THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1989 Ship Production Symposium

Paper No. 23: Combining Welding Expert Systems with Welding Databases to Improve Shipbuilding Production

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

	Form Approved OMB No. 0704-0188
Report Documentation Page	

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1. REPORT DATE **SEP 1989**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **The National Shipbuilding Research Program 1989 Ship Production Symposium Paper No. 23: Combining Welding Expert Systems With Welding Databases to Improve Shipbuilding Production**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Bldg 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **24**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

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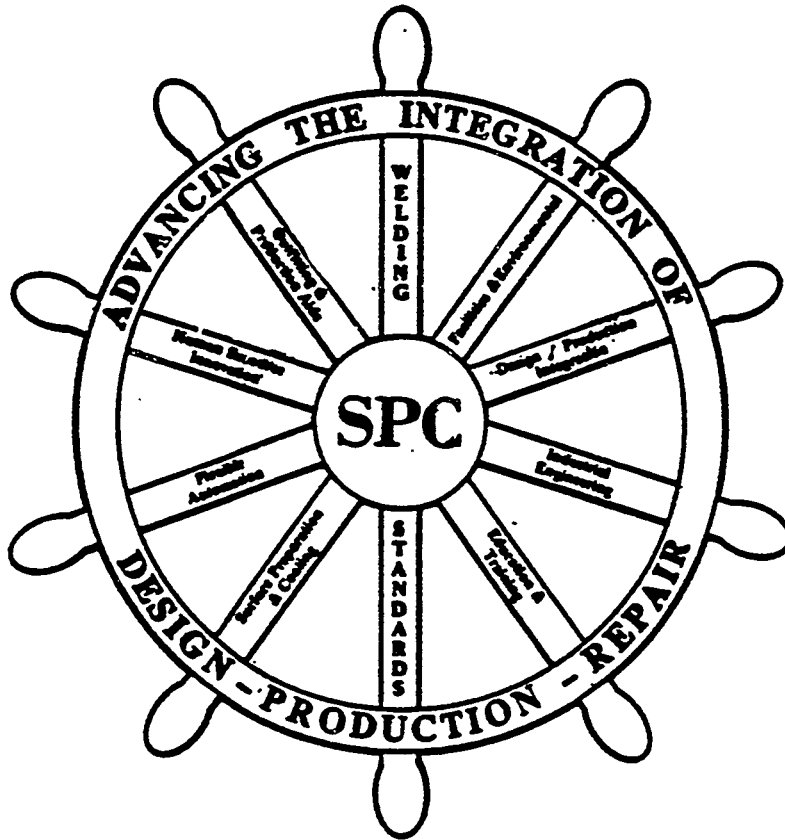
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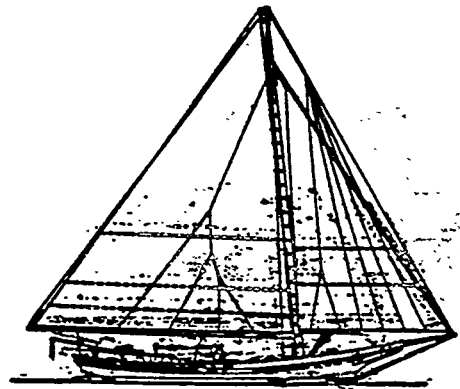
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THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS

Combining Welding Expert Systems with Welding Databases to Improve Shipbuilding Production

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ABSTRACT

Construction of a large ship requires many thousands of feet of welding. Whenever the welding process can be streamlined or automated, tremendous cost savings can be ob tained. The WELDEXCELL system is a WELDing EXpert manufacturing CELL that provides computerized technical support information, off-line weld planning, and an intepated welding robot/welding system/vision system controller. The first of two subsystems, the Welding Job Planner (WJP) accomplishes off-line intelligent weld planning for both automated and manual welding processes. The second subsystem, the Welding Job Controller (WJC) provides a fully integrated hardware control environment with associated software for combined control of a welding robot, welding equipment and a robotic vision system. In the WELDEXCELL system, a series of expert systems and databases have been combined in a new type of computer software environment called a blackboard. There are as many as 19 separate components of the Welding Job Planner subsystem of WELDEXCELL which fall into five interrelated functional groups. WELDEXCELL will be used by design engineers, welding engineers, mechanical engineers, and NDT engineers for both manual welding and to interface to automated and robotic welding systems and vision systems. WELDEXCELL also includes the control system hardware and software to provide off-line intelligent adaptive control of the welding process itself.

The development of WELDEXCELL is a multi-year effort involving a partnership of government, industry, university research, and technology transfer. The project has already generated new concepts with potential for future spin-off benefits. The ultimate payback in productivity will be large for the American welding, fabrication, manufacturing, and construction industries.

OVERVIEW

The American Welding Institute (AWI), together with the other WELDEXCELL team members, the Colorado School of Mines (CSM), and MTS Systems, Incorporated (MTS), is developing an intelligent weld process planner for flexible welded fabrication known as the WELDing EXpert manufacturing CELL (WELDEXCELL). This project entails the development of a computerized blackboard with a series of linked expert systems acting as a welding engineers' assistant, and software to download welding procedures from the weld designer to a welding workcell for automatic execution of the planned welds. The system will also employ sensors to record actual weld process parameters and a postweld analysis capability to examine these parameters and update the welding procedure between passes. These sensors include a seam trackerwhich will provide path corrections to the welding robot during a weld.

Many parts of the system software have already been developed, and some of the software is commercially available as in-

dividual expert systems and databases. But, the heart of WELDEXCELL is a new computer architecture called a "blackboard". This blackboard system allows the interconnection of multiple expert systems and databases with a central goal. WELDEXCELL will be one of the first commercial computerized application blackboards ever developed.

BACKGROUND

The joining of metals into fabricated components and structures is a difficult task. The most common method of joining metals is welding, but the welding process is complex and requires several important steps to be performed in a carefully integrated manner. Although the process may seem simple to an experienced welding engineer, when analyzed in sufficient detail, the engineering/planning processes are extremely complex. Such an analysis was performed in developing the task description for the WELDEXCELL Welding Job Planner (WJP). The weld joint is first designed and engineered properly, then that design must be correctly communicated to the fabrication facility. The appropriate welding consumables, including filler metal and protective flux orinert gas, are chosen. Then the welding procedure is specified, including preheating schedules; welding variables such as voltage, current and travel speed and postweld heat treating. Finally, the weld must be performed under highly skilled human guidance and control. A minor error in any of these steps, if undetected, can create an unsuitable welded component, which in later use may result in a catastrophic failure and perhaps loss of life.

An extremely complex and interrelated system of codes, specifications, tests, and inspections ensures that the vast majority of welds will never fail in service. Fortunately, a large number of engineers, designers, and welders work within the system of codes and specifications to ensure the high quality of welded joints, but this system is very expensive and requires the careful attention of many human experts. Consequently, welding is an ideal application for computerized expert system technology. However, no single expert system could be expected to perform the myriad of tasks required to make a welded joint. For example, there are over 100 welding processes ranging from simple flame heating to exotic laser welding; there are several hundred welding filler metals – from plane carbon steel to elaborate chemical mixtures of alloying ingredients; and there are over 1000 different grades of weldable steels classified by the American Society for Testing and Materials (ASTM). The possible combinations of welding process, filler metal, and steel base metal would number into the millions.

The expert systems needed for welding include materials selection, joint design, welding process and procedure selection, and a CAD system interface to draw the design and communicate that design to the welder. The ultimate goal also includes an intelligent system to instruct a complex welding workcell to perform the weld; and a workcell simulator to allow off-line automated weld planning.

WELDEXCELL SYSTEM BLACKBOARD

It is clear that the type of distributed problem-solving in multiple knowledge domains involved in this multidisciplinary engineering problem cannot be addressed using a single knowledge source (KS). Rather, multiple knowledge sources and humans will cooperate to solve a broad problem. The technique to be applied to this data and knowledge-integration problem is the computer blackboard architecture.

The concept of blackboard architectures was discussed in the literature a early as 1962; however, no applications were built until the 1970s. A blackboard is being used for this expert integration environment because it possesses capabilities to support problem solving while accounting for diverse types of information, methods for combining various types of data while resolving conflicts, and the ability to

accommodate different program modules without requiring a complex interface.

The problem solving technique which has been applied to the blackboard model is to divide the problem into loosely coupled sub-tasks which are then operated on by specialized programs with access to various information sources. The information sources consist of knowledge bases, expert systems, databases, and interfaces to human experts. The advantage of such a system is that much larger quantities of information can be used in a fully integrated manner to solve the problem and develop the weld plan. The human experts supply the external information about the required welding task and then review the intermediate and final plans. The system also includes facilities to query a human expert in the event that conflicts outside of the system's domain of expertise occur. The time required by a human expert will be substantially reduced, thus allowing more design and planning to be accomplished with higher overall quality and reliability by the same number of human experts. Also, the system will reduce the time required to tesy qualify, and practice automated welds. This will substantially reduce the problem of small batch size automated welding.

The blackboard software architecture is analogous to a group of experts seated before a blackboard, with only one expert allowed to approach the backboard at a time. A monitor is empowered to call on the experts individually to modify the blackboard's contents. Following each contribution, the monitor evaluates the state of the blackboard's contents and, based on its planning algorithms, considers which expert to call on next. If the "experts" described in this scenario are replaced by knowledge sources (KS's), which include expert systems, databases, knowledge bases, human users, graphical data and information, etc., a blackboard system results. The monitoring and control functions are performed by what is essentially another expert system with planning algorithms designed to move the expert system toward a problem solution.

The blackboard's purpose is to provide a framework for the interaction of the multiple independent knowledge sources and to respond opportunistically to the changing contents of the blackboard to achieve a solution. There are eight behavioral goals for the intelligent blackboard control system to accomplish this task. They are as follows:

1. Make explicit control decisions that solve. the control problem of multiple independent knowledge sources.

2. Decide what actions to perform by determining what actions are desirable and what actions are feasible.

3. Adopt variable task size control heuristics.

4. Adopt control heuristics that focus on action attributes which are useful in the current problem solving situation.

5. Adopt retain, and discard individual control heuristics in response to dynamic problem soving situations.

6. Decide how to integrate multiple control heuristics of varying importance.

7. Dynamically plan strategic sequences of actions.

8. Reason about the relative priorities of domain and control actions.

The blackboard controller controls the blackboard, monitoring the activities of the knowledge sources attempting to find a solution to the weld design problem. At various levels ranging from abstract to very detailed, decisions are made such as which problem to solve next, whether forward or backward chaining reasoning is to be used and which knowledge source to activate. While building a master expert system to control the problem solving blackboard is a complex solution, it provides the

flexibility to solve both broad planning problems and perform detailed scheduling.

The blackboard control system contains more explicit support for meta-level facilities. The blackboard is divided into multiple partitions which contain classes. The classes contain objects. The objects, which contain the data used by the KS's to solve a problem are placed in the blackboard by KS's or by external processes such as human interactions or interaction with the databases.

Another concept for organizing problem solving with multiple, diverse cooperatirig sources of knowledge is being applied to the blackboard. A hypothesize-and-test paradigm is a mechanism which can provide a high degree of cooperation among the knowledge sources. Thus, the solution finding is an iterative process, which involves two steps:

> Ž Create a hypothesis (an educated guess about some aspect of the problem)

> Ž Test the plausibility of the hypothesis

As the blackboard proceeds toward a solution, the system will build on the knowledge about the problem contained in its knowledge sources and the changes in the state of the system knowledge (i.e., in the contents of the blackboard) produced by previous hypothesis. This iterative process ends when the contents of the blackboard form a consistent hypothesis which satisfies the requirements of an overall weld design solution.

WELDEXCELL SYSTEM DESCRIPTION

WELDEXCELL is logically divided into two major subsystems: the Welding Job Planner (WJP) and the Welding Job Controller (WJC). A high level block diagram is shown in Figure 1.

Welding Job Planner

The WJP will use various expert systems knowledge/databases, and user input to Solve welding engineering design problems. The user will interact with the computerized knowledge resources and the computerized "blackboard" to design the joint and then locate or assist in developing an appropriate welding path and procedure.

The WJP configures this information in the form of a Job Description (weld schedule) which is in turn passed to the WJC for the actual execution of the weld. The user interface for the WJP is primarily the blackboard output file which is represented as a Welding Procedure Specification (WPS) and displayed on the screen. As information is determined by the expert systems and other systems, the onscreen WPS will be updated. The display shows initial information (such as material type and joint geometry) and the evolution of the WPS as it is developed, including the joint design, robot path planning, and simulation information.

Welding Job Controller

The WJC is responsible for ensuring that the various equipment used for the weld, including the welding power supply, the manipulator, the vision system, and other support equipment are coordinated as appropriate to execute the weld schedule from the WJP. During the course of a weld, the WJC will record several weld process parameters (such as voltage, current, wire feed rate, gas flow, travel speed, and temperature as appropriate to the type of welding taking place) as well as any offsets between the planned path and the actual seam location. This data is saved for later inter-pass analysis by the WJP, but the seam offsets will also be used in real time by the controller for adjustments to the robot's planned trajectory (i.e. seamtracking). At the end of a weld pass, a weld results file containing the recorded weld process parameters and seam offsets is prepared by the WJC and passed back to the WJP for
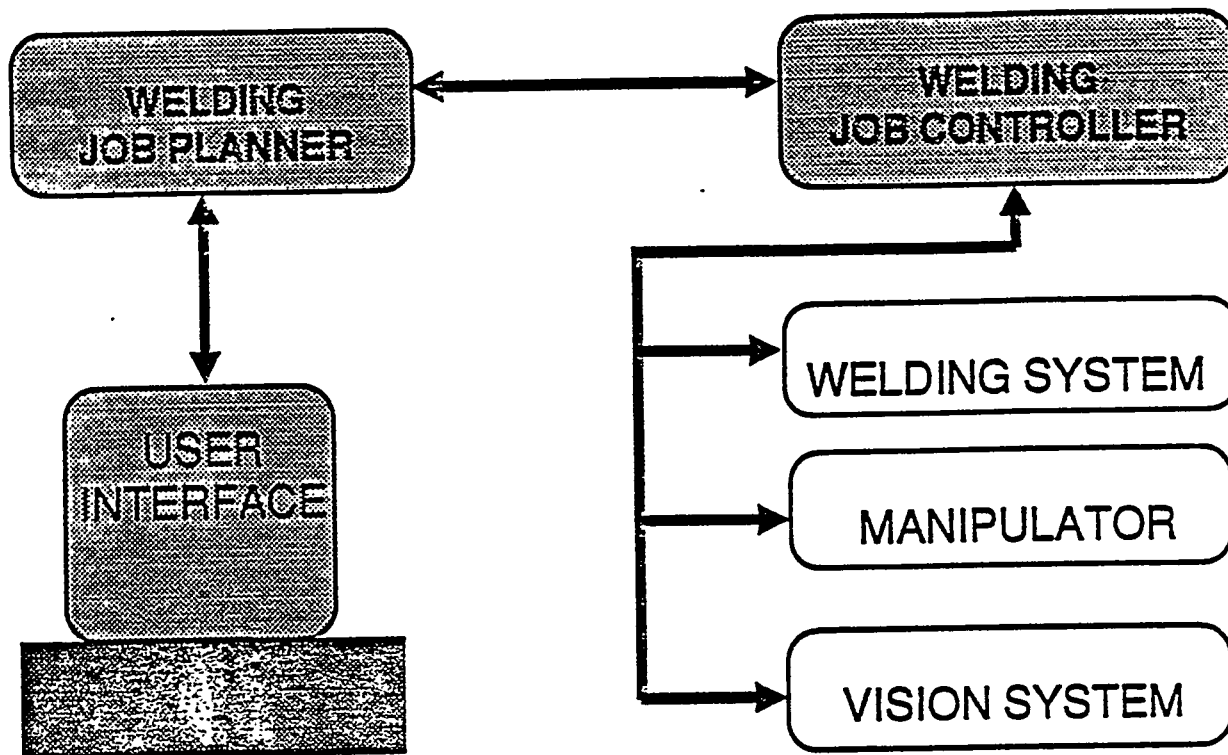
Figure 1. High level block diagram of the WELDEXCELL System

analysis and possible modification to the job description for the next pass.

WELDING JOB PLANNER

The traditional method of creating a new weld procedure specification is similar to the following scenario. First, given a specific metal to be welded, the welding filler metal or electrode is chosen, then the joint design and welding procedure are selected. Finally, the information must be communicated to the fabrication facility in the form of a joint design drawing with a welding symbol. Each of these tasks is not completely independent and, in the existing manual mode of operation, they are often done in an iterative manner. Thus, the

WJP must be able to do distributed problem solving in multiple simultaneous knowledge domains.

The WELDEXCELL blackboard is functionally organized into a frame-based structure of sub-blackboards. Each of the sub-blackboards has a specific functional use in the overall system. These sub-blackboards are described by a series of attribute (i.e. specific goal parameters) values which are determined, through operation of the system, to the greatest extent possible whenever that sub-blackboards is instantiated during a consultation. Each sub-blackboard also inherits the attribute values of the parent (main) blackboard. The blackboard structurehas the ability to go through a scenario repeatedly with minor changes so that engineer-

ing iterative solutions ("what-iffhg") techniques can be applied.

The major components (sub-blackboards and other routines) of the WJP are the Joint Designer, the Structural Integrity Analyzer, the Material Analyzer, the Procedure Specifier, the Path Planner and the Main Blackboard. Each of the sub-blackboards are made up of several cooperating expert systems and databases. Each of these major components is described below in greater detail.

Most of the expert systems and databases have been previously developed or prototyped by AWI and the Colorado School of Mines (CSM) as individual modules. In development of these expert systems, it was important to use recognized standards, codes, and existing tested procedures in the operation of the expert system. Two principal organizations in the United States are primarily responsible for the technical standards and procedures of welding (besides the United States government): the American Welding Society (AWS), and the Welding Research Council (WRC). Selected committees of each organization were approached to enlist their cooperation and input with respect to the development of the expert systems. These committees have supplied expert knowledge, evaluation, and beta test sites for the prototype expert systems. Future beta testing will also be performed by U. S. Navy shipyards.

Wherever possible, expert systems which already existed, or which had been prototype by AWI/CSM are being used in WELDEX-CELL. AWI and CSM, as part of the Welding Information Network (W.I.N.^{Tm}) system, have previously developed, and in some cases AWI is commercially marketing, a fill range of expert systems for use in welding engineering decision support. In addition to the expert systems, several technical databases are used by the Welding Job Planner. Each database is structured as summarized in Table I. Figure 2 illustrates the overall breakdown of the WJP.

Weld Joint Designer

The JointDesigner Sub-blackboard (JDS functions to prepare a welding joint design and communicate the joint design information in a graphical format to the engineer, as well as to the shop floor. Standard joint design formats (consistent with the AWS standard graphica description) are being employed for the basic joint design. Also, the welding symbo prepared by JDS conforms to AWS/ANS standard A2.4-86.

WELDSYMPLE. A large amount of information is needed to describe a weld procedure on a mechanical drawing. The welding technique and testing must be specified as wel as the joint design and machining requirements. A shorthand way of describing a weld, known as a welding symbol, is used on a mechanica drawing to describe the specified weld. The technique for developing a weld symbol is like that of constructing a word in the English language. A set of symbol elements (the alphabet for the word construction analogy) is available. By choosing appropriate symbol elements and assembling them in an appropriate manner, a symbol (a word in the English analogy) can be constructed. There is a nearly unlimited number of symbol element combinations which could be used to generate welding symbols, so generating a CAD library of symbols is, for general application, not practical. The appropriate weld symbol must be generated each time it is to be used.

The expert system WELDSYM.PLE is designed to use a symbol base (database of graphic welding symbol information) and input li-em a human user or the blackboard regarding the weld joint desigdapplication to draw the appropriate welding symbol using a CAD system. WELDSYMPLE uses the same logic processes which would be applied by a welding engineer to develop a welding symbol. The symbol is generated according to the rules established by AWS in documentation reflecting the standardized use of welding symbols (AWS A2.4-86 "Standard Symbols for Welding, Braz-

Welding Procedure Database (WPS)

The welding procedure database consists of process, material, and parameter information for the weld. This database is structured in accordance with the proposed AWS/ANSI Standard A6.1-90 for welding procedure specifications.

Procedure Qualification Record Database (PQRDB)

This database consists of information similar to WPSDB, but includes test results. Full PQRs are stored in this database conforming to the proposed AWS/ANSI Standard A6.1-90.

Electrode Database (ELDB)

Contains data about welding electrodes and filler metals. The information includes not only the designated AWS A.5 standards but also manufacturer published data. The records include typical/recommended usage, composition, operating parameter ranges, etc.

Steels Database (MATDB)

Contains ASTM, AISI, ACI, and UNS weldable steel information, including composition and mechanical properties. Recommended electrode/filler metal usage data is also incorporated.

Heat Treatment Database (HEATDB)

Contains pre- and postweld heating schedule information. Includes data for carbon equivalent (CE), Pcm, and PHa analysis, as well as WRC-published recommend temperatures/times.

Joints Database (JOINTDB)

Contains welding joint design detail information, including data for root opening, included angle(s), tolerances, etc. Curmtly, the data is not CAD compatible but if necessary for system operation, the data will be converted.

Welding Symbols Database (SYMDB)

Contains AWS/ANSI D2.4-86 standard welding symbol information for developing standard welding symbols on mechanical drawings. This data is already CAD compatible and will be maintained in Navy CALS compatible format.

Table I. Welding Databases

Weld Path Planner

Path Planning (ES)
Path Updater (ES)

Weld Joint Designer

CAD System
WELDJOINT (ES)
WELDSYMPLE (ES)
CADDB (DB)
SYMBOLDB (DB)
JOINTDB (DB)

Weld Procedure Specifier

WELDPROSPEC (ES)
WELDPROCGEN (ES)
WPSDB (DB)
PQRDB (DB)

Structural Integrity Analyzer

SIPREDICTOR (ES)

Weld Material Analyzer

WELDSELECTOR (ES)
FERRITEPREDICTOR (ES)
WELDHEAT (ES)
WELDSTAINLESS (ES)
ELECTRODEDB (DB)
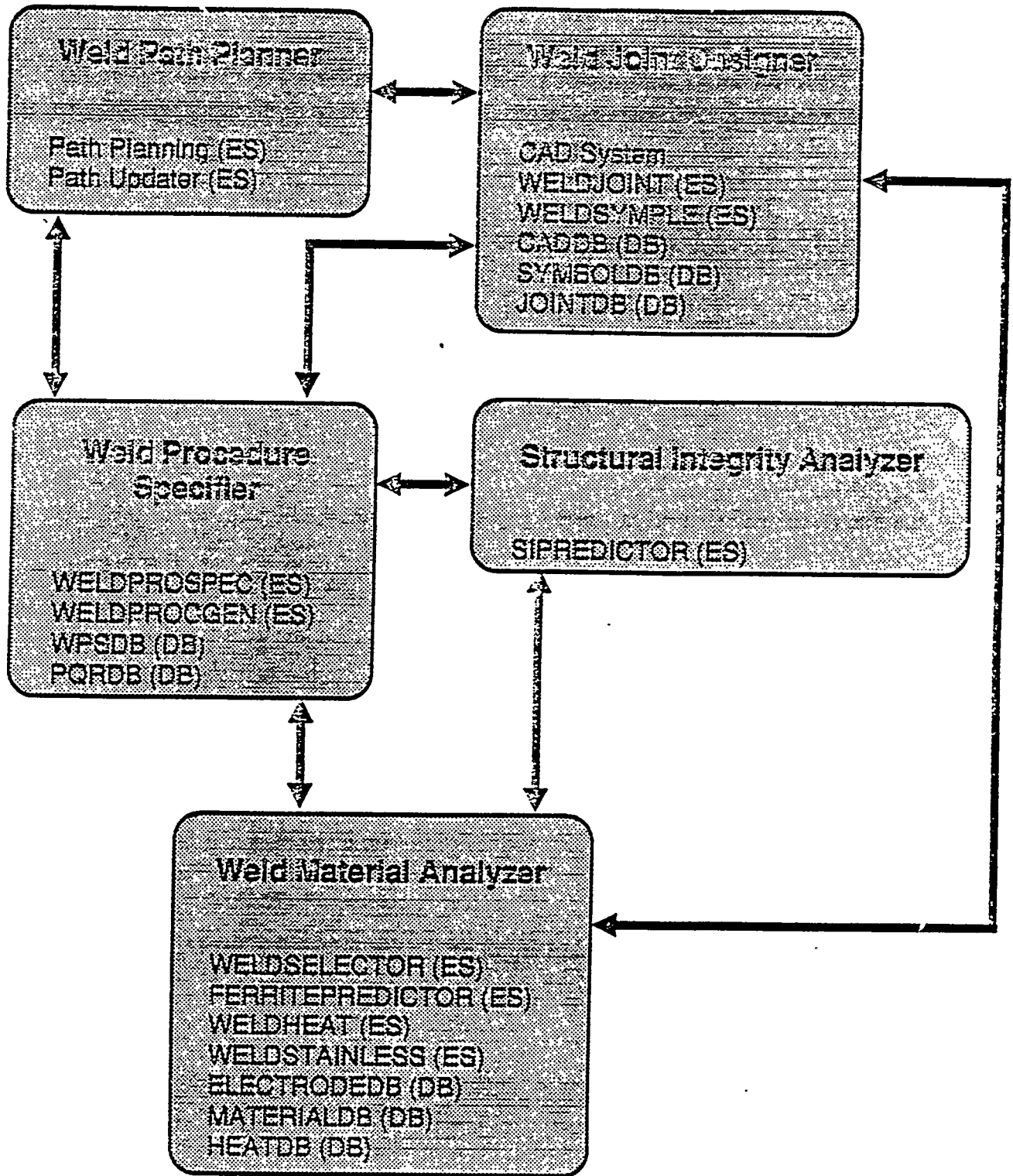MATERIALDB (DB)
HEATDB (DB)

Figure 2. Overall Breakdown of the Welding Job Planner Sub-system

ing, and Nondestructive Examination"). This expert system is currently available as a stand alone system and was tested by AWS prior to its commercial release.

WELDJOINT. The design of a welded joint is, as with many engineering decisions, a delicate balance of compromises. The joint design attempts to combine several criteria simultaneously, some of which may conflict. The joint must be machined to allow sufficient clearance for the weldling operation, but with a minimum of open space to fill with the expensive filler metal and time consuming welding operations. The design must accommodate the configuration of the structural shapes to be joined, but also minimize the stresses which occur on the joint in service and the residual stresses that develop as the weld shrinks due to non-uniform temperature distribution during solidification and cooling.

The WELDJOINT expert system interacts with a graphics-based data system to produce a drawing of the weldjoint. In addition, the expert system provides much of the output information so that the welding symbol can be produced for the mechanical drawing. The data and graphical layout of the figure are in accordance with AWS/ANSI standard joint design, as described in AWS D1.1, "Structural Welding Code."

Structural Integrity Analyzer

The Structural Integrity Analyzer Sub-blackboard (S1S) will function to provide the design engineer with basic structural integrity information and help to set the NDE criteria. The system utilizes the basic Linear Elastic Fracture Mechanics (LEFM) criteria for defect size limit setting. However, the SIS will have provisions to include more complex analyses in future implementations.

SI-PREDICTOR A structural integrity analysis is a necessary part of the overall system. The SI-PREDICTOR expert system provides a fracture mechanics approach to the analysis of structural safety. The system utilizes basic information about the structural geometry type, mode of loading, and structural dimensions, and also about the material being used (tensile properties and fracture toughness). SI-PREDICTOR is currently based upon a LEFM approach; consequently, solutions are checked to see whether the limits of linear elasticity are violated. SI-PREDICTOR determines a critical defect size for a structural component geometry. Six component geometries are available: Vessel, Truss, Plate, Beam, Girder, and Pipe.

The SI-PREDICTOR expert system program calculations have been verified independently for numerous test cases to ensure that the program is error free. The accuracy of the critical defect sizes calculated are dependent only upon the accuracy of the input; component dimensions, applied loading, and material properties.

Material Analyzer

The Material Analyzer Sub-blackboard (MAS) will enable the design engineer to perform optimum selection of welding consumables and to set pre- and postweld heat treatment (PWHT) to optimize the weld properties. This system utilizes all applicable Mil. Spec's. and standards, and AWS welding electrode and filler metal specifications are included in the databases. The weld preheat and PWHT will be based on Mil. Spec's. and Welding Research Council (WRC) published guidelines. In addition, the MAS will provide the user with the latest state-of-the-art technology for analysis of special nonstandard materials, or universal weld heating requirements.

WELDSELECTOR. The selection Of a welding electrode or filler metal is a complex task requiting detailed information about the base metal to be welded and the properties of the electrode and filler metal. In addition, several aspects of the welding operation must be examined and decisions made regarding the specific application in order to narrow the list

of possible electrode choices. A weld, which is a small bit of solidified metal, is expected to have the same (or perhaps better) properties as the base metal that it joins. The base metal may have undergone hours of careful and expensive heat treating and processing, yet the weld metal must be as corrosion resistant, as strong, as ductile, and as fracture resistant as that base metal.

The WELDSELECTOR expert system is able to access data about the welding materials through the use of extensive databases which contain information about base metals and electrodes. The base metals database currently contains over 1,000 grades of steel identified by ASTM classification. Navy-used steels are being added to the database, including the HY and HSLA steels commonly used in shipbuilding. The electrode database contains all of the AWS classified welding electrodes which are used in the United States for three welding processes: Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW) and Flux-Cored Arc Welding (FCAW). The various military qualified electrodes are currently being added to the cross-reference listing.

WELDSELECTOR follows the logic processes which are used by a human expert to determine an appropriate filler metal. Given basic information regarding the material to be welded and using the databases of the base metals and electrode properties, an initial feasible list of electrodes is produced. The list is then ranked based on decision factors about the required weld. Examples of the type of decision factors include: (1) the type of welding equipment to be used, AC or DC (to partially determine the chemical design of the welding flux); (2) the degree of hydrogen contamination coupled with the sensitivity of the base metal to hydrogen damage; and (3) the position in which the weld is to be made (e.g., flat, vertical, or overhead).

WELDSELECTOR only uses decision factor data as necessary. The system can prompt the human user for more details when needed.

As with any decision making process, conflicting input must be weighed and evaluated based on its resulting impact. This is accomplished in WELDSELECTOR with the use of a numerical rating system of certainty factors (CFS). WELDSELECTOR produces a CF-ranked list of electrodes from which the top choices are selected. These top choices can then be used in the design of an overall welding procedure.

WELDHEAT. The arc welding process often requires additional heat treatment in the form of applying external heat to the weld area before interpass and during and following the welding process. This external application of heat treatment is referred to as interpass heating, preheating, and postweld heat treatment respectively. By minimizing the temperature differential during and after welding, the welded area will have lower residual stresses and is less susceptible to cracking and other metallurgical problems such as hydrogen damage.

The WELDHEAT system uses the same decision making procedure that an expert metallurgical engineer uses to establish weld heating schedules. However WELDHEAT provides a fast and efficient procedure to evaluate the heating requirements using several different methods. The system will interact with the user to choose the best analysis method (WRC recommendation, carbon equivalent, Pcm, or PHa) to use for preheating determination. Then the expert system will be called upon to assist with generation of a WPS and to verify that a standard or a developed WPS has the appropriate choice of heating schedules.

The database system incorporated with WELDHEAT contains "typical" composition values for over 500 ASTM classified steels. WELDHEAT will include in the decision process one or more of several important parameters, depending on the specific situation: cooling rate, potential hydrogen content, joint type, plate thickness, energy input, and electrode choice. The various methods can run in parallel. Based on the user's selection, one or

more of the methods can be used to provide a "best estimate" of the preheat and interpass temperature, as well as the recommended postweld heat treatment. If the user or the black-board does not have information about all of these parameters, WELDHEAT will use all of the available information to provide a "best estimate" of the preheat and interpass tempera-ture as well as the recommended postweld heat treatment.

Weld Procedure Specifier

The objective of the Procedure Specifier Sub-blackboard (PSS) is to obtain a Welding procedure which can be used to develop a weld schedule. That weld schedule is then passed to the welding job controller. There are three op-tions which are available within PSS. First if an applicable welding procedure spedication (WPS) is available in the database which meets the requirements of the weld to be performed, then that WPS(s) is extracted. If there is more than one, the list is ranked in order of ap-plicability and presented to the human user. Second, if no WPS is already available, then pre-existing welding procedure qualification records (PQRs) are extracted from the database which are applicable to the weld to be per-formed. Then a WPS is generated from these PQRs. Finally, if no applicable PQRs can be found, a PQR plan is developed which can be tested to produce PQRs in an actual weld testing operation.

WELDPRO-*- Expert Systems. This suite of expert systems is an important part of the WELDEXCELL WJP. Each expert system in the suite deals with weld procedure data. They work together to select an appropriate procedure (WPS) or to generate one, and then to develop a welding schedule based on the welding procedure data. The schedule is then used to direct the welding tasks to be performed.

The WELDPROSPEC expert system chooses a previously tested WPS from a database. If a WPS is not found which will meet the specific application needs, then WELDPROSPEC selects all of the PQRs from the database which are applicable to the weld to be performed. The PQRs which are selected are used to backup a WPS to be generated from the PQRs by WELDPROGEN. Additional rules are being added to the existing WELDPROSPEC system to include Mil. Spec. requirements; currently, it is based on the AWS D1.1 Code guidelines for WPS generation. PQRs are currently selected so that the WPS data specified falls within the allowed variance of the PQR essential variables as specified by AWS D1.1 code. The selected PQR data is passed to the WELDPROGEN expert system which is then called upon to generate a WPS. If appropriate PQRs cannot be located, the WELDPROPLAN expert system is called upon to develop a PQR test plan. WELDPROGEN will generate a WPS which conforms to the appropriate rules or guidelines horn the set of PQRs which were selected by WELDPROSPEC. The expert system produces a WPS which contains all of the neces-sary data required to develop a weld schedule and which confirms to the applicable code or Mil. Spec. and which is adequately "backed up" by PQR's.

WELDPROSCHED develops a suitable welding schedule which is supplied to a manual welder, an automatic welder, or to the robotic welding system. Specific values and allowable ranges are supplied to define machine settings during the welding operation. The schdule considers position, thickness, and joint design changes and is able to adjust for multiple passes.

Weld Path Planner

The Path Planner System (PPS) includes the basic design implementation of a welding path from a CAD-based design of the part to be produced. The three aspects of the system are (1) the CAD system which will be compatible with many commercial CAD systems including the Navy CAD system; (2) the path planner which takes the CAD drawing and plans the welding path; and (3) a robot welding graphic

simulator which includes collision avoidance assistance.

A computer-aided design (CAD) system is used that works in the specific hardware and software environment defined by this project. Currently the system uses AutoCAD. Drawings of the assembly pieces are created in three dimensions, and details of the joining of these pieces will be included. The CAD system must have the ability to allow the engineer to select the path to be followed by the welding torch/end effecter of the welding robot, In addition, CAD code is being developed which allows the human user to identify objects in the CAD drawing. The three types of objects to be identified are (1) the weld line, (2) the objects to be joined, and (3) other objects which are potential collision objects or are important to the weld process (e.g. fixturing).

A separate system to be operated with the Welding Job Planner blackboard is available to do the path planning so that the path will be able to be associated with welding schedule data provided by the WELDPROSCHED system. Considerations are made for part accessibility, and/or possible obstructions on the part itself. It will also be necessary to simulate the robot movement relative to the parts to be welded. The simulation assists in path planning and collision avoidance.

A robot simulator has been developed for an articulated arm and foragantry robot system. The simulator is capable of reproducing all of the robot motions including operating envelope limitations. The robot end effecter world coordinates, and joint positions are displayed in real-time on the graphics screen. A specially designed collision avoidance system was developed by the Colorado School of Mines to operate in parallel with the real-time robot simulator.

WELDING   JOB   CONTROLLER

Functional Description

The Welding Job Controller (WJC) is responsible for all real time activities within the WELDEXCELL system. The WJC can accept a weld description horn the Weld Job Planner (WJP) and accordingly control the welding hardware. The WJC will also collect data during the welding process for analysis on the WJP workstation. Figure 3 shows the top level organization of the WJC software components.

The WJC operator interface supports direct interaction between the end user and the welding system. Animated graphical control panels allow the operator to configure the hardware, adjust system parameters, load weld descriptions, and monitor the real time welding pcess. The WJC system is currently under development by the WELDEXCELL team at the MTS Systems facility in Minneapolis.

Operator Interface

The operator interface will allow the welding hardware operator to perform the following functions:,

- Load, limited edit, and execute a Weld Job Planner description

- Configure the hardware interface components

l Perform sensor and transducer calibration

- Monitor execution of the welding plan

- Monitor real time welding process variables

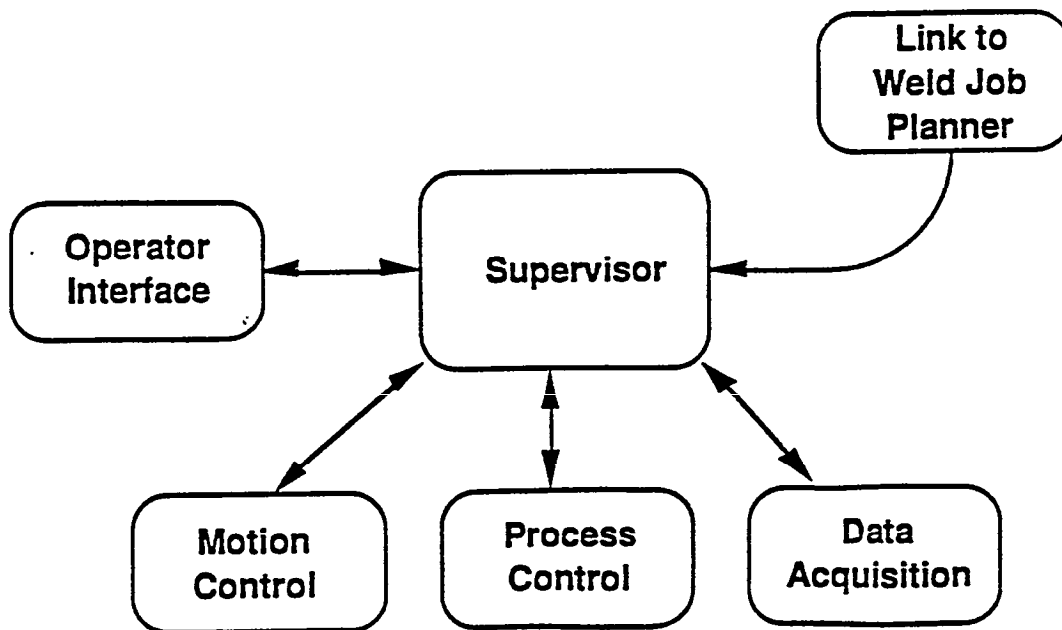Ž Monitor and adjust the robot motion control system

Figure 3. Overall Welding Job Controller Software Breakdown

1 Configure and display the data acquisition processes

The operator interface will present a set of animated control panels to the end user. These panels will be displayed in workstation windows. The user will manipulate a picture of electronic controls using a pointing device. Input components will include push buttons, toggle switches, slide controls and radio button clusters. Animated displays will show the state of the welding process and provide immediate feedback when the controls are adjusted. Displays will include virtual graphic representations of indicator lamps, digital readouts, oscilloscopes and chart recorders.

The organization of the operator interface will follow object oriented design principles: Each major hardware subsystem will have an associated graphical control panel. The panel allows the welding specialist to adjust and monitor familiar welding process parameters. The operator will be able to control which panels are displayed and interact with any con-

trol panel at any time. All visible displays will be continuously updated to reflect the current state of the welding process. All active input controls will provide immediate feedback to the operator when their values are changed.

The Real-Time System

As described above, the real time system will consist of a supervisor module and three major real time processes:

• Motion control system

1 Welding process control system

• Data acquisition system

The supervisor module will handle the interface between these three subsystems, the operator interface and the Weld Job Planner. The supervisor will be the main control program within the WJC although the user interface will

be reactive: consequently, the operator will at all times be able to adjust or even override the execution of the welding plan;

The Supervisor will implement the following major functions:

l Download weld job descriptions from the Weld Job Planner using a LAN interfaee.

l Interpret the weld job description as a program by sending commands to the other real time system modules.

l Monitor the execution of the Weld Job Description and support operator interventions such as pause/resume and single stepping.

Ž Monitor the status of other major components of the WJC for display on the Operator Interfaee.

l Implement commands from the Operator Interface for system configuration, adjustment and control.

Motion Control

The motion controller will move the welding torch along a programmed path using a robot arm. Figure 4 is a signal flow diagram showing the top level organization of the motion controller.

The motion controller will work with three coordinate systems. The world system will be used to specify points in a fixed Cartesian coordinate system. The pan coordinate system will be aligned with the part to be welded. The tool system will be aligned with the welding torch tip. During the welding process the motion controller will keep one axis of the tool coordinate system aligned with the seam.

The signal flow diagram shows thre coordinate conversion modules. The world joint module will take a vector signal of wor coordinates and convert it to a vector signal joint angles. The part to world module wil take a part relative vector signal and convert to the joint system. The tool 10 joint modul will convert a tool relative vector signal to tl joint system.

The Path Generators will be responsibl for providing a position command to the robo arm that moves the welding torch. The super visor will provide a sparse sequence of gaug points in either part or worId coordinates al the desired tool veloeity along the seam. Tl world path generator will receive the gaug points specified in world coordinates while tl part path generator will receive gauge point speeified in part coordinates. In either case, tl path generator will interpolate additional point along the trajectory uniformly spaced in time (i upsamples the position signal).

The joint controller command wilI be tl sum of three input signals: the desired trajector from the supervisor, the correction form tl seam finder and the feedback from the robc joint resolvers. The joint controller will calcu late a new command for the joint servos base on these values.

The robot interface will accept a stream c joint angle vectors and use this to a apply proportional signal to the joint actuators. Th output of the robot interface will be a vecto signal of actual (measured) angles taken fro the joint resolvers.

The seam finder will send adjustments t the joint controller based on real time visua information about the seam location.

The seam finder will be responsible fo updating the path of the robot in real time (actua update rates will be approximately 10Hz) b analyzing the gray scale or laser imaging dat to determine an offset in the coordinate syste of the torch (i.e. tool coordinates). This relativ
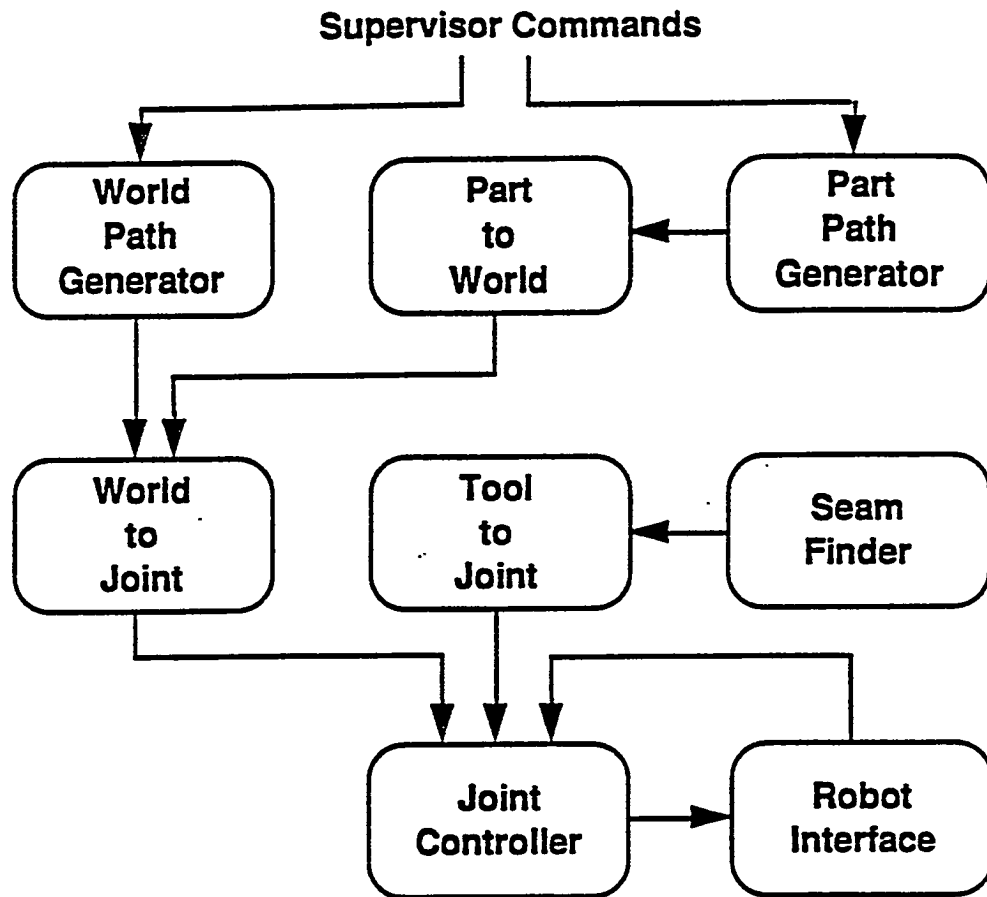
Supervisor Commands

```
                              Supervisor Commands
                                    |        |
        +---------------------------+        +---------------------------+
        |                                                                |
        v                                                                v
  +------------+         +------------+                          +------------+
  |   World    |         |    Part    |                          |    Part    |
  |   Path     |         |     to     | <----------------------- |    Path    |
  | Generator  |         |   World    |                          | Generator  |
  +------------+         +------------+                          +------------+
        |          +----------+    |
        v          v               |
  +------------+         +------------+                          +------------+
  |   World    |         |    Tool    |                          |    Seam    |
  |     to     |         |     to     | <----------------------- |   Finder   |
  |   Joint    |         |   Joint    |                          |            |
  +------------+         +------------+                          +------------+
        |                  |   |                                      |
        +----------+       v   v                                      |
                   v       v   v <-------------------------------------+
                  +------------+                          +------------+
                  |   Joint    | -----------------------> |   Robot    |
                  | Controller |                          | Interface  |
                  +------------+                          +------------+
```

Figure 4. Signal Flow Diagram for the Motion Controller

offset will be passed to the joint controller via the tool to joint converter.

The data acquisition system preprocesses and record weld process parameter data such as weld travel speed, wire feed rate, gas flow, current velocity and temperature. The raw results may be examined from the operator interface and/or sent back to the Weld Job Planner workstation for further analysis. The data ac-. quisition system has several modules specifically designed to capture data from the different types of sensors and perform preliminary sampling and filtering operations as shown in Figure 5 below.

USER INTERFACE

The objective is to develop a user interface which makes maximum use of advanced interface design technology. Extensive use of windows, mouse active screen elements, icons, and object-oriented interface philosophy. Occasionally, the user may be asked to type in a response but in most interactions, the user will be presented with a list of parameter values or icons from which to choose.

The user interface will be designed for a variety of potential users. These users will include mechanical engineers (ME), NDE engineering personnel (NDE), welding engineers (WE), welding system operators (WO), and

data system operators (DO). The major functions of the interface and anticipated users are as follows

- Welding Procedure Specification (WE)

- Materials Analysis (WE, ME)

- Structural Integrity Analysis (ME, NDE)

- Weld Schedule Specification (WE, WO)

- Data Systems Interaction (WE, ME, DO)

- Knowledge Systems Interface (ME)

- CAD System (WE, ME)

Interface System Components

The interface will consist of several virtual components. Most of the functions required of the WJP system require that the system acquire information from the user each step in the analysis. For example, when determining the welding consumables for operation, the user should only need to specify the gas type after the process has been determined to be GMAW or shielded FCAW. The main technique to be employed will be one
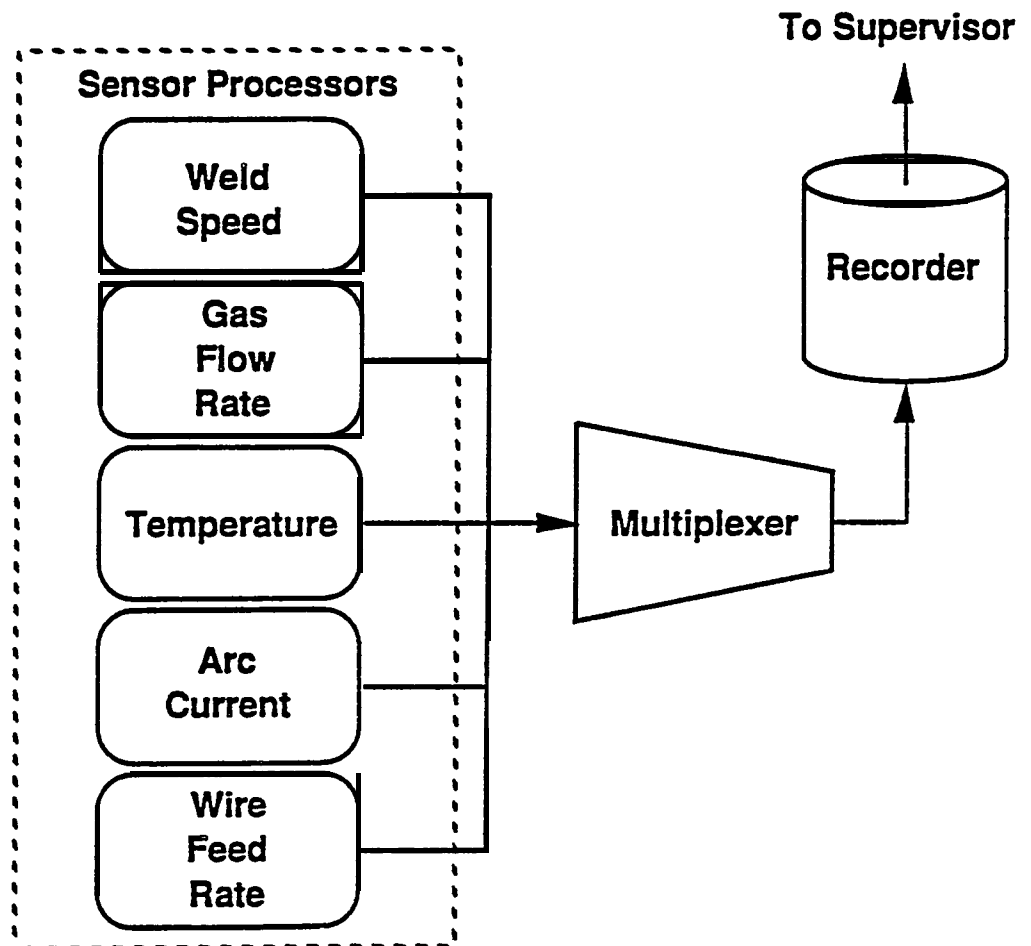

Figure 5. Welding Job Controller Data Acquisition System

overlapping windows in a layered hierarchical frame-type knowledge representation schema.

Whenever possible, the user will have available a series of icons which represent the necessary and/or system-required information needed from the user. For example, a small icon of a gas cylinder would be used which the user could manipulate with a mouse and open a window which would allow the user to provide information or get back information relative to shielding gas decision making.
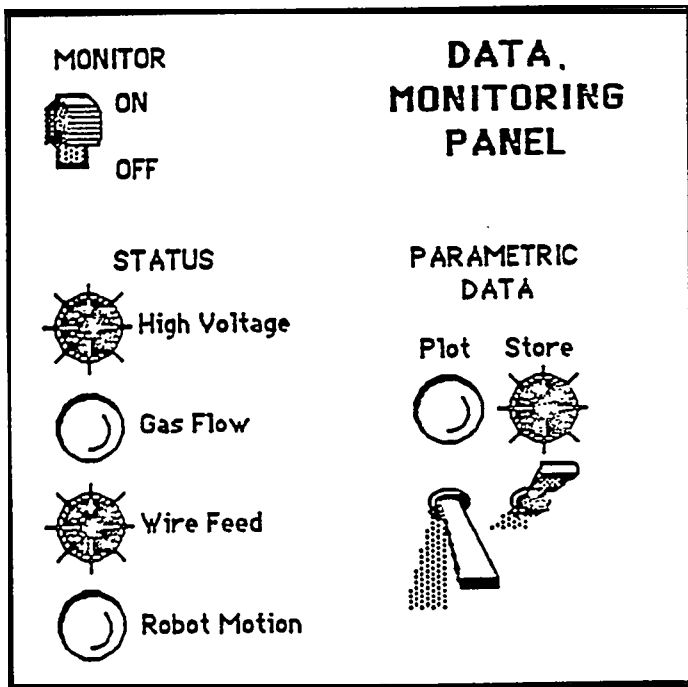

Figure 6. AGraphical representation of an example control panel.

COMPUTER SYSTEM

The WJP will be implemented on a Texas Instruments Explorer Artificial Intelligence Workstation, which is an ideal choice for fast execution of the various expert systems and databases which make up the WJP. An Ethernet link will be used for transferring files to and from the WJC. The WJC will be implemented on a VME-based Unix system consisting of several Motorola 680X0 microprocessors. This architecture is a proven platform for real-time welding workcell control and provides the

openness which will be required to interface to different manipulators, welding equipment and process parameters.

Welding Job Controller/Planner Interface

The interface between the WJC and WJP has specific requirements that are primarily driven by the needs of the WJC. This interface is exclusively one of file transfer through a TCP/IP protocol LAN. The two primary activities of the interface are to pass weld schedule data from the WJP to the WJC and second to provide interpass weld history data to the WJP for interpass intelligent update of the process variables.

In order to provide maximum flexibility and modularity, the system was divided into two component subsystems at a point where minimum communication was necessary. This design provides for enhanced throughput and autonomy of operation. It also lends itself to a simple broad band LAN rather than to a bus structure. Finally, by subdividing the problem at this point, the engineering workstation can be remote to the actual workcell environment.

Artificial Neural System Based Vision System

An Artificial Neural System (ANS) simulation of a robot tracking a welding seam in the presence of a large amount of noise has been developed by the Colorado School of Mines . It consists of an image input subsystem, a neural network subsystem, an output robot control signal subsystem, and an interactive display interface. The software for the simulation is a 3-layer, back propagation network The number of input nodes is equal to the number of pixels in the input image. Connection strengths are determined by the training of the network for the specific welding problem. The output nodes provide the guidance information to the welding robot.

During a weld, the Artificial Neural system on the WJC (i.e. the Seam Finder) will be run in a "feed forward", or non-learning mode

where images are processed into control signals without any adjustments to the strengths of the connections between processing elements. A detailed descripton of this ANS based vision system can be found in the literature (A. Rock, 1988; A. Rock, 1989)

Real-Time System Implementation Strategy

The real-time processing components of the Weld Job Controller will be implemented using HOSE, a tool for programming industrial control systems. HOSE allows the designer/implementer to draw data flow diagrams that are automatically implemented on the real time hardware. The diagrams maybe used for system design, simulation, implementation and diagnostics.

HOSE is used for both rapid prototyping and final implementation of industrial control systems at MTS. The graphical interactive nature of HOSE allows client feedback to be incorporated in the control system design process. Most of the diagrams used to illustrate the WJC real time systems in the previous sections are suitable for direct representation in HOSE. In many cases, the top level diagrams in a HOSE program are the design documentation.

Welding Control

The welding control system is designed to provide two capabilities. First, the system can set and hold a constant welding parameter schedule as specified by the WJP Subsystem. Second, the controller can ramp the welding parameters between physical set points in the welding path -- also as specified by the WJP. The welding control system provides the welding operator with the capability to view and, to a limited extent, to edit the weld schedule.

WJP User Interface Implementation Strategy

The interface will be developed through the use of the windowing facility in the Knowledge Engineering Environment (KEE) software and will interact with the X-windows software interface to provide easy accessibility to the user. If appropriate, the AllTalk language software, from MTS Systems, will be utilized. In addition, a significant effort is being made to unify the basic "feel" of the WJC and WJP user interfaces. This is not always possible, however, since the two interfaces require significantly different functions for different classes of users.

CONCLUSION

Based on the development of the prototype blackboard, expert systems, and databases for this project, it can be concluded that the ability to combine welding expert systems and databases is technologically very feasible. It has been estimated that the potential savings for the shipbuilding industry alone could be quite substantial if this technology is integrated into the welding activities of shipyards. Finally, it is the intent of the AWI/MTS/CSM team to complete the development of this system and to transfer this technology both to the shipbuilding industry as well as other welding intensive industries in the United States.

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