onboard batteries supply all power for the robots and the control system, making the system cordless and truly remotely operated. Control system communication will be done via RF modems. Inside the decay pipe the transport cart is driven by a looped drive cable. The cart has a set of wheels designed to keep the cart aligned to the center of the pipe. The top of the transport cart is a rotating platter to allow the robotic manipulators to be rotated 360 degrees. The axis adjacent to the platter provides 90 degrees of movement for the arms to be in a collapsed position when traveling under the spiders. The transport cart with all of its components will have enough mass to avoid any lever arm effects and to help keep the robotic manipulators stable.

.7 Transport System

The drive mechanism consists of a loop of cable that is stretched from one end of the pipe to the other. The cable is looped with several revolutions around a drive drum, and held with significant tension to eliminate any slippage. The cable is 5/16 stainless steel and has break strength of 9,000 lbs. The cable runs on idle wheels located every 50' though out the pipe to keep cable from dragging on the bottom surface of the pipe. A variable speed reducer will power the system, providing speeds from 0 to 10 miles per hour. The speed reducer will be located outside the pipe in a low radiation area. All components to the drive mechanism for both upstream and downstream are easily removed for any inspections or possible maintenance. Lock pins will index the robot on the cable, and keep the robot in a known location and eliminate slippage. The drive mechanism will incorporate a high-resolution encoder to provide accurate knowledge of the robot location within the decay pipe.

.8 Precision Video System

A stereoscopic vision system will be used to monitor fine placement of the Hadronic Hose wire. This is an off the shelf item available from several vision system companies.

.9 Low Resolution Video System

It is anticipated that two low-resolution video cameras will be needed to monitor motions inside the decay pipe. These cameras will have auto focus and zoom capabilities.

.10 Video Monitor

A large screen video monitor will be used to monitor all cameras simultaneously.

.11 RF Video System

A RF broadcast system will send each of the video camera feeds back to the user interface area for display on a video monitor. The video cameras will be multiplexed together and displayed simultaneously to provide several visual perspectives inside the decay pipe.

.12 Lighting System

A lighting system will be needed to illuminate the work areas inside the decay pipe. The system will utilize various lamps to provide a natural looking light in the direction of view.

.13 UPS Power System

A commercial UPS system will be used to power the repair / installation robot. The UPS will be sized to allow for a minimum of four to six hours of typical operation between charges.

4 Survey and Alignment

As noted in NuMI-B-542, the needed alignment specification is +/- 2.0-mm maximum deviation of the central conductor wire from a straight line. Plans for establishment of the alignment network inside the decay pipe would be as described in this reference. We would, however, make use of an additional alignment step during mapping of the radial support wire (spider) brackets. The support fixtures would be designed such that alignment fiducialization would be expanded to also include setting the support brackets to provide an equal distance from each support to the central wire. This will enable the use of equal-length spider wire segments to provide alignment to specification for the central conductor.

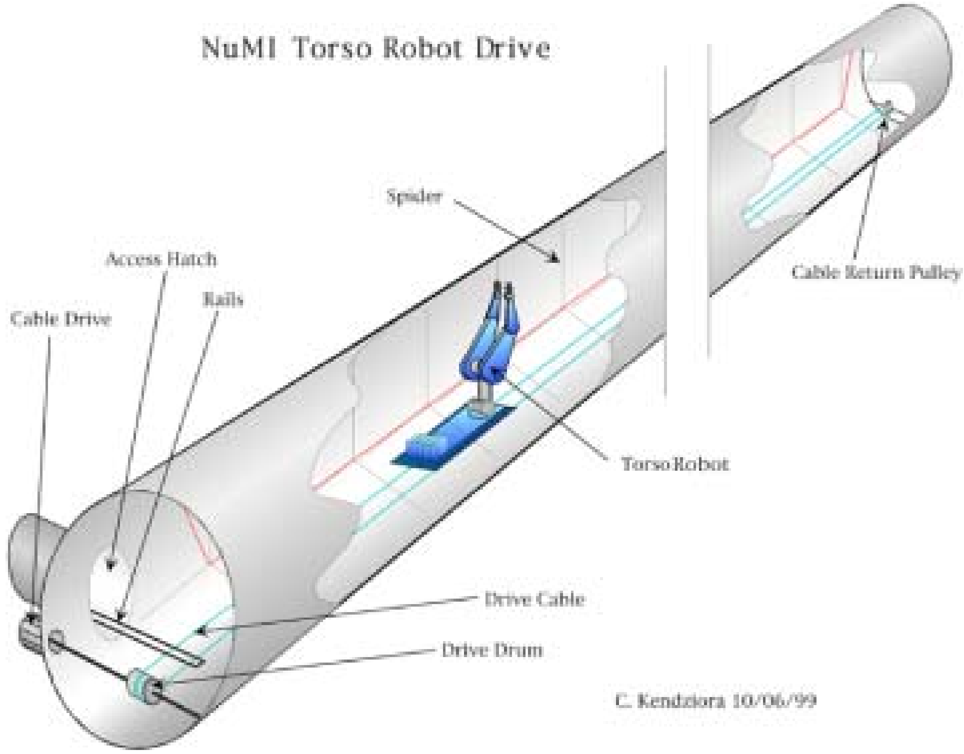
The positioning and referencing accuracy capability of the robotic manipulators should also provide a means of checking central wire alignment accuracy.

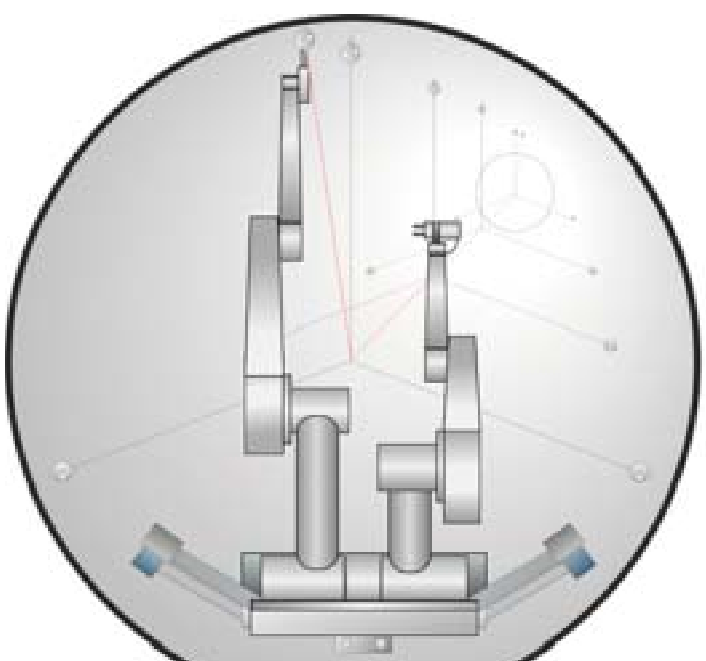
5 Sequence of Operation: Installation of one Wire Segment

The Torso Robot and controls will be tested and inspected prior to any remote work, and the cart loaded with the necessary tools and equipment to complete an installation. The system, with transport cart, will be installed on a set of rails through an access hatch located on the side of the decay pipe near the downstream end. The rails continue into the pipe, and allow the indexing of the cart onto the drive cable. An indexing lock pin will be installed to insure both that the transport cart is indexed into a specific location on the cable, and firmly coupled to the cable.

The drive with its precision encoder will move the robot along the pipe while providing the exact location of the robot. Cameras will also be used to visually verify the robot location, and to observe the transportation process. The robotic arms will travel in a collapsed mode, which will allow them to pass under installed spiders. When the transport cart has reached its determined destination, the robot will be initialized. This will include moving the appropriate axis to acquire a specific position for performing an assigned task. Once in this starting position for the specific task, it will then switch over to a manual mode in which an operator will have control of the robotic arms within the control limits. All movements will have software-programmed limits to the range of motion depending on the position. At no time will the operator be allowed to accidentally damage the robot or installed spiders.

Shown in the top figure on the following page is a concept drawing of the Torso Robot drive system within the NuMI decay pipe. The second figure shows a cross-section of the pipe, with the Torso Robot to scale and robotic arms in an operating position. Included in the figure are spider supports, and center conductor wire for the Hadron Hose. In the collapsed position (not shown), the reduced robot height enables passage under the wire and spider supports.





C.Kendziora 10/03/99

The Torso Robot will first move to the upstream end of the appropriate wire segment location. The wire feed will be set at this location and locked in place by connecting it to a fixed mount. The robot will now reach for the first spider stored on the transport cart, lifting it by the spider's top support. At the end of this support is an indexing pin that will be attached into the top mount, previously welded and aligned during initial survey of the decay pipe. Once the top support has been secured, the two bottom supports will be indexed and locked into place. All spider supports have a common well-defined length. This same procedure will be used until all of the spiders for this wire segment have been installed. Once all the spiders are in place, the Torso Robot will collapse and move back upstream to the wire feed, passing under the installed spiders.

The wire feed is designed to feed out the center wire when pulled upon, and retract when there is slack in the wire. This will provide a specific tension to the wire at all times. An optical limit switch prevents the wire being retracted to the point were it can no longer be fed back out. The center wire will be fed into the gripper of the Torso Robot and secured with a few inches of wire extending beyond the gripper.

The Torso will now spread both arms, such that the arm with the wire is pointing upstream and other arm is pointing downstream. The drive will now position the torso so that the first spider is in between the two arms. The arm with the wire will pass the wire through a hole located in the transportation fixture of each spider. The spider transportation fixture holds the three intersecting legs of the spider together, defines the center of the spider and provides a large aperture for the wire to be fed through the center of the spider support. Once the wire has extended through the hole, the other arm will grab and take control of the wire. The Torso will now collapse the upstream arm and proceed downstream. Before reaching the next spider a choreographed movement will be exercised that accomplishes a transfer of the wire between upstream and downstream arms. The drive will move the torso to the next spider and so forth until all spiders have the wire pass through them.

At the downstream end of the last spider is an electrical feedthru that the wire will be attached to by the robotic arms. Excess wire will then be cut off. The robot will collapse and move upstream under each of the spiders, removing the spider transportation fixtures. Once it has arrived upstream at the wire feed, it will cut the wire and secure it to the upstream wire mount. The wire mount will be adjusted to provide a specific amount of tension on the center wire. The Torso will now move to each of the spiders and adjust the top mount to place a specific tension on the spider. Once tension has been applied to all the spiders the Torso Robot will move to the exit hatch for extraction.

6 Design Prototyping

A crucial part of the design process for the robotic repair system is extensive prototyping for all needed manipulation steps, both individually and sequenced together. This process has already begun, with the setup of an existing robotic arm in the Proton Assembly Building shop, along with construction of a 2-meter diameter ring to simulate the decay pipe perimeter.

The use of controlled mechanical steps will be an important feature in design of all aspects of the Hadronic Hose installation. It is very important that the capability for both installation procedures and alignment checks be well established before a severe radiation environment is encountered.

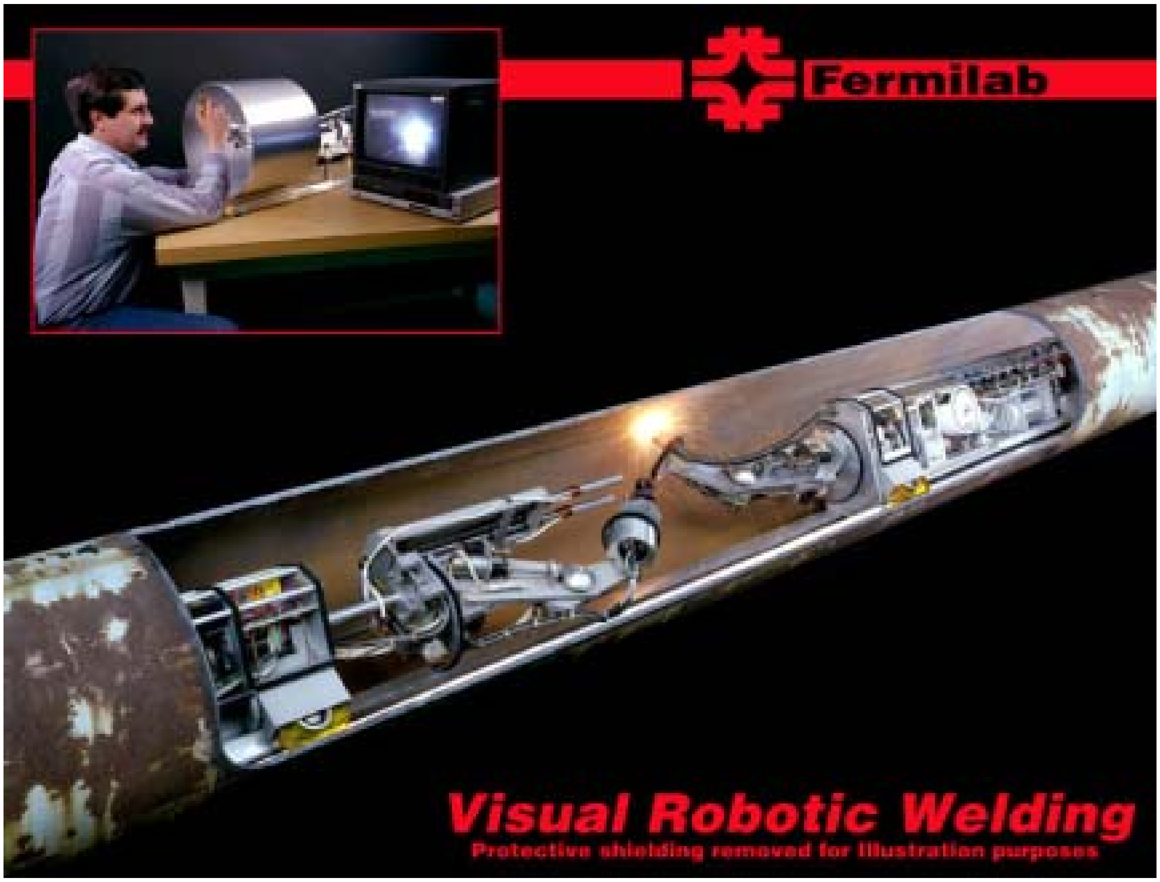
At an early stage of the effort, we will establish a full size segment of decay pipe (20 – 30 ft. length) in the shop, which will also be tilted at a 58 mr. angle. Capability for installation and repair steps including alignment, spider supports, spider assembly, central wire installation and electrical attachment, all Torso Robot manipulations among the spider assemblies, etc. will be well established in the Lab environment. For test of other capabilities potentially impacted by distance, such as RF wireless control, we can utilize the existing Neutrino Area decay pipe.

This process of comprehensive prototyping as an integral part of the system design has proven very important in the success of previous challenging development efforts, and should aid considerably the development of the NuMI Torso Robot repair system.

7 Prior Experience

At Fermilab, we have obtained considerable experience in developing remote controlled hardware to work inside pipes. During the experimental run of 1991 a major vacuum leak developed in the buried beam transport pipe linking the Proton experimental area to the Switchyard. The leak rate increased rapidly, and water leaking into the pipe threatened to shut down the run for all experiments in the Proton area. Working on a time scale of a few weeks, we developed a device which could be operated remotely within the several hundred feet long pipe, find the leak, clean the surrounding surface area, and install an epoxy patch especially designed to seal under water. This was accomplished successfully, and the pipe remained leak tight for remaining months of the experiential run. The figure below is a photograph of this hardware being inserted into a test pipe matching the beam transport pipe diameter.

During the extended downtime prior to the next Fixed Target experimental run, this development effort continued to acquire a permanent remote repair capability for the large Laboratory network of buried beam transport pipes. No commercial system was available which could accomplish the task of welding at distances hundreds of feet inside a 12 to 16-inch diameter pipe. Hence, we developed such a system, called Visual Robotic Welding.



The VRW process, illustrated in the figure above, allows for free hand welding in areas inaccessible to a human. It combines closed loop master / slave control of a specially developed robotic welding arm and also includes an adjacent robotic camera arm. Both arms articulate and have the ability to move about five independent axes. An operator, who may be located at considerable distances away, remotely controls each arm. Welding can be accomplished 1000 feet inside a pipe; the remote control was tested at much greater distances.

An additional surface preparation robotic arm was also developed for treatment of the pipe surface before and after repair. This arm is equipped to grind and wire brush the surface, and is articulated about the same five axes of motion as the welding arm. A separate camera arm also monitors the surface preparation process.

Some considerable challenges have been met in welding inside beam transport pipes at Fermilab. Typically, the pipes are located in the underground aquifer and are frequently also coated with tar. We have had to weld with water and tar pouring though the hole being repaired. The robotic arms on VRW must operate accurately and in real time to make precise welding repairs, which consistently test as helium leak tight in quality. Overall cost of VRW was less than $250 k including materials and labor. The system was completely designed and constructed at Fermilab.

In comparison of the challenge presented by previous development efforts with the robotic repair of the Hadronic Hose, we believe the overall level of difficulty to be similar, although details are quite different. Development of the remote welding process for VRW is believed to be considerably more difficult than any procedure to be performed by the Torso Robot. Additionally, the much larger diameter of the NuMI decay pipe enables much more flexibility in design, as well as the ready option for the use of commercial robotic manipulators. For the current design, the need for precise alignment is new, along with a more complex choreography of manipulator motions to work amongst the needed spider support system for the central conductor wire. A considerable advantage of the current effort is the ability to use a RF control system, eliminating the need for a cabled umbilical to the robot.

8 Cost Estimate

An estimate of materials and contracted services costs for the complete robotic repair system is provided in the following table. Not covered here are other costs required for the Hadronic Hose (see NuMI-B-542), or for civil construction modifications to incorporate the system. It should be noted that 65% of the projected M&CS cost estimate of $210 k is based on recent vendor quotes or actual recent purchases. Based on good costing information for the more expensive components, it is the authors' estimation that a contingency of 25-30% be applied to total M&CS cost.

Labor cost projections remain to be developed. The ability to significantly utilize commercial hardware should make the effort less labor intensive than was development of the VRW system.

9 Conclusion

Design plans have been presented for a robotic system, which can both install and repair the NuMI Hadronic Hose. We believe the capability for system repair is fundamental to adoption of this innovative focusing system for the NuMI beam, and that this capability is attainable at reasonable cost. Extensive experience of the design team with other challenging remote controlled systems should provide a solid base for successful development of the NuMI Torso Robot system.

HADRON HOSE COST ESTIMATE DETAIL SHEET
MATERIALS AND CONTRACTED SERVICES

WORK PACKAGE WBS CODE: x.y.z.1

WBS DESCRIPTION (Level 4): Repair Robot M&CS

PREPARED BY: John Anderson Jr.
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WBS ITEM	MATERIAL or CONTRACTED SERVICES DESCRIPTION	UNIT MEASURE	NUMBER UNITS REQUIRED	COST BASIS	Ayy$ COST PER UNIT	FY99$ COST PER UNIT	TOTAL M&CS COST (FY99$)	RELATED LABOR (Y or N)	RESOURCE NAME	REMARKS
x.y.z.1.1	RX-90 Robotic Manipulators	Each	2	Q99	57,000	57,000	114,000	Y		
x.y.z.1.2	Control Computer	Each	1	EE	3,000	3,000	3,000	Y		
x.y.z.1.3	RF Control System	Each	3	A97	1,400	1,484	4,452	Y		
x.y.z.1.4	Gripper	Each	2	EE	7,000	7,000	14,000	Y		
x.y.z.1.5	Wire Feed System	Each	1	EE	4,000	4,000	4,000	Y		
x.y.z.1.6	Transport Cart	Each	1	EE	20,000	20,000	20,000	Y		
x.y.z.1.7	Transport System	Each	1	EE	23,000	23,000	23,000	N		
x.y.z.1.8	Precision Video System	Each	1	Q99	14,000	14,000	14,000	Y		
x.y.z.1.9	Low Resolution Video System	Each	2	EE	3,000	3,000	6,000	Y		
x.y.z.1.10	Video Monitor	Each	1	EE	1,000	1,000	1,000	Y		
x.y.z.1.11	RF Video System	Each	1	EE	2,000	2,000	2,000	N		
x.y.z.1.12	Lighting System	Each	1	EE	1,000	1,000	1,000	N		
x.y.z.1.13	UPS Power System	Each	1	Q99	3,700	3,700	3,700	Y		
x.y.z.1.14		Each				0	0			
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