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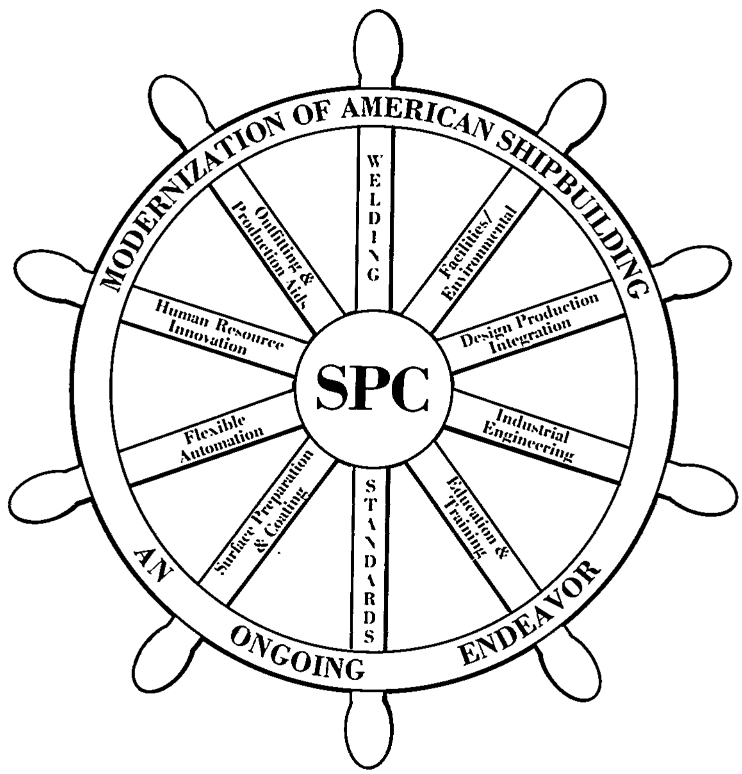

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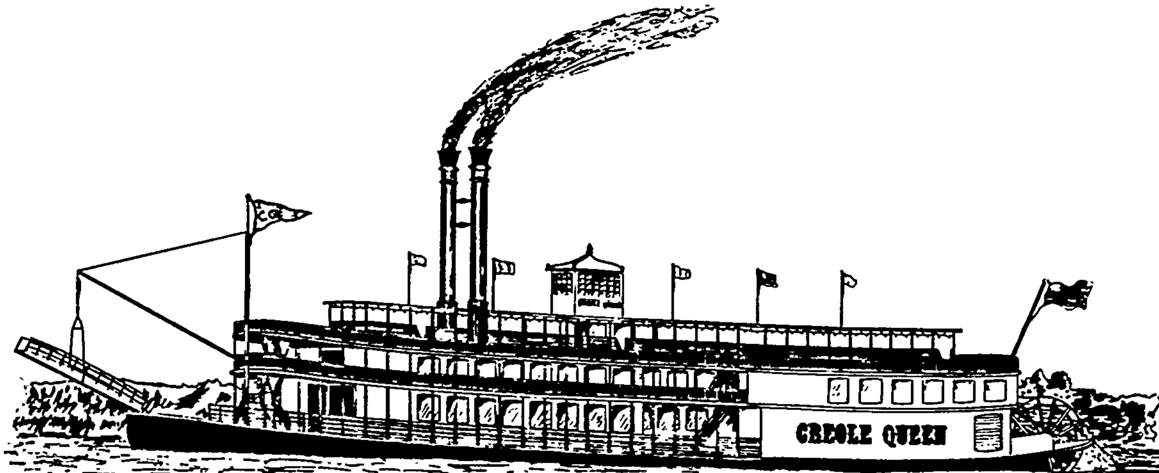

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Development of an Intelligent System for Flame Straightening Panel Structures—Devices and Algorithms to be Used with Robots

No. 13

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ABSTRACT

Distortions which occur during the assembly of steel panel structures can be removed by flame straightening. This has been used for a number of years in the shipbuilding industry. Correct skill to perform this technique is acquired by many years of experience. The industry is concerned now about the decreasing number of skilled workers.

What is needed to improve the situation is to develop a robot capable of not necessarily replacing a human worker but helping a human worker. This paper discusses results obtained thus far in a research program of which the ultimate objective is to develop an intelligent machine capable of performing flame straightening on a deck of a ship superstructure. Discussions are given on (a) a concept of an algorithm to determine heating conditions, and (b) sensors needed for "in-process" sensing and controlling the robot movements.

INTRODUCTION

The flame straightening method has been used for many years to remove distortions of a welded structure. An oxyacetylene torch is usually used as a heat source to produce counter distortions to remove distortion that exists. Many years of experience are normally required to master the skill of distortion removal. The skill has been handed down from generation to generation.

Researchers in the academic community also have tried to study the technology of distortion removal. They have succeeded in studying mechanisms of flame straightening and flame forming in simple cases[1,2,3,4,5]. However, in most cases their research has been limited within laboratories. This is because it is extremely difficult, if not impossible, to simulate in a laboratory the complex situations of a real structure.

On the basis of recent developments of robotic technologies together with artificial intelligence (AI), sensing technologies, and small but powerful computers, the authors believe that there is a good possibility to fill the gap between a laboratory and a factory. Information collected on site in an actual structure should be useful for researchers in developing mathematical models for studying distortion removal. This will improve the level of academic research and its relevance to industry. From the industrial manager's viewpoint, the number of workers experienced in flame straightening is decreasing causing serious concern over the availability of skilled workers in the future. New technologies related to AI including expert systems may be able to fill the void created by the lack of experienced workers. The authors believe that now is the appropriate time to develop a robot capable of flame straightening.

This paper describes current R & D efforts for developing a flame straightening robot. Since the efforts have not been completed, this paper should be regarded to be a preliminary report. The robot being developed will not replace the experienced worker, since it requires human supervision. However, one worker will be able to supervise several robots. The robot should be able to perform the following:

(1) Move by itself on a deck of a ship superstructure (See Figure 1)
(2) Remove most of the residual distortions in panels on the deck.

The robot being developed will not be automatic nor a stand alone robot, but an "intelligent aid" robot designed to help the worker by reducing his labor and increasing his productivity. The idea was initiated in a Japanese shipyard that needed a practical machine which could be developed with today's technology and introduced quickly into production, not a dream for the future.

In order to meet these requirements, the authors have decided that the robot being developed should be capable of:

(1) Recognizing its own location
(2) Measuring distortion
(3) Deciding how and where to apply

the heat

(4) Learning from a previous operation.

Again, the robot will not be able to perform these functions unassisted by the worker. It will still need human supervision. The degrees of automatization and mechanization in the system are described in this paper.

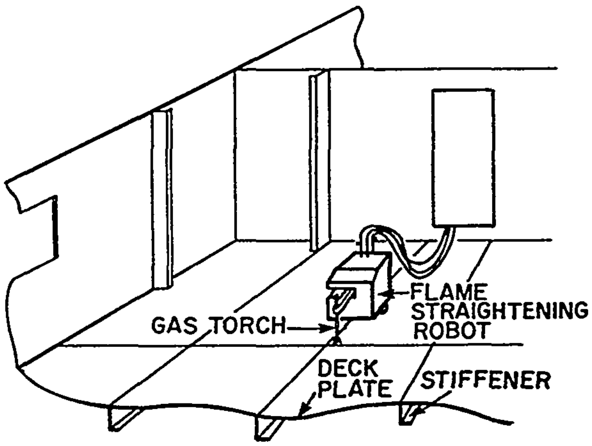

Fig. 1 Conceptual figure showing a flame straightening robot removing distortion of a deck panel of a superstructure

DISTORTIONS IN DECK STRUCTURES

This section discusses typical uses of the robot being studied: The type of structure and typical distortions.

A deck of a superstructure consists of stiffened panels. Stiffeners are welded on the bottom side of the deck which is the ceiling of the deck below. Aspect ratios of the panels are larger than two in most cases. Since a superstructure must be light and does not support large external loads, it is made of thin plates on the order of several millimeters.

Figure 2 shows typical distortions of a panel structure. Two major causes of the distortions are:

(a) Angular distortions produced at fillet welds between stiffeners and the plate

(b) Buckling distortion of the plate due to compressive residual stresses in the plate.

Regarding residual stresses, they are produced not only by welding but also by flame cutting that is used to cut large plates into specified sizes. The distortions may also be produced by joint mismatch and other causes.

Since the robot must rest on the horizontal surface of a deck, straightening can only be performed from above the deck. It is not feasible even for a human operator to apply the heat to a ceiling (unless he is 9 feet tall and tools are weightless). So flame straightening must be accomplished from one side of the deck. This is more difficult than straightening from both sides.

In addition, the work must be performed in an unpleasant environment. It is humid, hot, dirty, noisy, and wet on the floor because of the gas heating and water spraying. Uses of robots should provide some relief to workers.

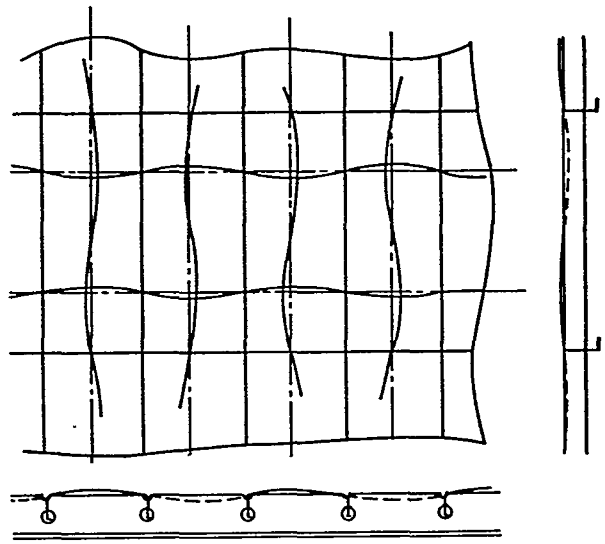

Fig. 2 Typical distortions of a panel structure

FLAME STRAIGHTENING METHODS

There are several different types of flame straightening methods, as shown in Figure 3. They are classified into two major groups: (1) line heating and (2) spot heating. In line heating, an operator moves a torch linearly. In spot heating, a torch stays at one location for a few seconds and moves away. The former is basically used to remove angular distortions and the latter to remove buckling type distortions, which are caused by in-plane forces. Each group of heating, shown in Figure 3, is applied to a specific type of structure and shape of residual distortions.

The heat source is usually an oxy-acetylene flame. The highest temperature reaches 3000 degrees centigrade. The flame heating is usually followed by water spraying to avoid excessive heating and to cool down the structure quickly. It has been noted that the procedure used in one factory may be different from that used in another, depending upon the worker's preference. The process is more of an art than a technological operation.

Parameters which are adjusted in the operation include torch traveling speed, torch height, water spray intensity, relative location of water spray to the heat source, angle of the flame with respect to the structure surface, etc. These are intended to change the

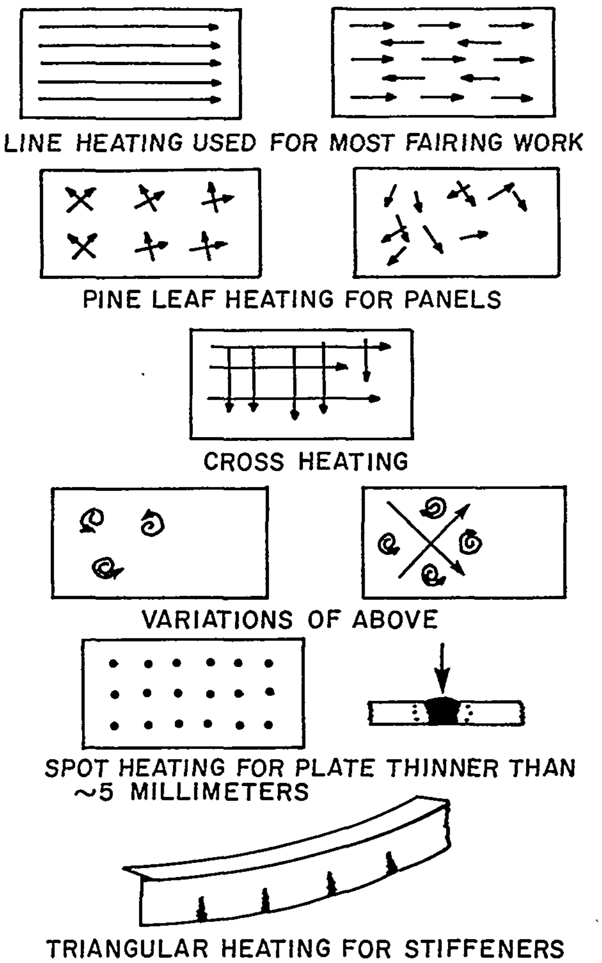

Fig. 3 Various methods of flame straightening

temperature distribution of the structure being treated. The selection of a proper torch tip size is also important. An experienced worker chooses the best tip for a specific structure and its material. The gas flow rate and gas pressure are not regarded as adjustable parameters, since they are usually optimized for the lowest operational cost.

Previous researchers found that water spray reduces the effectiveness of flame heating [3,5]. Thus, less angular distortion is removed when water spray is applied during flame heating. However, there are three major reasons to use water spray as follows:

(1) Water spray increases the productivity because it cools down the structure quickly so that the next operation can start without a long waiting time.
(2) If a mistake is made in the flame heating operation, the operator can cool down the material immediately.
(3) In the case of spot heating, excessive heating of a plate can be prevented by water spraying.

In many cases, the distortion cannot be removed by a single heating operation because there is a temperature limitation above which materials are degraded. Depending on the amount of distortion, the heating must be repeated so that the distortion is removed gradually while the temperature of the material is maintained below this critical limit. For the subsequent operation, the operator has to wait until the material cools down. Otherwise, the material shows different movements which are unpredictable. Water spray is necessary to shorten this waiting period.

An experienced operator knows how the structure moves during heating. While he performs the operation, he watches the movements of the structure. If he finds something wrong, he stops heating immediately and sprays water all over the structure.

In the case of spot heating, of which the major objective is to reduce in-plane forces, the temperature deviation through the plate thickness must be kept to a minimum. If the temperature difference is large, additional out-of-plane deformations will occur and this process will not remove the distortions. Unfortunately, both sides of the plate cannot be heated at the same time to give the symmetrical temperature distributions needed through the thickness of the material. Also, gas torches distribute the high temperature gas into large areas. Water spray minimizes this undesirable heating. Thus, a water spray nozzle will be installed on the robot to minimize the undesirable heat input and spreading.

Three heating patterns have been selected to be used with the robot. They include (see Figure 4):

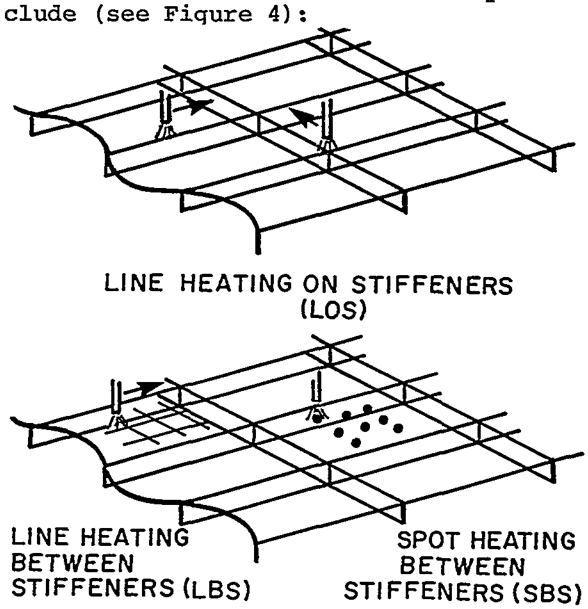

Fig. 4 Three heating patterns selected to be used with the robot

(1) Line heating on stiffener lines (LOS)
(2) Line heating between stiffeners (LBS)
(3) Spot heating between stiffeners (SBS).

Combinations of these heating patterns have been used for many years in Japanese shipyards for removing distortions of panel structures. Almost all types of distortions can be removed by proper combinations of the three heating patterns. Algorithms to apply these three methods are described later.

CAPABILITIES OF A HUMAN OPERATOR VERSUS CAPABILITIES OF A ROBOT

In order to develop an intelligent system, we must know what a human operator does in a shipyard. An experienced flame straightening operator must be able to:
(1) manipulate the tools of his trade
(2) use the best techniques for a given type of distortion
(3) learn from past experiences
(4) make the correct decision in a new situation.

First of all, he must have the ability to move a torch maintaining constant conditions such as the speed and the torch tip height. He may have to occasionally check the gas pressure and flow rate. Secondly, he must know how and where to apply the heat to remove a specific type of deformation. He makes the decision based on past experience. Thirdly, he learns from his past experiences. He memorizes conditions that give good results and bad results. He makes fewer mistakes as he gains experience. Fourthly, he must have the ability to handle a new situation not encountered before. The worker must be able to choose the correct technique with a minimum amount of trial and error. The experienced worker can solve flame straightening problems faster than a novice worker. This is because he has a lot of data based on his experience and he knows how to improve his performance by using this data.

At the present time, even the most sophisticated robot does not have all of these abilities. The authors think that it is impossible with the present state-of-the-art technology to replace the human operator.. Then, what is a robot capable of doing today? A robot can easily perform the first function of manipulating flame straightening tools by incorporating feed-back control systems. To perform functions two, three, and four is more difficult. A system having these functions, which have been intensely studied for several years, should be called an "expert system." The intelligence that this robot will need is discussed in the next section.

ALGORITHMS FOR HEATING OPERATIONS

A noticeable feature in this research is "in-process sensing." Data collected by in-process sensing are used to modify coefficients in equations which give the relationship between the torch velocity and the amount of distortion removal. This is the most important point in this research. Because of this feature, it can apply theories found in a laboratory to a structure in actual situations. Coefficients modified according to the data are supposed to include actual conditions.

The term "in-process" is somewhat different from "in-process" used in other fields. For example, during the welding operation, data like voltage, current, and diameter of the molten metal pool are collected in real time. On the contrary in flame heating, while the gas flame heats panels, nothing is measured in real time except the location of the stiffener line. Measurements of distortion are not usually carried out during the heating process. Since a change of the state in one panel may affect a neighboring panel, measurements of distortion during flame heating may not be useful. Distortion measurements must be taken after all heating is completed. The flame heating process is not finished until the deformations of the entire deck are removed. It may take a few hours or even a few days. In this sense, any measurements during the flame heating operation can be called "in-process sensing."

An algorithm is shown in Figure 5. Before applying any flame heating, deformation measurements are taken along the entire deck. Flame heating patterns and other parameters are determined once the displacement distributions are known. To ensure that the material's critical temperature is not exceeded, the torch traveling speed must be faster than the minimum heating velocity. The first heating operation is carried out using these determined conditions.

After the first heating, deformations are measured again to calculate values of removed deformations, and coefficients in the equations are modified using the actual data. (See Appendix for details.) Then a second heating is performed. The deformations are measured and compared to the allowable values. If they are not within allowable values, the heating is repeated until the conditions are satisfied.

It may take three or four heating operations to reduce deformations to allowable values. If maximum deformation limits are not achieved by four heating operations, the robot judges that the task is too difficult and leaves it to a human operator.

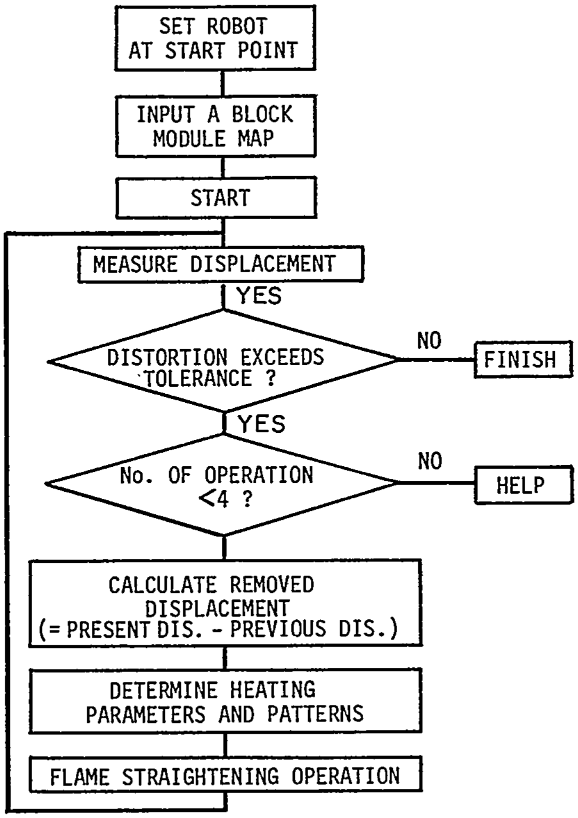

Fig. 5 An algorithm of flame straightening operation

The equations calculating the plate displacements are based on an assumption that the removed displacement corresponds linearly to a free angular distortion[6]. The free angular distortion is defined in Figure 6. The plate has no constraint with regards to angular distortion. The relationship between the free angular distortion and the torch velocity is obtained in experiments completed before the robot's operation. The experimental data is input into the computer that controls the robot.

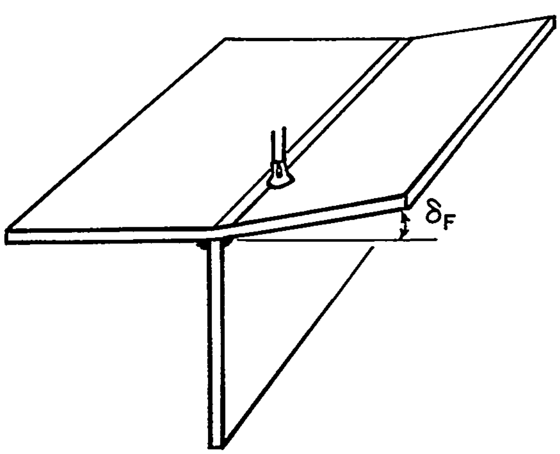

Fig. 6 Free angular distortion

As mentioned before, three heating patterns are selected to be used by the robot:

(1) Line heating on the stiffener line (LOS) (See Figure 4)
(2) Line heating between the stiffener lines (LBS) (See Figure 4)
(3) Spot heating between the stiffener lines (SBS) (See Figure 4).

LOS is for the angular distortion caused by fillet welding. It produces counter distortion against the residual angular distortion. In principle if the displacement is convex, this is not applied. LBS is applied to an area where the displacement is convex. This produces a local concaved distortion to reduce the deformation as shown in Figure 7. The pattern is like a lattice.

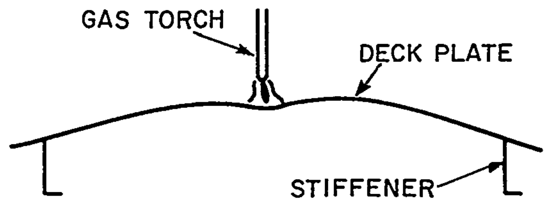

Fig. 7 Distortions due to LBS

SBS reduces in-plane-forces causing positive displacements. This is applied between the lattice lines of LBS.

After the panel displacement measurements are completed and this data is input into the robot's computer, the computer decides which pattern to use on each part of the panel

SENSING SYSTEMS

A sensing system is indispensable for an intelligent machine. A sensing device should be durable in a dirty, dusty, humid, warm, and noisy environment. If possible, a non-contact sensing system is preferred since the surface of the plate is wet. In flame straightening, a robot must have a sensing system to detect the following:

(1) Location of a stiffener line
(2) Out-of-plane displacements of panels.

A stiffener line must be recognized by the robot as it moves across the deck. The robot uses the stiffener line as a reference for its own location and for the location to apply heating. The stiffener line is also used as a reference line for displacement measurements.

As a sensing method for locating stiffener lines, the following four methods have been studied:

(1) Magnetic field difference caused by plastic strains due to the welding on the other side of the plate. This is detected by an

electromagnetic detector
(2) Detection of thickness difference using ultrasonics.
(3) Sound difference produced by hitting the plate surface and detected by microphones
(4) Color difference between the painted part and the burned-paint part due to the heat of welding on the other side of the plate. This is detected by vision sensors.

The electromagnetic detector that was studied could penetrate only a few millimeters in thickness. Usual thicknesses of plates used in ship superstructures range from 6 to 8 mm, which are too thick for this method.

When an ultrasonic method is used for determining a stiffener line, echoes are affected by the presence of the weld metal (fillet weld) between the plate and the stiffener. A probe must make contact with the surface, which may be dirty and wet due to water spray. It is extremely difficult to maintain good contacts between the probe and the surface under such conditions, and therefore is not acceptable.

When the plate surface is hit by a small hammer, an FFT (Fast Fourier Transform) analyzer is needed to locate a stiffener. This analysis is too time consuming for the computer to carry out in real time.

A human operator locates stiffeners by recognizing color changes in the paint. If there is a weldment on the other side of the plate, the heat penetrates through the thickness and burns the paint on the surface. Figure 8 shows an example.

Fig. 8 Welding mark on deck

As long as a robot works on the superstructure, plate thickness is thin enough to produce this color change. Details of a vision system are described in a later section.

Out-of-plane displacements can be measured using linear transducers. The transducer's leg needs to be in continuous contact with the plate surface. Since the electronic transducer for this instrument is placed above an indicator leg, it is protected from the environments. The accuracy of the device may be 0.2 to 0.4 mm which is sufficient for this purpose.

In addition to the above mentioned two measurements (i.e., the location of a stiffener line and the out-of-plane displacement of a panel), temperature distributions may have to be measured during heating. For mild steel, there is a critical torch velocity below which the material is degraded because of the high peak temperature. It can be determined in advance by experiments using a simple structural element. The peak temperature is checked by referring to the critical velocity. Therefore, temperature measurement is not necessary during heating of mild steels.

In the case of high strength steels, on the other hand, the temperature must be carefully checked so that not only the peak temperature condition but also cooling down temperature conditions are satisfied. Water spray is not allowed as a general rule. This strict condition makes flame straightening very difficult. In this research the material is assumed to be only mild steel. Further discussions on this subject will be given in a later part of this paper (Future Work).

Vision Systems

The most practical sensor that can be used by a robot to detect a stiffener line is an image sensor (7). In a shipyard a human operator uses his eyes to detect the stiffener position. As shown in Figure 8, there is a color change on the surface. This color change is called "welding mark" in this paper. It can be recognized by a TV camera.

Figure 9 shows a fundamental measurement system using a TV camera. The camera monitors the panel surface and detects the welding marks. The original image before data processing (Image I) is shown in Figure 10-A. Identification of the spots from the image is important. There are many methods to obtain the contours of the spots, however, processing the whole flame image takes a long time. PCVISION (8) by Imaging Technology Incorporated, a TV camera, and an image processing system were used to estimate the performance of the sensor system. The image processing unit used 8086 CPU(9). It took over 30 sec. to process the whole image flame. This is too long to be used in real time control without modifications. To improve the processing time, it has been decided that only crucial and best portions of the

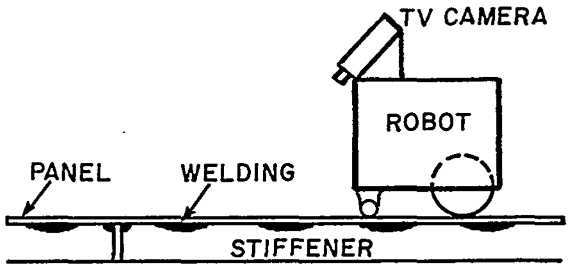

Fig. 9 TV camera and robot

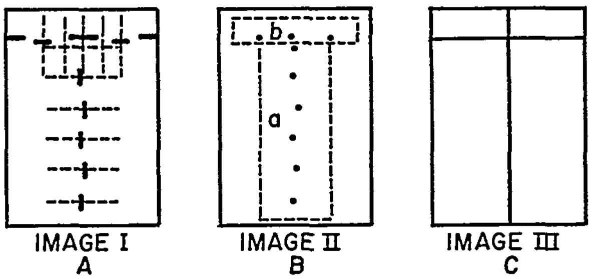

Fig. 10 Image processing of welding marks

image to be processed. The welding is done intermittently as shown in Figure 8. Dotted lines in Figure 10-A represent the image processed area and the area of contour-strengthening operations done to detect the stiffener line. The image in Figure 10-B is obtained after the data processing.

The image has two zones which are called Zone a and Zone b. Zone a is for a stiffener sitting along the moving direction of the robot. Zone b is for a stiffener sitting transversely across the moving direction of the robot. In both zones, the stiffener line is determined by interpolation.

Figure 10-C shows the image after the interpolation. Two lines represent locations of the stiffeners. The relative position of the robot is calculated from data of the crossing point of the stiffeners. This information is used to control the robot movement.

The image signal processing is described further in detail (10). An image taken by a TV camera is converted into digital signals and stored in a frame memory. The PCVISION has 256x256 frame memory for each image and each pixel has 8bit data. An original image has continuous signals and noises. Using filtering technique, the original image is changed to a binary image. Discrete Fourier Transformation is used for reduction of noise. When high and low frequencies are rejected from the original image, the processed image becomes smooth. The derivative of the frame helps the detection of the edge. However, in the experiment at MIT, it was not used. Lighting conditions were so good that the edge was easily detected. After getting the smooth image, a binary image is obtained by defining the threshold value.

When using the TV camera as shown in Figure 9, the shape of the image is distorted because of the perspective effect. Figure 11 shows the image of the welded panel taken by the TV camera. Although all welds have the same length, L; L1,L2, and L3 appear to have different lengths (L1>L2>L3.)

As described before, processed lines must be chosen to reduce computation time. Figure 12 shows the relationship of the space between the processed lines and possibility of detection. When the space distance is 2L and the processed lines are between the welding marks (right side of the figure), it is impossible to detect the welding marks. On the contrary, if the space distance is L, the welding marks can be detected under any conditions. Considering that the stiffener line may not be perpendicular to the process line, if the robot is not moving parallel to the stiffener line, the space distance must be set shorter than L.

In order to detect the stiffener line transverse to the robot's moving direction, another arrangement of process lines is necessary as shown in Figure 13. If the robot fails to find the transverse stiffener, it will stop the operations by checking the map of the stiffeners given by an operator in advance.

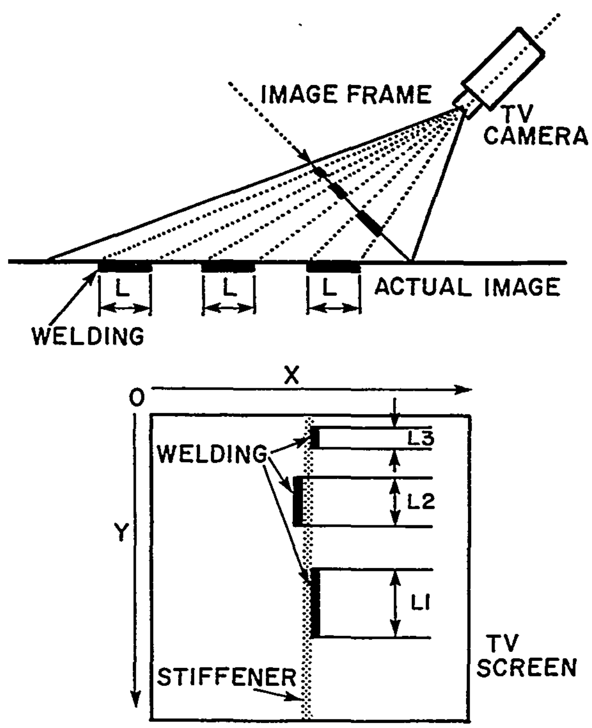

Fig. 11 Image of welding mark

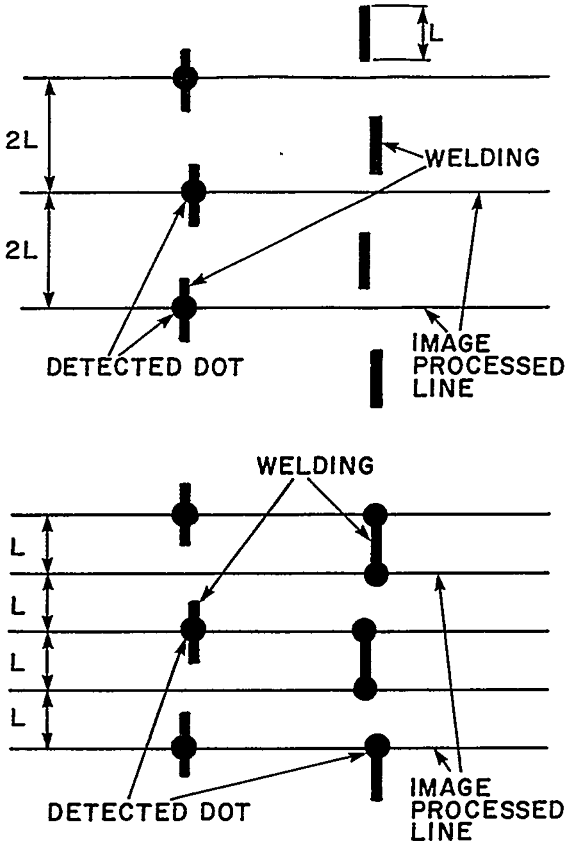

Fig. 12 Length between processed lines

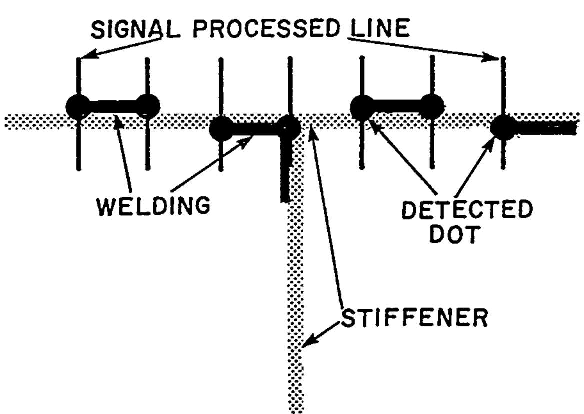

Fig. 13 Perpendicular stiffener detection

Tests On A Vision System

Experiments using a simple structural element were carried out at the MIT Welding Systems Lab. Figure 14 shows a plate having welding marks on the surface and a CCD camera. Thickness of the plate was 1/4 in. Length of the welding bead was 3 in. and spacing between the beads was 3 in. in longitudinal direction and 1/4 in. in transverse direction.

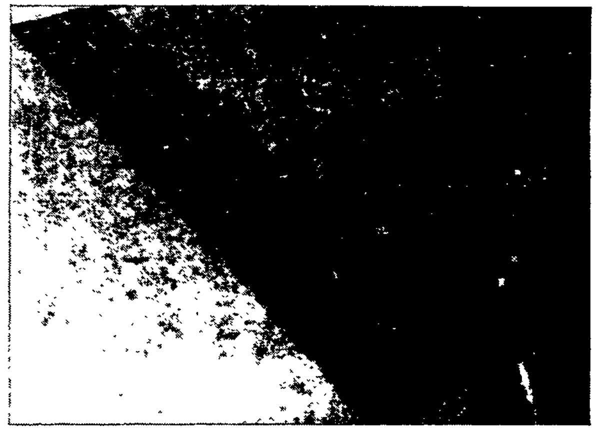

Fig. 14 CCD camera and welding mark

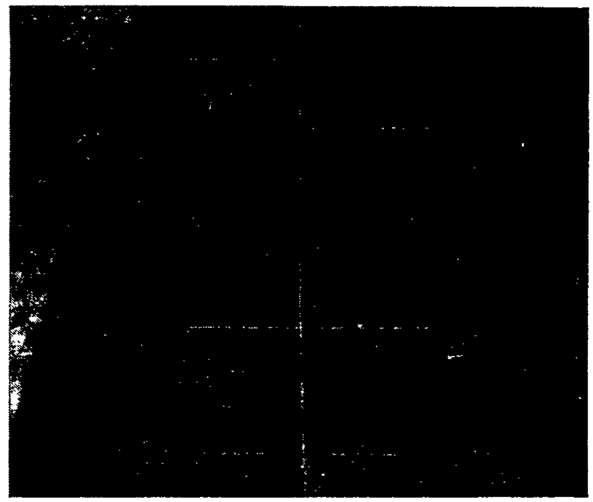

Fig. 15 Imaginary stiffener line

The CCD TV camera was set about one foot above the plate surface. Figure 15 gives five image processing lines and calculated center of the welding marks on the monitor screen. A center line of an imaginary stiffener was then calculated and drawn on the screen using the least square method between the welding mark centers. (See Figure 15.) Processing time was about 0.3 seconds which is fast enough to be used in real time control of the robot movement.

FUTURE WORK

The authors believe that there are three major tasks to be performed in the future, as follows:

(1) Verification of the algorithm
(2) Integration of robot hard- and soft-wares including displacement measuring sensors, vision systems, driving mechanisms, torch movement control, etc.
(3) Develop appropriate methods for removing distortion in materials other than low carbon steel, including high-strength steels,

and aluminum alloys. The current research is focused on mild steel only.

The algorithm described before must be verified by experiments using a test piece (model) consisting of more than one panel in order to investigate interactions between neighboring panels. Model sizes must be as close to the actual structural dimensions as possible, since a scale effect is unknown with regard to a heat source. This kind of experiment does not perfectly simulate every condition that could occur in an actual structure, however, if the algorithm is not effective on a model structure, it will never be valid on an actual ship structure. In the end, field tests must be conducted on the actual deck of a ship superstructure.

The interaction of the robot soft- and hard-wares should be completed before a field test. Mechanisms and their movements can be checked using the model structure. The remaining sensing system to be developed is a displacement measuring system. One candidate was mentioned in a former section (Sensing System). The robot's computer must be capable of vision system data processing, displacement data processing, determining heating pattern and conditions, controlling driving motors, and controlling torch movement. All of the hard-wares and system components should be integrated into the total system so as to enable the robot to move and perform the operations smoothly.

As demands for reducing structural weights have been increasing, higher strength steels are used for structural materials to utilize thinner plates. Usually, such materials require more stringent temperature controls. It would be extremely difficult to measure surface temperatures on the plate if a gas flame is used as the heat source. An alternate heating method is an electromagnetic induction since there is no high temperature gas (from gas flame) interfering with the temperature monitoring. This heat source should be investigated further. New straightening methods and conditions may have to be established for materials other than conventional mild steel, even if gas flame is used as the heat source.

Even if the above mentioned three tasks are completed, there are other problems to be solved by R & D engineers, production engineers, and structural designers, before this robot can be used for production.

R & D engineers and production engineers have to cooperate to change the present production sites into robot friendly environments. For examples: (1) how to organize gas and water hoses so that the robot movements are not disturbed, (2) how to keep gas and water pressure constant, (3) how to check gas and water flow rates, (4) how to handle three robots, (5) what kind of safety regulations are necessary, and so. Gas and water pressure, from main distribution piping, are not constant, but depend upon consumption in the factory at that moment. Therefore, gas and water supply for flame heating must be independent of the main supply lines. The deck floor should be as clean as possible. The surface must be painted with an appropriate paint so that weld marks can be visually sensed. Lighting may be required for proper TV camera operation.

Not only the production site but also structural design may have to be changed in order to utilize the robot. The welding size may have to be standardized to enable the robot to perform tasks easily. A special welding configuration may need to be adopted to give reference points for robot vision.

It is very important to recognize that this robot does not behave like a human and needs a friendly environment. In order to develop and use the most efficient and practical robotic system, there must be good communication between all related engineers and the working flame straghtening experts.

CONCLUSIONS

There are two areas of difficulty in developing a flame straightening robot. One is developing an algorithm for removing the residual distortion in the panels. The other is developing a sensing system to detect stiffener line location.

The algorithm presented in this paper has to be verified in the field. The most noticeable feature in this algorithm is "in-process sensing" during the flame straightening operation. The data collected by "in-process sensing" is used for modifying the relationship between the torch traveling speed and the amount of distortion removal. The robot's performance is improved by referring to this up-dated relationship in order to determine the torch traveling speed for the next operation.

A vision sensor is adopted to locate stiffener lines. It uses a TV camera aided by a computer to find welding marks on the deck plate. With this visual sensing system, the robot moves along the deck and performs flame straightening operations. Some basic elements of the system have been evaluated in the laboratory.

It will take one or two years to complete the R & D program. After assembly of the hardware, the robot will be tested using a model. Further modifications may be required during the field test.

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APPENDIX

Before a flame straightening operation is performed on a deck structure, experiments need to be conducted on unrestrained samples of material to determine the relationship between free angular distortions and torch traveling speeds. An example of the result is shown in Figure A-1. Vc is the minimum velocity limit. The torch must travel faster than this speed, or damage/degradation of the material will occur. A reduction rate from one pass to the next pass is also determined in the experiment by heating on the same line as the previous pass. (See Figure A-2). Test pieces must have the same material and the same weld dimensions of the actual structure. The experimental results are then input into a computer on the robot.

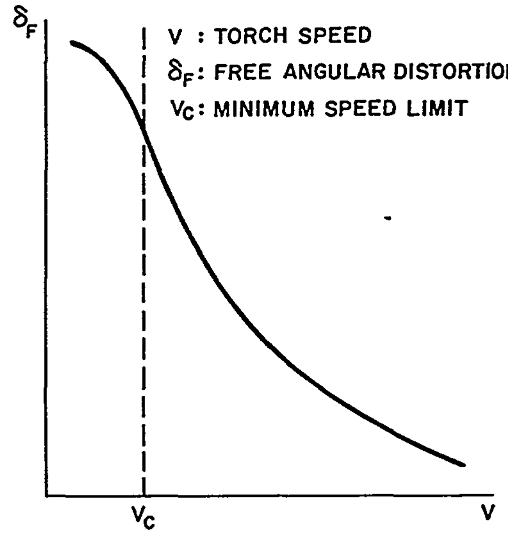

Fig. A-1 Torch speed and free angular distortion

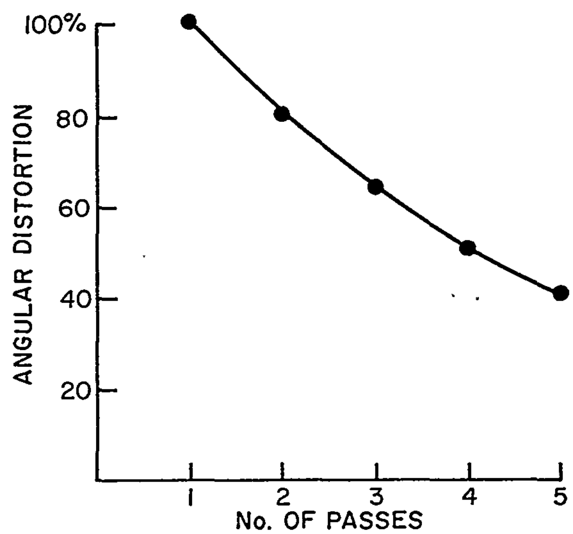

Fig. A-2 Reduction rate due to superimposing

For a simple example, suppose that the four panels shown in Figure A-3 are assigned to a robot. As the robot moves along the panels, indicated by arrows in Figure A-3, the distortion pattern shown in Figure A-4 is obtained. The computer of the robot determines heating patterns and torch velocities for the removal of distortion based on this measured distortion. For the given distortion, a heating pattern as shown in Figure A-5 may be used. SBS and LBS are applied to the positive displacement region. LOS is applied to the negative displacement region.

Torch velocities and the periods of spot heating are assigned according to experimental data and opinions of experienced human operators. A 20% removal from the original distortion may be sufficient for the first operation.

After the first heating operation, displacements are measured again. Assume that the displacement distributions shown in Figure A-6 are obtained in this second measurement. To obtain the amount of distortion removed during the first flame heating operation, the values of distortion measured after the flame heating are subtracted from those values measured prior to the first heating. (See Figure A-7.) For example, in panel P1, after the first flame heating pass, distortion removal of -4 mm(9-13) and +3 mm(-8-(-11)) were accomplished. The remaining displacements are 9 mm in negative region and

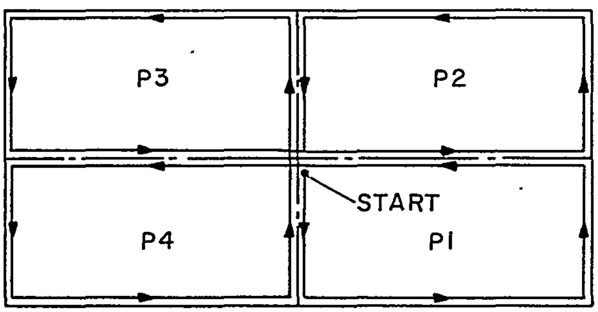

Fig. A-3 Panel arrangement and robot pass for displacement measuring

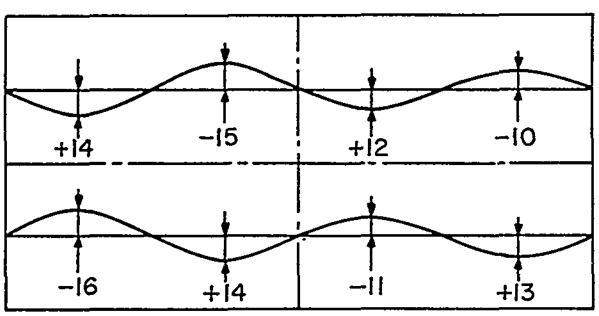

Fig. A-4 Displacement distribution prior to heating

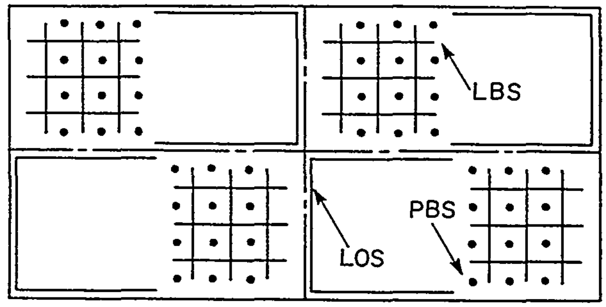

Fig. A-5 Heating pattern

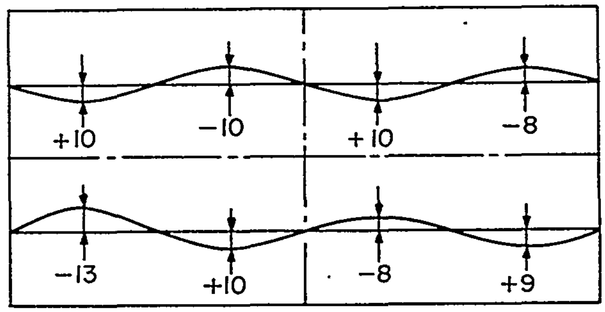

Fig. A-6 Displacement distribution after the heating operation

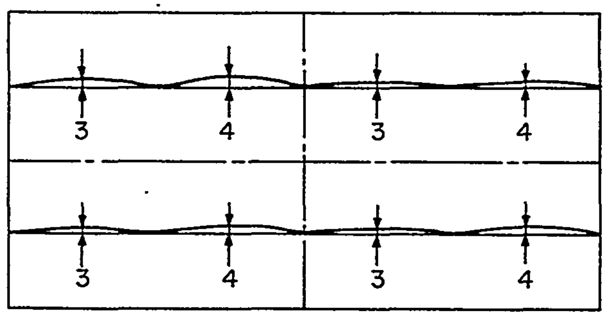

Fig. A-7 Removed displacement

8 mm in positive region. The robot is now programmed to remove 50% of the remaining distortion (i.e., 4.5 mm negative and 4.0 mm positive).

During the first heating operation, VLos1 removed 4 mm and VLbs1 with SBS removed 3 mm of distortion. In order to remove 4.5 mm in the negative region and 4.0 mm in the positive region, the necessary free angular distortions are δ Los1x4.5/4 for negative and δ Lbs1x4/3 for positive. (See Figure A-8.) Velocities are, therefore, VLos2 for negative and VLbs2 for positive. This calculation is based on the assumption that the amount of distortion removed is linearly related to the given free angular distortion. Velocities for other panels are determined in the same manner

Heating and measuring operations are repeated until the distortion is reduced to allowable values. If any problems that the robot is not able to handle occur, the robot stops the operation and waits for human instruction. A panel having a strong singularity may be left for treatment by a human operator.

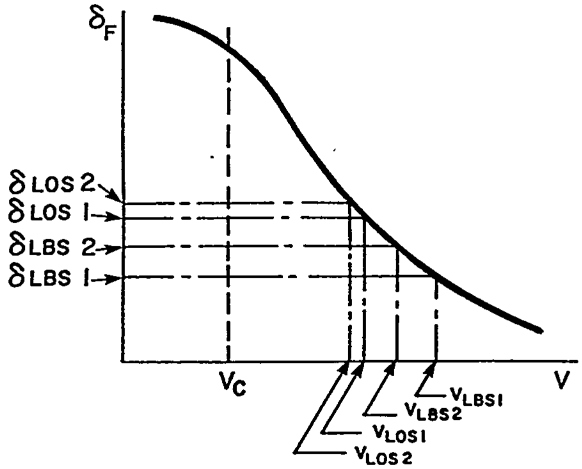

Fig. A-8 Velocities for the next operation

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