EXPERT SYSTEMS APPLICATIONS FOR SPACE SHUTTLE PAYLOAD INTEGRATION AUTOMATION

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ABSTRACT

Expert systems technologies have been and are continuing to be applied to NASA's Space Shuttle orbiter payload integration problems to provide a level of automation previously unrealizable. The NASA's Space Shuttle orbiter was designed to be extremely flexible in its ability to accommodate many different types and combinations of satellites and experiments (payloads) within its payload bay. This flexibility results in different and unique engineering resource requirements for each of its payloads, creating recurring payload and cargo integration problems. Expert systems provide a successful solution for these recurring problems. The Orbiter Payload Bay Cabling Expert (EXCABL) was the first expert system, developed to solve the electrical services provisioning problem. A second expert system, EXMATCH, was developed to generate a list of the reusable installation drawings available for each EXCABL solution. These successes have proved the applicability of expert systems technologies to payload integration problems and consequently a third expert system is currently in work. This paper describes these three expert systems, the manner in which they resolve payload problems and how they will be integrated.

INTRODUCTION

Extreme flexibility, provided by the NASA Space Shuttle orbiter to accommodate diverse payload and cargo elements, makes payload and cargo planning, design, and integration a major activity. Each Shuttle mission carries a different set of payload elements, making the integration of these payloads into the orbiter payload bay a recurring complex planning, design, and installation problem. Expert systems technologies have been applied to these problems, providing automation to decrease these labor-intensive activities. The success of its first delivered expert-system-based automation tool inspired the Space Technology Systems Division (STSD) of Rockwell International to investigate the possibility of applying this technology to other payload planning, design, and integration problems. A second expert system was subsequently successfully delivered, confirming the value of expert systems in this problem domain. On the basis of these successes, a third expert system is currently being developed and additional payload integration problem areas are being examined for potential future expert systems applications.

THE PAYLOAD AND CARGO INTEGRATION AUTOMATION PROBLEM

The delivery of satellites and experiments into low earth orbit by the Space Shuttle involves many preflight engineering planning, design, and integration tasks. These tasks include selecting appropriate satellites and experiments to make up a mission payload set, locating each payload element within the payload bay, determining standard and unique services required by each payload, developing and documenting the payload to Space Shuttle orbiter interface requirements, selecting the individual cables necessary for providing the electrical services, preparing the electrical services cabling layout schematic, and preparing the technical instructions for mission payload installation and integration. A major goal for all payload planning, design, and integration tasks is to minimize the amount of change from mission to mission, thereby reducing paperwork, labor hours and turnaround time.

Complexity requires that payload integration planning and design tasks be carried out by teams of engineers. Each team uses both common and specialized engineering tools, some of which are extremely complex with rigid constraints. Any changes in planning and design methods have to take the use of these existing tools into consideration. The products of each team are used as initial planning and design data by one or more other teams. Likewise, the initial planning and design data for each team consist of the products of several other teams. Because of their interdependence, the products of these teams are integrated into a master mission plan and schedule.

Team technical support is supplied by one or more highly trained experts. These experts have many years of practical, as well as task related, experience. These task experts are rapidly reaching the age of retirement. Loss of an expert, regardless of cause, is an undesirable event not only with respect to the affected team's productivity, but also to the total payload integration design task productivity as a whole.

Real-world experience with space flight mission provisioning has shown that the ability to make mission manifest changes is mandatory. Certain other types of changes are to be anticipated because of further engineering analysis or design refinement. Changes caused by erroneous data or design omissions and errors are also to be expected.

Thus, change is a normal mode of operation and provisions must be made for change even close to launch time. Standardization and automation are two powerful methods used in the payload integration process to accommodate these changes.

To summarize, Space Shuttle payload and cargo integration planning and design tasks are a collection of iterative interrelated activities, supported by complex specialized tools, responsive to change, and led by vanishing experts. Automation, to be successful, must be tempered by these considerations. The following major objectives were established for each planning and design automation effort:

1. reduce engineering labor hours
2. retain technical expertise
3. reduce end-to-end process time
4. adapt to the existing operating techniques and environment

PAYLOAD BAY CABLING LAYOUT PLANNING AND DESIGN AUTOMATION

The Problem

The Space Shuttle payload cabling layout planning and design problem involves provision of the details required for the installation of cables to connect orbiter electrical services to the individual payload elements. Each Shuttle mission entails a different payload manifest, constituting a recurring planning and design problem. Mission payload manifest changes compound the problem further.

Standardized orbiter electrical services are provided through cables that connect the experiments and satellites to either the forward or aft orbiter payload bay bulkhead using standard mixed cargo harness (SMCH) panels. These cables are routed from the specific payloads to port and/or starboard standard interface panels (SIP's) and, from these SIP's, to covered cabling trays for further routing to either the forward or aft bulkhead (Figure 1). For efficiency, these cables are provided from a standardized orbiter cable inventory.

Since these standardized cables must service all payloads, regardless of their location within the payload bay, they are almost always too long. The excess length of each cable must be dispositioned either by forming a foldback or loop (double foldback) within the routing tray. The trays are closed by covers that are located at designated locations along the tray. Cables with a diameter greater than 0.62 inch cannot be folded within the normal dimensions of the trays because of radius bend constraints. Therefore, a special height appending foldback cover is required to replace the normal tray cover at the location of such a fold. Also, at the point where the cable leaves the tray to be routed to the SIP or elsewhere, a special egress cover is required to replace the normal cover. Cables must also be separated by electromagnetic compatibility (EMC) class through special channels provided in the routing trays.

Cabling installation practices are also governed by numerous constraints and standard operating procedures. Based on heuristic knowledge, the above considerations, and the specific payload manifest, the cabling expert generates a hand drawn schematic that describes the cable routing solution. This schematic is subsequently used by a CAD/CAM specialist to produce a technical order (TO) schematic drawing of the cabling layout. An example of a typical TO schematic drawing is shown in Figure 2.

The Solution

The NASA Space Shuttle's payload bay cabling design task was the first automation problem that applied expert systems technology. An expert system, the Orbiter Payload Bay Cabling Expert (EXCABL), was completed in September of 1986 and has been in operational use since delivery. An overview of the EXCABL system is shown in Figure 3. The EXCABL system has completely automated payload bay cabling layout planning and design tasks. The cabling expert needs only to define the mission-unique payload requirements and constraints to generate the cabling solution CAD/CAM TO drawings and printed reports. This was facilitated by the initial construction of a mission-independent data base,

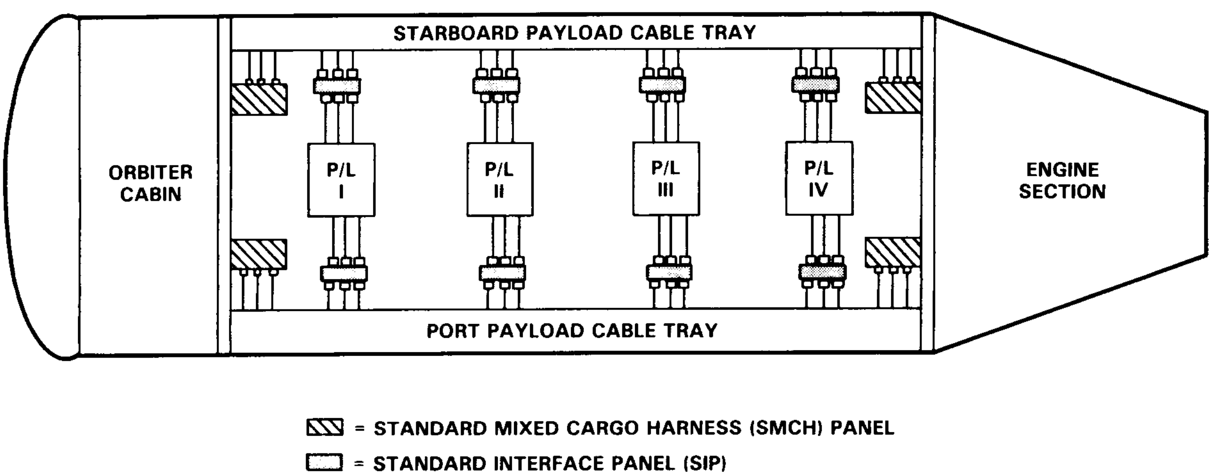

Figure 1. Shuttle Orbiter Payload Bay

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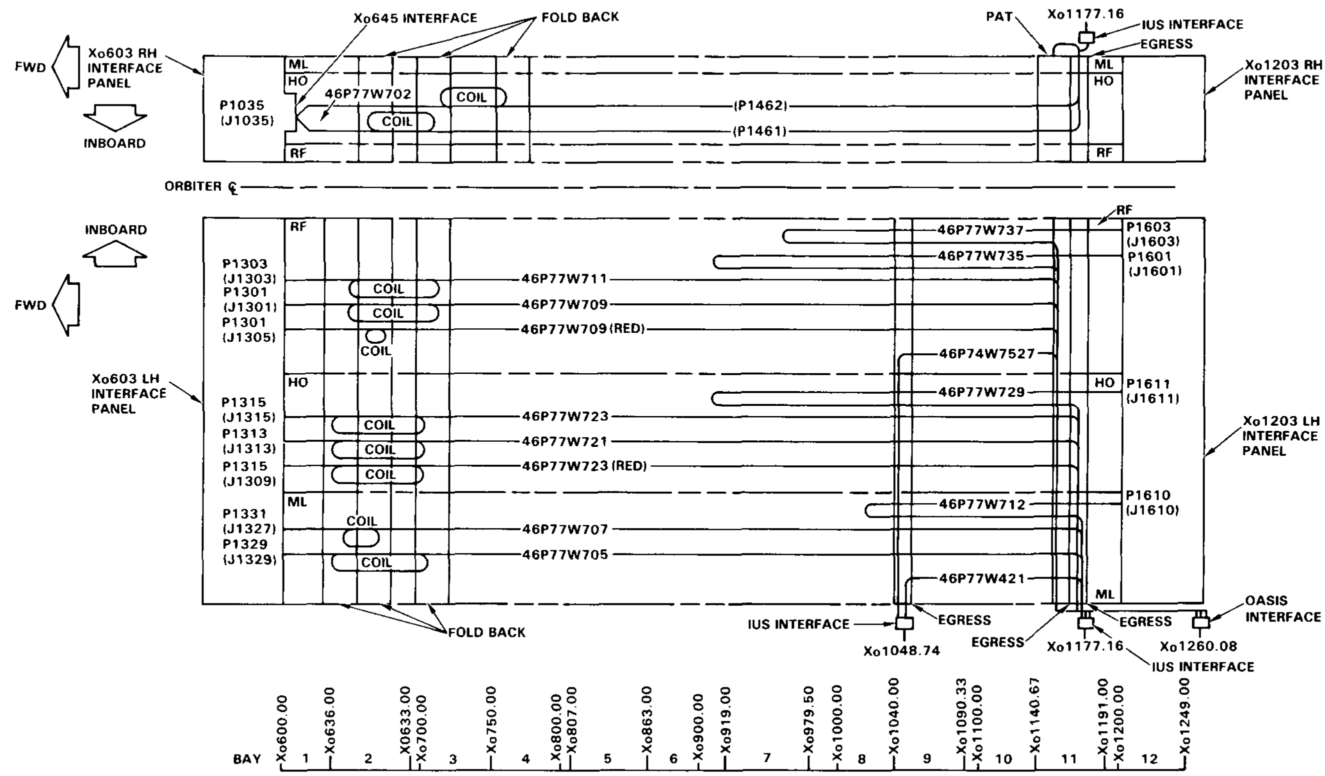

Figure 2. Typical EXCABL Drawing

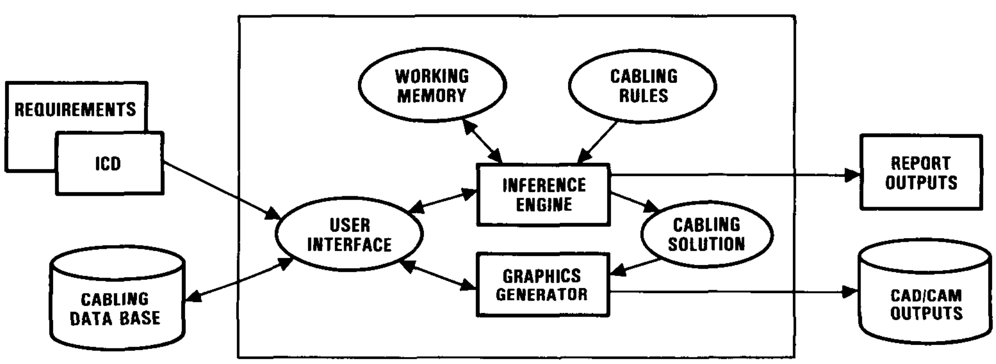

Figure 3. EXCABL System Overview

containing all of the necessary payload bay hardware information required to perform Space Shuttle's cabling. The cabling experts' previously required hand drawn cabling schematic is now automatically generated by the system and transferred into CAD/CAM inputs.

All major automation objectives were met in the initial delivered system. The system has captured the required technical expertise and also provided a significant improvement in productivity. The cabling capabilities of EXCABL are such that only a small percentage of actual cabling design tasks cannot be handled. Since the end product is a cabling installation drawing, any EXCABL solution can be manually modified or augmented to produce a more acceptable solution. The productivity improvement realized by this new capability is such that a typical mission cabling manifest, formerly taking a few labor-intensive days for several cabling engineers, now takes only a few minutes.

The expert system portion of the operational version of EXCABL was implemented using Production Systems Technology's C-based version of OPS83. The remaining portion was implemented using C. It is currently hosted on a CAD/CAM interfacing DEC MicroVax II system and integrated into the operational environment. The literature contains documentation of an early prototype version of EXCABL (Reference 1), problems associated with converting from a development system to a delivery system (Reference 2), and a case study of the development effort and lessons learned (Reference 3).

PAYLOAD BAY CABLE INSTALLATION TECHNICAL ORDERS

The Problem

The cabling layout solution schematic produced by EXCABL is only one of many Space Shuttle planning and design products necessary to accomplish the actual electrical services provisioning of its payload bay. Among the other products required are the installation configuration TO's for the cables and related hardware devices. These TO's contain the detailed instructions that are used by the payload integration crew to perform the actual cable and hardware device installation. The cabling TO's required for each flight are unique and dependent on the cabling solution generated by EXCABL.

In order to increase productivity, the concept of modularization was developed by the cabling design engineering group. This concept is to reuse previously generated TO's whenever possible, thereby, eliminating the need to repeat labor-intensive documentation for the same installation. Implementation is accomplished by assigning basic TO numbers for each device, connector or cable installation and by assigning dash numbers for the different configurations. If an existing TO is not available, a new TO is generated, and a new dash number is assigned. The modularization, or reuse concept, is only made feasible by the standardization of cables, connectors, devices, mounting positions, etc.

Identifying the set of all reusable cabling installation TO's for each given mission is a recurring integration problem. Since the set of cabling TO's for each mission is dependent on the EXCABL solution, any automation of this process should interface easily with existing EXCABL outputs. Furthermore, maximum usage should be made of any intermediate information generated by EXCABL to support its final products. EXCABL changes to support the TO identification and generation process would be undesirable and should be kept to an absolute minimum. The desirability of integrating this process into the existing work environment, while cooperating with the EXCABL process, placed serious constraints on the design and development of any automated system solution.

Simply stated, the problem was to develop an automated system that has the capability to identify and generate a list of all TO's required to perform the payload cabling installation for any Space Shuttle mission. If any required TO does not currently exist, that fact should be identified by the system to the user in order for the deficiency to be corrected and the process completed.

The Solution

There were two basic motivators for this project: the demonstrated success of the EXCABL project and the practicality of automation based on the new concept of modularization and reuse. Furthermore, it was assumed that application of the experience and techniques gained from the EXCABL project would make this a low risk development effort (Reference 3.) Those assumptions proved to be correct in practice, and the entire development effort was straightforward and completed without any major problems within six months of project initiation.

An expert system, called the Expert Drawing Matching System (EXMATCH), was placed in operational usage in January of 1988. The EXMATCH system has successfully automated the payload bay cabling installation TO generation task. Closely integrated with the EXCABL system, the cabling solution provided by EXCABL is automatically input to EXMATCH and a master listing of all required payload cabling installation TO's is generated. If a required TO does not currently exist, the system not only identifies this deficiency, but also suggests a similar drawing (best match) that may be modified to satisfy the deficiency. An example of a typical output is shown in Figure 4.

To facilitate this system, an initial data base containing all current payload cabling installation TO numbers was constructed. For user convenience, the interface to maintain this data base was made an integral part of the EXCABL system. The development of the initial TO documentation and maintenance of the TO data base are the only functions not fully automated. Modifications to EXCABL were limited to providing the user with an EXMATCH option selection capability, providing and relinquishing program control to EXMATCH, and providing the user interface for maintenance of the TO data base. An overview of the integration of EXMATCH and EXCABL is shown in Figure 5.

```
                 Installation T.O. Dash Number Listing

                   Device Installation Dash Numbers
panel kind        panel side      panel fwdx0     dash number
sip               left            1043.560        *** no dash number *
pat               right           1141.770        M072-710427-058
egress            left            1153.770        M072-710425-077
foldcover         left             631.750        M072-710426-001
longeron          left            1140.000        M072-710005-019
standoff          left            1140.000        M072-710006-019
inst instl-payload, dynamics, (m0771a)            M072-754117
wire tray, cover and gap filler                   M072-710012-002
                                  . . .
                                  . . .

                 Connector Installation Dash Numbers
sip               left            1043.560
number of connectors: 1
j402
number of required unmounted connectors: 1
j401
dash number: *** M072-710028-024 ***

                   Cable Installation Dash Numbers
number of devices with cables: 1
sip               left            1043.560
number of cables: 2
j402              p402            46p77w421
j401              j401            46p74w7527
number of devices with no cables: 1
egress            left            1041.990
*** no dash number ***
                                  . . .
                                  . . .

                     Best Matched Dash Numbers
sip               left            1043.560
is very close to the following installation:
sip               left            1045.000        M072-710305-001
                                  . . .
                                  . . .
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Figure 4. Typical EXMATCH Listing

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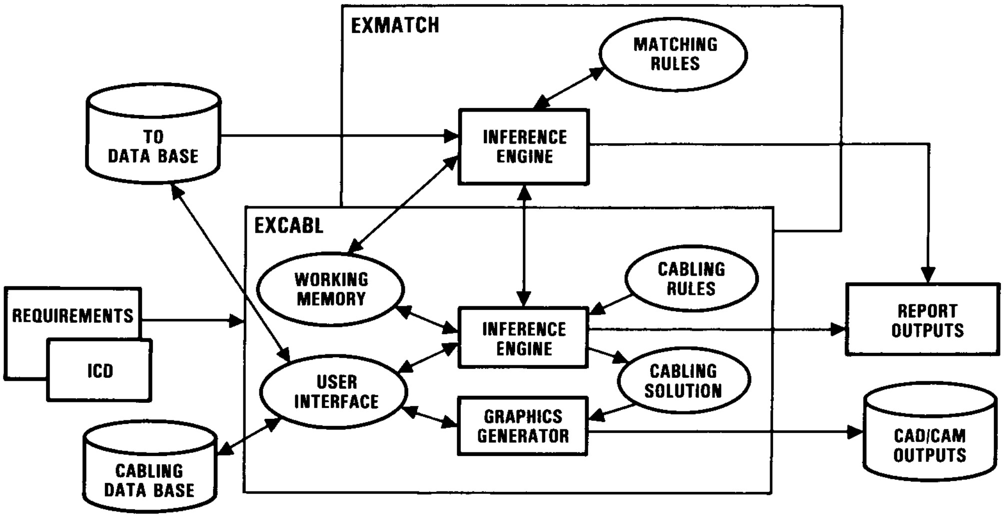

Figure 5. EXMATCH/EXCABL System Integration

The expert system portion of EXMATCH was implemented using Production Systems Technology's C-based version of OPS83. The remaining portion was implemented in DOD's registered trademarked language, Ada. EXMATCH is currently cohosted with EXCABL on CAD/CAM interfacing DEC MicroVax II systems in the cabling design work place.

TECHNICAL ORDERS FOR TOTAL PAYLOAD INTEGRATION

The Problem

The Space Shuttle payload integration planning and design process culminates in the provision of a complete set of TO's containing all of the installation instructions needed to accomplish the total payload bay accommodation and installation task. To assist in the planning and installation process, a complete list of all applicable TO's for a mission is specified in a single document, the Mission Equipment Cargo Support Launch Site Installation (MECSLSI) drawing. Since each Space Shuttle mission is basically unique and many design changes occur subsequent to initial payload manifesting, the identification of all required TO's for the production of this drawing constitutes a continuing and complex integration problem.

Mission requirements are categorized as either mission-common or mission-unique. Mission-common requirements are those requirements that, once established, are standardized for all future missions. Mission-unique requirements are dependent on each mission's objectives. Since the payload manifest is basically unique, the payload cabling layout schematic TO produced by EXCABL is mission-unique. However, it has been estimated that 90 percent of mission requirements fall in the mission-common category.

On the basis of flight requirements documentation, interface control documents (ICD's), mission-unique TO's, common TO's, similarities to previous missions, etc., the mission-MECSLSI development expert utilizes heuristic knowledge to generate the required drawing. Due to the preponderance of mission common TO's, if a design automation system could be developed to produce an initial MECSLSI containing only those TO's, labor requirements would be reduced considerably.

The Solution

A feasibility study was initiated in Fiscal Year 1987 to determine the practicality of developing an expert system to automate the production of the initial MECSLSI drawing. As a consequence of positive study results, it is expected that development of an expert system based design automation tool, the Technical Order Listing Expert System (EXTOL), will be started in the near future. Not only will EXTOL produce the initial MECSLSI drawing; but using heuristics and data from previous missions will assist the user by producing a list of the best matches for missing TO's in the mission-unique category. If a close match cannot be found, it will identify that fact and provide further assistance to the user by presenting essential configuration information. An example of the information processing of EXTOL is shown in Figure 6. It is reasonable to expect that a working prototype could be produced in Fiscal Year 1988, and an operational system delivered in Calendar Year 1989.

TOTAL PAYLOAD AND CARGO INTEGRATION AUTOMATION

The EXCABL system produces the mission-unique cabling layout schematic TO product. EXMATCH uses information generated by EXCABL in its solution process to augment its knowledge and produce a list of all existing TO that will be required to accomplish the cabling installation. If a required TO does not already exist, a best match or similar existing TO is identified. When all of the required TO's are generated and this information is input to EXMATCH, a complete list of cabling TO's is generated. Together, these data will be furnished as electronic inputs to the EXTOL system currently under consideration. These improvements should allow EXTOL to produce initial MECSLSI drawings that are over 90 percent complete. For TO's identified as needed, but not in existence, best match and configuration information to greatly facilitate their generation will also be produced.

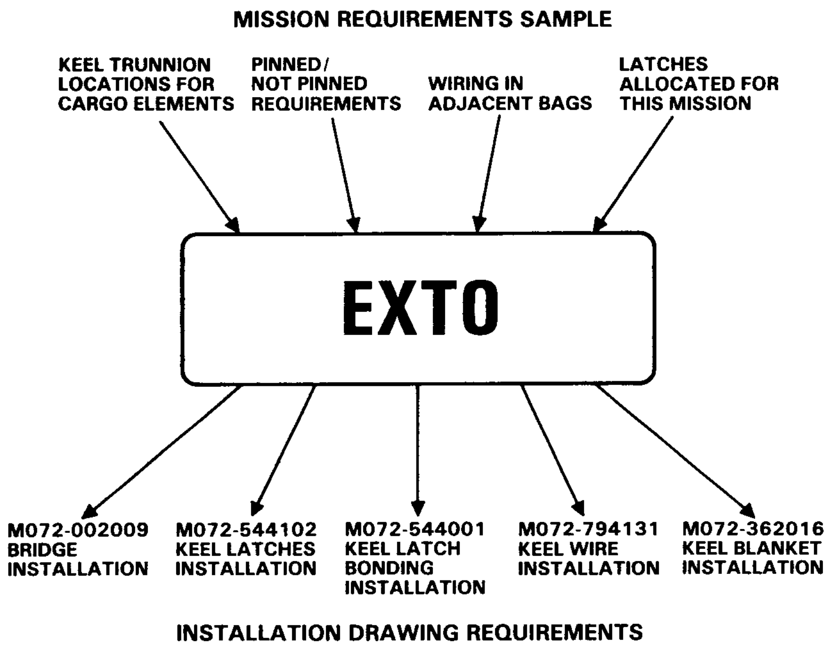

Figure 6. EXTO Processing Example

Together, EXCABL, EXMATCH, and EXTOL constitute a real-world demonstration of the feasibility and benefits of applying expert systems technologies to the payload bay integration automation problem. Two of these systems have been integrated into the engineering work environment and cooperate to automate the overall payload integration management task. The third, when completed, will be integrated with the other two to further the goal of total payload bay integration automation. Since each expert system feeds its outputs directly to its successor, the productivity improvements of the group as a whole are greater than individual stand-alone systems could achieve. An overview of the integration management of these expert systems is shown in Figure 7. Using these systems as the core, other expert systems aimed at supporting the automation goal are in the concept development stage.

SUMMARY

The high level of flexibility to handle diverse payloads provided by NASA's Space Shuttle orbiter presents recurring payload and cargo integration problems. Expert system technologies are being applied to these problems to provide a level of automation that was previously unrealizable.

EXCABL is an example of a highly successful, nontrivial, demonstration of the applicability of using artificial intelligence techniques to solve real-life design automation problems. It met the design automation objectives of reducing engineering-labor hours and end-to-end process time, captured corporate technical planning and design expertise, and demonstrated that expert

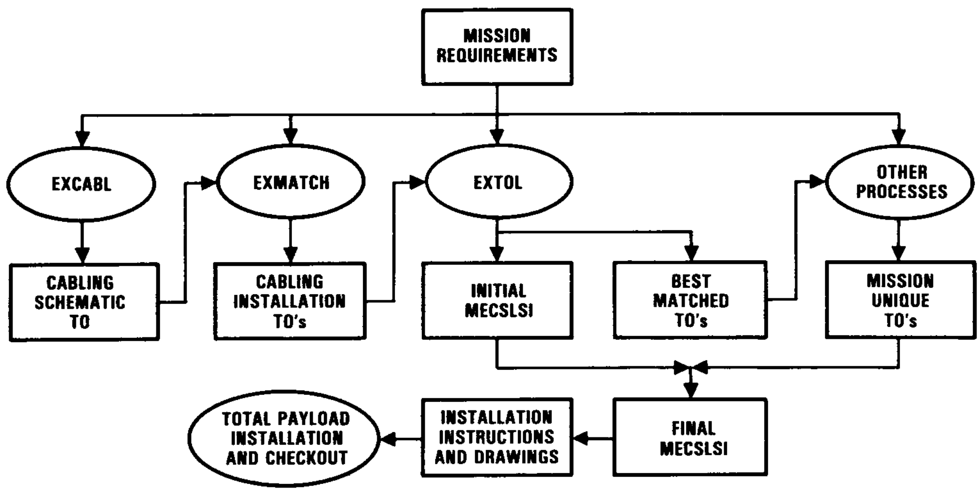

Figure 7. Payload and Cargo Integration Management

systems methods can successfully be integrated into existing operational systems.

EXMATCH is a second example of the appropriate application of expert system technologies to solve automation problems. Its inception was driven by the success of the EXCABL system. It was implemented quickly without major development problems and successfully integrated into the existing work place along with EXCABL.

The development of another expert system based design automation tool (EXTOL) is currently under consideration. These three separate systems when implemented will work together to support overall payload integration management automation.

ACKNOWLEDGEMENTS

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REFERENCES

1. Saxon, C.R., and Schultz, R. "EXCABL: An Expert System for Space Shuttle Cabling," AI-85, *Proceedings of the First Artificial Intelligence and Advanced Computer Technology Conference*, Long Beach, California, 1985, pp. 127-140

2. Saxon, C.R. "Converting a Demonstration to a Delivery Expert System: Lessons From EXCABL." *Proceedings of IEEE Westex-86 Expert Systems Conference*, Anaheim, California, 1986

3. Morris, K.E., Nixon, G.A. and Rejai, B. "EXCABL—Orbiter Payload Bay Cabling Expert System, A Case Study," *Proceedings of IEEE Westex-87 Expert Systems Conference*, Anaheim, California, 1987