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Development of an Automated Guided Vehicle System for Large Scale Materials Handling of Optics in the National Ignition Facility

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Abstract

The National Ignition Facility is a high-power laser facility used for research in inertial confinement fusion. It will help resolve issues about the performance of nuclear weapons and reproduce conditions that exist in stars. When completed, the NIF will house 192 beamlines that contain 8,000 large (40 cm square) optical components, packaged into "line replaceable units (LRUs) and more than 15,000 smaller ones. The NIF Operations Engineering Group is tasked with installation, run-time transport and handling of many of these LRUs. In addition to the sheer number of LRUs, these precisely aligned optics packages weigh hundreds of pounds and must be delivered, via relatively narrow corridors, to numerous locations in cleanroom containers (or delivery systems) within prescribed vibration limits. The unique combination of all of these requirements precludes the use of most manual delivery techniques. Hence, NIF Operations has adopted the use of a system of automated guided vehicles or Laser Bay Transport System (LBTS).

The LBTS consists of two primary components: a configureable commercial-off-the-shelf (COTS) traffic management system and several custom automated guided vehicles or transporters. The traffic management system processes LRU material handling information, coordinates and monitors transporter activities, and archives traffic and transporter information for system querying and trending analyses. The transporters are responsible for implementing material handling commands, route guidance, accurate/repeatable transporter parking, delivery system docking and alignment. The transporters also communicate with the traffic management computer for command and status information, implement local collision avoidance, and provide utility connections for the delivery systems. Additionally, the LBTS has been incorporated into a multi-layered distributed control architecture. Critical integration tasks involve coordinating transporter control maneuvers with its delivery system cargo, interfacing the transporter with other supervisory control system applications, and ensuring compatibility with the NIF wireless local area network. The resulting LBTS design is a modular, scaleable flexible automation environment aptly suited for the 30-year life expectancy of NIF.

1.0 Introduction:

1.1 The National Ignition Facility:

The National Ignition Facility (NIF), currently under design and construction at Lawrence Livermore National Laboratory, will be the world's largest laser when complete. The National Ignition Facility, larger than a football stadium, will be a high-power laser facility used for research in inertial confinement fusion. It will help resolve issues about the performance of nuclear weapons and reproduce conditions that exist in stars. The NIF is a key component in the US Stockpile Stewardship Program.

The NIF will use about 8,000 large optics of 26 different types to focus up to 192 laser beams on a dime-size target. A primary goal of NIF is to achieve "ignition" or break even in a fusion reaction where the energy produced equals or exceeds the energy used to create ignition. Scheduled for completion in 2003 and to have a 30-year life cycle the NIF will be utilized by numerous government, academia, and private sector groups.

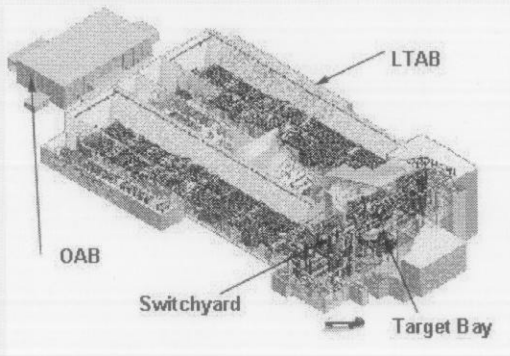

Figure 1: The National Ignition Facility.

1.2 Operations Engineering:

The design of the NIF includes many divisions tasked with various aspects of operation, construction, and maintenance of the facility. The Operations Engineering Group is responsible for the assembly, installation, run-time transport and handling of most of the NIF laser optical line replaceable units. The LRUs are assembled in the Optics Assembly Area and transported to the Laser Target Area Building (LTAB) (see Figure 1) via three primary types of delivery systems and an automated guided vehicle system or Laser Bay Transport System (LBTS) (see Figure 2).

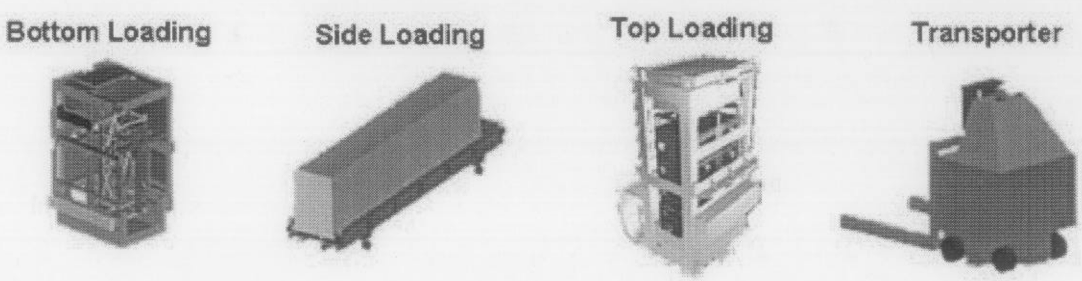

Figure 2: T&H Delivery systems and Automated Guided Vehicle (Transporter)

The three primary delivery system configurations (canisters or slids) were dictated by the installation requirements of the optic. The bottom-loading canister inserts and removes LRUs upward into the structure from underneath. A crane picks up the top-loading canister and lowers it on top of the laser structure for lowering of the optics into the beamline. The side-loading skid inserts self-contained LRUs into the structure laterally into the structure. Since the bottom and top loading LRUs consists of exposed optics the canisters and transporter combination must also maintain specified clean room levels.

The LBTS is a central component to the Transport and Handling (T&H) Group's Optical Delivery Systems. The LBTS consists of a guidance system and four or more transporters which will transport the bottom, top, and side loading delivery systems, lift, align, and assist in the final mating of the delivery system with the laser structure. The LBTS must service numerous locations in the LTAB. These include 528 bottom-loading parking locations split between 384 low-lift and 144 high-lift locations, 48 side-loading parking locations along PASS structure, and 4 top-loading parking locations (2 in each Laser Bay center aisle).

There are also six parking locations associated with bottom and top loading for exchange of LRUs in the OAB.

The LBTS consists of two primary components: a commercial-off-the-shelf (COTS) traffic management system and transporters. The traffic management system processes LRU material handling information, coordinates and monitors transporter activities, and archives traffic and transporter information. The transporters are responsible for implementing material handling commands, route guidance, accurate/repeatable transporter parking, delivery system docking and alignment. The transporters also communicate with the traffic management computer for command and status information, implement local collision avoidance, and provide utility connections for the delivery systems. The LBTS has also been integrated into a multi-layered distributed control architecture.

1.3 System Architecture

All Operations activities are coordinated and controlled from the Operations Engineering Special Equipment Control System (OSECS). The OSECS is a multi-layered distributed control system that will support the semi-autonomous and autonomous transport of Line Replaceable Units (LRUs) using the Laser Bay Transporters. It consists of a supervisory system layer, a front-end processor (FEP) layer, and a low-level device control layer. The OSECS consists of approximately 4,000 control points, 35 Front End Processors (FEPs), and a Supervisory System.

The supervisory layer controls all high level functionality of the FEPs, coordinates inter-FEP controls, provides integrated human machine interfaces (HMIs) to the FEP layer, processes information flow for coordination of all Operations activities (e.g. LRU refurbishment, assembly, transport, and manpower scheduling), and archives data. The supervisory layer provides inventory tracking, traffic management (vendor supplied), data archiving & retrieval, automated controls, and error handling. In addition, OSECS will support the assembly, and disassembly of LRUs in the NIF Optics Assembly Building (OAB).

The FEPs are responsible for direct control of the low-level system mechanisms (e.g. motors, sensors, actuators, and vision systems) [See Mark's Paper]. FEP units consist of a variety of hardware including embedded controllers, a real-time control OS running under Windows NT, and the on-board transporter computer. The FEPs provide the interfaces and distributed services to operate all control points from the supervisory system. Systems requiring real time functions are provided by software resident on the FEP and generally do not require communication over the network.

An integral component to this design is the Safety Interlock System (SIS) [See Brett's Paper]. Each SIS resides on-board the delivery systems for personnel & equipment protection. These systems provide critical functions in the delivery systems and the transporter to ensure safe and proper sequence of control activities, in particular during coordinated maneuvers.

The control system architecture attempts to mitigate risk and allow for flexible design changes by emphasizing modularity, segmentation, and open-systems standards. The system must also interface (via the NIF LAN) to the NIF Integrated Control System (ICCS) which is responsible for all run-time operations of the laser facility.

This layered system maintains communication via the NIF 10/100 Mbit/sec Ethernet network and a 10 Mbit/sec wireless LAN network. The wireless LAN is necessary to allow for networked mobile systems and un-tethered operator interfaces in the LTAB and OAB. All systems on these networks will be communicating using TCP.

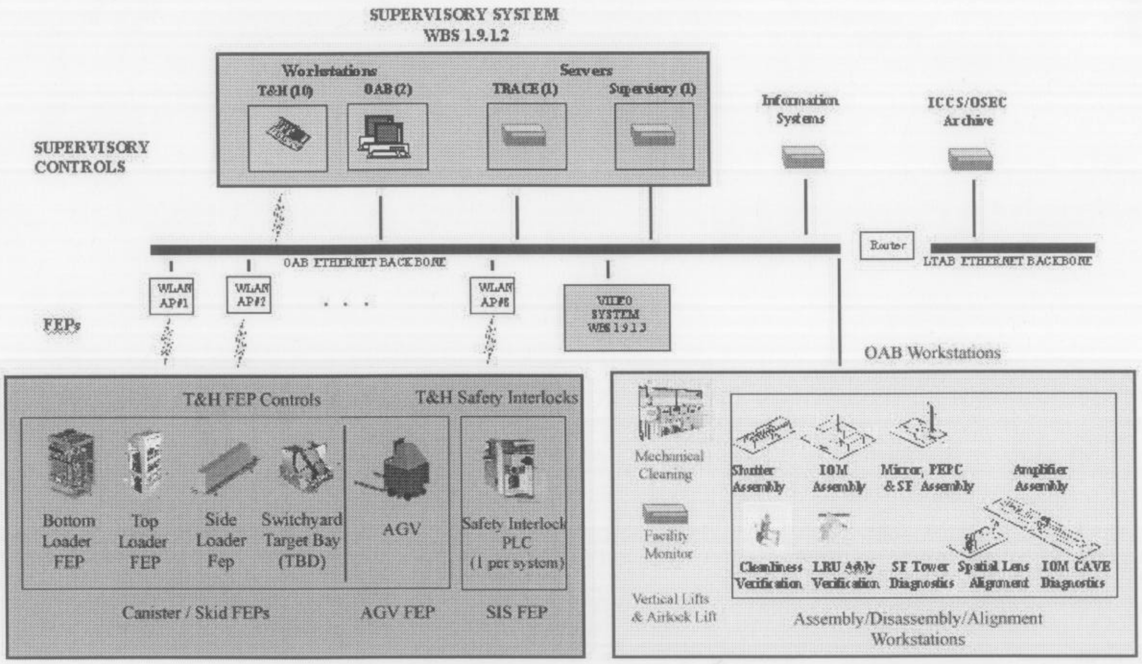

Figure 3: OSECS architecture

2.0 Laser Bay Transport System (LBTS) Functional Requirements:

In order to meet the global requirements of the LBTS mentioned in Section 1.2 a detailed specification was developed. A summary of these of these requirements is given below. For a more complete description see Ref. [X].

2.1Transport of Load

The LBTS must be capable of transporting the three types of delivery systems. The lift platform will be capable of carrying bottom and top loading canisters and side loading skids. The LBTS will be able to support and lift a maximum 3,630 kg (8,000 lb) load.

2.2 Maneuver Constraints

The LBTS needs to maneuver efficiently and with complete repeatability in confined areas with minimal clearances. The LBTS must be able to position on the floor within ±12 mm (1/2 in) of the target position. The system must also take into consideration that the top and side loading system extend beyond the allowable foot print of the transporter.

2.3 Autonomous Operation

The LBTS must be capable of functioning in various levels of autonomous control based on the application and the degree of operator intervention required. It must be capable of operating in a completely autonomous mode when traveling from point to point but allow for operator intervention before engaging any load-handling operations.

2.4 Position and Orientation Accuracy

The system must be able to position (a vertical axis through the geometric center of) the load in both horizontal directions to within $\pm$12.5 mm ($\pm$0.5 in) of a specified location. The load must be kept level so that a vertical axis through the geometric center is within ± 0.53 degrees of the gravity vector. The combination of these requirements should place the bottom and side loading delivery systems within the range of their compliant systems [see Det's Paper].

2.5 Lifting, Stability and Leveling of Loads

When the LBTS is in a final parking positioning for canister or skid docking, the system must be locked in position by engaging brakes on the drive wheels. For all lift operations a means must be provided to lift the vehicle off its wheels while providing a stable and level platform for lifting of the loads. The lift mast must provide sufficient strength to resist docking forces in the bottom load operations.

2.6 LRU Utilities

Each transporter must provide 110 VAC power for operation of the delivery system control system components (FEPs, motors, sensors, etc.) and an air compressor and vacuum pump (resident on each transporters). Air and vacuum connections must be available for use by the bottom loading system. The vehicle is also required to carry a Nitrogen cylinder to provide a pressurized gas supply for use by the bottom loading delivery system. The specification calls for pass through connections for power, compressed air and vacuum.

2.7 Traffic Control System

The traffic control computer must perform all functions pertinent to traffic flow, fleet management, fleet coordination and control of individual transporters. The traffic control computer must be capable of accepting requests for transporter orders and status both manually and via an OSECS supervisory application.

2.8 Communication

Data flow between traffic management and the individual transporters must take place over the NIF 2.4 GHz wireless LAN. Contact must be maintained in all areas of travel of the vehicles. The LBTS system must be capable of communications with the supervisory systems of the NIF.

2.9 Failure Modes and Diagnosis

The design of the transporter and traffic control system must incorporate features that allow for fail-safe operation in all modes of operation.

2.10 Safety Features

Each transporter must be equipped with appropriate safety features, including obstacle detection, bump stop switches, emergency stop switches, warning lights and horn, and controlled acceleration and deceleration

3.0 LBTS Design

Given the constraints of the operating environment, the tasks associated with LRU interchange required a novel, versatile transport system. A system level perspective has been adopted for this paper and hence particular emphasis has been placed on the control system components and the interfaces to NIF systems. A description of the mechanical design is given in Ref [*RedZone paper*]. A more complete treatment of the 6 degree-of-freedom alignment process of the canisters and skids is contained in [Det's paper].

3.1 Transporter Sub-Systems Design

The transporter design can be principally segmented into the following four electro-mechanical sub-systems: Transporter and load lift mechanisms, Load platform and fine positioning system, Power system and batteries, and Control and communications systems. The following briefly summarizes the first three areas while a more detailed treatment of the forth is given in Section 3.3.

Transporter and load lift mechanism

The transporter is a four-wheeled forklift type device where the two front wheels being steered and driven. Unlike a forklift, the front drive wheels are the two furthest from the vehicle's forks. The rear wheels have two positions (0 and 90 degrees) in order to permit crab steering for accessing difficult areas in the Laser Bay. The transporter's forks are a nested with a set of outriggers, which provide additional support for the load during travel and seismic events. Three jacks provide load stability and leveling during lifting operations.

Load platform and fine positioning system:

The fine positioning system is a key component of the 6 degree of freedom placement of the canisters and skid is the NIF LTAB and OAB. It uses a vision system on-board the canisters and skids to locate targets near the docking location for the Line Replaceable Units (LRU). The image is processed by the canister/skid FEP and offset information is sent to the transporter FEP for alignment of the load. The load carrying platform has three axes of precise motion that permit the load to be aligned with the docking receptors in the Laser Bay support structures.

Power system and batteries:

The transporter is a battery powered system that will automatically returns to a station to recharge during idle periods. The battery capacity is approximately 48 VDC 1120 Amp-Hours. This battery contains sufficient capacity to sustain all transporter activities during approximately 3 bottom loading delivery cycles. The transporter provides sources of power for the various LLNL AC and DC control devices and equipment.

Guidance system:

The guidance system is a combination of inertial and laser scanner reflective feedback. The laser system uses the angle to retro-reflective targets and time of flight to triangulate transporter location. A Kalman filter combines the laser scanner triangulated position with inertial guidance data obtained from an on-board rate gyro and wheel encoders to determine the transporters position along the guide path within 1 inch.

3.2 Trace2000, Traffic Management System

The Traffic Management Control System is the supervisory level controls system for the LBTS. The main component of the system is AGV Products' standard Traffic Routing AGV Command Executive (Trace2000) system. It is a COTS Windows NT based stationary control software for complete Automated Guided Vehicle material handling systems (traffic flow, fleet management, fleet coordination and control of individual transporters). The client/server TRACE system software is written in Microsoft Visual C++ and using the Microsoft Foundation Class Library. Trace2000 will take requests for material handling from either the client interface or the OSECS supervisor, queues them, and then assigns them to transporters for execution. After a request is assigned to an AGV, Trace2000 breaks down the request into discrete AGV commands, communicates with the AGV in order to send it those commands, monitors the status of the AGV through execution of the commands, and reports on the progress of the material handling request. This system will be configured for the NIF specific layout and material handling scenarios. It has also been modified to accommodate to interface to the necessary NIF and OSECS systems (see Section 3.4).

The system hardware will consist of an IBM PC compatible server running Windows NT™. This server will interface via the NIF Ethernet to provide communications for the following controls:

- Communication to the AGVs via wireless Ethernet link access points
- Controlling and monitoring of external I/O needed in the system.

- Interface to the OSECS Transport and Handling Computer for Order Dispatch and Status Notification

3.3 Transporter FEP design

The transporter FEP is responsible for implementing material handling commands, route guidance, accurate/repeatable transporter parking, delivery system docking and alignment. The transporter FEP must also communicate with the traffic management computer for command and status information, implement local collision avoidance, and provide utility connections for the delivery systems. The message protocol utilized by the AGV System is of a proprietary nature. In this protocol the stationary system functions as master and the AGVs are as slaves. This means that Trace2000 initiates the communication and the AGVs only send messages in response to the received message. Since message numbers are used, the strict sequence of messages and corresponding responses is followed. When transmitting messages to AGVs, a unique vehicle may be addressed by polling using the AGV identity. The protocol is based on asynchronous transmission using ASCII characters in full duplex. The maximum baud rate is 19200 for the CB12. The maximum message length is 128 characters including start and end characters.

AGV Controller:

The on-board control board or CB12, is based on a 16 bit Z380 microprocessor. The board handles all the functions required in an AGV, e.g. motor control, antennas, encoders, potentiometers, serial communication, keyboard panel DIS20, safety functions, general digital inputs and outputs. One control board can handle up to four INT20 interface boards. Four interface boards will be used in this system to obtain the required motor drive amplifier outputs, encoder signals, and sensor inputs. The CB12 board contains the **BASE** software for the vehicle, which is responsible for the low level machine control for all of the AGV functions. It also contains the movement tables for each specific project which are custom programmed with the AGV Command Executive (**ACE**) programming language by the user.

Communications:

Communication between the individual transporters and the Trace2000 is accomplished utilizing an RF modem link to the NIF wireless access points. The transporters will use the Nomadic Mercury RF1 for transporter communications. These systems will operate at 2.4 GHz and also use the TCP protocol.

3.3 Interface Designs:

The operational activities of the LBTS require that it be an integral part of the OSECS architecture. There are 4 mediums that the LBTS requires for interfacing to systems external to itself. These are network communications, peer-to-peer serial communications, peer-to-peer optical communications, and physical utility cabling. The interface components and their respective mediums are discussed below.

OSECS Supervisor:

In the LBTS, an interface is required to handle specified transactions with the LLNL OSECS Supervisor. These transactions are order generation/routing requests or system status requests. The OSECS supervisor allows for generating orders automatically or manually via the TRACE client. In the automatic generation mode the OSECS supervisor has a specific set of transactions that it can request of Trace2000. These orders define to the TRACE System the specific locations to perform canister and skid handling throughout the NIF facility. This module is application specific and varies depending on the system that the TRACE computer is required to interface with. These communications will utilize the NIF Ethernet backbone.

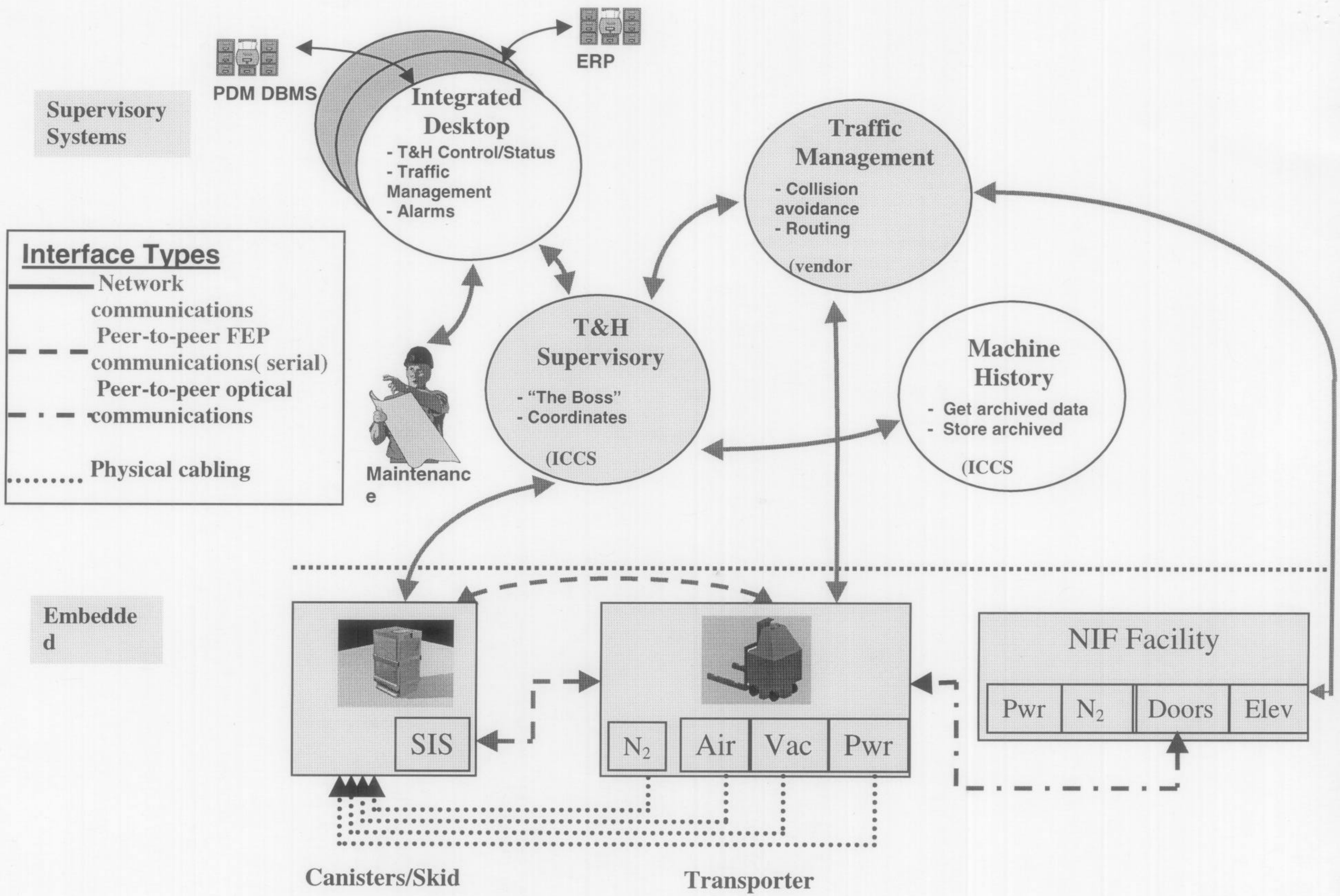

Figure 4: LBTS interfaces

LTAB Roll-up Door

The traffic routing in the NIF between the OAB, OAB corridor and the LTAB will require passage of transporters through two roll-up climate doors. These doors are controlled by the NIF Integrated Computer Control System. Two infrared transceivers are located on each transporter and the walls adjacent to the roll-up door for open/close control request (see Figure 5). These are aligned with a forward-facing and rearward-facing transceiver so that the transporter can requested opening and closure of the doors while traveling in one direction. Interlock signals are monitored by the ICCS granting or denying permission for operation of the roll-up doors by the transporters.

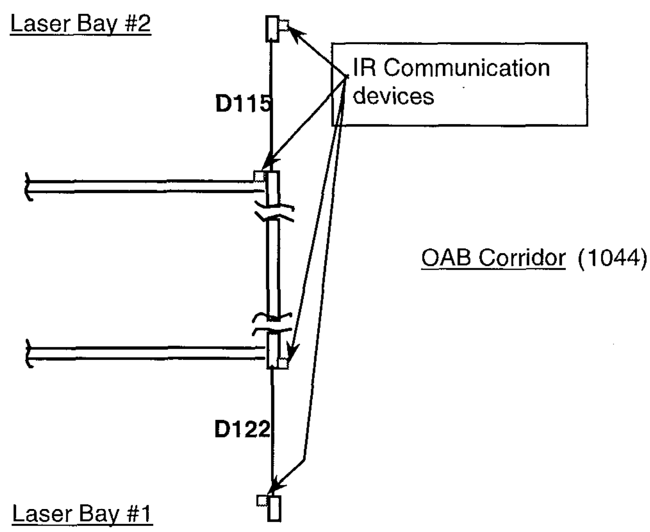

Figure 5: IR Transceiver placement along the LTAB roll-up doors.

OAB Vertical Lift:

The traffic routing in the NIF between the OAB and the LTAB for receipt or return of bottom loading LRUs will require movement of transporters via one of two vertical lifts located in the OAB. These lifts move between the main LTAB/ OAB corridor level and the OAB basement. They are controlled by an Allen-Bradley SLC 505 PLC on the NIF Ethernet backbone. The protocol for operation of the lift by a transporter is shown using an example of a request for the lift to the transporter's level:

- The transporter stops in front of the vertical lift and requests it to its level.
- Trace2000 routes this request to the SLC 505 PLC input address.
- The PLC executes the maneuver if permissible and sends status to the PLC output address
- Trace2000 reads the lift status and commands the transporter to continue.
- The transporter proceeds onto the lift.

Request for other lift movements will follow the same protocol.

Docking, Alignment, and Safety Systems

The alignment and docking of bottom and side loading systems required a coordinated control effort with the transporter. Resident on the canisters and skid are vision system and alignment sensors that provide feedback for the lift and fine alignment systems on the transporters. This information is packaged by the canister/skid FEP and passed to the transporters subject to a polling request via a serial line between the respective FEPs. To assure proper coordination of the sequences of control safety interlock system on-board the canister/skids and the transporters monitor control signals/requests. In addition to lines for safety and alignment information, emergency stops (E-stops) on the two systems are also link during transport.

4.0 Failure Modes

Operation of the NIF requires careful analysis of the impact that failures associated with any system can have on the facility. As part of the OSECS architecture the LBTS is subject to this analysis as well. The requirements are typically characterized by a RAM (Reliability, Availability, and Maintainability) Analysis. Reliability is defined as the probability of meeting the minimum requirements of the experiment per no-yield shot (NIF experiment). Since OSECS will operate between shots, the overall reliability goal will be approximately 100%. Availability is characterized in terms of the time the system is unavailable due to unplanned maintenance. Since OSECS can delay a shot, it will be allocated some fraction of the ICCS budget. Maintainability is characterized by the number of days allocated for scheduled maintenance per year. The OSECS software shall have a maintenance plan that fits within the overall plant goal of 69 days per year.

We have identified failure modes within the LBTS as well as their potential impact, times to repair (Mean Time to Repair, MTTR), and Mean Time between failures (MTBF). The latter data is utilized in the calculation of the Reliability, Availability, and Maintainability of the LBTS. Failure modes associated with the LBTS generally fall into a hardware or software failure. Hardware failures may occur in such systems as computers or components (e.g. data acquisition, interface boars), network components (access points, routers), mechanical systems (e.g. drive mechanisms), and sensors. It is beyond the scope of this paper to discuss all identified failure modes. To mitigate such failures an emphasis has been placed on a modular design using COTS products where possible. Also, inventories of spare parts and manual or work-around solutions have been designed into the systems in the event of failure.

6.0 Conclusions

References

Trace2000 Software Operations Manual

Det's 6 DOF paper

Bretts SIS paper

Mark's FEP paper

LLNL TSDR

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