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Paper

Introduction of welding robots in shipyards

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Abstract—The great participation of direct human work characterizes today's shipbuilding industry. The actual status in the development of science and technology makes possible the replacement of humans with industrial robots in a large number of these work places.

The strategy of the introduction of industrial robots in shipyards has to be adapted to existing working conditions, and the introduction has to be done gradually.

This paper deals with a new method for priority setting of industrial robot work places and structures for welding operations in shipyards, based on the analytic hierarchy process. The numerical measure of priority of work places is based on the comparative pairwise judgments of social, psychological, technological, technical, safety, productivity and economical factors on different working locations. After the priority work places and priority working operations are chosen, the priority structures of adequate industrial robots are suggested according to their geometric, kinematic, dynamic and control characteristics.

1. INTRODUCTION

The use of industrial robots in production operations is a relatively new aspect of manufacturing engineering. The development and implementation of robot applications generally follow the same basic sequence as any other manufacturing process. However, the unique combinations of a robot requires some special considerations for successful application [1].

The use of industrial robots in the shipbuilding industry is quite a new aspect, so there is not much experience from this field and existing data are very poor and unattainable [2–7].

Today's shipbuilding industry is characterized by great participation of direct human work on hard, dangerous and tiring jobs. The actual status in the development of science and technology enables humans to be replaced by industrial robots or by other automatic machines in a large number of these work places. Surface cleaning, surface protection, coating, painting and welding are operations which can be done successfully by today's industrial robots [8].

The strategy of the introduction of industrial robots in shipyards has to be adapted to existing working conditions, and the introduction has to be done gradually. Experience from other fields [1, 9] confirms that the first robot installed at any location is the most important, and this fact was uppermost in our minds throughout the entire project and investigation. Our efforts in this project were oriented in the following directions:

(a) to become thoroughly familiar with the working locations and operations;
(b) to include workers and foremen in the project in order to hear their ideas and to make them feel that they were taking an active part;

(c) to get management back-up, because total commitment by everyone is necessary for success;
(d) to answer workers' questions honestly;
(e) to provide comprehensive maintenance training of sufficient staff to cover all shifts and to give them the tools necessary to do their jobs;
(f) to use our imagination and consider alternatives to the usual floor mounting of robots, or not to simply imitate a man with a robot because there may be better ways; and
(g) to start with simple applications. (Corollary of Murphy's law says that if you have a 50%–50% chance of success, there is a 75% chance of failure.)

The success of the first robot application in a shipyard is dependent on the efforts made to apply the above considerations. Anything less than maximum dedication to all of the above could result in some degree of failure.

It is obvious that the introduction of welding robots in shipyards is a decision-making problem *par excellence*. There are many influential factors and many possible solutions, so it is very hard to give the final decision, i.e. the priority setting of welding robot working places and structures, without some conceptually simple and decisively robust procedure.

The analytic hierarchy process (AHP) derived by Saaty [10, 11] is such a problem-solving framework. It is a systematic procedure for representing the elements of any problem. It organizes the basic rationality by breaking down a problem into its smaller constituent parts and calls for only simple pairwise comparison judgements to develop priorities in each hierarchy.

The AHP does not insist on explanations. It provides a comprehensive framework to cope with the intuitive, the rational, and the irrational in us, all at the same time. It is a method we can use to integrate our perceptions and purposes into an overall synthesis. The AHP does not require that judgements be consistent or even transitive. The degree of consistency of the judgements is revealed at the end of the process.

2. PRIORITY SETTING OF WELDING WORKING AREAS AND LOCATIONS IN SHIPYARDS

Welding operations in shipyards are very important, hard, dangerous and tiring jobs. They cover approximately 28–30% of the total operations in the shipbuilding industry, and about 38–40% of the energy consumption in shipyards [5, 7]. For these reasons, mechanization or even robotization of these operations has to be one of the vital goals in terms of increasing productivity and efficiency in the shipbuilding industry.

Welding operations in Split Shipbuilding are divided into two main areas:

(1) welding operations for ship hull construction (SH); and
(2) all other welding operations (O).

This global division is made after detailed inspection of all the places and locations in the 'Split' shipbuilding industry where welding operations take place.

In these main areas we distinguish ten (5 + 5) main locations; these locations are given below.

2.1. Area SH (ship hull construction)

2.1.1. PL—panel line. In this location the REL and gravity welding operations with CO_2 are present. In Table 1. the lengths of weldments for four typical ship sizes are given.

Table 1.
Lengths of weldments in locations PL, SA + A and P for four typical ship sizes

		Ship size (DWt)			
Location	Weldment lengths × 10^3(m)	16000	45000	80000	115000
PL	Fillet	10	26	30	50
	Butt	5	11	14	18
SA + A	Fillet	120	220	320	410
	Butt	25	35	40	67
P	Fillet	80	170	240	260
	Butt	10	22	25	43

2.1.2. SA—small assembly line. The erection and welding of the smaller sections (structure parts, chimneys, masts, rudder parts, etc.) of a ship take place in this location.

2.1.3. A—assembly line. In this location, the erection and welding of almost all the ship's hull sections take place (flat stiffened sections, regular space sections, curved stiffened sections irregular space sections). In Table 1 the lengths of weldments for four typical ship sizes in locations SA and A (with approximately 85% in A) are also given.

2.1.4. P—ship on pedestal. In this location, the final ship construction takes place and approximately 30% of the welding operations on ship hull construction in Split Shipbuilding are done here. The different welding operations (REL, gravitors, vertomats, BUGO, systems) are present in the pedestal location. In Table 1 the lengths of weldments in this location are also given.

The weldment lengths have to be the most influential factor but we also have to keep in mind energy consumption, the volume of the melt material, operators' working hours, specific working conditions, type of weldments, etc.

2.1.5. S—special product line. This product line is separated technologically from the other locations, and the main products are ring-shaped (radii from 0.3 to 5 m; lengths from 2 to 4 m). Welding operations are special (MIG/MAG, CO_2, argon).

2.2. Area O (all other locations)

This area is characterized by welding operations on particular ship equipment as well as on other products of Split Shipbuilding.

2.2.1. CW—crane wheels.
2.2.2. AP—autocrane parts.
2.2.3. PM—motor and pump supports.
2.2.4. PT—pipes and tubes.
2.2.5. HE—heat exchangers.

All these locations are inspected carefully and welding operations and methods are investigated systematically. The aim of this project is to decide which working locations and operations to choose for the first application of an industrial robot for welding. The first step, according to the analytic hierarchy process procedure [10, 11], is decomposition of this complex problem as a hierarchy. In the first level of the hierarchy is the overall goal: 'The right location for the first application of a welding robot in a shipyard'. In the second level are seven critical factors and in the last, third, level are all the locations divided into two areas (Fig. 1).

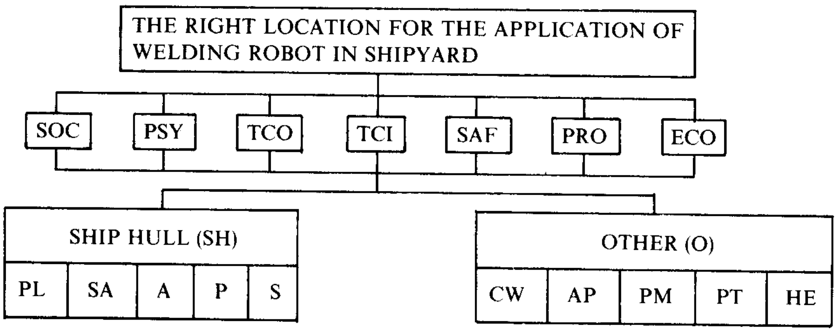

Figure 1. Decomposition of the complex problem as a three-level hierarchy.

The overall goal is clear and we have to decide which critical factors to choose and to obtain the influence of each factor on the final decision. Because there are many critical factors and a large number of possible locations, we grouped these locations into two main areas (ship hull and others), to get the global priority or areas which will lead us to the final conclusion which of the locations is really the priority one. After deriving the priority location, we have to decide which robot (or robots) will be the most suitable for welding from different points of view.

The critical factors are:

SOC: sociological factor, which includes all possible influences of the introduction of welding robots in a shipyard on manpower fluctuation;
PSY: psychological factor, which includes all possible influences of the introduction of welding robots in a shipyard on manpower motivation;
TCO: technological factor, which includes all possible influences of the introduction of welding robots in a shipyard on the technological process of welding in ships and other marine construction production;
TCI: technical factor, which includes all possible influences of the introduction of welding robots in a shipyard on technical equipment, tools, methods and principles for welding;

SAF: safety factor, which includes all possible influences of the introduction of welding robots in shipyards on safety on manpower, equipment, tools, material and products;

PRO: productivity factor, which includes all possible influences of the introduction of welding robots in a shipyard on productivity in welding operations;

ECO: economic factor, which includes all possible influences of the introduction of welding robots in a shipyard on labour cost saving, material saving, energy saving, etc., in welding operations.

These critical factors were proposed after detailed discussions with engineers, foremen, managers and workers, keeping in mind all the problems involved with the introduction of flexible manufacturing in such a traditional industry as shipbuilding.

The different categories of the personnel involved were classified into three groups (managers, engineers and foremen and workers) with different 'weighting factors' because of the different knowledge, experience, and influence of these groups. These 'weighting factors' are, for various reasons, unknown to all the persons involved except the authors.

The second step of the AHP is to construct a pairwise comparison matrix of the critical factors with an appropriate priority vector (Table 3), according to the scale of relative importance proposed by Satty (Table 2).

Table 2.
Scale of relative importance [10, 11]

Intensity of relative importance	Definition	Explanation
1	Equal importance	Two activities contribute equally
3	Moderate importance	Experience and judgment slightly favour the first activity
5	Essential or strong importance	Experience and judgment strongly favour the first activity
7	Very strong importance	The dominance of the first activity is strongly demonstrated in practice
9	Absolute importance	The evidence favouring the first activity is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	
Reciprocals of the above non-zero numbers	If the first activity (*i*) has one of the above non-zero numbers assigned to it when compared with the second activity (*j*), then *j* has the reciprocal value when compared to *i*	

After deriving the priority vector of the critical factors (with SAF in the first place with 0.374, PRO in the second place with 0.206, etc.), the set of pairwise comparison matrices of the main areas (SH and O) for all the critical factors have to be constructed (Table 4). Application of the principle of the composition of priorities gives the vector of global priority of the main areas (Table 5), which will help us, as the global intermediate result, to get the vector of global priority of all the locations.

Table 3.
Pairwise comparison matrix for the critical factors

	SAF	PRO	ECO	TCI	TCO	PSY	SOC	Priority vector
SAF	1	3	4	4	4	5	7	0.3740
PRO	1/3	1	2	3	3	4	6	0.2060
ECO	1/4	1/2	1	4	4	4	5	0.1810
TCI	1/4	1/3	1/4	1	2	3	4	0.0931
TCO	1/4	1/3	1/4	1/2	1	2	3	0.0675
PSY	1/5	1/4	1/4	1/3	1/2	1	3	0.0495
SOC	1/7	1/6	1/5	1/4	1/3	1/3	1	0.0286

Table 4.
Pairwise comparison matrices of the main areas for all the critical factors

SAF			
	SH	O	VP
SH	1	7	0.875
O	1/7	1	0.125

PRO			
	SH	O	VP
SH	1	5	0.833
O	1/5	1	0.166

ECO			
	SH	O	VP
SH	1	4	0.8
O	1/4	1	0.2

TCI			
	BT	O	VP
SH	1	5	0.833
O	1/5	1	0.166

TCO			
	BT	O	VP
SH	1	5	0.833
O	1/5	1	0.166

PSY			
	BT	O	VP
SH	1	5	0.833
O	1/5	1	0.166

SOC			
	BT	O	VP
SH	1	7	0.875
O	1/7	1	0.125

Table 5.
Application of the principle of the composition of priorities for deriving the vector of global priority of the main areas

	SOC	PSY	TCO	TCI	SAF	PRO	ECO	
	0.0286	0.0495	0.0675	0.0931	0.3740	0.2060	0.1810	GPV
SH	0.875	0.833	0.833	0.833	0.875	0.833	0.8	0.8437
O	0.125	0.166	0.166	0.166	0.125	0.166	0.2	0.1563

The pairwise comparison matrices for all the locations from areas SH and O for the four main (of seven) critical factors are given in Tables 6 and 7, respectively.

Table 6.
Pairwise comparison matrices for five locations of area SH for the four main (of seven) critical factors

	SAF					
	S	P	PL	A	SA	VP
S	1	1/2	3	1/3	1	0.135
P	2	1	4	1/2	5	0.302
PL	1/3	1/4	1	1/5	1/3	0.056
A	3	2	5	1	3	0.389
SA	1	1/5	3	1/3	1	0.117

	PRO					
	S	P	PL	A	SA	VP
S	1	1/4	1/3	1/5	1/4	0.055
P	4	1	1/2	1/3	1/2	0.137
PL	3	2	1	1/2	1/3	0.165
A	5	3	2	1	2	0.374
SA	4	2	1	1/2	1	0.270

	ECO					
	S	P	PL	A	SA	VP
S	1	1/3	1/5	1/6	2	0.075
P	3	1	1/3	1/4	2	0.135
PL	5	3	1	1/2	3	0.285
A	6	4	2	1	4	0.434
SA	1/2	1/2	1/3	1/4	1	0.072

	TCI					
	S	P	PL	A	SA	VP
S	1	1/3	1/4	1/5	1/4	0.054
P	3	1	1/2	1/3	1/2	0.121
PL	4	2	1	1/2	1	0.214
A	5	3	2	1	1/3	0.270
SA	4	2	1	3	1	0.341

Table 7.
Pairwise comparison matrices for five locations of area O for the four main (of seven) critical factors

	PRO					
	CW	AP	PM	PC	HE	VP
CW	1	3	5	3	5	0.465
AP	1/3	1	1/2	1/3	2	0.105
PM	1/5	2	1	1/3	1	0.109
PC	1/3	3	3	1	3	0.243
HE	1/5	1/2	1	1/3	1	0.079

	SAF					
	CW	AP	PM	PC	HE	VP
CW	1	1/3	1/5	1/4	1/3	0.056
AP	3	1	1/3	1/2	1	0.135
PM	5	3	1	2	3	0.389
PC	4	2	1/2	1	5	0.302
HE	3	1	1/3	1/5	1	0.117

	ECO					
	CW	AP	PM	PC	HE	VP
CW	1	1/3	1/4	1/4	1/2	0.067
AP	3	1	1/2	1/2	2	0.180
PM	4	2	1	2	3	0.368
PC	4	2	1/2	1	3	0.277
HE	2	1/2	1/3	1/3	1	0.107

	TCI					
	CW	AP	PM	PC	HE	VP
CW	1	1/2	1/5	1/4	1/3	0.061
AP	2	1	1/4	1/3	1/2	0.095
PM	5	4	1	2	3	0.412
PC	4	3	1/2	1	3	0.285
HE	3	2	1/3	1/3	1	0.147

After applying the principle of the composition of priority, the global priority vector of all the locations is obtained (Table 8).

Table 8.
Global priority vector of all the locations

Area	Location	Area priority vector	Priority vector of location in areas	Global priority vector
SH	A	0.8437	0.3675	0.3100
	P		0.2037	0.1719
	SA		0.1768	0.1491
	PL		0.1645	0.1388
	S		0.0875	0.0738
O	PM	0.1563	0.3276	0.0512
	PT		0.2866	0.0448
	CW		0.1463	0.0229
	AP		0.1303	0.0204
	HE		0.1090	0.0170

From Table 8 it is obvious that locations from area SH are at the top of the priorities, and that location A (assembly line) is in first place with a 'weighting factor' of 0.31. The conclusion is that location A (assembly line) from area SH (ship hull construction) is the right location for the first application of an industrial robot on welding operation in the Split Shipyard.

3. PRIORITY SETTING OF SHIP HULL SECTIONS IN LOCATION A (ASSEMBLY LINE) FOR THE FIRST APPLICATION OF A WELDING ROBOT

The technological process of welding operations in location A is based on the production of relatively standardized ship hull sections, grouped into four main groups (Fig. 3):

FS — flat stiffened sections,
RS — regular space sections,
CS — curved stiffened sections, and
IS — irregular space sections.

If we choose these groups of sections as alternatives, and if the new critical factors can be defined, a new three-level hierarchy occurs (Fig. 2). The goal is to define the priority of the groups of the ship hull sections in location A for the introduction of a welding robot.

The new critical factors are:

GEO: weldment geometry, which includes the type of weldment (butt, fillet, etc.), the cross-section size of the weldment and the shape of the weldment (straight or curved);
APP: weldment approachability, which includes the possibility of reaching the weldment (one side or both sides welded), the volume of the working area, the

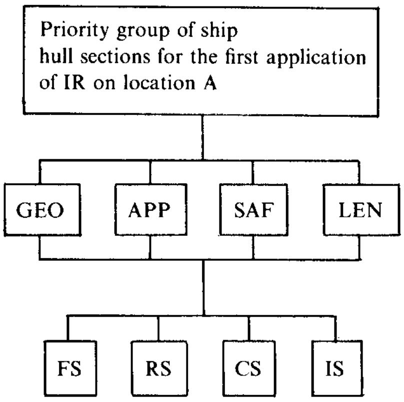

Figure 2. Decomposition of the problem as a three-level hierarchy.

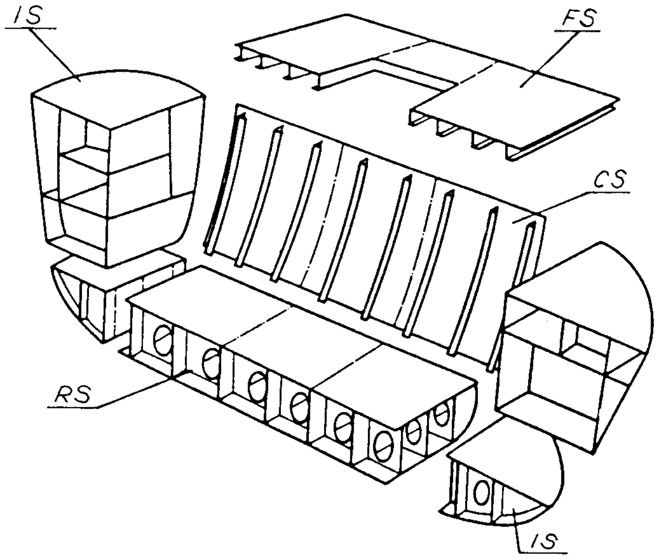

Figure 3. Standard ship hull sections.

position of welding (horizontal, vertical, or overhead), the distances from the power supply and control unit, etc.;

SAF: safety, which includes limited space, the presence of toxic and explosive materials, visibility and ventilation, the presence of electricity and other power supplies presence, the influence on the safety of the operators and equipment;

LEN: weldment lengths, which include the length of one continuous, welding sequence, the type and size of sections, the required number of torch positions and re-orientations, the type of weldment (original or repair).

Pairwise comparison matrices for the new critical factors are given in Table 9.

Table 9.
Pairwise comparison matrix for the new critical factors

	APP	LEN	GEO	SAF	VP
APP	1	2	4	5	0.497
LEN	1/2	1	3	3	0.290
GEO	1/4	1/3	1	2	0.128
SAF	1/5	1/3	1/2	1	0.085

Pairwise comparison matrices for four groups of ship sections for four critical factors are shown in Table 10. Application of the principle of the composition of priorities gives the global priority vectors of standardized sections (Table 11).

Table 10.
Pairwise comparison matrices for four groups of ship hull sections for four critical factors

	GEO				
	FS	RS	CS	IS	VP
FS	1	2	6	9	0.526
RS	1/2	1	5	8	0.344
CS	1/6	1/5	1	2	0.082
IS	1/9	1/8	1/2	1	0.047

	APP				
	FS	RS	CS	IS	VP
FS	1	6	2	9	0.540
RS	1/6	1	1/5	2	0.086
CS	1/2	5	1	5	0.319
IS	1/9	1/2	1/5	1	0.055

	SAF				
	FS	RS	CS	IS	VP
FS	1	5	2	7	0.528
RS	1/5	1	1/4	2	0.105
CS	1/2	4	1	3	0.294
IS	1/7	1/2	1/3	1	0.073

	LEN				
	FS	RS	CS	IS	VP
FS	1	1/2	5	5	0.322
RS	2	1	7	7	0.538
CS	1/5	1/7	1	1	0.070
IS	1/5	1/7	1	1	0.070

Table 11.
Application of the principle of the composition of priorities

	GEO 0.128	APP 0.497	SAF 0.085	LEN 0.290	GPV
FS	0.526	0.540	0.528	0.322	0.4740
RS	0.344	0.086	0.105	0.538	0.2517
CS	0.082	0.319	0.294	0.070	0.2143
IS	0.047	0.055	0.073	0.070	0.0599

The results derived and presented in Table 11 show that in the priority location A (assembly line) the priority sections for the first application of an industrial robot for welding operations are flat stiffened (FS) and regular space (RS) sections.

4. THE STRUCTURE AND CONFIGURATION OF INDUSTRIAL WELDING ROBOTS/MANIPULATORS IN THE PRIORITY LOCATION A (ASSEMBLY LINE)—HTE PRELIMINARY DESIGN

After detailed analysis on the priority location A (assembly line) and after consultations with the foremen, engineers and workers involved, the next decision is made.

The robotization of welding operations in this location has to be realized by two different types of robots/manipulators:

(1) *Great portal robot* for welding of butt and fillet weldments on floor, vertical and horizontal positions; and
(2) *a universal portable lightweight robot* for fillet overhead weldments, but also for the other types and positions of welding.

This combination gives great flexibility to the welding operations in location A, and proper choice of the operations and type of welding for a particular type, shape, and dimensions of particular ship hull sections has to be made.

4.1. Great portal robot

The basic assignment of a great portal robot is the welding of butt and fillet weldments on floor, vertical and horizontal weldments in location A (assembly line).

The manipulator of such a robot has two main parts, constructively separated but functionally connected in one entirety. These parts are the *portal carrier* for *a priori* positioning of manipulator arm(s) and the *flexible arm(s)* (Fig. 4). The dimensions of the portal carrier are defined by the dimensions of standard sections, and typical sections (Fig. 5) in Split Shipbuilding have the following basic dimensions:

length	10–14 m,	extreme 16 m
width	6–12 m,	extreme 16 m
height	0.85–2.5 m	

The manipulator arm has to be very flexible, with 5, 6 or even 7 degrees of freedom; of robust construction, with all the necessary welding MIG/MAG equipment, actuators, sensors, etc. (Fig. 6). Axis 1 is fixed during the welding operations, and axes 2 and 3 are sufficient for all welding paths on the ship hull sections, even for extremely long ones (16 m). Axes 4–9 are sufficient for all welding operations except overhead welding, when cover panels have to be welded and the portable lightweight robot takes its role.

Other details such as type of welding equipment, wire feeders, sensors, etc., cannot be elaborated at this time, because this is a preliminary design and a detailed project has to be done after the global decision of investment in this kind of modernization of ship production.

The very different dimensions and shapes of ship hull sections and appropriate weldments imply special requirements for the programming and control of a portal

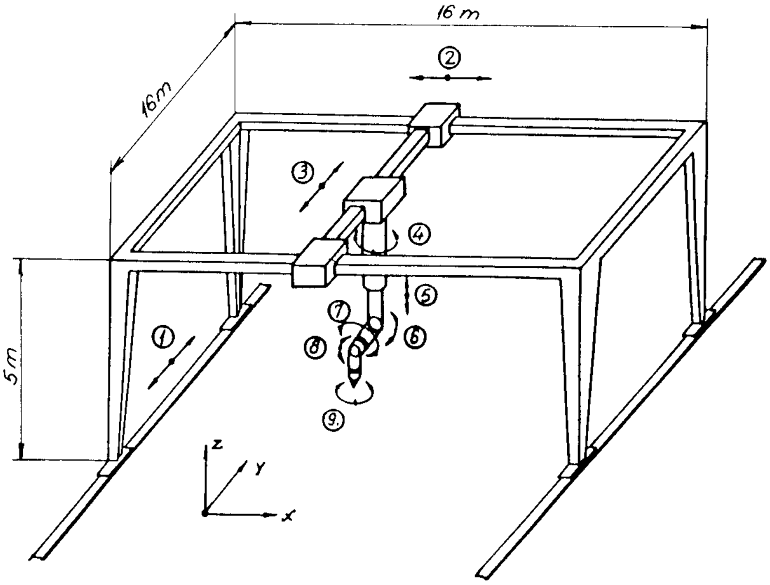

Figure 4. Great portal robot.

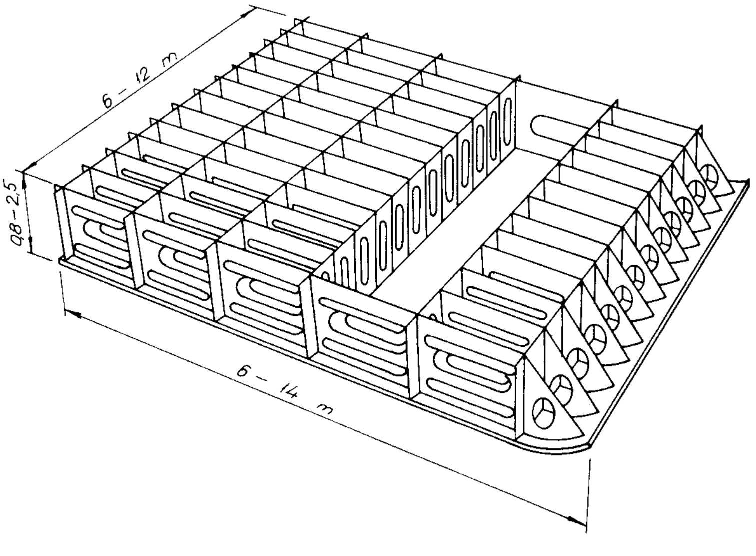

Figure 5. Typical ship hull section.

robot. Complete exploitation of the possibilities of a portal robot could be achieved with off-line programming, and two different approaches to this goal exist:

(a) The robot control unit is a constituent part of the computer system for ship hull design. All the data on the geometry and dimensions of a section are communicated directly to the robot automatic control system. This is a CAM (computer-

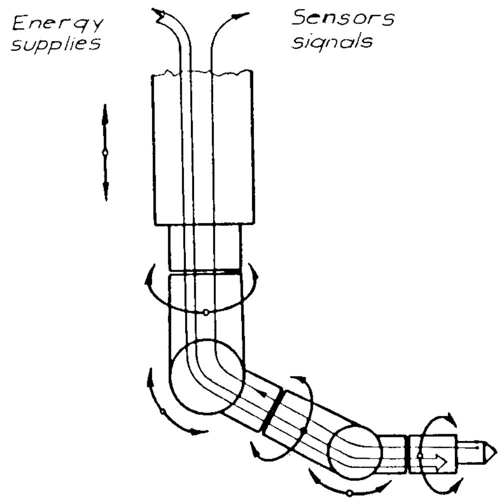

Figure 6. Flexible portal robot arm.

aided manufacturing) system based on a CAD (computer-aided design) system for ship hull deisgn.

(b) The other approach is, in fact, a compromise between hi-tech robotized production and a relatively primitive deisgn stage. The data on the geometry and dimensions of a section are taken from documentation and communicated in the memory of the robot automatic control system.

Off-line programming is also used to input all the data about the welding method, welding velocity, initial and final weldment points, etc.

4.2. Universal portable robot

The primary task of a universal portable robot is the welding of fillet overhead weldments in space sections but also other types and positions of welding if necessary.

The basic characteristics of this robot are as follows:

(a) *Lightweight*: the robot must be compact and portable to weld in confined remote areas.
(b) *Versatility*: the robot must have multichannel control and the ability to do out-of-position welding.
(c) *Reliability*: the welding environment requires equipment that is rugged and reliable.
(d) *Ease of operation*: because of the non-repetitive nature of shipboard and heavy industrial welding.
(e) *Servicability*: the robot should be of modular construction for ease of repair.
(f) *Safety*: the robot must be taught in confined areas without danger to the operator.

One possible choice for the configuration of the manipulator for such a robot could be the telescopic type, with four main degrees of freedom: translation Z, rotations θ, ψ and δ, and with the rotation of a welding gun gripper (Fig. 7). The working area is

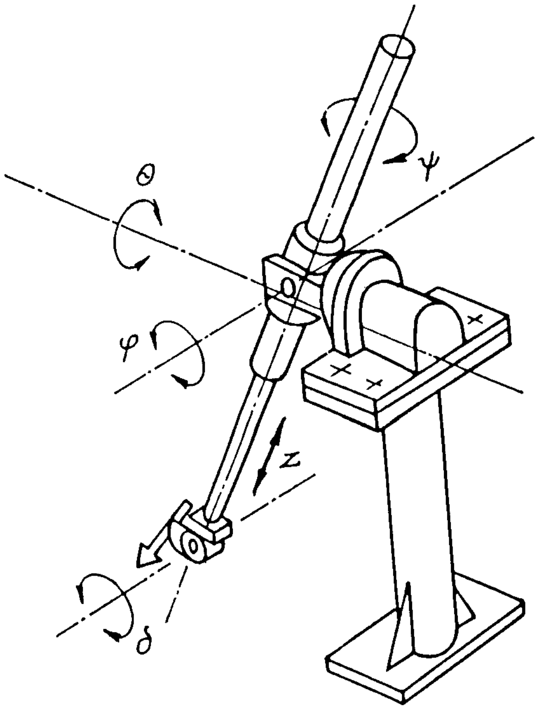

Figure 7. Universal portable robot.

presented approximately in Fig. 8. A schematic presentation of typical working operations of such a robot is given in Fig. 9.

Technical characteristics of the universal portable lightweight robot are given in Table 12.

This type of manipulator is quite simple and flexible, and with it all the operations of hard and tiring overhead welding can be done successfully. Of course, proper installation for a particular size and dimension of ship hull section has to be done. There exists also the possibility of installing this type of manipulator in a trailer for welding very long seams.

The programming and control of this robot involves a three-phase process:

(I) *The programming phase* consists of instructing the robot on the sequence and types of weldments to be performed, welding speeds, weaving parameters, voltages, and wire speeds (these settings are done on the program panel in the control unit).

(II) *The teaching phase* consists of first moving the welding gun into the initial position and then moving the gun along the weldment trajectory by an experienced operator. The weldment trajectory has to be stored in the control unit memory. If desired, the program can be checked for accuracy by quickly running through the program and observing the motions of the arm before welding is started.

(III) *The welding phase* consists of welding the desired weldment with the welding program from phase (I), and by repetition of the trajectory taught in phase (II).

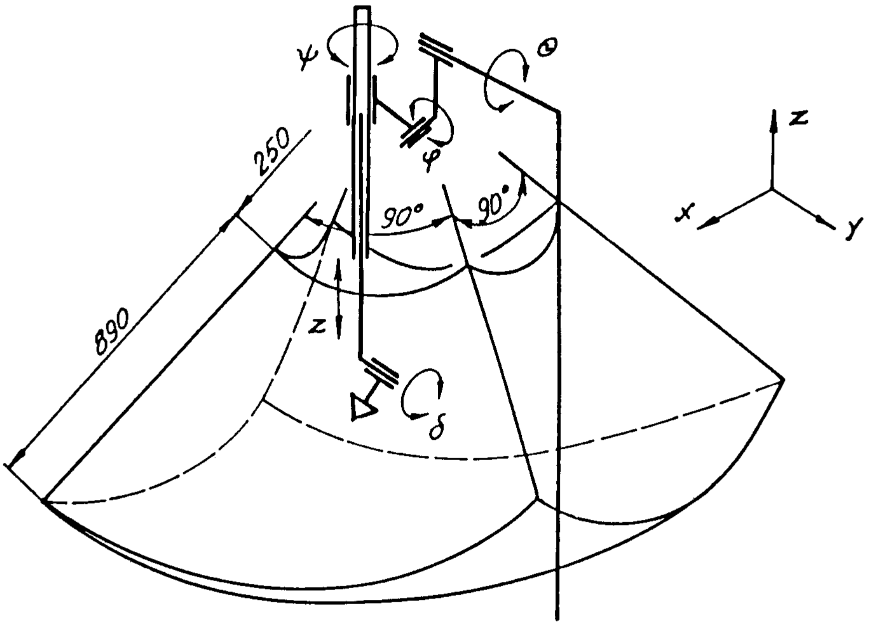

Figure 8. Working area of universal portable robot

5. CONCLUDING REMARKS

The conception of the introduction of an industrial robot in shipyards has been developed. The AHP approach has been used a complex problem-solving framework. The welding operations have been derived. The priority structures and configuration of adequate manipulators for priority location have been determined and their basic preliminary designs have been suggested. The workers, foremen, and authors have worked together throughout the entire project and the results seem to be objective and real.

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Epilogue

We are now waiting for the final decision, based on this project, to be reached by the management and Board of Directors of Split Shipbuilding. Whatever the decision, our opinion is clear: 'The mechanization, i.e. the robotization, of the shipbuilding industry is *conditio sine qua non* for survival in the brutal ship world market in the next decades'.

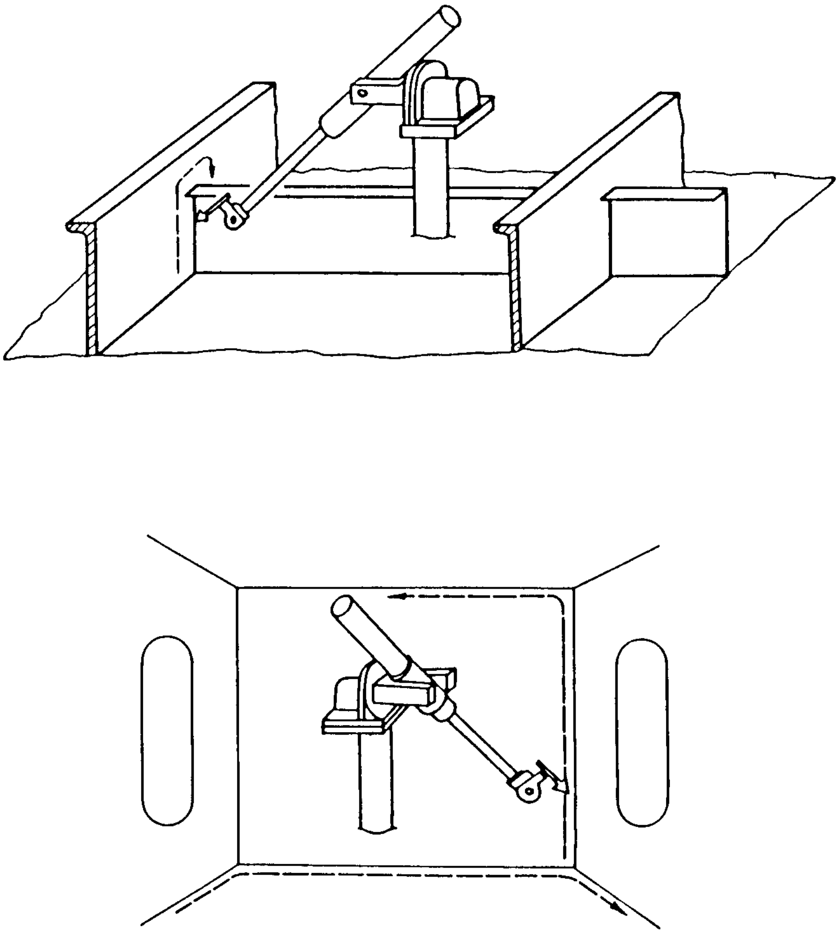

Figure 9. Schematic presentation of typical working operations of universal portable robot.

Table 12.
Technical characteristics of a universal portable lightweight robot

Trajectory "teach-in" velocity	3000	mm/min
Welding velocity	0–1000	mm/min
Accuracy	±1	mm
Manipulator mass	30–50	kg
Welding gun mass	5	kg
	Working area	
Translation	250 + 890	mm
Rotation θ	±45°	
Rotation ϕ	±180°	
Gun gripper rotation δ	±45°	

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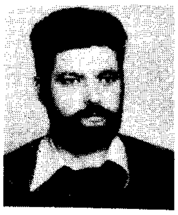

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