Portable Weld Inspection Management System

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ABSTRACT

Manual visual inspection is by far the most widely utilized weld inspection method. A given weld may be visually examined multiple times as parts are joined and made into assemblies. Because visual inspection is somewhat subjective, and prone to error (a typical inspector only identifies about 85% of the visible defects); welds which pass one inspection may fail subsequent inspections, resulting in multiple inspection and repair cycles. This paper discusses a project that tested the benefits and limitations of a semi-automated weld inspection system. The goal of this semi-automated inspection approach is to provide quantitative, non-subjective quality measurements of welded structures in order to: eliminate redundant inspections, reduce unnecessary multiple repair cycles, avoid repair of welds which meet minimum size requirements, and enable recording of weld size so that over-welding can be identified and reduce. The technology would also allow tracking of weld quality and statistical analysis of welding process capability to support lean/six-sigma continuous improvement initiatives. A prototype system was assembled and field tested by inspecting actual ship structures. The equipment evaluated has potential, but needs both hardware and software modifications before it can be used as a tool on a regular basis in a shipbuilding environment. As is, it will be useful as an audit tool to gauge the health of the visual inspection process and to further document the inherent variability of the visual inspection process. Recommendations were made for improvements to refine the prototype tool prior to broader deployment.

KEY WORDS: Visual Inspection; Laser; Defects; Welds

SUMMARY

Visual weld inspections are performed manually by shipyard inspectors. Current weld inspection acceptance criteria specify absolute minimum requirements for structural fillet welds based on traditional workmanship limitations. The tendency in shipbuilding is to be over-conservative on weld size and inspection. The result is a culture of over-welding that deposits two to three times more weld metal than is needed for structural integrity. In addition, many welds are visually examined multiple times as panels are built into units and then into larger assemblies. Since visual inspection is somewhat subjective, welds which pass one inspection may fail subsequent inspections, leading to redundant and unnecessary inspection and repair cycles.

Over-welding and over-repair adversely affects cost, schedule, and performance. The cost to produce a weld is proportional to the amount of weld metal deposited, so over-welding adds directly to welding production costs. Additionally, the cost to repair a weld can easily exceed the original cost to produce the weld. Over-welding also causes excessive distortion which adds to the ship fabrication cost. The cost of flame straightening alone is estimated to exceed 11% of structure costs, the fitting costs for every assembly operation are further compounded by distortion. Over-welding, over-repair, and distortion mitigation also causes schedule disruption which increases delivery time. Finally, the performance of the ship is reduced as tons of excess weld metal is added.

An inspection tool is needed which performs quantitative, non-subjective quality measurements and then records the results in an easily accessible format. Such a system would offer the following benefits:

- Eliminate redundant inspections,
- Eliminate unnecessary multiple repair cycles,
- Eliminate repair of welds which meet minimum size requirements,
- Enable recording of weld size so that over-welding can be identified and reduced,
- Allow tracking of weld quality and statistical analysis of welding process capability to support lean/six-sigma continuous improvement initiatives,

The equipment evaluated has potential, but needs both hardware and software modifications before it can be used as a tool on a regular basis in a shipbuilding environment. As is, it will be useful as an audit tool to gauge the health of the visual inspection process and to further document the inherent variability of the visual inspection process.

INTRODUCTION

The Portable Weld Inspection Management System (PWIMS) project received funding in November of 2004 from the Center for Naval Shipbuilding Technology (CNST). The project team consisted of representatives from Bath Iron Works (project lead), Edison Welding Institute and Servo-Robot. The goal was to take an off-the-shelf inspection device (Servo-Robot's WISC ®) and determine what its capabilities were in terms of performing inspections in a shipbuilding environment.

Around the same time, a similar research project, Automated Weld Inspection (AWI) received funding from the Gulf Coast Region Maritime Technology Center. Lead by Northrop Grumman Ship Systems – Avondale Operations and collaborating with the University of New Orleans, the objective was to determine whether an alternative process exists that could combine flexibility, robustness, and versatility of human inspection with the impartial accuracy of an automated inspection system.

The two teams, PWIMS and AWI, met in January 2005, and agreed to work together to test whether the Servo-Robot WISC ® could be integrated into the shipyard environment to create a better weld inspection system.

BACKGROUND

Welding is the primary means of joining structural components in naval vessels. All structural welds are inspected to ensure compliance with the governing specifications. A variety of standards may apply depending on the application, such as MIL-STD-1689 for ship structure, MIL-STD-1688 and 1681 for submarine HY steel structure, and ABS rules for commercial ships.

Visual inspection is by far the most widely utilized weld inspection method. All structural welds are visually inspected for compliance with workmanship and geometric (i.e., weld size) requirements. Redundant inspections are usually performed, first by front-line supervisors, then by shipyard QC inspectors, and finally by Navy SUPSHIP inspectors or ABS surveyors.

Shipyard inspectors/supervisors must "buy-off" on a component as meeting requirements during each step in the fabrication process (panel or bulkhead fabrication, unit erection, and ship erection). The same weld details are often inspected multiple times as smaller structures are assembled into larger structures. Because visual inspection is somewhat subjective (estimated that visual inspection is only 80-85% accurate), welds details which were initially accepted may be subsequently rejected during a re-inspection, leading to unnecessary multiple repair cycles.

Current standards set requirements for minimum (but not maximum) weld dimensions. Minimum weld size requirements are marked on the work by the fitting trade. Mechanical gauges allow inspectors to measure weld sizes only at discrete locations along a weld. Inspectors do not have tools to cost effectively measure weld dimensions along the entire length of a weld. In practice an inspector may look for areas of smaller than average weld size and reject the location as an undersized weld. Repair welding is performed by welding over an area with insufficient weld size and then contour grinding to remove the excess reinforcement. An average stiffener with a few rejected areas may require twice the time to repair as was needed to make the original weld.

As a consequence of the current weld inspection approach, a culture of over-welding has developed. For example, a typical minimum fillet weld size required for thin panels is 5 mm. As illustrated in Figure 1(A), the weld size is defined as the length of the smaller leg of the fillet weld. For manual and semiautomatic welding, the weld size typically varies such that one leg is often shorter, as illustrated in Figure 1(B). A repair would be required if one leg of the fillet was less than 5 mm. To avoid repairs, 7 mm or larger fillet welds are routinely produced. The volume of a 7 mm weld is twice that of a 5 mm weld.

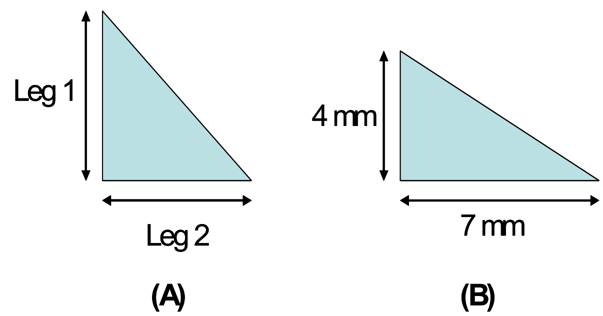

Figure 1:
(A) Fillet weld size based on leg length
(B) The asymmetric weld shown has a size of 4mm

Routine over-welding has negative financial and performance repercussions. Since the time to produce a weld is directly related to the weld volume, over-welding and unnecessary repairs adds significant labor costs. Excessive welding has also been shown to be a major contributor to distortion (Conrardy, 1995). As distortion increases, additional labor is required to straighten and fit distorted components, which adds to the cost and adversely impacts the build schedule. Finally, excess weld metal increases the overall weight of the ship and hence reduces performance.

Many ship design engineers acknowledge that most welds on structures are larger than needed for structural and shock performance. The 5-mm weld size routinely used on many ships is invoked because this is considered the minimum fillet size within the manufacturing capability of shipyards. For many ship structures a smaller leg size would provide adequate performance. As shipyards move towards complete finite element analysis (FEA) and modeling of all ship design structures, improved acceptance criteria could be developed. Weld acceptance criteria could be based on fitness-for-service (FFS) or performance-based analysis (PBA) using the structural model instead of over-conservative workmanship criteria.

PBA weld acceptance criteria would enable deployment of smaller precision fillet welds using automation. Precision fillet welds have been demonstrated as small as 3-mm using through the arc seam tracking automation. However, some small percentage had insufficient leg size due to fit-up gaps. FFS or PBA base criteria might allow acceptance of such welds for non-critical areas if the leg size in these regions was within 0.5 mm of the target. Significant gains could be made in first time quality and reduced distortion by developing better inspection criteria centered on a target weld size and allowances for normal variation.

An inspection tool is needed which performs quantitative, non-subjective quality measurements and then records the results in an easily accessible format. Such a system would offer the following benefits:

- Eliminate redundant inspections,
- Eliminate unnecessary multiple repair cycles,
- Eliminate repair of welds which meet minimum size requirements,
- Enable recording of weld size so that over-welding can be identified and reduced,
- Allow tracking of weld quality and statistical analysis of welding process capability to support lean/six-sigma continuous improvement initiatives,
- Permit the development of new inspection criteria which is fitness-for-service (FFS) based, rather than workmanship based.

PROPOSED SOLUTION

The Team proposed to develop a Portable Weld Inspection Management System (PWIMS) for shipyards. The system will uniquely allow U.S. shipyards to:

1) Quantifiably visually inspect structural welds,
2) Capture the inspection results to a central database,
3) Compile and analyze the inspection results to produce statistical process control (SPC) reports.

The purpose of the PWIMS is to reduce redundant inspections, unnecessary repairs, and over-welding. The PWIMS could also provide data to support Performance-Based Analysis (PBA) for establishing weld requirements, which meet fitness-for-service (FFS), goals. PWIMS data could provide confidence that the structures have sufficient weld quality by mapping the actual weld profiles for each structure back into the FEM models.

The PWIMS is based on commercially-available, technically-proven components which are integrated and customized to meet shipyard inspection needs. The PWIMS includes the following:

- A portable hand-held laser profile sensor and manipulation tools - Servo-Robot's WISC ® Unit was selected, which consists of:
  - Palm Interface
  - Laser Sensor Device
  - Data Storage Device
- A portable computer for data collection
  - A Motion Computing Tablet was selected
- Data reporting software tools for "buy-offs" and SPC charting
  - EWI created a software program

Figure 2
Servo-Robot commercial weld profile laser sensor

Servo-Robot's involvement will ensure that there is a commercial source and long-term support for a key element of the system. Laser profile sensors employ the principle of laser triangulation to measure the weld surface features. Figure 2 shows the Servo Robot sensor.

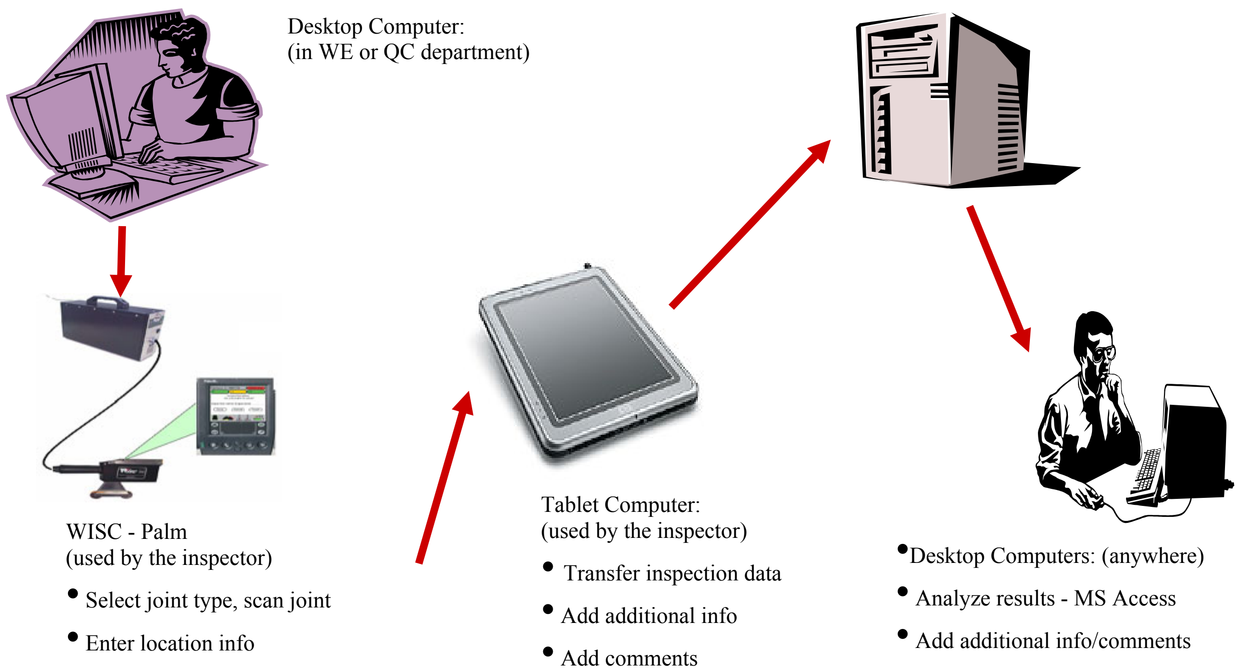

Figure 3
Portable Weld Inspection System Architecture

The schematic of Figure 3 illustrates the relationship of the major system components, and the flow of data from inspection to analysis. The inspector carries the laser profile sensor and data collection device to the component being inspected. The inspector selects the weld type and inspection requirements and enters the location of the weld via the user interface. The inspector then moves the sensor along the length of the weld, and the sensor measures critical features and determines acceptance. After each weld is scanned, the weld quality data is uploaded from the sensor to the portable data collection device. The data collection device acts as a temporary data store and allows the user to generate a summary inspection report to identify repair areas or for "buy-offs". At the completion of the inspection, or at another convenient time, the inspection data is uploaded from the collection device to a central repository via a network connection.

INITIAL EVALUATION & FUNCTIONAL SPECIFICATION

One of the first tasks undertaken in this project was to test the commercial WISC unit as it is sold in the marketplace. This evaluation allowed the team to get a feel for the unit and to determine what functions were good, bad or needed to make the unit an effective tool and to develop a functional specification that would be the basis for standardizing the PWIMS. The principal investigator received training on the operation of the unit and the associated software functions. Initial experimentation of the WISC unit revealed the following items/functions required addition or modification:

- The existing Palm ® software would not allow the entry of weld location identifiers such as hull number, deck number, unit number, frame number, etc which are commonly used to identify the location of structural welds in the shipbuilding industry.
- The inspection data provided by the WISC ® software was not directly useable for standard SPC analysis.

Functional Specification

The next step of the project was to create a functional specification that would ensure all team members understood the requirements for the PWIMS prior to customizing the unit and associated software. Some key elements in the Functional Specification are detailed in Appendix A.

The data collected from the PWIMS would be stored in a relational database. A graphical user interface would allow the database to be queried in order to produce reports. Reports will be of two types:

- Tabular reports – listing the results of one or more inspection
- Graphical reports – providing statistical summaries of the quality information

The system reporting software would allow knowledgeable users to modify search and chart options in order to create new report types.

Pareto Charts

Charting is a powerful tool for understanding trends and relationships between data. The Pareto chart is one of the mostly widely used shipyard report formats. Interrogating and charting PWIMS data could provide the following:

- Trends in minimum, maximum, and average weld sizes over time
- Relative occurrence of various types of weld visual defects
- Trends in repair rates as expressed by defective weld length per total weld length
- Comparison of weld sizes produced or defect occurrence by
  - welding position,
  - process implementation (e.g., manual vs. mechanized),
  - material thickness,
  - joint type (e.g., lap vs. T-joint fillet),
  - detail type (e.g., collar, longitudinal stiffener, transverse stiffener, etc.)

SOFTWARE DEVELOPMENT

An Integrated Product Team (IPT) was formed to develop a functional specification for the PWIMS system. The IPT included shipyard representatives (BIW-welding engineering), the commercial sensor supplier (Servo-Robot), and the system integrator (EWI). The PWIMS functional specification defined both the shipyard inspection requirements and the PWIMS operational requirements.

The PWIMS software development effort involved integrating a commercial weld inspection sensor with custom user interface and database software to meet the functional specification requirements. The software development involved the following steps:

- Selecting the software architecture and tools
- Identifying the data flow requirements
- Implementing the sensor communications protocols
- Interpreting and transforming the data to meet shipyard requirements
- Developing a database format
- Building flexible data analysis and reporting tools
- Testing the integrated PWIMS system in the laboratory
- Deploying the PWIMS to the shipyard and providing on-going support.

Figure 4 illustrates the general flow of data between various software modules. The starting point (Weld Profile Sensor data) and ending point (shipyard Reports) were well defined. The blocks in between were designed to provide a flexible framework to transform and archive the data. This modular design was key to isolate the impact of frequent software modifications as the shipyard data collection, interpretation, and archiving requirements evolved throughout the development effort.

The Communication Interface module implemented the protocol needed to retrieve data from the weld profile sensor. This module was updated frequently as new features were added to the weld profile sensor. The Tablet Graphical User Interface (GUI) module allows the user to view the inspection results and enter additional information about the weld being inspected (such as comments or additional defects not detected by the sensor). The Database Interface software module served two purposes: 1) to translate the sensor data into shipyard standard quality information, and 2) to isolate the database structure from the tablet communications and GUI software (so that changes to the database structure did not affect other modules). Finally, the reporting GUI software implemented searching, sorting, filtering, and data presentation tools.

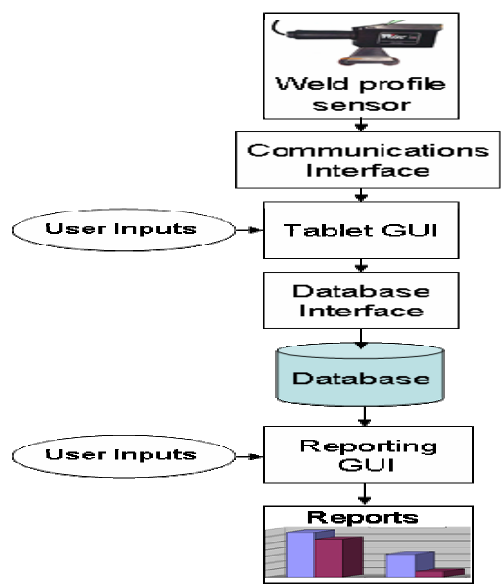

Figure 4
Data Flow between Major Software Modules

Appendix C summarizes the software architecture for the prototype PWIMS data repository computer. The software was developed using a variety of tools. The paragraphs which follow describe the various modules in more detail.

The Tablet GUI software is a custom C++ application which invokes the Communications Interface and the Database Interface modules to retrieve the sensor data and store it to the database. The user can enter general information about the inspection, such as the ship unit number, inspection procedure number, etc. The GUI also allows the user to initiate the data retrieval from the sensor. If desired, the inspector can scan multiple welds and subsequently download all of the data for archiving. For each scan, the user can enter the location where the inspection was performed (e.g., frame number, deck number, etc.), as shown in Figure 5. The user can also view and modify (if the user is granted edit authority) which was collected by the sensor; allowing the user to add comments or identify additional features outside of the sensor field of view. Finally, the GUI allows the user to choose when data should be uploaded to the database for permanent archiving.

Figure 5 Tablet GUI developed for collecting, reviewing, and augmenting inspection data

The Communications Interface retrieves individual inspection results via RS232 serial communications. When a weld is scanned the sensor measures the weld profile at many discrete locations and compares the results to pre-defined pass/fail criteria for the particular application. For each weld, the Communications Interface module retrieves all of these discrete inspection results and reduces the data to a list of defect types, defect length, and other geometric information. This reduced data is temporarily stored in a neutral data format (comma delimited text file) until it is uploaded to the database for permanent archiving.

The Database Interface module is a C++ application which reads the data stored in the neutral format file and converts the data to the relational-database format. Two types of data are archived: 1) the reduced data is stored to searchable fields, 2) raw data is stored as a binary-large-object. The structure of the Database Interface module closely parallels the structure of the database. A change in the database format must therefore be reflected in a change to the interface module.

An SQL-Server database was developed for this application, since it is used at BIW and is expandable to a support an unlimited quantity of data and number of users. Also, the database could be deployed on a central server, allowing multiple users throughout the yard to store inspection results or generate quality control reports. A simple relational database structure was employed with three linked tables to store the application data, user-entered location data, and sensor data. Figure 6 illustrates this structure. A given application (e.g., hull number, unit, etc.) can have multiple entries of user-entered location information (e.g., longitudinal number, frame, deck, etc.). At each location there can be multiple rows of sensor scan data, including both detailed scan results at locations along the weld and a summary for the entire weld.

To simplify the deployment of the initial prototype for testing, the database was housed on the tablet computer rather than on a separate server computer. This allowed duplicate tablet computers to be quickly exchanged between EWI and BIW when database software updates were required.

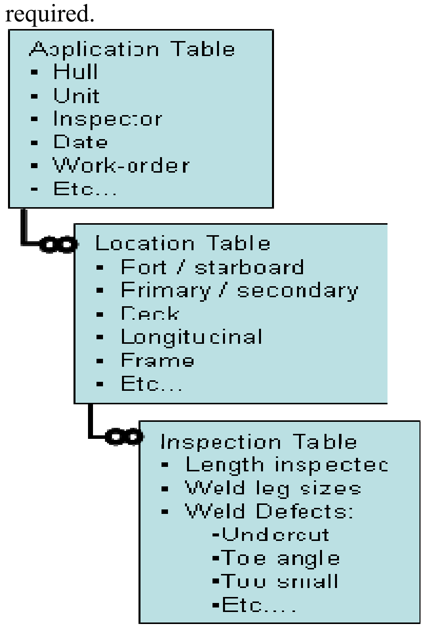

Figure 6 Simple Relational Database Structures

The data analysis and reporting software made use of MS Access and supporting visual basic code along with SQL Server database views and stored procedures. MS Access was selected because the shipyard has familiarity with the software and could modify or expand the reporting tools as needed. A variety of forms were developed based on the shipyard data analysis requirements. Figure 7 summarizes the types of forms which were developed. An example form is shown in Figure 8 to illustrate some of the filtering options available. A variety of report types can be produced, including a "Unit Inspection Report" (Figure 9), which matches the report format produced during manual visual inspection.

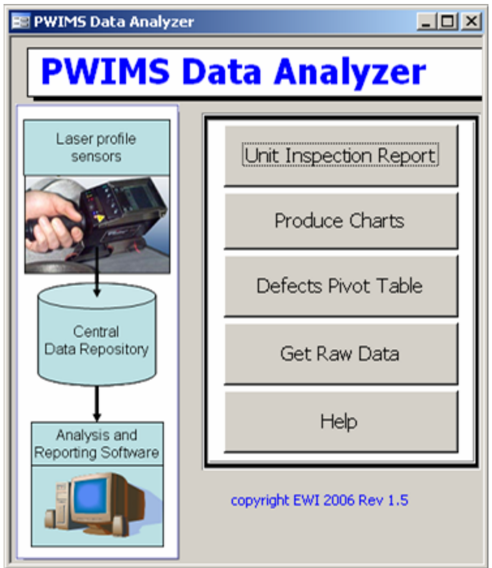

Figure 7 Analysis/Reporting Options

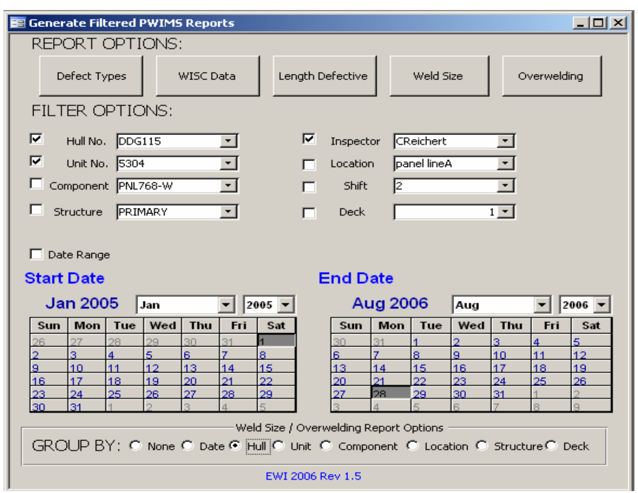

Figure 8 Example Form w/Filtering Options

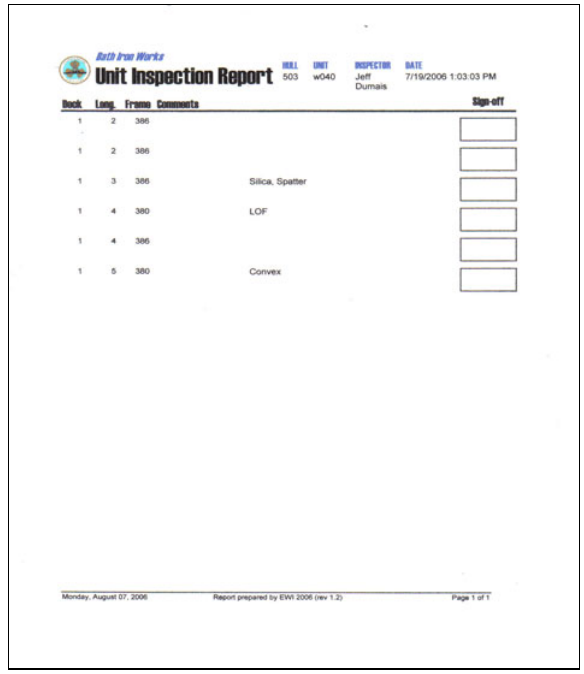

Figure 9 Example of Unit Inspection Report

DETAIL EVALUATION

A detail evaluation was conducted on the prototype system by having a VT Level III Examiner use the system during his surveillance of visual inspection personnel. This allowed for the collection of data both in terms of weld attribute data and equipment operational data. The evaluation was conducted on actual production welds under production conditions.

Operational Issues

The first major issue is the size of the unit. The sensor head measures 10" L x 7" H x 3.5" W. The physical size of the sensor head precludes its use in corners and confined areas. The sensor head is connected to the temporary data collection unit via ½" diameter 6.5' long coaxial cable. This cable is not very flexible. The data collection unit is 12" H x 15" L x 4" W and weighs about 3 pounds. Due to the configuration of the system the data collection portion needs to be carried via a shoulder strap. This becomes cumbersome as one crawls around on a ship unit. See Figure 10.

Figure 10
Unit in use

The inflexible cord coupled with the data collection unit on ones shoulder makes the manipulation of the sensor head difficult. A backpack was purchased to carry the unit, which reduces the possibility of damage to the unit, shifts the weight to a more favorable location and allows more freedom for the operator.

The actual use of the sensor is not complicated. After a couple of tries the operator can determine the correct angle and speeds necessary for the machine to be able to scan the weld. The PDA provides a Go-No Go visual indicator that the unit is in the proper orientation for scanning. See Figure 11.

Figure 11
Unit working with weld profile shown

However, long welds prove to be challenging since it is difficult to scan while crawling along the joint. Use of the unit in the overhead can be fatiguing due to its weight and the fact that the operator has to place the unit on the weld.

If the system detects a defect it is difficult to identify the area on the work piece (so production knows where to repair) while running the scan.

In the initial phase of the project the Palm ® software was not user friendly. There were no provisions for entering supplemental data. The Palm ® is an older version and has limited data entry capabilities and data entry was problematic due to the Graffiti ® character recognition program. This unit does not have the ability to incorporate a memory card in order to store additional data.

Tablet Software Issues

The software developed for the prototype system was designed to allow limited field testing of the unit in order to assess the benefits of the semiautomatic inspection technology. While the prototype system functioned well for this purpose, a number of areas for improvement were identified prior to broader use. The following are a summary of the software issues which were identified:

- Serial communication is slow, requiring an inconveniently long time to upload data from the WISC unit to the tablet PC. A higher-speed data-transfer approach (e.g., USB or wireless Ethernet) would be preferable.
- Permanent storage of data on the tablet PC does not allow for easy sharing of data and does not provide a robust means of securing the data. Moving the database to a network server would address these issues.
- Some of the data-manipulation software routines incorporated shipyard specific rules to interpret the data and identify out-of-tolerance conditions. A more general toolkit of rules would offer broader flexibility to adjust the data processing to meet individual application requirements.
- No tools were developed for remotely maintaining the software (e.g., automatic update functionality). Consequently, frequent manual updating of the various software modules were required. More user-friendly updating tools are needed.

None of these issues were a surprise, since the prototype software was designed with limited functionality. Future software versions should build upon the current functionality to address these shortcomings.

DISCUSSION OF DATA RESULTS

The first comparison was to have certified Visual Inspectors inspect a controlled weld to determine what level of variability exists in the manual inspection process. A test weld was fabricated that had either barely acceptable or barely rejectable attributes. Ten visual inspectors were asked to inspect the controlled sample for the following:

- Weld Size
- Undercut acceptability
- Roll Over / Reentrant angle acceptability

Table 1

Inspector	Weld Size	Undercut	Roll Over	Other
1	UNSAT	UNSAT	UNSAT	
2	UNSAT	UNSAT	UNSAT	
3	UNSAT	UNSAT	UNSAT	*
4	UNSAT	UNSAT	UNSAT	
5	UNSAT	UNSAT	UNSAT	
6	UNSAT	UNSAT	UNSAT	
7	UNSAT	UNSAT	UNSAT	*
8	UNSAT	UNSAT	UNSAT	
9	UNSAT	UNSAT	UNSAT	
10	UNSAT	UNSAT	UNSAT	

Based on the data above there appears to be good consistency among the different inspectors, however there were 2 instances (*) where the inspector would have rejected an area that was technically acceptable. Inspection with the unit showed the area of concern (roll over) to be within the tolerances. It should be noted that the test weld was in good lighting and sitting on a desk making the environment very good for inspecting.

A series of field trials was accomplished using the unit. Bath Iron Works Level III VT Examiner took the unit into production to gauge its ease of use and to evaluate the units' repeatability. The VT Examiner would first inspect the weld and determine acceptability. Then he would use the PWIMS unit to determine acceptability. The data of this trial is summarized in the two charts (Figures 12 & 13) that follow.

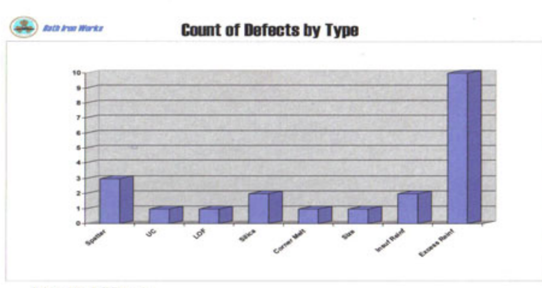

Figure 12 Example Report - Defect Count

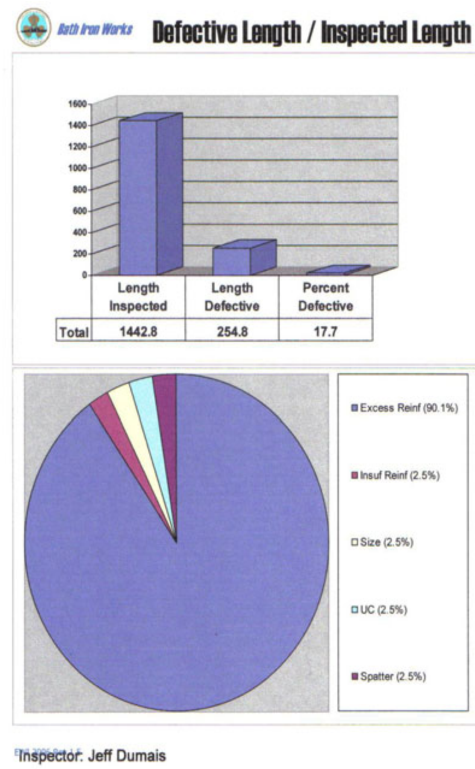

Figure 13 Example Report - Length Defective

The unit was able to detect everything that the VT Level III detected. There were some instances where the VT examiner was debating about rejecting a weld for weld size and the PWIMS was indicating a warning (yellow light). This indicated that the weld was slightly out of tolerance but the unit was programmed not to reject the weld until a reasonable tolerance (typically .015") was exceeded. This means that if the weld size was supposed to be 1/8" (0.125") that the unit would not reject the weld unless it was less than 0.110". It is expected that the average inspector would not be able to detect this small of anomaly and therefore represents reasonable inspection tolerance.

One issue that appeared during the field trials is the sensor's inability to inspect the weld when there was some level of silica on the welds. The silica is a result of welding process and is amplified by welding over primer coated surfaces especially with metal core wire and the GMAW-Pulse process.

RECOMMENDATIONS

The equipment evaluated has potential, but needs both hardware and software modifications before it can be used as a tool on a regular basis in a shipbuilding environment. As is, it will be useful as an audit tool to gauge the health of the visual inspection process and to further document the inherent variability of the visual inspection process.

The WISC portion of the PWIMS needs to be updated to make it more efficient and user friendly. Specific recommendations include:

- As a minimum the unit needs to be wireless. The large control cables that tethered the sensor to the control box made the functionality of the sensor limited. Wireless technology would allow the sensor to get into confined areas better.
- Battery life appears to be a concern. The WISC battery only lasted about 1 hour before it had to be plugged in.
- The control box needs to be made smaller or possibly eliminated. It is recommended that a device such as the Motion Computing Tablet used as a software platform be considered as the primary control box. This would reduce the system components to just two.
- The PDA interface needs to be upgrade to allow for the use of a memory card. Consideration should also be given to using a Windows ® based PDA that will allow a much smoother interface and data transfer to the lap top. A PDA that incorporates a miniature keyboard into the unit in order to more efficiently enter data would be beneficial.
- The entire sensor and PDA interface needs to be miniaturized to the size of a cordless drill. Currently today there exist portable miniaturized X-ray fluorescence analyzers for material identification. These devices are approximately the size of cordless drill and can be carried on a belt. With the advances in computing and sensing technology this recommendation should be within reach.
- The unit needs to have some way to apply a mark on the work piece when a defect is detected. It is recommended that this be manually controlled by the operator.
- The unit should have capability to be operated with an extension in order to reduce having the operator crawling on their knees and to reduce shoulder fatigue while inspecting overhead.
- The use of English units and terminology should be seriously considered for marketing the unit in the US.
- Improve editing functionality such as copy and paste in order to allow for easier modifications of joint tolerances in the joint libraries.

The software side of the system needs a few tweaks to make it more user friendly in order to produce reports that can be distributed (via email and presentations) to management. Specific recommendations include:

- Tablet should have all programs that the reports can be exported to (i.e. Excel)
- There needs to be a way to file inspection data by hull and a way to easily delete data from the Analyzer module.
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CONCLUSIONS

The PWIMS can be a powerful inspection tool but needs to be made more ergonomic in order to be used as an effective tool for visual inspection tasks and statistical process control analysis on a routine basis in a shipbuilding environment. As is, it will be useful for VT examiners to efficiently audit visual inspectors' performance and objectively resolve varying interpretations on the acceptability of a weld between two parties.

It is the authors hope that further funding will be made available in order to take the system developed to the next level and make a tool that all of the welding industry could use routinely for managing the visual inspection process.

ACKNOWLEDGEMENTS

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APPENDIX A
PWIMS Functional Specification

BASE REQUIREMENTS

Attribute and Defect Detection Capabilities

The following weld dimensions are required to be measured and compared to allowable ranges:

The following dimensions and defects shall be detected for BUTT welds:
- Missing weld
- Excessive reinforcement
- Insufficient reinforcement (including unfilled craters)
- Re-entrant angle
- Undercut depth
- Weld width (may not be accurate for butt welds with minimal reinforcement or of width greater than ½-inch)

The following dimensions and defects shall be measured for FILLET welds
- Missing weld
- Weld size (provide a caution for oversized welds)
- Leg length 1 min
- Leg length 1 max
- Leg length 2 min
- Leg length 2 max
- Weld theoretical throat min
- Weld theoretical throat max
- Re-entrant angle
- Undercut depth
- Plate angle

The system will allow manual entry of features which it can not accurately measure, including the following:
- Butt weld width
- End Melt
- Corner Melt
- Lack of Fusion
- Cracks
- Porosity Max
- Porosity Sum in 2" (non-primer)
- Porosity Sum in 6"(over primer)
- Slag
- Silica
- Spatter Category 1 (remove all weld spatter)
  - Max Spatter category 2 (remove all spatter for cosmetic reasons AND spatter > 1/8" diameter)
  - Max Spatter Category 3 (leave all tightly adhered spatter < 1/8" diameter AND remove all > 1/8" diameter)
  - Nicks, gouges, arc strikes
  - Other indications identified by the inspector

APPENDIX A
PWIMS Functional Specification

Measurement accuracy

The following is the required size and accuracy of dimensional measurements:

Feature	Minimum Size (in.)	Target Accuracy
Weld size	1/8	+/- 0.015”
Throat	1/16	+/- 0.015”
Undercut	1/32	+/- 0.010”
Re-entrant angle	90 degree	+/- 5°

Surface Conditions

The PWIMS will meet the minimum accuracy requirements for the following material surface conditions:
- As-welded bare steel
- As-welded primered steel
- Sand-blasted steel
- Abrasive ground steel with grinding marks either parallel or perpendicular to the weld direction
- Lightly rusted steel
- As welded stainless steel
- Ground stainless steel with grinding marks either parallel or perpendicular to the weld direction
- Wire brushed stainless steel
- As welded aluminum
- Wire brushed aluminum
- Surface to be measured must be clean, dry and free from moisture
- Surface to be measured must be free of loose, foreign matters

Portability, sensor access, and reach

The sensor head must be capable of inspecting welds with the following access restrictions:
- Fillet weld inspection under a 4-inch tall T-stiffener
- To within 2 inches from a transverse obstruction

OPERATOR REQUIREMENTS
The following summarizes the operator data entry and operation requirements before, during, and after inspection.

Before Inspection

- Operator must manually set up a joint type, size and inspection criteria on the desktop computer, before any inspection can be made and before the WISC handheld unit is brought to the part to be inspected
- Before inspecting a particular weld, the user must enter the following (e.g., via the “joint library”):
  - The weld joint type
  - The minimum weld size
  - Whether surface primary hull structure (for undercut criteria)
  - Hull Number, Unit number, component, location
  - Shift, Date and time of test/inspection
  - Procedure number
  - Product work order number to be tested / inspected
  - Above deck number or below deck number
  - Frame number, Longitudinal number
  - Inboard/outboard (or port/starboard) side
- Operator must verify that the WISC handheld unit is operational by triggering and viewing the laser line

APPENDIX A
PWIMS Functional Specification

During Inspection

- Operator (and other personnel within the inspection vicinity) must follow ANSI Z136.1 for laser safety practices
- Operator must position the WISC within the following positional tolerance:

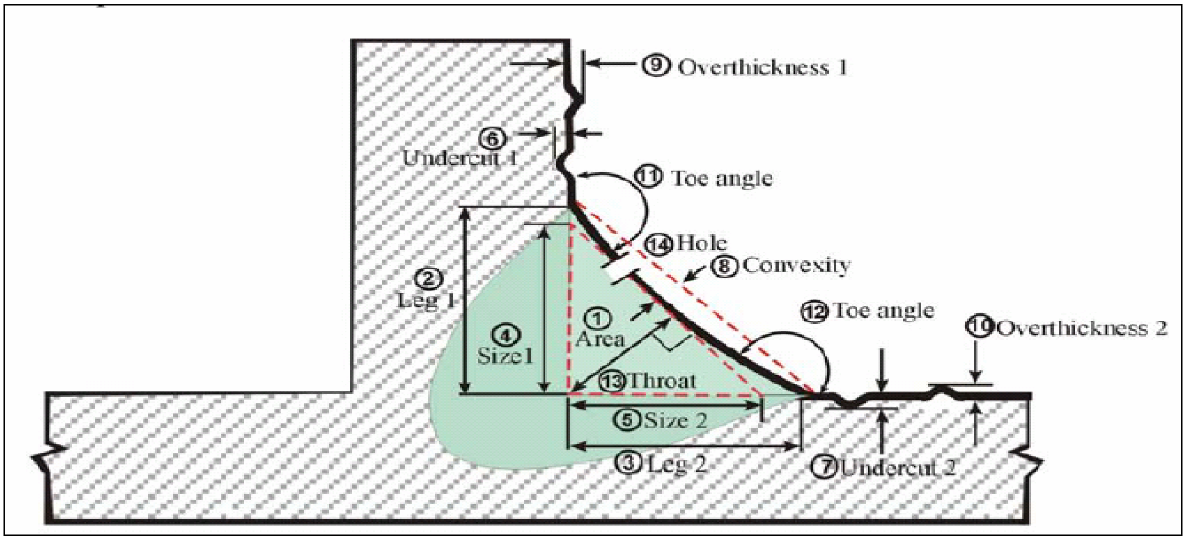
Position	Accuracy
Wheel location	+/- 1/8 inch from weld center line
Lateral angle	+/- 20 degrees
Forward-backward angle	Both wheels must be contacting

- Operator must manually move the WISC over the joint to be inspected at a reasonably constant speed
- In order to maintain consistent quality records, the operator may be required to use a consistent inspection sequence (e.g., start at fore and work aft).
- For each defect which is found, the operator must have the option to enter/select the following:
    - Comment describing the specific location of the defect on the PC running WinUser
- Because the PWIMS will not be capable of inspecting all joints and features, the user must have the option to select/enter defect type on the PC running WinUser. The Following information will be available for entry:
    - Defect type
    - Defect size
    - Comments describing the specific defect

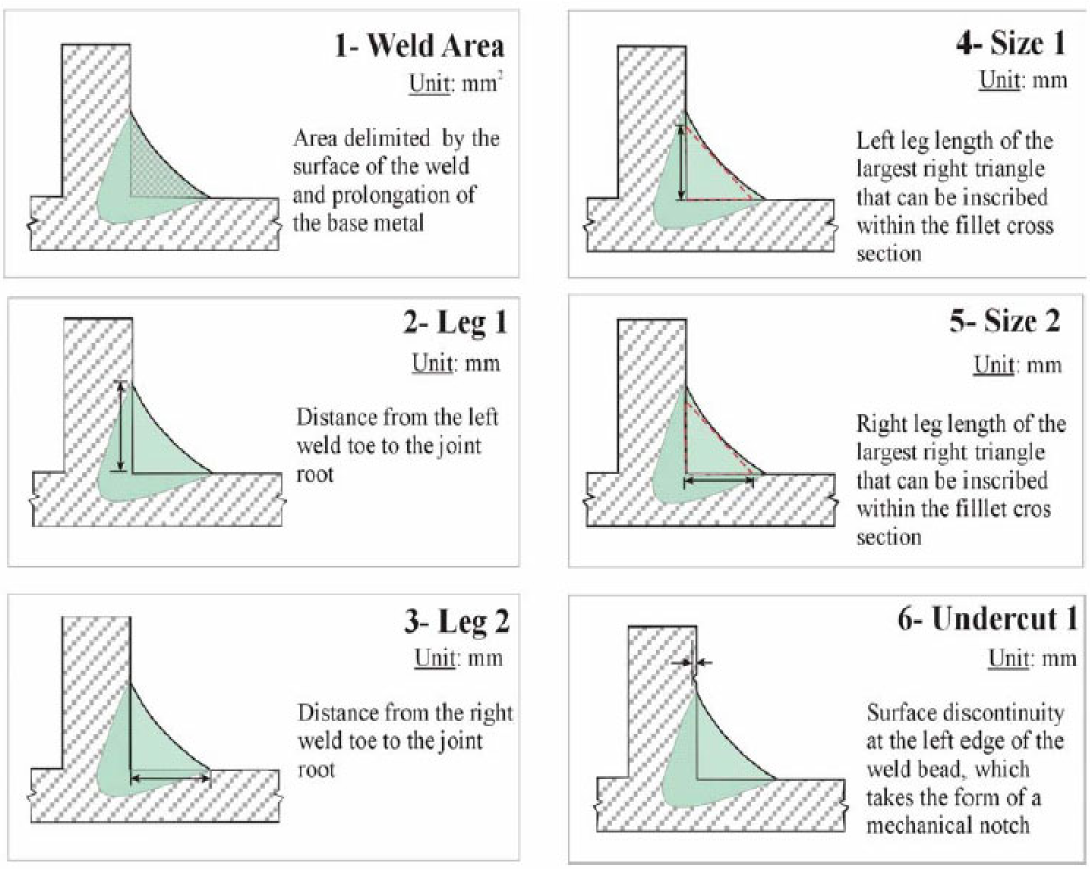
After Inspection

- Operator must choose to save or delete the inspection results as well as name the inspection record.
- Operator must periodically download inspection data results from the WISC to a desktop computer
- Operator can view and create report on the desktop computer using the WinUser software

APPENDIX B
Butt and Fillet Weld Dimensions and Defect Descriptions



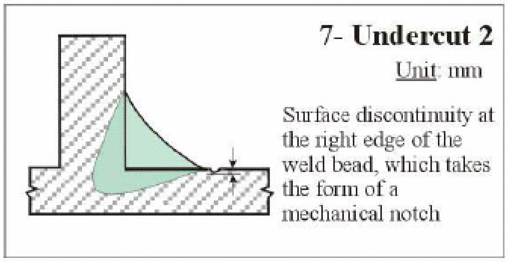
Fillet Weld Attributes Correspond with Numbers Above

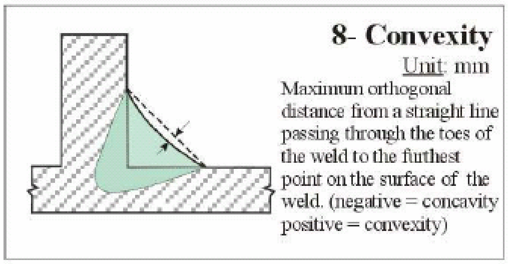


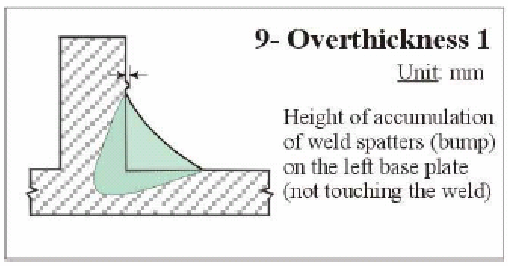
Fillet Weld Attributes 1 – 6

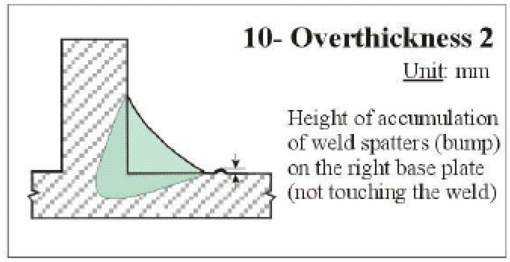
APPENDIX B

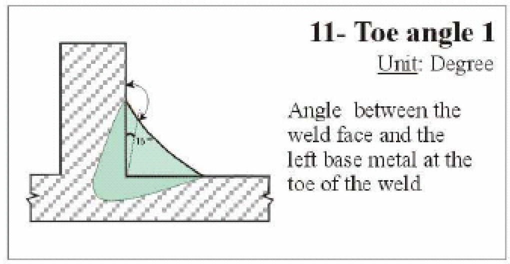
Butt and Fillet Weld Dimensions and Defect Descriptions

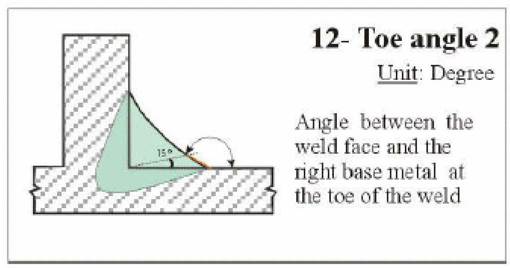




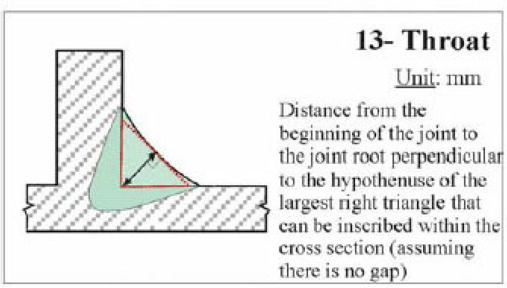


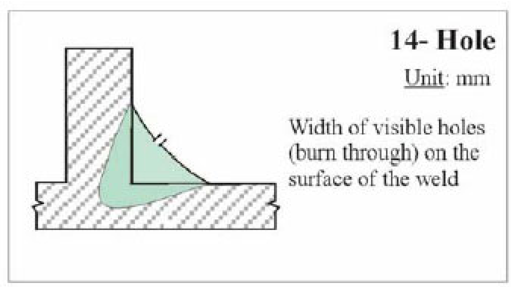


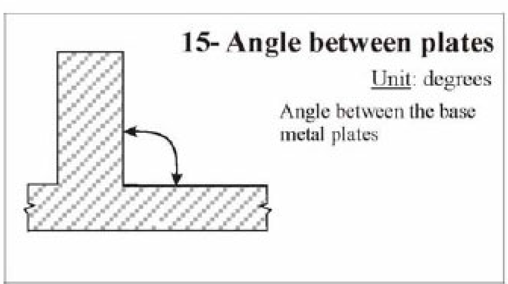




Fillet Weld Attributes 7 – 12



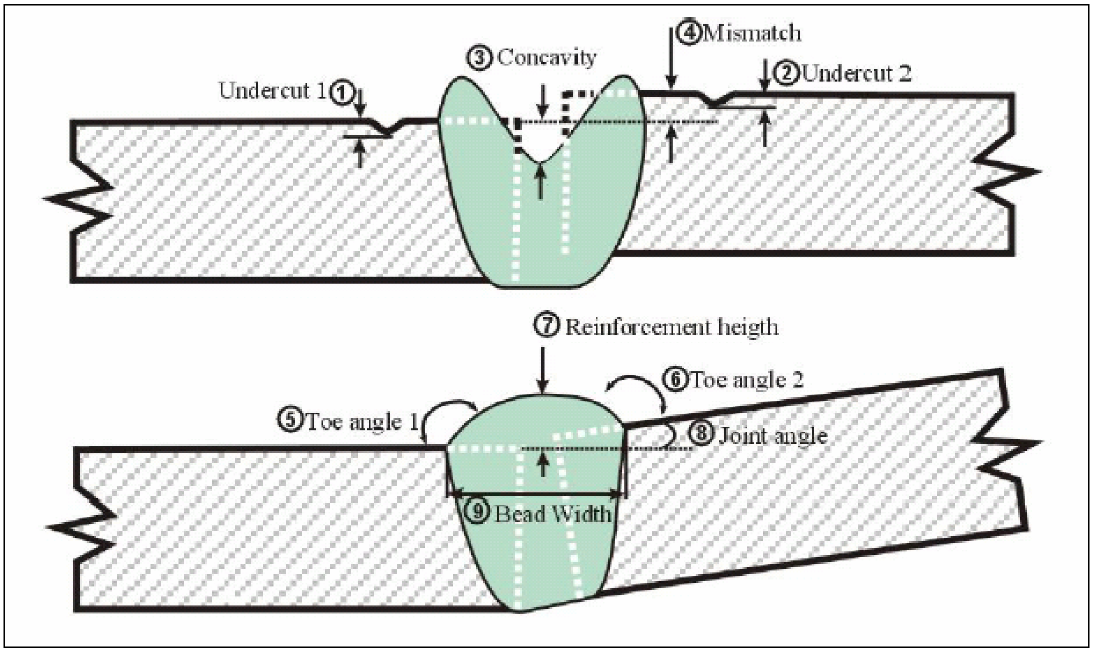




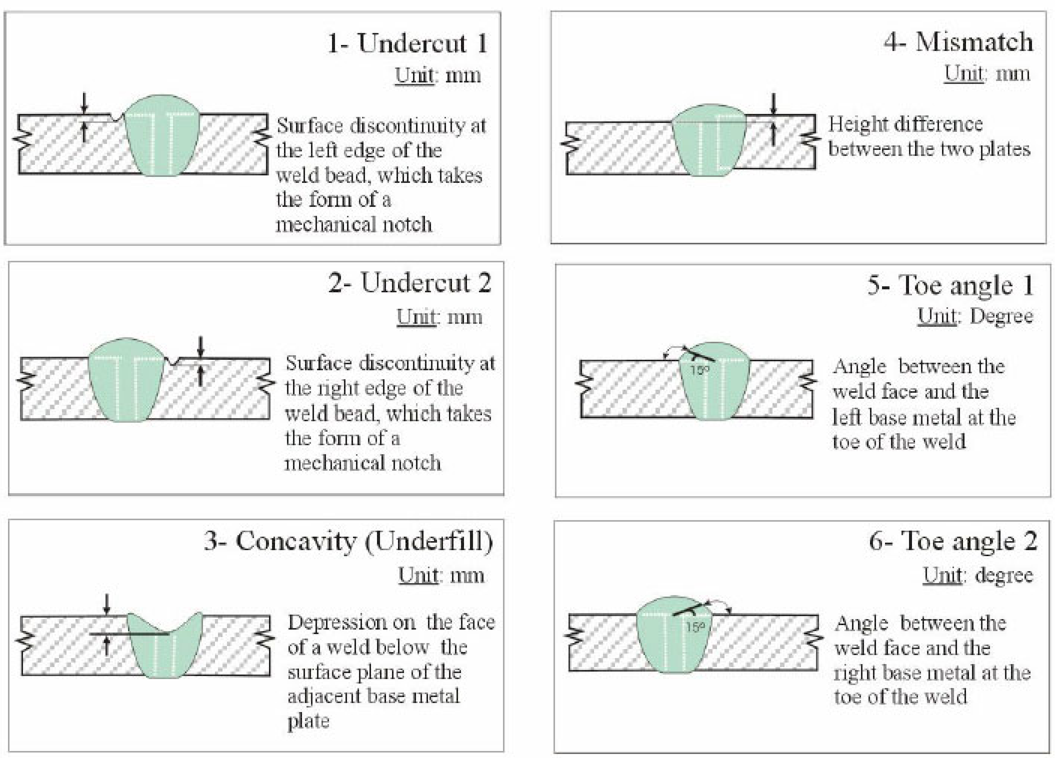
Fillet Weld Attributes 13 - 15

APPENDIX B

Butt and Fillet Weld Dimensions and Defect Descriptions



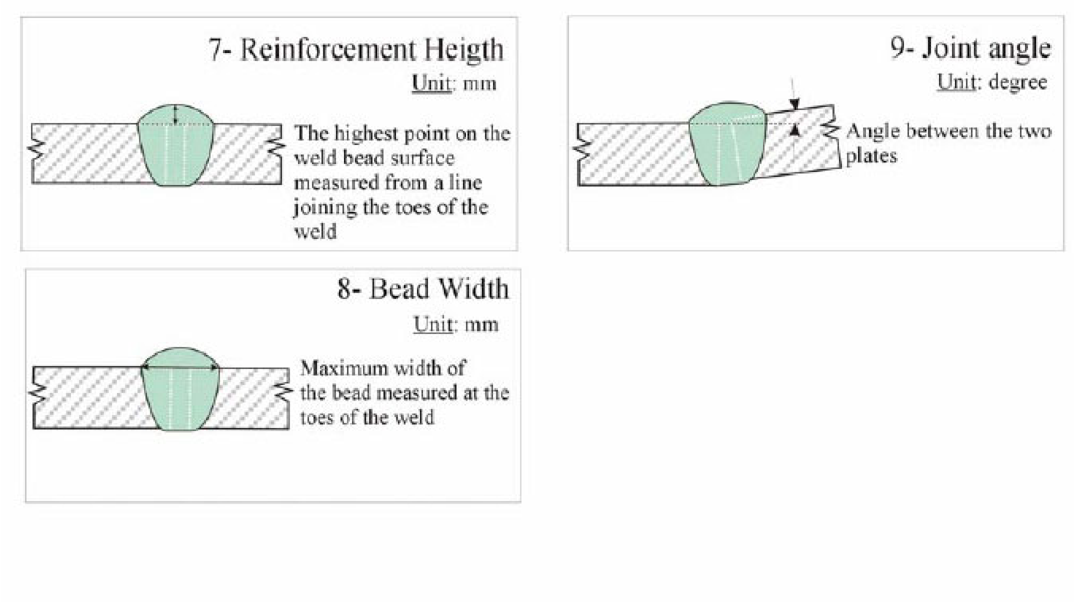
Butt Weld Attributes Correspond with Numbers Above



Butt Weld Attributes 1 - 6

APPENDIX B

Butt and Fillet Weld Dimensions and Defect Descriptions



Butt Weld Attributes 7 - 9

APPENDIX C
PWIMS Data Repository Software Architecture

PWIMS sensor data is transferred to a data repository for long-term storage, analysis, and reporting. For the current project the data repository will take the physical form of a PC. The following summarizes the software platform which will be used for the prototype along with rationale for the choices.

Operating System:

For the purpose of feasibility testing, the Windows XP operating system will be used. This operating system supports all of the selected software tools and can be easily upgraded to a distributed (i.e., server based) architecture.

Database Engine:

The Microsoft Data Engine (MSDE) will be used for the prototype PWIMS database. This database engine is the heart of the more-powerful Microsoft SQL Server software, employed for large distributed database systems. Databases developed with the MSDE can be directly transferred to a SQL Server database without any modifications, providing additional data storage capacity and data protection functionality. The MSDE data engine also supports all of the necessary relational database features (e.g., support for SQL queries) needed to store, search, and retrieve data from the PWIMS database. Storing data in a powerful relational database, such as MSDE, also allows convenient transfer to other relational database structures used by other database engines, such as Oracle.

Analysis Software:

The data analysis software will provide a graphic user interface (GUI) to allow reports to be produced. For example, the GUI will provide selections to allow sorting and searching the database and to generate a variety of report types. Microsoft Access will be employed in order to provide a familiar and expandable GUI. Recent versions of MS Access are designed to seamlessly connect to the MSDE engine in order to retrieve the requested data. Visual basic code can be used to produce powerful customized GUI screens that automate many of the most common operations. For future expandability, MS Access can also be used to connect to SQL Databases on networked servers.

Data Transfer Software:

A serial port connection will be used to transfer the data from the Servo-Robot system to the PC. The actual data transfer will be accomplished with Servo-Robot supplied "WinUser" software.

Data Conversion Software:

Once the data is transferred from the Servo-Robot system to the PC, it is stored in a Microsoft Access file format. Data translation software will be used to convert the data from the Access file format and to store it into the MSDE database. SQL Server database tools will be used to generate an executable which performs the data translation

General Comments

1. Forward angle compensation must be always on.
2. Archive path must be able to be set by operator in WinUser before going to inspect.
3. BIW should test the effect of "Weld Aspect" parameter on accuracy of the measurement for different surface conditions.