THE APPLICATION OF A WELDING ROBOT

FOR SMALL BATCH MANUFACTURING

IN SHIPBUILDING

BY

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5TH JUNE, 1987

A Thesis submitted to the Department of Mechanical & Process Engineering, Ship & Marine Technology Division, of the University of Strathclyde, Glasgow, Scotland for the Degree of Doctor of Philosophy.

To all those who taught me in life,
intentionally and unintentionally.

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ABSTRACT

This thesis is concerned with the application of a welding robot in a shipyard. It outlines the results and experiences gained from a research project on the application of a standard welding robot for small batch manufacturing.

The theoretical work of this study was carried-out at the University, while all practical experiments were carried-out using a CM-T3-566 Industrial robot in a real shipyard environment. In particular, the concept of robotic welding for small batch manufacturing of minor steelwork and outfit items was practised and as a result the robot workcell was successfully taken to a production situation, producing components for ship and shipyard use. The experiments enabled a number of parameters that influenced the successful implementation of robotics on the shopfloor to be examined, while the feedback obtained opened and pointed the way for further robot applications in shipbuilding.

The thesis begins by making the case for robots in shipbuilding and reviewing shipyard automation and robotic developments. The need for welding robots is then emphasised and the small batch manufacturing problem is explained. It then details the practical implementation of the welding robot and examines the lessons learned. The economic justification and areas for further development are also discussed. Finally, the expected future use of robots in shipbuilding is examined, describing a number of shipyard areas for robotisation and presenting the Flexible Automation in Shipbuilding Technology (FAST) concept, for advancing the use of robots from stand alone applications to Computer Integrated Manufacturing (CIM).

The main conclusions are that robotic manufacture of small batches offers viable production benefits, that certain critical parameters exist which can enhance the effectiveness of robotic workstations and finally, that considerable scope still exists for further application of robotics, integrated with computer based manufacturing systems.

1. INTRODUCTION

Shipbuilding is a highly competitive international business and shipyards must ensure that they are using the most efficient and effective methods of production, if they are to have a continued share of the market. Today, the low labour cost countries are presenting serious competition to the high labour cost countries who are now very keen to investigate, develop and apply computer technology to increase productivity and reduce manufacturing costs for maintaining future competitiveness.

Nevertheless, the value added per production manhour in shipbuilding still remains one of the lowest among heavy industries. It is by far the most labour intensive when compared to other major heavy industries.

The organisation and operations of those shipbuilders who prior to the VLCC revolution achieved exceptional levels of production, is considered today to be very basic. They possessed the essential plant and equipment to maintain a high output, but had not invested much in the way of mechanisation and automation of the manpower intensive work stages of assembly and construction. Their strength lay in the organisation of production and in the motivation of their human resources.

When the tanker revolution arrived, shipyards, mainly Japanese, did not hesitate to invest in various forms of single-purpose automatic equipment. 'Automation' was very much thought of during that time.

Orders for series-built ships only came to encourage automation even further. When the oil crisis arose, the lesson was clear; the concept of the future shipyard would call for more flexibility in its operation, to accommodate changes in market demands concerning ship sizes and types, while on the other hand, a high degree of mechanisation and automation was called for, to ensure the requisite level of productivity.

However, the crippling recession that followed the oil crisis, kept funding for Research and Development and for capital investment in shipyard equipment, to a minimum.

During this past decade of stagnation in shipyard innovation, spectacular advances have been made in the domain of computer technology and its derivatives such as microprocessors, CAD, CAM, CAE, Robotics, etc.

Many shipbuilders have missed out in understanding such technologies and to the mind of many 'automation' is understood to mean 'hard automation'. That is, custom built systems to perform only certain functions or to produce only a specific part or family of parts in large volumes. In an uncertain economy where one cannot always count on these volumes, hard automation is a greater risk than some potential users would care to assume for any industry, let alone shipbuilding. Robotic systems overcome this reluctance with their inherent flexibility. If demand for one part dries up, the robotic system can be re-programmed to produce a completely different part, and with robotic off-line programming, a large volume of parts is no longer a required condition.

The dramatic market changes of the 1970's demonstrated conclusively that extensive application of single purpose (hard) automation, is not appropriate in the shipbuilding environment. Today, the market situation is such that the desire to maintain product flexibility is as important a consideration as reduction in product cost and improvement in quality. These can be achieved by using the latest computer and microprocessor technology and opting for flexible automation through the use of robotic devices.

Industrial robots are becoming an integral part of our factory workforce. This is not happening overnight, it is the result of an evolution spanning more than three decades.

Today's industrial robot has its origins in two devices; the numerically controlled machine tool and the tele-operator. Both were initiated by military research. The tele-operator was developed during World War II for remote handling of radio-active materials, and the NC machines were first demonstrated in the early 1950's to mill aircraft parts. It was the marriage of these two technologies in the mid 1950's that gave birth to our current concept of an industrial robot, one with both the programmability of an NC machine tool and the manipulatory capability of the tele-operator.

The first robot models had very limited capabilities and were useful only for simple material-handling tasks. However, the industrial robot has acquired significant new skills since its humble beginning. It is now capable of a variety of complex manipulatory tasks, and a wide range of processing abilities. Each new generation of robots has a new awareness of its environment, because of enhanced sensory systems, and each employs more and more intelligence to make decisions autonomously.

The installation of a welding robot at Swan Hunter's shipyard in 1982 posed two big questions for everyone in that shipyard, and for the U.K. shipbuilding industry in general. The first was whether such an advanced machine tool could make a real impact on shipbuilding. Shipyards are traditionally resistant to new ideas and it has always been difficult to persuade a workforce to accept new technology, particularly when the expertise within an organisation is limited. The second question was whether this innovation could contribute positively towards reducing production costs.

So far the use of robots has normally been linked to the automation of assembly lines, e.g. in the motor industry, while at Swan Hunter the welding robot was an "isolated" facility. Even if it was capable of increasing production efficiency in its own area, it might cause bottlenecks elsewhere in the production line.

Initial study revealed the following important facts:

a) Expertise on the potential of such a facility was generally lacking within the shipyard and the possible role of a welding robot had not been defined.

b) External interest and offered help was mainly directed with performance deficiencies and not with applicability to production.

It was therefore felt that a completely new approach had to be implemented if there was to be progress in developing the use of this welding robot.

The research contract had been awarded to the University of Strathclyde for a study of the whole question and it was decided that from the start the work and the project would take place on two interactive fronts. The "thinking" component had to be handled at the University because the various solutions and options could be systematically examined there without pressures of day-to-day work. The "action" or practical component, on the other hand, had to be implemented at the shipyard in order to verify the concepts developed, and experiment with production potential. However, the two components would need to interact continuously throughout the whole development period.

This thesis examines the application of a standard, commercially available welding robot for small batch production at Swan Hunter's shipyard.

2. OBJECTIVES

The main objectives of the research project undertaken, were:

1. To review the application of robots in shipbuilding.

2. To examine the applicability of a standard welding robot in shipbuilding.

3. To apply it in practice in the field of small batch manufacturing of minor steelwork and outfit items.

4. To identify some of the critical factors which influence its successful implementation in a real shipyard environment.

5. To make recommendations as to the future use of robots in shipbuilding, based on experience gained.

3. THE CASE FOR ROBOTS IN SHIPBUILDING

3.1 GENERAL

Industrial robots have been developing fast in the last few years and today many industries benefit from them. New technology is continuously developing at a rapid rate and every industrial organisation should seriously consider making good use of it, if it wishes to increase productivity and stay competitive. Shipbuilding cannot afford to ignore any technological advancements, but must examine them thoroughly, to assess their applicability in shipyards, and to guide researchers for specific answers to shipbuilding problems.

Shipbuilding remains a labour-intensive industry with a very skilled labour force, that is often called upon to undertake heavy, dirty, unhealthy and dangerous operations. The challenge facing the shipbuilding industry today, involves developing uses of flexible automation as tools to interface with various processes. The basic tool today that can provide us with such flexible automation as that required in shipbuilding, is the industrial robot.

The prime consideration for the introduction of robots to the shipbuilding industry has been the 'human aspects' of the production operations. Japan pioneered the robotisation of shipbuilding by introducing 'robots' which evolved around the principle of replacing workers from heavy, dirty and dangerous operations. Although the mechanisation and automation of certain production operations is apparent in present shipyards, it has not yet reached a level that will allow shipbuilding to be freed from the stigma of unhealthy and hazardous environmental conditions, or to have relieved the workers from heavy, dirty and dangerous work.

Added to the present harsh industrial environment is the threat of future shortage of skilled labour. Shipbuilding still remains not only a labour-intensive industry, but a highly skilled one too. For years Naval Architects have relied upon their skilled labour force to cope with the complications of the designs produced. In turn workers traditionally take pride in being able to cope with such requirements.

However, with increasingly sophisticated designs being required by the market, 'design for production' and uses of 'flexible automation' have become of the utmost importance to the shipbuilder in coping with the tight economic environment imposed on the shipbuilding industry.

3.2 HUMAN CONSIDERATIONS

Ship construction operations inherently involve dirty and noisy work, with rust from steel, fumes from welding, painting cutting and dust almost permanently present in the working environment.

Many production operations often require toilsome exertion of physical strength, as well as working at a height. Also, working in confined spaces inside block units, either on the assembly hall or on the berth, often requires working in awkward positions. Such situations demand measures for their elimination, particularly when workers of increasing age have to be engaged. Shipbuilding operations must have among others, as an aim, the realisation of a more humane industrial environment.

A recent speculation is that there is a rise in the average age of the workforce population, as young persons are attracted to the more modern industries, where sophisticated machines and high technology are employed to provide a pleasant working environment.[8],[12] For similar reasons, a future shortage of skilled manpower has been predicted, as youngsters will prefer to learn skills that are competent with technology, instead of going 'backwards' to heavy manual labour. [8],[9],[11],[12],[13]

At the present level of financial status, the shipbuilding industry is also faced with the unemployment problem. But it is not robots that have caused unemployment, nor is there a direct link between the introduction of new technology and unemployment. New technology usually creates employment (but in other sectors of the industry). New technology is better linked to increased productivity rather than unemployment. Unemployment was increasing even before robots appeared in the industrial scene.

However, the introduction of new technology will increase productivity and help the country's economy. Although some jobs will be undertaken by robots, new jobs will be created. Unemployment in the UK is the result of a more general nationwide economic depression.

To beat this depression industry must raise its competitive-ness and its productivity, and at the same time reduce manufacturing costs. Profits will then result, and profits must be the key for increased salaries and low unemployment levels. Employing more people or granting wage increases without a corresponding increase in productivity, will result in dramatic levels of inflation.

The efficient and flexible robots can release humans to become creative creatures, and this will undoubtedly involve a great deal of economic upheaval. If robots are merely allowed to replace people without creating new jobs the resulting unemployment will simply cause the economy to collapse. For the future, it is envisaged that humans will concentrate on what they do best, ie creativity, intelligent thinking, supervising and the feeding-back of experience gained.

3.3 PRODUCTION CONSIDERATIONS

Shipbuilding by nature involves the manipulation of large and heavy parts. After initial preparatory work, the process basically starts by small parts being joined together to form sub-assemblies. These are then combined through several manufacturing levels to produce increasingly larger assemblies. Out of these, large blocks or units are constructed which are then transported to berth for erection.

An overview of the production process, reveals several points:

(i) All processes and operations are designed to suit manual production and consequently rely on human experience, judgement and intermittent feed-back.

(ii) Work flow is discontinuous, resulting often in idle work stations with workers waiting for parts to arrive. Planning and timing is therefore critical for the smooth flow of processes.

(iii) Most handled parts are large and heavy. Consequently most operations are 'large scale'.

(iv) A subsequent operation is often not decided until prefabricating and assembling conditions are identified and fed back.

(v) It is very difficult to control the working environment from the variety and changes caused by a number of disturbances such as welding distortion, sunshine, wind, snow, rain, etc.

(vi) While marking and cutting in the prefabrication process is done mostly in two-dimensions, the work area and amount of work increases along with the progress of production, and in assembly and berth most processes are done in three-dimensions.

(vii) Standardisation although highly desired, does not often occur. Standardisation of operations can only be achieved with a full and continuous order book, while standardisation of units can only be achieved with either series production of ships, or with particular designs, eg tankers.

(viii) Accuracy is very difficult to maintain, control, or predict, with small deviations in sub-assembly resulting in very large ones on berth. [21]

(ix) Modifications of the design or processes are frequently performed in all stages of production. It is often the case that a lot of time is spent on berth for rework and alterations. [21]

(x) The complexity of structures increases continuously and on berth a lot of human judgement and 'intelligence' is required, eg for co-ordinating final outfitting, shaft alignment, etc.

(xi) Finally, access constraints increase as production progresses and on berth some operations have to be done in very confined spaces, resulting in discomfort, danger and on a high degree of flexibility being required by human bodies.

3.4 THE ADVANTAGES AND DISADVANTAGES OF EMPLOYING ROBOTS IN THE SHIPBUILDING INDUSTRY

Today, most shipbuilders around the world are starting to consider the use of robots in their shipyards, not only the Japanese. The emphasis though is increasingly placed upon increased productivity and reduced manufacturing costs, while releasing workers from unhealthy work is a secondary consideration.

Certain shipyards have put involvement with new technology and uses of computer controlled equipment on the shopfloor (for future integration and CIM) as their main consideration. Other shipyards even adopt the tactic 'if the well-off competitor is doing it, we must be doing it too!'. Various other reasons have provided the case for robots in shipbuilding for many companies. There is no single reason why one should consider robotics on the shop floor, simply because robotics offer many advantages, both tangible and intangible and not just one. Regarding the weight and value of such advantages:

- the Safety Officer will place first the enhanced safety offered.

- the Chairman, the enhanced company image.

- the Personnel Director, the technological development of the employees.

- the Planning Director, the accurate manufacturing times with the increased ability to plan and schedule work.

- the Production Director, the increased productivity offered.

A number of economic, technical and social factors provide the motivation for employing robots. More specifically, these reasons include the following (see also Table 1):

<u>FLEXIBILITY</u> The prime advantage of a robot, when compared to any other piece of machinery, is its flexibility. It can be programmed to function as a dedicated system, but the ease of changing the robot programme, provides high speed change-over capabilities from one product to another. In shipbuilding, it is this flexibility, adaptability and reprogrammability of robots that makes them most welcome.

<u>INCREASED PRODUCTIVITY</u> In most manufacturing operations robots hold the promise of increasing the productivity and efficiency of labour. This means greater output per hour of labour input. Higher production rates are achieved when compared with the corresponding manual operations, and thus an increased annual throughput will be possible.

<u>SAFETY</u> Robots allow the transfer of the operator from an active participation, to a supervisory role and so working conditions are made safer. The safety and physical well-being of the worker are important issues in all industries and nations. Shipbuilding in particular, has been associated with a hazardous environment. The robot is a positive move towards improved working conditions.

<u>IMPROVED QUALITY, ACCURACY AND CONSISTENCY</u> Robotic work stations will not only produce parts at a faster rate than their manual counterparts, but will also produce with greater consistency and conformity to quality specifications. Increased quality is very much desired in shipbuilding. Quality control is of great importance and robots do lend themselves to a very high consistency and repeatability in the production of parts involved. They can work with a precision and accuracy not always possible by human application.

REDUCED MANUFACTURING LEAD TIME Because robots operate at higher than manual rates (eg increased arc cycle in welding, etc) whenever they are involved, production will be speeded up with a consequent reduction in lead times. This gives the shipbuilder a competitive advantage in promoting good customer service.

REDUCTION OF INVENTORY ITEMS Holding large inventories represents a significant cost to the shipbuilder because it ties up capital. Consequently it is to the shipbuilder's advantage to reduce inventories to a minimum. Robots tend to accomplish this goal by reducing the time a work part spends in the yard and with good planning, inventories should drop.

SKILLED LABOUR SHORTAGE In many advanced nations there has been a general shortage of labour. West Germany, for example, has been forced to import labour to augment its own supply. Such shortages also stimulate the development of robotics as a substitute for labour. Great Britain faces no labour shortage at present, but for the future a shortage of skilled labour has been predicted. Since shipbuilding is a highly skilled industry it must be prepared to face this problem and robots provide the answer.

MATERIAL SAVINGS The high costs of raw materials in shipbuilding results in the need for greater efficiency in using these materials. Fewer rejects and the reduction of scrap are some of the benefits in employing robots, eg paint robots can work more accurately than humans eliminating over-spraying, thus saving paint, and so on.

JOB ENRICHMENT Robots take the boredom out of routine and repetitive operations. They release the workers concerned for more interesting and challenging work, more suitable to the human brain. The limitation of human involvement to simple tasks, represents the most dramatic of human potential.

INCREASED TECHNOLOGICAL DEVELOPMENT OF EMPLOYEES Robotics will educate the shipbuilders with respect to high technology and prepare them today for the inevitable progress towards the automation of tomorrow. Shipbuilders will be expected to master these 'flexible powerful tools' and become more creative in the production process. This represents a challenge to the ever-growing standard of the shipbuilder. After all, the real wealth of any nation lies in the education of its people.

REDUCED LABOUR COSTS The trend in the industrialised societies of the world has been towards ever-increasing labour costs. As a result, higher investment in robotic equipment has become economically justifiable to replace manual operations. The high costs of labour is forcing all industries to substitute wherever they can, human labour by robots. Because robots can work at higher rates their use results in a lower cost and reduced manhours per tonne.

CONTINUITY OF PRODUCTION Robots can work at a reliability and speed which allows for continuity of production without interruption, ie no tea-breaks, lunch-breaks, rest time, sick leave, absenteeism; no influence from environmental conditions, ie snow, rain, sunshine, etc (hydraulic robots may be influenced by extreme temperatures while electric ones are not) and at the same time they lend themselves to shift work, allowing for some flexibility in planning.

ACCURATE MANUFACTURING TIMES The use of robotics on the shop floor offers a high degree of timing information, which is difficult to predict with manual labour. For example, the manufacturing of ten square manholes we now know will take 79 minutes 10 seconds!

INCREASED ABILITY TO PLAN & SCHEDULE WORK Accurate manufacturing times in turn offer an increased ability to do precise scheduling and planning.

OTHER BENEFITS Robotics is the key to the shorter working week. There has been, and is, a trend toward fewer working hours and more leisure time for the workers. Around the turn of the century the average working week was about 70 hours; the standard is currently 40 hours per week. The argument holds that robotics will allow the average number of working hours per week to decline fast, thereby allowing greater leisure hours and a higher quality of life.

Robotics will promote the prestige of the company and the image of shipbuilding as an advanced industry.

Robotics is a good means of increasing our standard of living. Only through productivity increases brought about by new automated methods of production will we be able to advance our standard of living. Granting wage increases without a corresponding increase in productivity will result in inflation. In effect, this will reduce our standard of living. To afford a better society, we must increase productivity faster than we increase wages. Therefore, as this argument proposes, robotics is the key to achieve the desired increase in productivity.

Robotics will allow for easy work content calculation and in some instances, will help in Quality Assurance. For example, in welding they could provide automatic recording of welding data, and if the welding parameters fall within tolerance limits, and the sensing devices are functioning correctly, it can be assumed that the weld meets specification.

Finally, the growth of the robotics industry will itself provide large employment opportunities. Such an argument has been proven true previously with the expansion of the computer industry, where a vast number of new jobs have been created. The growth of the robotics industry will generate new jobs involving not only the workers directly employed by these companies but also computer programmers, system engineers, robot technicians and others needed to use, operate, service, maintain and provide parts for the robots.

DISADVANTAGES

The introduction of robots to any organisation must be the result of careful planning and selection. Robots do not offer solutions to all problems. Neither can they organise the production by themselves. It is the management who must sort out the production and employ robots to increase productivity. Robots are simply 'tools' for the management which in turn must use them wisely if their advantages are to be enjoyed.

A clear disadvantage is the high initial cost associated with them. However, their price is expected to fall in the next few years as they become widely available and mass produced (whilst labour costs will undoubtedly rise). Cheaper electronic components will also contribute to lower priced robots. Pay back periods can vary depending on utilisation but so far they have been reported to be as low as one year.

Eventually they will lead us to very tight production schedules, making down time very costly. As they are basically 'machines' they are liable to wear, so preventive and planned maintenance will be required. Their expected life is obviously limited, but is can be as high as a few million hours.

When robots are eventually implemented in the production process, one can easily imagine the problems that might occur in the case of failure of the system. It is therefore important to evaluate which steps should be taken concerning prevention, trouble shooting and rectification of any problems arising in the system.

Their main disadvantage, at present, when compared to human operators, is their limited intelligence, mobility and flexibility. A human worker could pass through confined spaces in a complicated structure to reach a fault, and when there, can make judgements by applying experience, as to how to rectify the fault. However, research on the above three fields is continuing and promising. (5)(16)(17)

Eventually (and if industry cannot absorb workers elsewhere) there may be a small reduction in the labour force, with resulting unemployment. Because robotics will increase productivity by a substantial margin, if the creation of new jobs in the industry does not occur fast enough to take up the slack of displaced workers, then as a consequence, unemployment rates will accelerate. Unemployment may reach epidemic proportions and the result may be a massive economic depression.

Robotics will result in the subjugation of the human-being by the machine. This is really an argument over whether workers jobs will be downgraded or upgraded by robotics.

On the one hand, robotics tend to transfer the skill required to perform work from human operators to machines. In doing so it reduces the need for skilled labour. Some manual work left by the robots require lower skill levels, and may tend to involve rather menial tasks (eg removing chips and spatter, etc). In this sense, robotics tend to downgrade industrial work.

However, industrial relation problems caused by the introduction of robots, might take some time to solve. For example, demarcation practices will have to be broken, and also in shipbuilding we should move towards a single steelworkers trade union, one which allows full interchangeability between the various trades involved, and has complete understanding of the need of robots. Robots will also have an impact on the product design, management structure and lines of communications. The effects of this must be critically assessed and weighed against the advantages.

The day that robots will replace humans in all their duties is certainly not here yet and might never come. However, the day that robots will relieve humans from tedious, dangerous, dirty, unhealthy and physical strength requiring operations, allowing them to concentrate on what they do best, ie take intelligent problems tackling decisions etc, is definitely here. The net result is that the overall level of manufacturing labour will be upgraded, and not downgraded.

SOME OF THE ADVANTAGES OF ROBOTIC WORKSTATIONS
- INCREASED PRODUCTIVITY WITH REDUCED MANUFACTURING TIME. - INCREASED ACCURACY, QUALITY AND CONSISTENCY OF FINISHED PRODUCTS. - INCREASED SAFETY. - REDUCED LABOUR COSTS. - ACCURATE MANUFACTURING TIMES WITH INCREASED ABILITY TO PLAN AND SCHEDULE WORK. - INCREASED QUALITY OF WORKING LIFE FOR EMPLOYEES. - CONTRIBUTION TO THE TECHNOLOGICAL DEVELOPMENT OF EMPLOYEES. - ENHANCED COMPANY IMAGE.

TABLE I

4. SHIPYARD AUTOMATION AND ROBOTS

In the past, shipyard automation has been seen principally in Scandinavia and Japan. (14) This was motivated by high wages in the first and massive expansion in the second case. The automation was 'hard' that is, dedicated to a single repetitive task. In almost every case, the task was the construction of tankers. However, the market today (and most likely in the future) requires a variety in type and size of ships to be constructed. Highly specialised ship types entered the market, while ships with non-repetitive structural construction (unlike tankers) dominate construction, but also at the same time, tankers are still produced. So the requirement for shipyards is clear: 'flexible automation'. And that is quite reasonable to request in the light of technology achieved.

New technology entered the shipyard environment with the recent introduction of CAD/CAM in the drawing office. CAD/CAM does not completely automate the drawing office, eliminating all draughtsmen. It is in fact, a powerful tool in the hands of the designers to increase the productivity of the department.

A CAD/CAM system, among others, will provide detailed design and drawings, production information as well as control of processes to a certain extent. Detailed design and drawings include: definition of production structures, parts definition, calculation of weights and centres of gravity, material ordering information, etc. Production information includes: nesting, cutting sequence, profile cutting, parts lists, flow of material, etc. Control of processes include: NC of flame cutters, NC of panel fabrication, etc. Such systems also possess great potential for future off-line programming of robots to perform different functions.

To-date a number of hard automation examples have been developed, and some of them are in use in shipyards around the world. Such examples include (1) steel treatment lines, panel production lines automated pipe shops, numerous NC equipment (eg for flame cutting plates, for plates forming for section bending, etc), portable semi-auto welding and flame cutting equipment, automatic sub-assembling machines, etc.

On the other hand, flexible automation was introduced when Swedish shipbuilders, Kockums, in co-operation with Unimation developed one of the first shipbuilding robots 'the Apprentice'. Its design however was not very carefully thought out and it was also a technological compromise instead of a technological breakthrough. (18)

At that time the Japanese had also started developing numerous robots, but they were trying to jump too far ahead technologically and developed prototypes to walk and climb the ship's structure. Some of their early prototypes include the PABOT (a plate adjusting robot), CLIMACS (a ship hull climbing robot), CUTTING AND TRAVELLING ROBOTS, PLATE JOINING and other welding and painting equipment that were not all carrying freely, but wrongly, the label 'robot'. They were also among the first to realise the importance and need for overhead mounted robots on travelling gantry structures. Some of the very early moves in that area were also noted in Japan at that time. [22]

The early involvement of the Japanese included numerous failures but also gave them invaluable experience to propose new projects that will probably be quite successful in the future.

In Finland, Wartsila Shipyards, have developed what is believed to be the world's most advanced robot for shipyard use. The robot is a tripartite development between Rosenlew Automation Kemppi Welding and Wartsila. At a cost of $3.36m the robot successfully introduces fully automated welding to complex bulkhead and block assembly tasks. Its first production work at the beginning of 1986, was the welding of large blocks for a nuclear Soviet icebreaker. Following the success of the first prototype there are plans for a total of three or four such robot structures in Helsinki and four or more at Wartsila's other yard at Perno, near Turka. (14)

AVONDALE SHIPYARD Inc, New Orleans, were also experimenting at that time with ESAB electric welding robots for welding pipe branches with saddle joints, water tight door components, small hatches, pipe hangers, small foundations and brackets. However, the tolerances required for robot welding were not obtained by the previous to welding processes such as cutting and bending. In addition, redesign for robot production was not achieved. Consequently the robot was sold to another subsidiary of the Corporation which fabricates drawers and cabinets.

Other robotic developments at Avondale include an automatic 'beam line' and 'CNC web line' facilities. (19)(15)

One of the more spectacular developments in the field of laser robotics for the US Navy has been the LARS welding workcell. The project of the Navy's Manufacturing Technology (MANTECH) programme (14) is known as Laser Articulated Robotic System and is funded to the level of £8 million, awarded to MTS Systems Corporation in July 1983. Primarily embodying techniques for manipulating a high powered laser beam, the system will perform metal working tasks such as welding and cutting on components of Navy ships. The system utilises control techniques and methods of integrating all the different systems that advances automation and state-of-the-art for laser metal working significantly. (14) Weld seam tracking, adaptive control of the welding process and automatic quality assurance will all be accomplished simultaneously during welding. The LARS seam tracking system is able to follow an irregular or curved weld seam path without being told the route. Robotic laser welding offers the advantage of higher speeds, in addition to the obvious productivity gains with lower heat generation resulting in a smaller heat affected zone, and thus less distortion and less post weld straightening.

In Japan, KAWASAKI HEAVY INDUSTRIES, is currently engaged in the robotisation of arc welding, punching, painting and on application of adhesives for metal structures. Robots range from small portable to large gantry structures, and can be found at its SAKAIDE AND KOBE yards.

NIPPON KOKAN is involved in the robotisation of large scale block assembly and in arc welding. Some portable welding robots are in operation at its TSURUMI yard.

SUMITOMO HEAVY INDUSTRIES are involved in the robotisation of arc welding with particular emphasis on small portable robots like the 'Sumi-Auto' which can be found at its OPPAMA yard. In the same yard a large gantry type robot is also in operation. Sumitomo is also currently developing electron and laser beam welding systems.

MITSUBISHI HEAVY INDUSTRIES are involved with the robotisation of welding, painting and blasting. A sandblasting and painting robot is now in operation at its KOBE shipyard. At its NOGOYA yard, a robot has been developed, capable of adding stiffeners to small plates and other small component work. A prototype robotic workstation has been running since September 1984. At its ARIAKE yard, four portable welding robots have been used for some time in ship block assembly. MHI have also incorporated a large cartesian arc welding robot, supplied by KOMATSU, at its KOBE yard for fillet welding of thick plates. MHI have also been experimenting with a flexible manufacturing system (FMS) at its machining shops. CIM is considered to be their final goal.

MITSUI SHIPYARDS have been engaged in the robotisation of painting and arc welding. A two arm welding robot with visual sensing is in operation at its TAMANO yard. Mitsui's Chiba yard have several robots in operation. Two are in the yard's pipeshops and are used to weld pipe flanges of various diameters as well as performing self-loading of components, but perhaps the most notable unit is their robot in the pre fabrication hall. This robot is positioned adjacent to a conveyor belt for locating profiles on various assortments of piece part plates and completing the weld, thereon. Also, a large cartesian arc welding robot, supplied by KOMATSU is in operation at the CHIBA yard. MITSUI are also actively involved in the integration of robots into CAD/CAM systems.

HITACHI ZOSEN is very active in the robotisation of arc welding (with particular emphasis to portable robots) painting, blasting and in 'mechatronising' its KAWASAKI CITY DOCK. At its ARIAKE yard, four portable welding robots are in operation in the block assembly area. By the end of 1985 HITACHI had introduced a total of 33 welding robots and had also automated its second repair dock at KANAGAWA. Experience with the Company's first dock with automated docking, cleaning and painting facilities, had obviously been sufficient to justify further investment. [14]

5. SMALL BATCH MANUFACTURING AND ROBOTS

All ships contain small assemblies which are identical, similar or unique and occur in small or large numbers throughout the vessel. A typical 14,000 tonnes cargo vessel requires more than 70,000 minor steel part pieces during its construction.

The majority of these pieces occur in relatively small batches but may be common to a number of ship types. Such items have been termed MINOR STEELWORK AND OUTFIT ITEMS (see Table 2 and Appendices 6 & 7. Although they are usually small in size, they have a high work content and a large number of manhours per tonne, when compared with other steelwork areas.

In shipyards with an established traditional trade base, these products are made in diverse jobbing shop environments. These are difficult to control and pre-plan in a manner compatible with the designs and ambitions of competitive contemporary shipbuilding.

It is in this area of operation that the flexibility of the industrial welding robot has been explored. Ample opportunity has arisen to enable familiarisation with all aspects of robot operations.

The philosophy for robot application being that for every batch of these items, a fixture is constructed and a program for the robot is produced and stored on a cassette. Every time such a batch is required, the corresponding fixture is loaded onto the turn-table and the corresponding cassette is loaded into the robot controller. The robot operator then loads and clamps the appropriate steel part pieces onto the fixture, and activates the robot cycle. The robot cycle is repeated according to the batch size (see Figure 1).

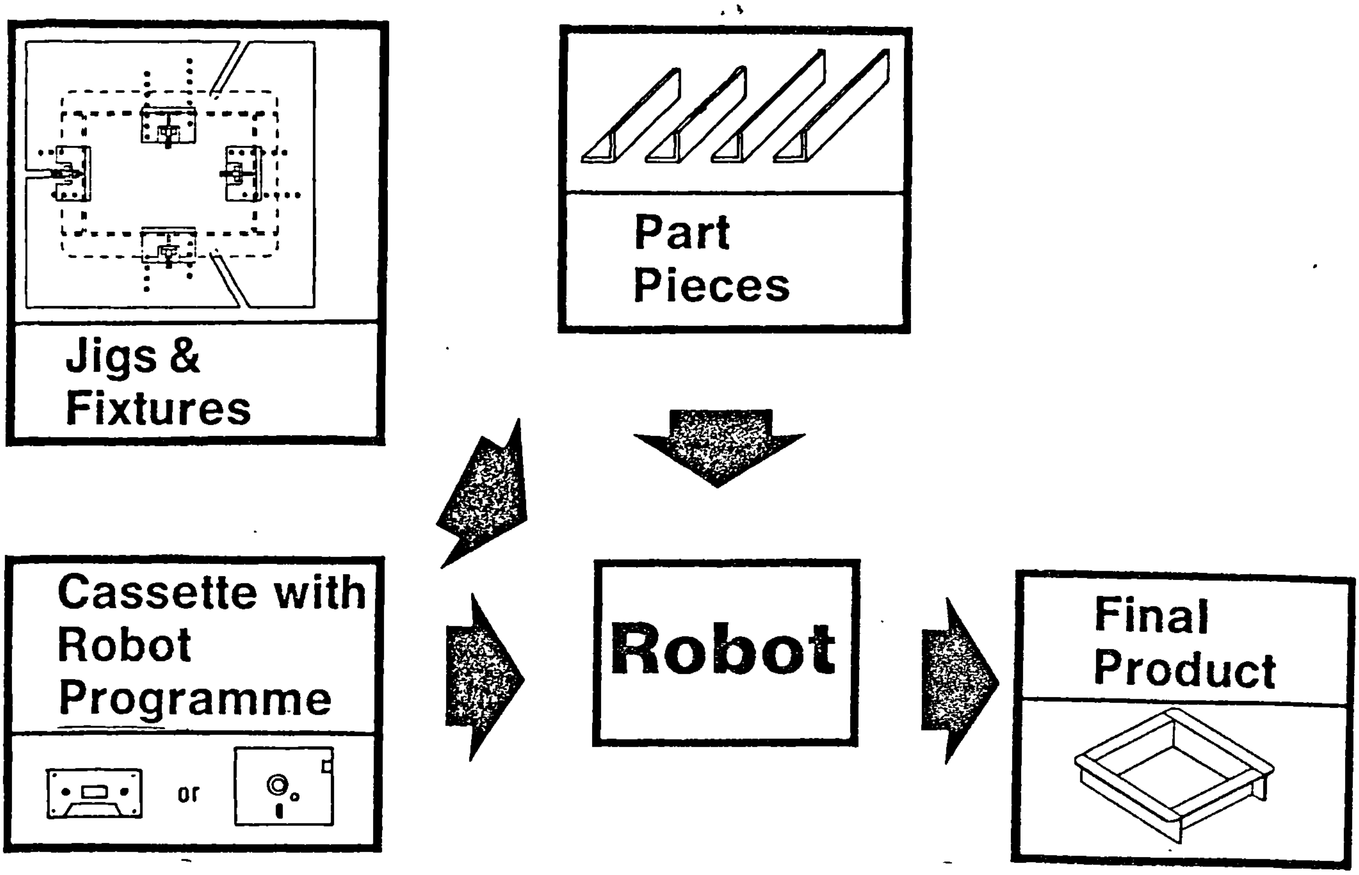


Figure 1 **Small Batch Manufacturing**

Initial programming seemed to be very time consuming. On average, one day of programming time was spent for every 15-30 minutes of robot welding. However, once a robot program is written and tested, it is stored and can be used repeatedly in the future, whenever the production of that item(s) is(are) required, allowing programming costs to be spread over the foreseeable future with regard to ships on order. It was observed however that operator experience and motivation were the main factors in significantly reducing programming time.

In robot welding for small batch manufacturing without "adaptive control", it must be ensured that the seams of the components are accurately and repeatedly positioned with respect to the robot and excessive or variable gaps do not exist, otherwise poor welds will result. In MIG welding, the arc is only melting and penetrating the weld root over approximately one wire diameter. Thus for a 1.2 mm filter wire the net accuracy of a seam displacement relative to the wire can be ± 0.6 mm.

At present varying gaps in the joints cannot be welded by robots. Consequently production tolerances for pieces to be fed to the robot workcell may have to be tightened and possible additional costs incurred for new manufacturing equipment, ie introduction of NC cutting, sawing, bending and so on.

In the economics of robotic arc welding using tape cassette programme storage, batch size alone is not a major criterion. Rather it is the number of different fabrications and the total welding content upon which savings can be made and equated against additional costs incurred, that are important.

In addition to the initial investment cost, the small quantity large variety problem for robotics lies in other hidden cost burdens which are directly attributable to using robotic welding. These include: redesign of fabrications for robot welding, changes in process routes, designing jigs and fixtures, improvements in part and assembly accuracy to facilitate robot welding, etc.

The predominant savings arise from the high speed movements between welding positions and the tireless operation of the robot. The interface with a manipulating table allows for flat position welding with minimal delays during workpiece manipulation. Thus the arc time of the robot can be up to 70-90%.

When robot welding is introduced, improvement in welding speed is not very significant and so proper attention is not paid to this opportunity. However, when large amounts of welding are to be done, a small saving in time, on every workpiece, can result into many hours saved per year. With robots, the use of high deposition rates and high welding currents is possible, through extensive use of flat position and since robots are unaffected by heat or fumes.

In the early days of the investigations, it was believed that for a component with a given set of conditions, a critical batch size could be determined. If a batch size below such a level was used, the efficiency of the cell, as measured by robot utilisation, would be reduced. Such a critical batch size could be reduced by either increasing the weld time of the component or decreasing the fixture change time. Since it is difficult to vary either of these significantly in practice, the main means available for increasing the cell efficiency was to increase the batch size. However, it is not normally possible to operate with large batches in shipbuilding. What was found to be of major importance was the number of batches used throughout the year, and the weld length deposited.

Alongside the investment costs, the economic justification of robotic arc welding is related particularly to the amount of welding a company carries out (ie annual weld metal deposition or weld length), the time required to perform this and the relative efficiency with which the welding can be done by robot, compared with a manual welder. The robot can be made to be welding (arc-on) for approximately 70-90% of the overall cycle time, whereas manual welders typically achieve a maximum of only 20%.

6. THE PRACTICAL IMPLEMENTATION OF THE WELDING ROBOT

6.1 BACKGROUND

Back in 1982 Swan Hunter Shipbuilders purchased a Cincinnati Milacron T3-566 robot with its associated welding equipment with a view to examining its applicability in the shipyard environment and eventually, if possible phase it into the production process, wherever it fitted best.

The author was doing at the time his MSc in Ship Production Technology with a thesis entitled ROBOTS IN SHIPBUILDING. The thesis examined various possible applications of robots in shipbuilding. When the author was introduced to the robot at Swan Hunter Shipbuilders - which during 1982-83 was doing neither structured R. & D. nor any production work - it was decided that it could be the perfect tool to test the concept of small batch manufacturing in practice. As it was also a standard, off the shelf available industrial robot, it was also considered important to examine whether such standard robots could be adopted by shipbuilders without changing its design. Another concern of the shipbuilder was the identification of the "critical factors" that could influence its successful implementation. Finally, in the future shipyard, in which areas and how that should be done. In 1983 the above concerns were turned into objectives for this unique PhD project.

The CMT3-566 was basically designed for spot-welding in the automobile industry. Its particular hydraulic system permits for a significant lifting capacity - in order to manipulate the heavy spot welding gun - and to a lesser extend for accuracy and repeatability. However, the manufacturers did claim that it was suitable for arc welding purposes. The robot also had a very large working envelope which permitted all of the minor steel and outfit items to be fitted in, which respect to their dimensions. Although robot redesigning was not considered, an American report was published in 1984 which basically evaluated the design of the CM-T3-566 for arc welding (28).

Robot specifications, size of working envelope and other robot details are included in Appendix 5.

6.2 THE BASIC HARDWARE USED

The equipment used in the workcell are as follows:

- The Robot (Cincinnati Milacron T3-566)
- The Robot Control Unit (Acramatic)
- The Hydraulic Unit
- The Welding Unit (Phillips)
- The Positioner table (Co-Weld)
- The Associated Mig Welding Equipment (Welding torch, wire, gas etc.

In the heart of the equipment is the CM-T3-566 Robot. It is a 6-axis computer controlled industrial robot with a jointed-arm construction providing the volume and flexibility needed to weld in difficult to reach places. Each of the axes is direct-driven by its own electro-hydraulic servo system. Each axis has its own position feed back device.

The Milacron-built Acramatic computer control provides infinitely variable 6-axis positioning and controlled path (straight line) motion, between programmed points.

The positioner table is a 2-ton, 2-axis manipulator fully interfaced with the robot controller and it is basically manipulating the fixture holding the workpiece to be welded, offering the best (downhand) position for welding to the robot. A fuller description of the robot is given in Appendix 5.

6.3 THE PRODUCT MIX

Three major areas have been identified as suitable for welding applications for the CM-T3 robot. These are the following:

AREA A: Items from the existing Company Standards

Most shipyards today maintain a large quantity of standard designs of minor steelwork and outfit items for use in most types of ships. Over the years and by building different ship designs, information was continuously up-dated and today designers have a large pool of information at their disposal to speed-up their work which consequently offers standard practices on the shop floor.

Most items in the product mix of the robotic workcell under consideration are drawn from this area. Fixtures and robot programs can be confidently made and stored for use as required.

AREA B: Items specifically designed for a particular ship

A situation often occurs where certain unique items occur in batches as 'tailor-made' products for a particular ship design. Such items do not exist in a shipyard Standards book. In certain instances the complexity of the product and the size of the batch may be such as to permit economic robotic manufacture.

However, fixtures and robot programmes need to be created and a new parameter - the time factor for creating them, becomes critical.

It is also quite likely that items from Area B are eventually taken to Area A and kept as standards for future ships. On the other hand, however, ship design might evolve in the future in such a way as to make no use of existing standards (Area A) and constantly require new designs (Area B). Although this is undesirable shipbuilding practice, no-one can confidently predict the ship designs that will be required in the future.

AREA C: Shipyard plant and other items

Supporting the proper functioning of shipyard production processes or maintaining a safe shipyard facility, necessitates occasionally the manufacture of certain items in batches.

For example, the palletisation of material and items requires a large number of certain types of pallets to be constructed. Such are for the exclusive use of the shipyard and do not constitute part of the ship. Other plant items may be ladders and platforms, burning tables, lifting lugs, fairing aids, etc.

Should any spare capacity exist in the robotic workcell, the manufacture of non-ship or shipyard items may be undertaken, acting as subcontractors to other industries and customers.

Items in Area C are tackled in a similar fashion to items in Area B, ie creating a fixture and robot program in a given time. Again, items from Area C may eventually become standard and be treated as items in Area A.

6.4 THE WORKCELL CONFIGURATION

The experimental workcell was configured initially as indicated in Figure 2. It contains a CM-T3 hydraulic robot, a two axis manipulating table and welding

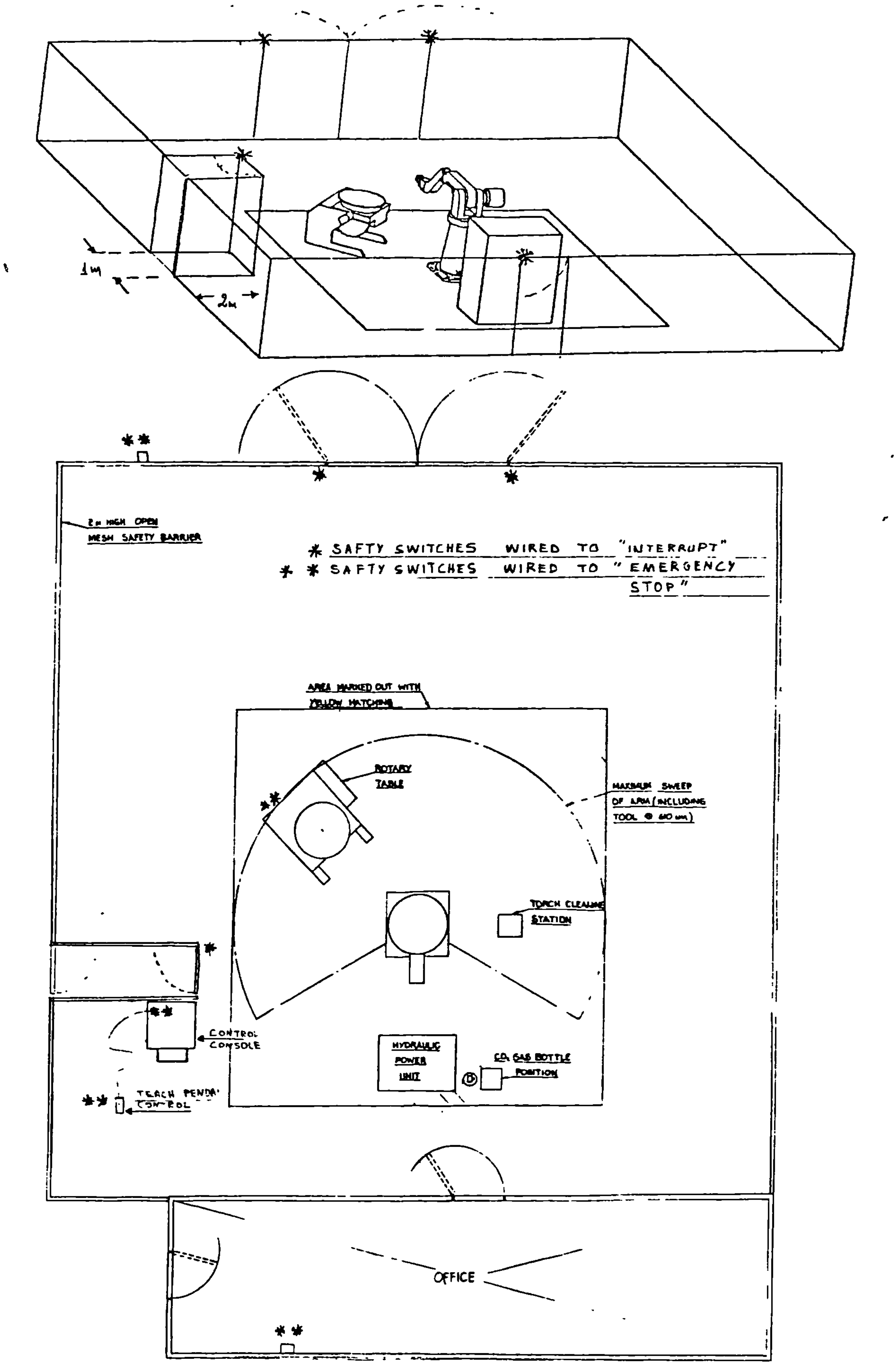


FIGURE 2 THE WORKCELL CONFIGURATION AT SHS LTD.

equipment. All are interfaced to the robot control system. Consecutive tool co-ordinates are taught by moving the robot with the teach pendant. The control system ensures subsequent straight line movement of the tool centre point between programmed points. Functions at each point are entered by commands normally input at the control console keyboard.

Perimeter guarding was left well clear of the working envelope of the robot to permit easy access and controlled storage of material during the development phases. This arrangement has proved satisfactory to test the concepts, without restricting the flexibility of the cell. All points of entry to the enclosure are interlocked to prevent access during automatic cycles which for production processes are initiated from a guarded position (see Figure 2).

The hardware used in the workcell are described in Appendix 5.

6.5 ANALYSIS OF A TYPICAL PRODUCT MIX

The product mix of applications for the robotic workcell under consideration may involve items from all three areas. As an example, fourteen such items are analysed in Table 2

Data was collected from three different ships: a small products carrier, a general purpose container carrier and roll-on/roll-off car and container carrier.

A small batch of items used per ship could be repeated on other ships and so over a period of time, medium to large batches, can result. With a well defined future order book shipyards should be able to spread the fixturing and programming costs over a number of ships. A typical item from every application was examined further with respect to weld length, number of welds and arc time.

Applications with a high number of welds and a small arc time were found to be equally as successful with applications with a large arc time but a small number of welds. Batch numbers can be deceiving and should not be used as the main criterion in deciding applications for the robotic workcell. A high number of welds implies that savings will occur in the floor-to-floor time of the application, due to the fast travel of the robot between welds. Similarly, applications with large arc times can be equally as successful due to the non-tiredness of the robot and its resulting ability to offer long duty cycles.

Although in the first instance applications were selected for robotic welding, the analysis of their manufacturing processes indicated that there were processes other than the welding that could be robotised too. An example of other processes which are used are shown on the right hand side of Table 2.

Actual experiments were directed towards using the robot to produce items from all three areas of the product mix. One example from each area is detailed further with respect to the results of investigations. (See Tables 3 4 and 5. For explanation of the cost comparisons see chapter 8.4).

From Area A the rectangular manhold coaming was selected, from Area B the released lashing box, while from Area C, the steel product was used.

The three examples were also selected so as to reflect an 'easy', a 'moderate' and a 'difficult' application, in all respects. The programming time used for each application is a good reflection of the complexity of the application (½ day, 1 day and 2½ days respectively).

Appendix 7 details the 'average' application (recessed lashing box - Area B) further.

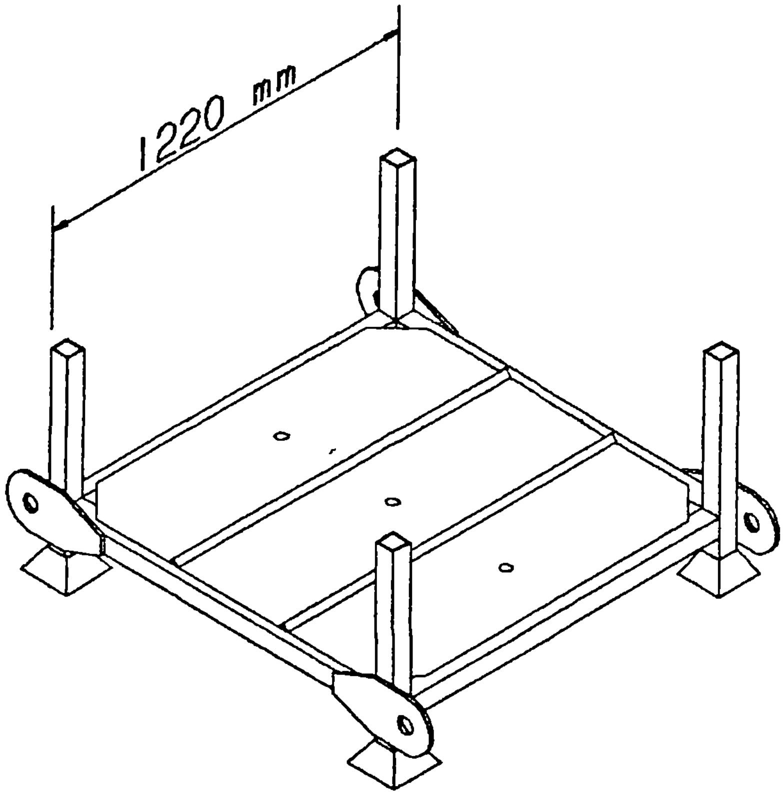
Nº	AREA	A TYPICAL PRODUCT MIX	TYPICAL NUMBERS OFF: SHIP A	SHIP B	SHIP C	TOTAL	FOR A TYPICAL (MOST USED) ITEM: WELD LENGTH (M)	NO. OF WELDS	ARC TIME (MIN)	PROCESSES: BURN	SAW OR SHEAR	WELD	ROLL OR BEND	GRIND OR BUFF	DRILL	PAINT
1	A	RECTANGULAR MANHOLE COAMINGS (RAISED)	9	12	17	38	2	16	6.5	✓	✓	✓		✓	✓	✓
2	A	ELIPTICAL MANHOLE COAMINGS (FLUSH)	-	14	66	80	5.5	6	18.5	✓	✓	✓	✓	✓	✓	✓
3	A	VERTICAL LADDERS (SINGLE RUNG)	195	144	204	543	3.2	160	11	✓	✓	✓		✓	✓	✓
4	A	SLOPING LADDERS (TRED STEP)	9	49	29	87	3.7	40	12.5	✓	✓	✓		✓	✓	✓
5	A	WATERTIGHT STEEL DOORS	48	92	54	194	5.5	15	19	✓	✓	✓		✓	✓	✓
6	A	SMALL WATERTIGHT HATCHES	32	17	21	70	10	20	34	✓	✓	✓	✓	✓	✓	✓
7	A	BOLLARDS	24	10	14	48	14.5	12	72.5	✓		✓	✓	✓		✓
8	A	FAIRLEADS	8	22	13	43	7	12	24	✓		✓		✓		✓
9	B	STAIRWAYS (CONTINUOUS STEP LADDERS)	8	16	17	41	18.5	80	63	✓	✓	✓		✓	✓	✓
10	B	RECESSED LASHING BOXES	-	274	-	274	2.3	24	9.5	✓	✓	✓		✓		✓
11	B	LASHING BINS	-	84	21	105	11.5	32	29	✓	✓	✓	✓	✓	✓	✓
12	B	BRACKETS	IN THE ORDER OF FEW 100S/SHIP				2	2	7	✓		✓		✓		✓
13	C	MATERIAL HANDLING STEEL PALLETS	ABOUT 700 IN USE 50 MORE WERE RECENTLY MADE BY THE ROBOT				8.2	116	27	✓	✓	✓		✓		✓
14	C	LIFTING LUGS	IN THE ORDER OF FEW 100S/SHIP				0.6	2	2	✓		✓		✓		✓

TABLE 2 ANALYSIS OF A TYPICAL PRODUCT MIX

TABLE 3

EXAMPLE FROM AREA C

PALLET



TOTAL WELD LENGTH	; 8160 mm
NO.OF WELDS	; 116
NO.OF PIECES	; 31
NO.OF TABLE MOVES	; 15
ARC TIME	; 27 mins
ROBOT DUTY TIME	; 43.5 mins
FLOOR TO FLOOR TIME	; 1hr.16mins
PROGRAMMING TIME	; 2.5 days

TABLE 4

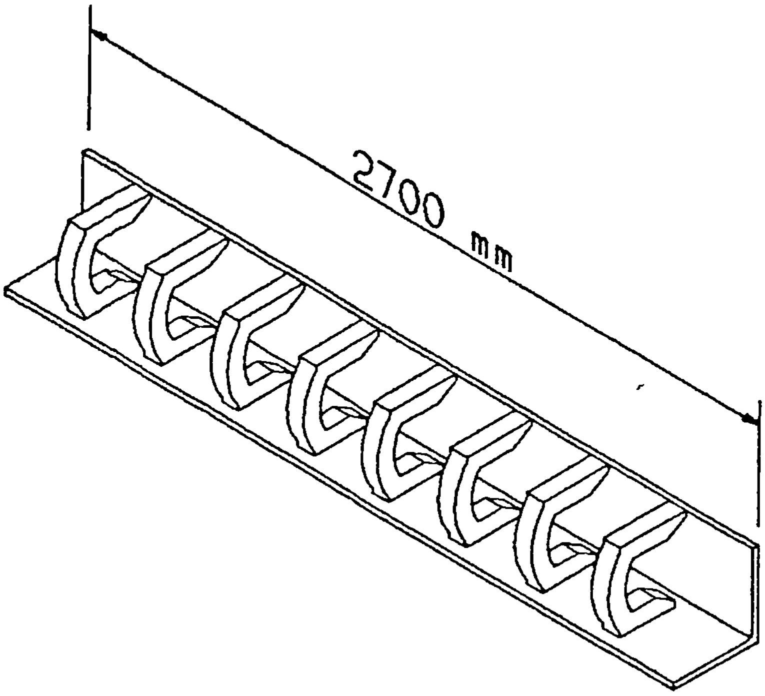
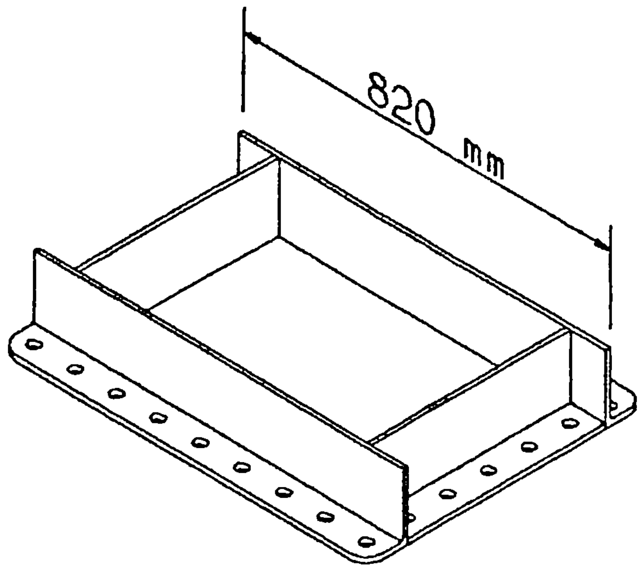
EXAMPLE FROM AREA B		
RECESSED LASHING BOX		
		
TOTAL WELD LENGTH	;	2352 mm
NO.OF WELDS	;	24
NO.OF PIECES	;	9
NO.OF TABLE MOVES	;	3
ARC TIME	;	9 mins
ROBOT DUTY TIME	;	14 mins
FLOOR TO FLOOR TIME	;	21 mins
PROGRAMMING TIME	;	1 day

TABLE 5

EXAMPLE FROM AREA A

RECTANGULAR MANHOLE COAMING



TOTAL WELD LENGTH	;	1840 mm
NO.OF WELDS	;	16
NO.OF PIECES	;	4
NO.OF TABLE MOVES	;	9
ARC TIME	;	6.25 mins
ROBOT DUTY TIME	;	11 mins
FLOOR TO FLOOR TIME	;	17 mins
PROGRAMMING TIME	;	0.5 day

6.6 TYPICAL PROBLEMS DURING PRODUCTION

During any initial production run of a product, problems are likely to occur and solutions must be found so that they can be eliminated for subsequent production runs. However, the more applications are investigated the less problems are expected as the robotics personnel will be more experienced.

To explain such problems, the initial production run of a complex product (the pallet) was analysed with respect to problems occurring with delaying effects on the overall production cycle. The results are shown in a tabulated form on Page (Table 6).

Pallets are some of the most complex products in terms of fixturing and programming anticipated for the robotic workcell. Their production has highlighted categories of problems which may occur on any product. Production of 'simple' products did not reveal all of these.

6.7 THE DEVELOPMENT AND PRODUCTION MODES

Every first-time-user of robots is faced with two conflicting robot working modes - the development mode and the production mode. The normal situation is that a several weeks/months development period is spent developing proposed robot applications, in addition to any installation, commissioning and testing periods. Such initial periods are the most expensive and labour intensive periods that the workcell is likely to face. Following that, the production mode starts, which is also the normal working mode of the cell's equipment throughout their useful life.

	PROBLEM AREA	CAUSE OF FAULT	RESULT	RESPONSIBLE FOR CAUSE	CORRECTIVE ACTION	PREVENTIVE ACTION	EFFECT ON FINISHED WORKPIECE	EFFECT ON ROBOT CYCLE	RELATIVE FREQUENCY OF OCCURANCE
1	LOADING OF WORKPIECES	INCORRECT LOADING	INEFFECTIVE WELDS, WELDS IN THE WRONG PLACE	ROBOT OPERATOR	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	TAKE CARE IN LOADING THE PIECES/USE SEAM TRACKER	NOT WELDED AS SPECIFIED BY DESIGN	NONE	3(MED)
2	CLAMPING	CLAMP LEVER LEFT OPEN	ROBOT (TORCH) TRIPS OVER AND STOPS	ROBOT OPERATOR	RESET TORCH & RESTART CYCLE	MAKE SURE ALL LEVERS ARE DOWN BEFORE ROBOT WELDING	NONE	DELAYED	2(LOW)
3	UNLOADING OF COMPLETE WORKPIECE	DISTORTION HAS ATACHED WORKPIECE TO FIXTURE	FIXTURE IS DAMAGED. ON REPAIR ORIGINAL PROGRAMME PATH MAY BE INVALID	ROBOT OPERATOR	REPAIR FIXTURE	DESIGN FIXTURE TO ACCOMMODATE DISTORTION	NONE	NONE	2(LOW)
4	FIXTURE DESIGN	FAILURE TO LOCATE PARTS FOR WELDING	WORKPIECE ELEMENTS SHIFT CAUSING INEFFECTIVE WELDS/ ROBOT STOPS	FIXTURE DESIGNER	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	USE AN EXPERIANCED FIXTURE DESIGNER/COMPUTER GRAPHICS TO SIMULATE FIXTURE OPERATION/SEAM TRACKER/ TACK WELD COMPONENTS	NOT WELDED AS SPECIFIED BY DESIGN	DELAYED	6(HIGH)
5	FIXTURE MANUFACTURE	MISALIGNMENT & POOR CONSTRUCTION DURING MANUFACTURING	LOCATING DEVICES MAY SHIFT INVALIDATING PROGRAMME i.e. INEFFECTIVE WELDS	MACHINE SHOP FORMAN	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	TACK WELD COMPONENTS /USE SEAM TRACKER	NOT WELDED AS SPECIFIED BY DESIGN	NONE	7(HIGH)
6	TOLERANCES ON COMPONENTS	UNDUE CARE IN PREVIOUS MANUFACTURING PROCESS	(+) INEFFECTIVE WELDS / (-) ROBOT STOPS	PRODUCTION FORMAN	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	USE SIMPLE JIGS, FIXTURES/ CARE DURING THE PRODUCTION OF COMPONENTS/AUTOMATE PROCESSES/ USE A SEAM TRACKER(+)	NOT WELDED AS SPECIFIED BY DESIGN	(+) NONE / (-) DELAYED	5(MED)
7	PROGRAMMING	INEXPERIENCE/ PROGRAMMING UNDER PRESSURE	UNNECESSARY POINTS ON ROBOT PATH	ROBOT PROGRAMER	REPROGRAM	OPTIMISE ROBOT MOVES /USE OFF-LINE PROGRAMMING	NONE	DELAYED	13(V.HIGH)
8	PROGRAMMING	PROGRAMME GENERATED ON PIECES WITH CERTAIN TOLLERANCES	INEFFECTIVE WELDS/ WELDS IN THE WRONG PLACE	ROBOT PROGRAMER	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	PROGRAM FOR DESIGNED DIMENSIONS, USING A REAL OR WOODEN MODEL WITH NO TOLLERANCES OR, USE OFF-LINE PROGRAMMING	NOT WELDED AS SPECIFIED BY DESIGN	NONE	11(V.HIGH)
9	WELDING SPATTER	INAPROPRIATE WELDING PARAMETERS	ROBOT STOPS/ WELD SPATTER BLOCKS TORCH NOZZLE	ROBOT PROGRAMER	CLEAN TORCH & RESTART ROBOT CYCLE	CHANGE THE WELDING PARAMETERS USE TORCH CLEANING STATION MORE OFTEN	NONE	DELAYED	16(V.HIGH)
10	SAFETY DOORS	ROBOT EMCLOSURE DOOR WAS OPENED DURING WELDING	ROBOT STOPS	ROBOT OPERATOR	CLOSE DOOR & RESTART ROBOT CYCLE	PUT UP MORE NOTICES TO EDUCATE EMPLOYEES NOT TO ENTER WHEN ROBOT CYCLE IS ON	NONE	DELAYED	2(LOW)
11	ROBOT SOFTWARE	?	ROBOT STOPS	CINCINNATI SOFTWARE/ HARDWARE	PRESS EMERGENCY STOP & RETURN ROBOT TO HOME POSITION	?	PARTIALY MANUALY WELDED (NOT WELDED AS SPECIFIED BY DESIGN)	SHORTENED	1(LOW)
12	WELDING WIRE	RUNNING OUT	ROBOT STOPS	ROBOT OPERATOR	USE NEW SPOOL OF WELDING WIRE	USE LARGE SPOOL OF WELDING WIRE	NONE	DELAYED	4(MED)
13	WELDING WIRE	COPPER FLAKES FROM WIRE COATING BLOCK PASSAGE	ROBOT STOPS	EQUIPMENT SPECIFIER	CLEAN WIREFEED MECHANISM	USE COPPER FREE WELDING WIRE	NONE	DELAYED	2(LOW)
14	ROBOT GUN (end-effector)	MISALIGNMENT	INEFFECTIVE WELDS, WELDS IN THE WRONG PLACE	ROBOT OPERATOR	REWELD THE WORKPIECE WHEN CYCLE IS FINISHED	USE A BETTER RIGITITY & DESIGN ROBOT GUN	NOT WELDED AS SPECIFIED BY DESIGN	NONE	20(V.HIGH)

TABLE 6

However, for users of robots in small batch manufacturing with such uncertainty about the future type of work, such as a shipbuilder, it was found necessary, in addition to the initial development period, that a development mode is maintained throughout the working life and run in a mixed situation with the production mode (or in parallel should the user opt for off-line programming and workcell simulation/evaluation using computer graphics).

The 'smooth marriage' of the two modes therefore becomes of high importance and should be one of the user's goals. Indeed, the work carried out for SHS Ltd, included both the development and production modes.

During the development mode, different applications are being brought to a stage where production personnel are supplied with:

- a fixture to position and hold pieces during welding
- a cassette containing the robot program
- a manual describing the production procedure to be followed

For known or standard applications the development process can take place well in advance of any such workpieces being required by production.

However, for specially designed applications adequate notice must be given for their development (ie for fixture design and manufacture, robot programming, etc).

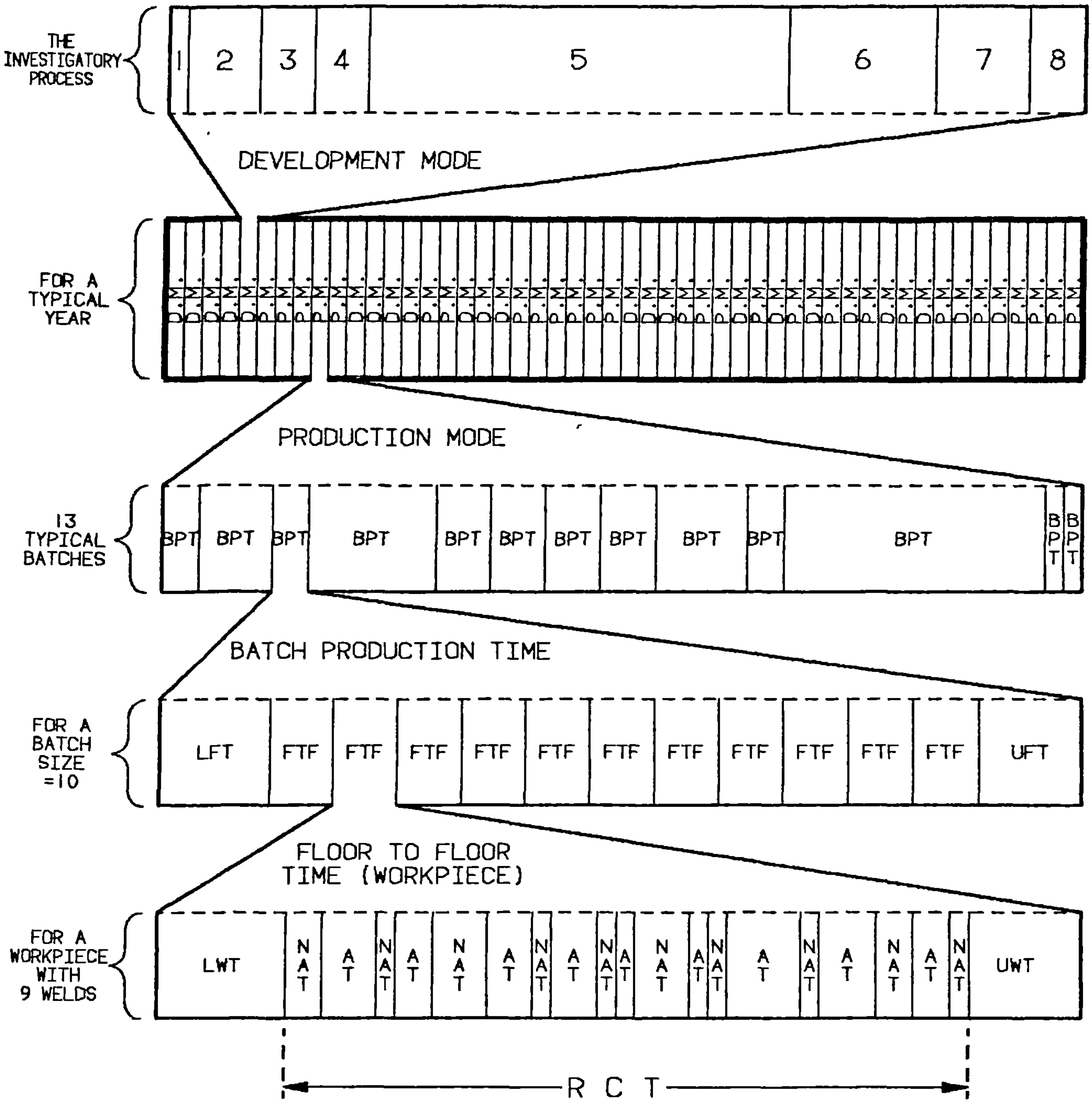
During the production mode, the welding of different fully developed applications takes place.

Ideally, batches of different applications should be mixed so as to achieve maximum robot utilisation. However, this is of secondary importance. Of primary importance is the scheduling of batches for robot production in such a way as required by other work cells further down the production line, ie products must leave the robot cell so as to arrive at the required time to other manual or robotic workcells.

In a production mode, typical functions of the robot operator include loading/unloading of workpieces and initiation/termination of robot routines. Occasionally it might be necessary to stop the robot and adjust according to any malfunctions of the system, to carry-out maintenance, etc.

Typical examples of patterns for the development and production modes are shown in Figure 3, while the development and production mode activities are listed in Table 7.

FIG 3 TYPICAL EXAMPLES OF PATTERNS FOR THE DEVELOPMENT AND PRODUCTION MODES



EXPLANATION OF SYMBOLS USED

1 = IDENTIFY POTENTIAL FAMILY
2 = INVESTIGATE DESIGN AND QUANTITIES REQUIRED FOR PRODUCT MIX ANTICIPATED
3 = INVESTIGATE CURRENT MANUFACTURING METHODS AND COSTS
4 = ESTIMATE ROBOT PRODUCTION COSTS, AND COSTS OF OUTSIDE CONTRACTORS
5 = DEVELOP A DESIGN FOR ROBOT PRODUCTION (INCLUDING JIGS AND FIXTURES AS NECESSARY)
6 = PROGRESS TRIAL MANUFACTURE AND REFINE ESTIMATED TIMES AND COSTS
7 = COMPARE COSTS AND FINALISE ROBOT PRODUCTION PROCEDURE
8 = PREPARE APPLICATION MANUAL

DM = DEVELOPMENT MODE
PM = PRODUCTION MODE
BPT = BATCH PRODUCTION TIME
LFT = LOAD FIXTURE TIME
UFT = UNLOAD FIXTURE TIME
FTF = FLOOR TO FLOOR TIME

LWT = LOAD WORKPIECE TIME
UWT = UNLOAD WORKPIECE TIME
NAT = NON ARCING TIME
AT = ARCING TIME
RCT = ROBOT CYCLE TIME

DEVELOPMENT	**PRODUCTION**
IDENTIFY POTENTIAL FAMILY	CARRY OUT BASIC MAINTAINANCE
↓	↓
INVESTIGATE DESIGN AND QUANTITIES REQUIRED FOR PRODUCT MIX ANTICIPATED	ENSURE ALL PART PIECES ARE AVAILABLE AS REQUIRED
↓	↓
INVESTIGATE CURRENT MANUFACTURING METHODS AND COSTS	LOAD / UNLOAD FIXTURE ONTO / FROM THE TURNTABLE
↓	↓
ESTIMATE ROBOT PRODUCTION COSTS AND COSTS OF OUTSIDE CONTRACTORS	LOAD CASSETTE WITH ROBOT PROGRAMME IN ROBOT CONTROLLER
↓	↓
DEVELOP A DESIGN FOR ROBOT PRODUCTION (INCL.FIXTURING)	LOAD / UNLOAD WORKPIECES
↓	↓
PROGRESS TRIAL MANUFACTURE AND REFINE MANUFACTURING TIMES AND COSTS	INITIATE / TERMINATE ROBOT CYCLE
↓	↓
COMPARE COSTS AND FINALISE ROBOT PRODUCTION PROCEDURE	SUPERVISE, CORRECT ANY MALFUNCTIONS AND REPROGRAM ROBOT AS NECESSARY
↓	↓
PREPARE APPLICATION MANUAL	ENSURE ALL COMPLETED WORKPIECES ARE READY FOR DESPATCH

TABLE 7 DEVELOPMENT AND PRODUCTION MODE ACTIVITIES

7. CRITICAL FACTORS

During the time the author spent researching the use of shipbuilding robots on the shipyard factory floor, a number of critical factors were studied which are fundamental to further positive application of robots in shipbuilding. Such factors are:

7.1 ACCURACY REQUIREMENTS

The success of a robotic welding cell, among other parameters, relies on a combination of the following:

- fit up and assembly accuracy (including fixturing accuracy)
- component manipulation accuracy
- control of welding process parameters
- robot positional accuracy
- repeatability and consistency in production run
- component part accuracy
- programming accuracy

Some of these factors will now be considered.

a) Fit up and assembly accuracy

In the absence of an adaptive control system it is essential that components are precisely located. The difficulty in achieving this is directly proportional to the complexity of the workpiece. Adaptive control systems reduce the demands in this respect. However, good and robust designs of fixtures were found to be the two most important parameters here.

b) Robot positional accuracy and repeatability

When on-line programming, the operator is concerned with the repeatability of the arm. With off-line programming the accuracy of the arc become important. Many people use the term 'accuracy' and 'repeatability' as if they meant the same thing. This is not the case.

Repeatability has to do with the expected variance in position each time the arm returns to a taught point along the same path and at the same speed. Repeatability is established by statistical means from test data.

Accuracy on the other hand, relates to the ability of the robot to follow commands rather than move between points physically taught. For example, assume a robot is instructed to move 45.69 cm, the actual move is measured and found to be 45.36 cm. Upon succeeding runs the arm continues to move exactly 45.36 cm. In this case the repeatability is perfect whilst the accuracy is not.

c) Component part accuracy

Ideally, the individual components of workpieces arriving for robot welding should be of exact specified dimensions, but this is unrealistic as it depends on such previous processes as flame cutting, sawing, rolling, etc. which naturally exhibit tolerances.

Tolerances on component sizes which we have experienced have been between ± 0.5 mm and ± 2 mm. Provisions have been made which accommodate these. Some difficulties have occurred because the tolerances exhibited by supporting processes have not been under control - there has been variation in the mean positions of the distribution of variations. Statistical Quality Control methods are now being implemented as a feature of workstation organisation at Swan Hunter Shipbuilders which together with worker self-checking assist in this respect.

d) Programming accuracy

Due to the possible tolerance of the individual components, programming inaccuracies may arise as the robot path is taught. Obtaining ideal 'as designed' dimensioned pieces for programming may be impractical and expensive. Wooden models may be less impractical and less expensive but still the need is for off-line programming, so that accurate programmes are created.

e) Accuracy control

Accuracy control is a production philosophy which continuously refines production processes by actions based on analysis of them and their infrastructure. It pervades the approach to development and productivity improvement at Swan Hunter Shipbuilders.

Robotic installations with:

- absolute consistency in quality
- highly predictable cycle times
- controllable operating characteristics

fit naturally in an accuracy controlled environment.

7.2 OPTIMISATION OF ROBOT PATH

It has been the author's experience that almost every initial robot programme can be further refined to give shorter robot cycles.

Numerous routes exist for the robot arm, in reaching for example the starting point of a weld seam. As a result the route decided by the robot programmer is not necessarily the 'optimum' one.

Welding considerations for avoiding distortion determine the welding sequence but not the robot routes. Although 'optimum' routes for the robot arm are highly desirable as they can save considerable time (eg original robot cycle for a pallet - 1hr 10mins; refined - 43.5 mins), it can be quite time consuming in finding them depending on workpiece complexity. (One extra day was spent for the above refinement).

However, with off-line programming using graphics such optimisation will become more viable and cost effective.

7.3 JIGS AND FIXTURES FOR ROBOTIC WELDING

The importance of jigs and fixtures for robotic welding in the area of minor steelwork and outfit items has been found paramount. However, for other areas in a shipyard (eg sub- assembly, panel lines, etc) where robotic welding will be introduced, it is considered adequate to tack weld the components together (eg stiffeners and brackets onto a base plate) provided that the overall dimensions and the connection areas were accurately located for joining purposes.

The difference between a jig and a fixture is that a jig is a device that accurately and repeatedly guides a tool (eg a drill) onto a component for processing, while a fixture accurately and repeatedly locates the seams through the components of a workpiece to be processed (eg welded by the robot).

In certain instances it was found that a combination of jigs and fixtures was needed for certain robotic applications. One such distinct example is the rectangular manhole coaming application. A fixture was devised for it which holds accurately and repeatedly four pieces of angle bar, for the robot to weld together. There is however a second stage of welding to be done before despatching the components further downstream the production process - that is the drilling of holes in the top face of the angle bars. The placing of an equivalent amount of bolts into the holes proved to be a complicated and perhaps costly exercise and it was decided to use the workpiece itself to act as a fixture. For this no tolerance on the size of holes was allowed and accurate drilling became a fundamental pre-requisite. A 'JIG' had to be designed which would carry a number of 'hardened bushes' on the exact location of each hole, which would be placed on top of the welded angle bar coaming and 'guide' the drill repeatedly in the required place.

THE ROLE OF FIXTURES

The function of a fixture for robotic welding is to accurately and repeatedly locate the seams formed by the components of the workpieces presented for robot welding. At the same time it must:

- allow for quick and accurate location onto the positioning table
- allow for good robot accessibility to all seams
- allow easy and quick workpiece removal after welding
- where possible, minimise distortion (caused by welding heat input) by suitable clamping
- be of good robust design and manufactured for a long working life.

Consequently, the cost of a fixture design and manufacture varies according to the complexity of the workpieces.

THE NEED FOR FLEXIBLE FIXTURES

The concept of flexible fixturing has been explored. A fixture could be used to produce more than one product if its clamping devices were either relocatable or strategically placed to accommodate different sizes and configurations of components. (See Figure 4 for a simple example of relocatable clamping devices offering accommodation to a limited number of configurations).

In the first instance flexible fixtures can be used for similar workpieces. However, the challenge is to take the concept beyond that and apply it to quite dissimilar workpieces. This in turn requires a creative and imaginative fixture designer.

Flexible fixtures would reduce the:
- overall fixture design and manufacturing costs
- batch production time
- fixture handling time
- need for a large fixture storage area

The level of automation of the fixture-workpiece relation can be increased by replacing all manual clamps with hydraulic or pneumatic clamps activated by the robot controller. Also, another robot could be used to load and unload the pieces on one fixture while the welding robot is welding on another. (Eg through the use of double turntables).

THE ULTIMATE FLEXIBLE FIXTURE

Welding fixtures are considered an integral part of a robotic workcell for welding minor steelwork and outfit items. However, they can be very expensive, take up storage area, deteriorate, might never be used for another batch and in general they are 'dead assets'. With time, money spent for fixturing may be well over the price of another robot in the first place.

Two robots can work in conjunction, one for example can be a welding robot and the other 'the ultimate flexible fixture' picking up and locating the workpieces for the welding robot to tack them in place, and then be welded by the welding robot, whilst the handling robot is picking up the next component to be manipulated. The handling robot could also have a tool changing station for the performance of other tasks within its working envelope, or even to manipulate the piece it picked up for welding in front of a light buffing tool for removing the primer on the edge of the piece that is likely to cause porosity when fully welded.

In such a system, sensors play a crucial role, eg vision and seam tracking capability for the respective robots. Also graphical workcell simulation and animation methods and off- line programming will be integral parts of the system, ensuring that such installations are most efficiently utilised.

Alternatively, both robots can be accommodated in a hybrid one, eg in a gantry type configuration, similar in principle to the illustration in Figure 5 where the welding robot is a small offset robot from the main materials handling one.

7.4 SENSORS AND ADAPTIVE CONTROL

Although the last generation of robots were programmed on-line and used virtually no sensors, this situation must now change for the most effective utilisation of robotic devices.

Robots need to be programmed off-line via a CAD/CAM system and then be expected to use their 'sensors' to account for

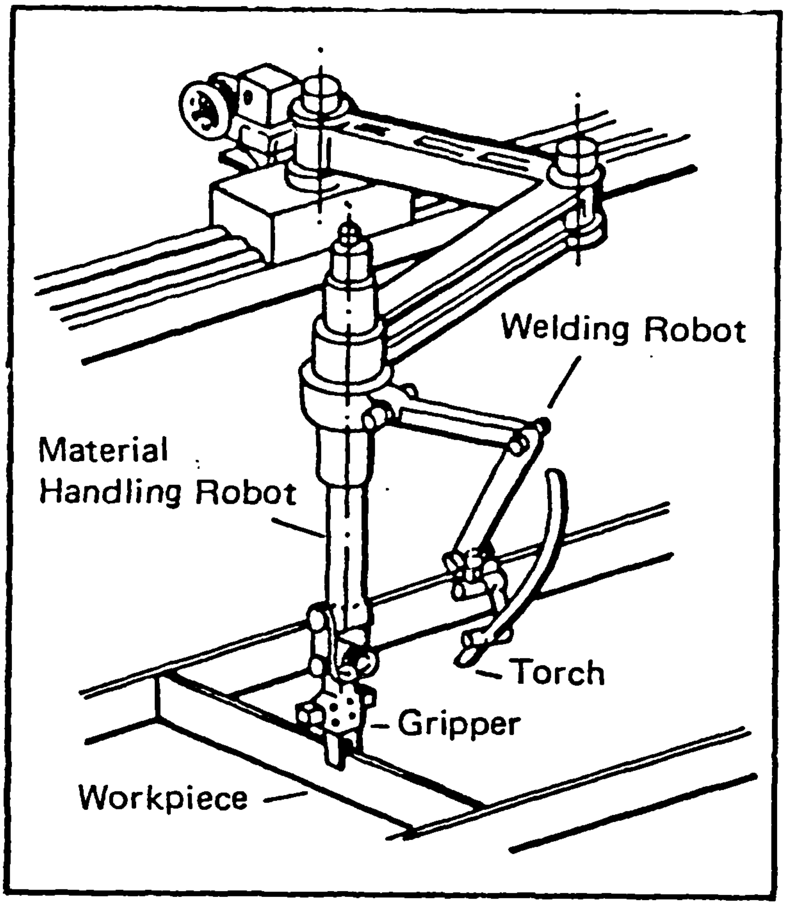


FIGURE 5. A TYPICAL HYBRID ROBOT FOR ASSEMBLING AND WELDING.(24)

any variations in the actual workcell. A variety of sensors are needed, according to the application (eg tactile, visual, through-the-arc, etc).

Robotic welding for example, necessitates the use of 'adaptive control'. 'Adaptive control' (also referred to as 'seam tracking') is a generic term defining the addition of a system to a welding robot which monitors changes in a particular welding variable (eg arc voltage, current, joint location, etc) and arranges the appropriate corrective action. A good adaptive control system for shipbuilding use, must include:

a) Joint Tracking

Monitoring changes in the location of the joint.

b) Joint Recognition

Recognising the joint to be welded and detecting changes in the joint geometry.

c) Weld Recognition

Recognising variations in the geometry - including penetration depth of the weld or weld pool being made.

d) Instruct the Welding Robot

To take the appropriate correcting action.

Adaptive control systems are expected to play a crucial role in reducing current robot production costs while they are deemed indispensable for the future.

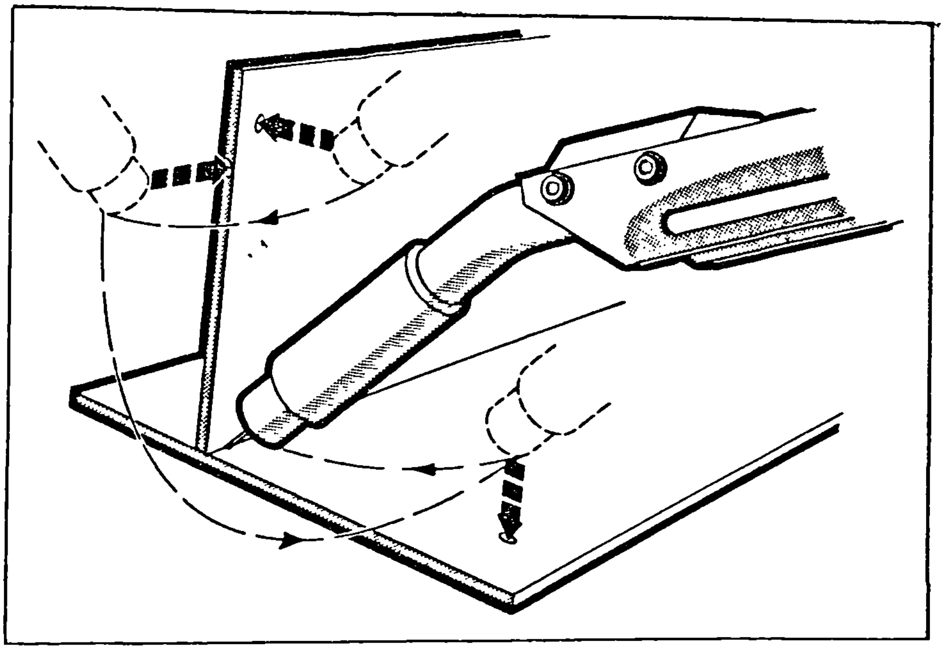
An adaptive control system for welding robots would be expected to compensate and make adjustments in real-time for:

- changes in fit up and assembly
- long term wear of jigs and fixtures
- possible misalignment of robot co-ordinates
- the unpredictable nature of spring-back which takes place in pressed components.
- distortion of parts during welding
- dislocation (due to various reasons) of the seam, relative to programmed robot paths.

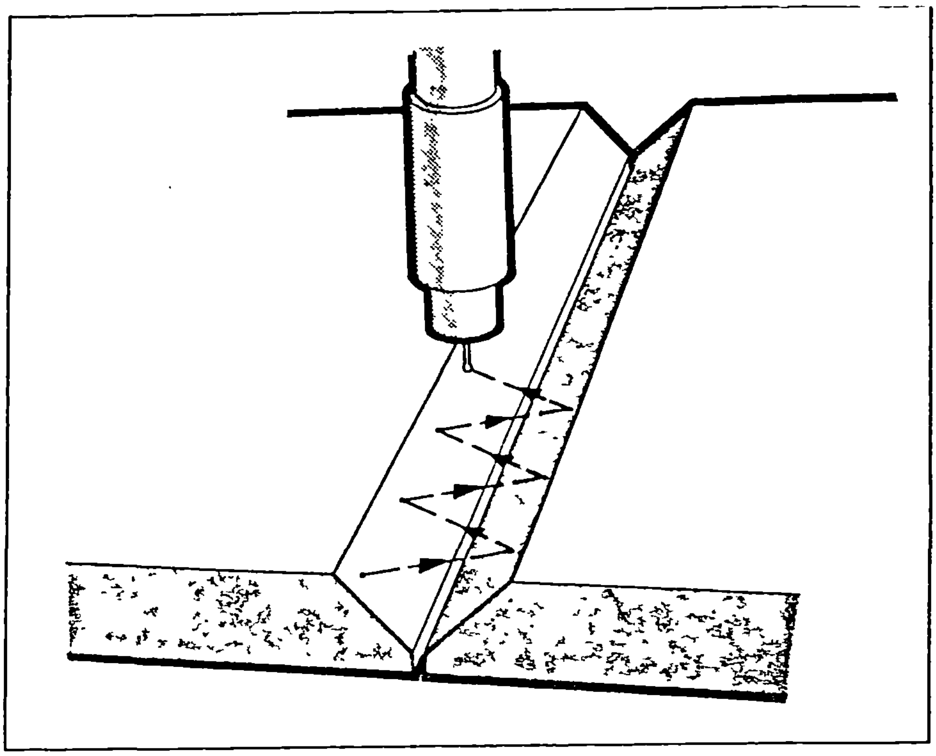
Currently, there is a variety of systems on the market which use tactile, visual, thru-the-arc, etc sensing and are either two pass systems (a scanning pass followed by a welding pass) or one pass system (a combined scanning and welding pass).

However, seam tracking systems can only (at present) correct for positional misalignment in the programmed path relative to the seam, not for varying gaps which are commonly found in the fit-up of shipbuilding components. It is therefore imperative that shipyards improve their joint repeatability and accuracy of processes as well as employing current seam tracking systems with welding robots, instead of waiting for further developments in adaptive control, that would allow for sensing gaps and take corrective actions accordingly.

Although a variety of seam tracking systems have been tested by the Author, for the experiments described in Tables 3,4, & 5, no such systems were used. As a result, in most cases robot production was not as effective as it could have been, with a seam tracking system. See figures 6a and 6b for seam tracking examples.



A. SEAM-START SEARCH AS USED BY ESAB WELDING ROBOTS (25)



B. THRU-THE-ARC SEAM TRACKING (25)

FIGURE 6 TYPICAL SEAM TRACKING AND START SENSING EXAMPLES

7.5 TOOL CHANGING AND MATERIAL HANDLING

Conventionally, there is one process performed per workstation and the usual practice is to transport materials between stations. If necessary, however, robots can become multi-functional with the incorporation of a tool-changing station within their working envelope. With tool changing stations, robots can use a variety of tools to perform a number of processes on the same or different workpiece, offering greater flexibility to the station or eliminating excessive materials handling that adds no value to the product. As most minor steelwork and outfit items require a number of different processes (see Table 2) it was realised early in the investigation that welding should not be the only process to be automated in such a workstation.

In the past we witnessed robot manufacturers offering tool changing stations for one process, eg grinding, with a variety of sizes and types of grind tools, while in the future greater flexibility in terms of processes should be offered. It is far better to have a tool lying idle than a complete workstation. An example of the concept of a tool changing station is shown in Figure 7.

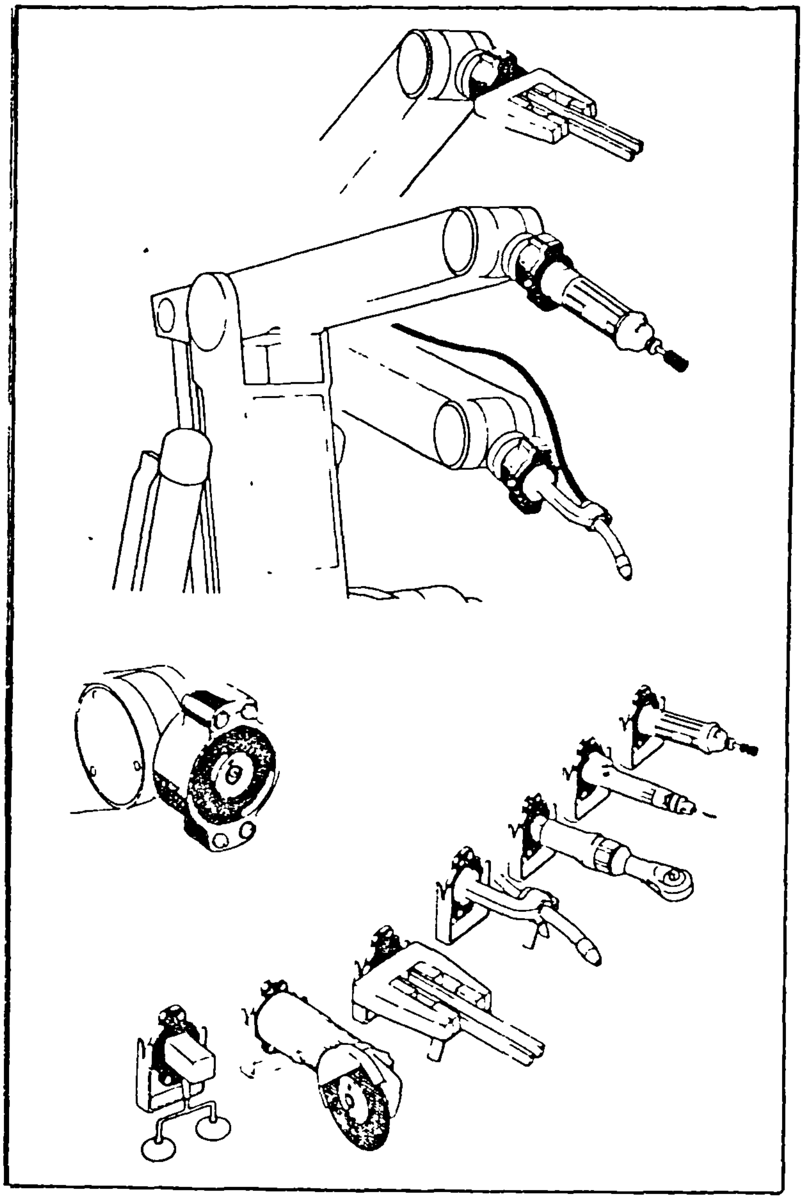


FIGURE 7 A TYPICAL EXAMPLE OF A TOOL CHANGING STATION FOR ROBOTS (26)

It was also thought possible that the CM-T3-566 robot could use a multi- purpose gripper to load all the components of a workpiece on the welding fixture, prior to picking up the welding torch and welding them. The concept was tried on the pallet application where it was desired that the robot loaded onto the pallet fixtures all the tubing associated with the pallet, the lifting lugs and the base plate. It was also thought possible to design the 'fingers' of the gripper so as to facilitate the handling of a variety of steel rods to be fed in a NC bending machine (incorporated into the robot's working envelope) for the production of pipe supports.

The building of the gripper was subcontracted to an outside agency and on trials it was proven that the gripper could successfully be fitted onto the robot and adequately lift and manipulate components. However, the gripper failed to manipulate certain components due to certain miscalculations on the agency's part, despite the fact that we had to redesign certain components to facilitate 'gripping'. The experiment indicated, however, that there is tremendous scope for further development in the area of multi-function robots and tool changing stations. (See Photographs 1 and 2). [27]

PHOTO 1 THE SHS ROBOT FITTED WITH THE SPECIALLY MADE GRIPPER, LOADING COMPONENTS IN A FIXTURE(27)

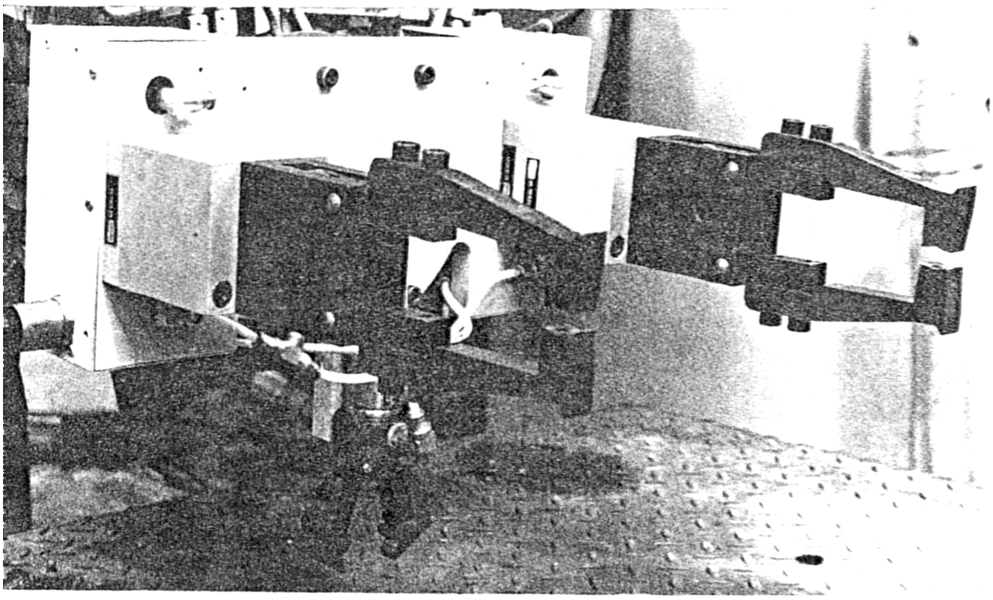


PHOTO 2 CLOSE UP OF THE (TRIPLE) GRIPPER(27)

7.6 OFF-LINE PROGRAMMING

Off-line programming can be defined as the task of programming robots through the use of remotely generated point co-ordinate data, function data and cycle logic. It eliminates the need for each point to be taught using standard 'lead-through' programming methods. With off-line programming the robot remains in operation while a new programme is being generated. This means more available productive time for both the robot and its associated equipment.

Such systems will allow robotic work cells to be developed, tested and programmed off-line without interrupting production work. This will eliminate the dangers of live tests on robotic prototypes, their associated equipment and on individuals, which are also very expensive and time consuming.

Fully evaluated robot programmes are generated according to the specified robot language and output directly to the robot. Such systems provide manufacturers with a wide range of features to maximise the use of robotics on the shopfloor.

The off-line programming capability eliminates the dependency on traditional 'teach' methods of robot programming and the system's graphic display allows robot programmers not only to create but also to visually verify programmes and to avoid collisions before the programmes are fed in.

The main obstacles in the industrial implementation of off-line programming are the need to adjust for inaccuracies associated with the real physical environment of the workcell when compared with the 'perfect model' in the computer, and the linkage of the robot controller with the off-line computer.

For the latter, special post processors are now available which make that link practical. Regarding the 'adjustment' to the real world, one solution adopted is for the robot to lift a probe from a tool changing station to sense a number of critical points on the workpiece prior to commencing operations and automatically adjust the programme to account for any inaccuracies of the loading, fixturing, etc. (Alternatively such probes can be incorporated on the end- effector design).

Through off-line programming the robot also becomes more integrated into the total manufacturing system. This is accomplished through the use of information from the main CAD/CAM data base that is also shared by other elements of the manufacturing system. This implies yet another step in the direction of the flexible automated shipyard in which productivity is maximised.

7.7 WORK CELL EVALUATION USING 3-D GRAPHICS

Computer graphics with solid modelling is a powerful tool for designing effectively and evaluating robotic work cells.

Programmers create a 3-D model of a robot and its working environment and then define the objects it is to manipulate. Details of each type of element of the robotic work cell can be maintained permanently on the system and thus enable their design geometry and parts specifications to be retrieved with ease. Such information will also define the limitations and capabilities of specific robots and other elements of the work cell which can be checked against the required functions and movement of the robot.

Different available and customised robots, robot end-effectors, work cells, workpieces, worktables, material handling equipment, jigs and fixtures, etc can be compared with respect to specific production line constraints and their inter-relationships evaluated.

Real time simulation will also allow the user to work effectively towards high utilisation of workstation. Production times can be noted. Exact arc cycle times, duty cycle times, complete batch production times, etc will help immensely the planners and schedulers in their functions. The lead time necessary to design, analyse, implement and modify work cells can thus be significantly reduced.

The designer can compare and evaluate the performances of several robots in the same work cell or the same robot in several work cells and find the most cost effective combination. The designer can also test and analyse many alternatives in a short time, producing better designs at a reduced cost, reducing the need to build prototypes.

Problems with the work cell can be identified and optimised prior to actually constructing the cell. The result is time and cost savings with efficient workstation layout. See also Figures 8, 9, 10, 11 and Photographs 3 and 4.

For this particular project, various off-line programming and workcell evaluation/simulation packages (GRASP, McAUTO, CATIA etc) were evaluated. Unfortunately none was capable of been interfaced with the real production situation. Contrary to their fancy brochures, all systems need a lot more development. However, in evaluating the systems, useful work was carried out which eased actual robot programming. See Figure 10.

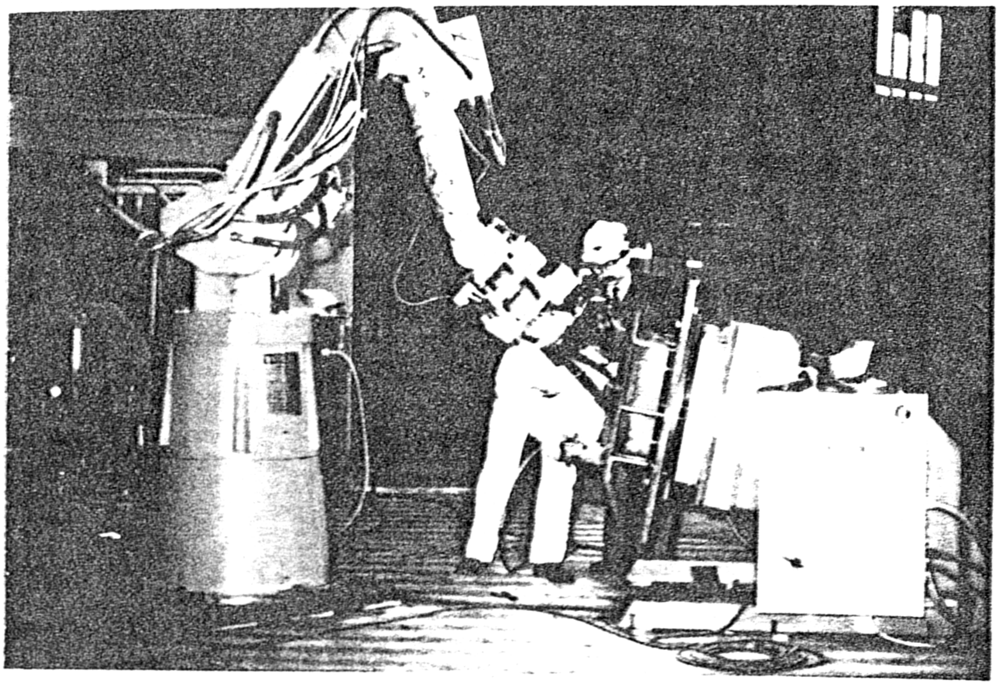


PHOTO 3 MANUAL ROBOT PROGRAMMING ON THE SHOP FLOOR, USING THE TEACH PENDANT

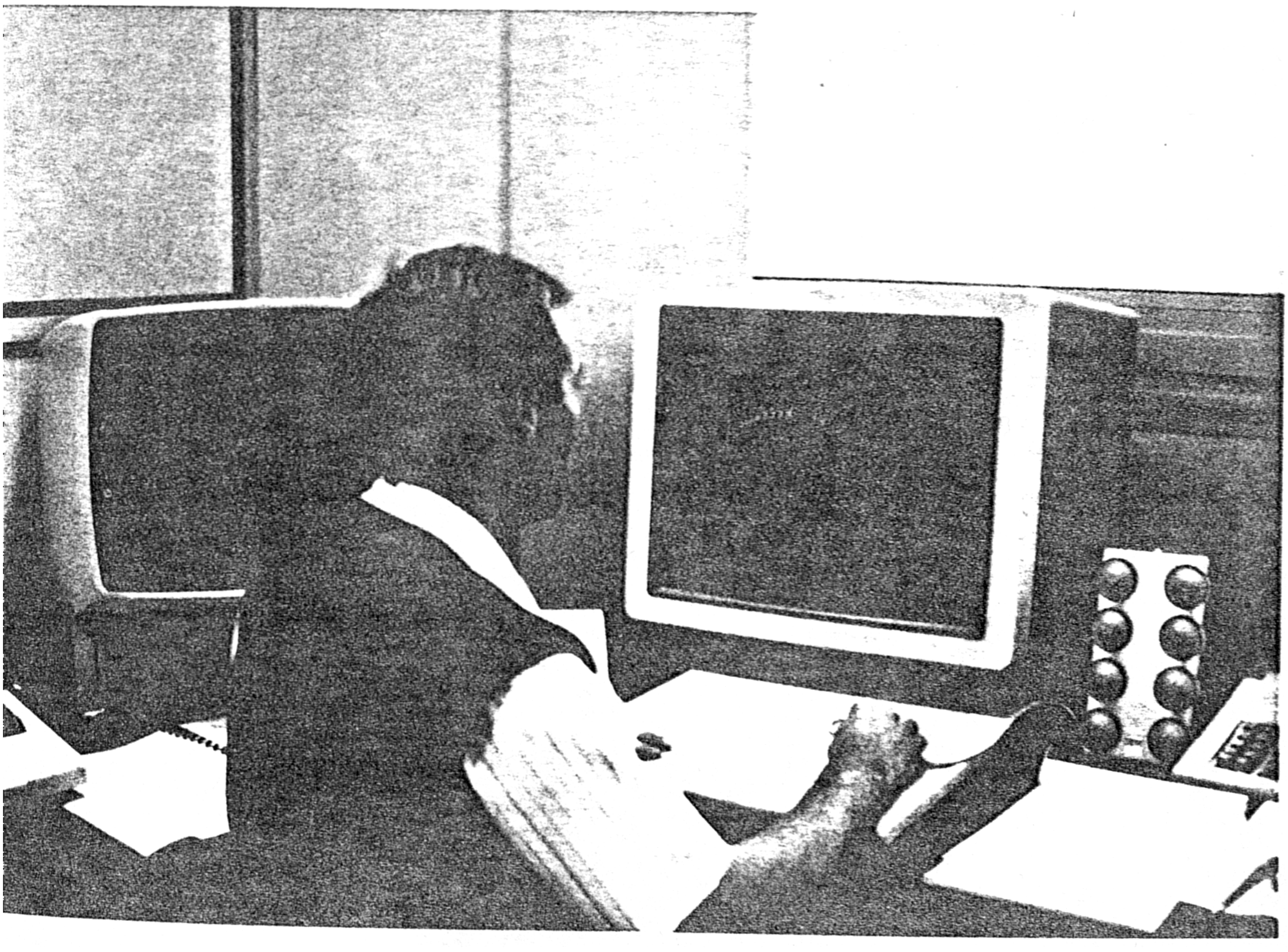


PHOTO 4 OFF-LINE ROBOT PROGRAMMING USING THE IBM 5080, WITH THE ROBOTICS MODULE OF CATIA

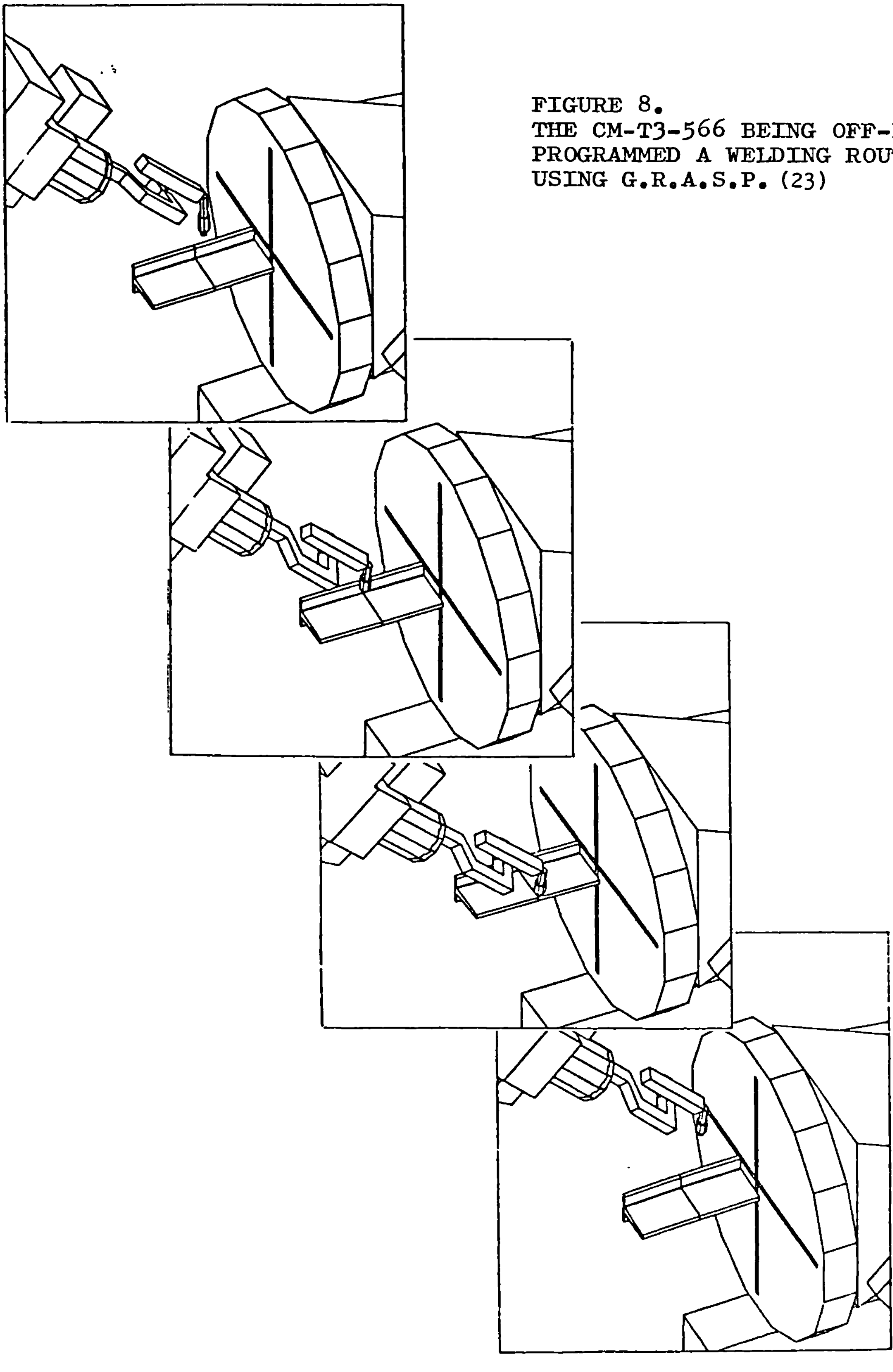


FIGURE 8.
THE CM-T3-566 BEING OFF-LINE PROGRAMMED A WELDING ROUTINE, USING G.R.A.S.P. (23)

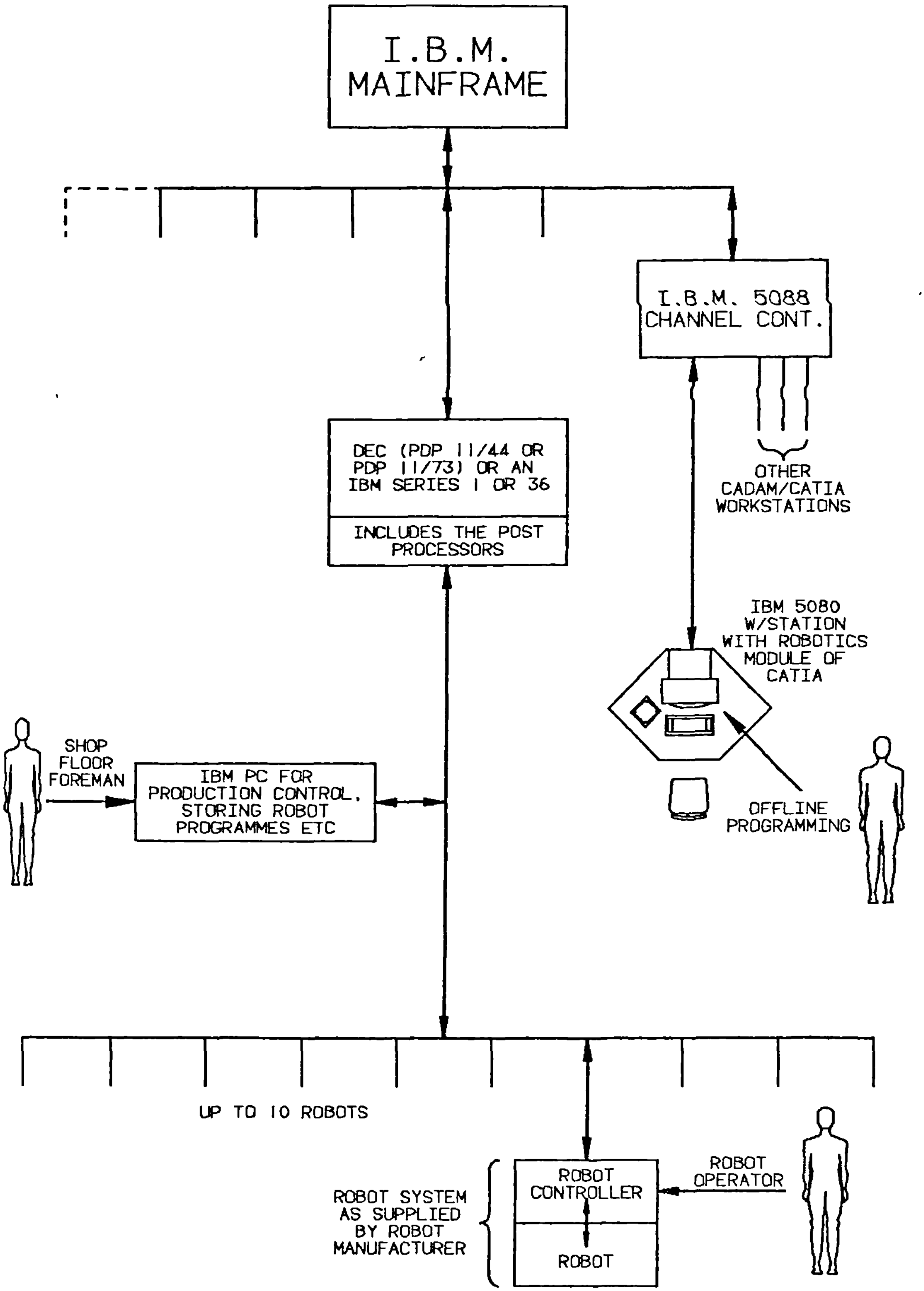
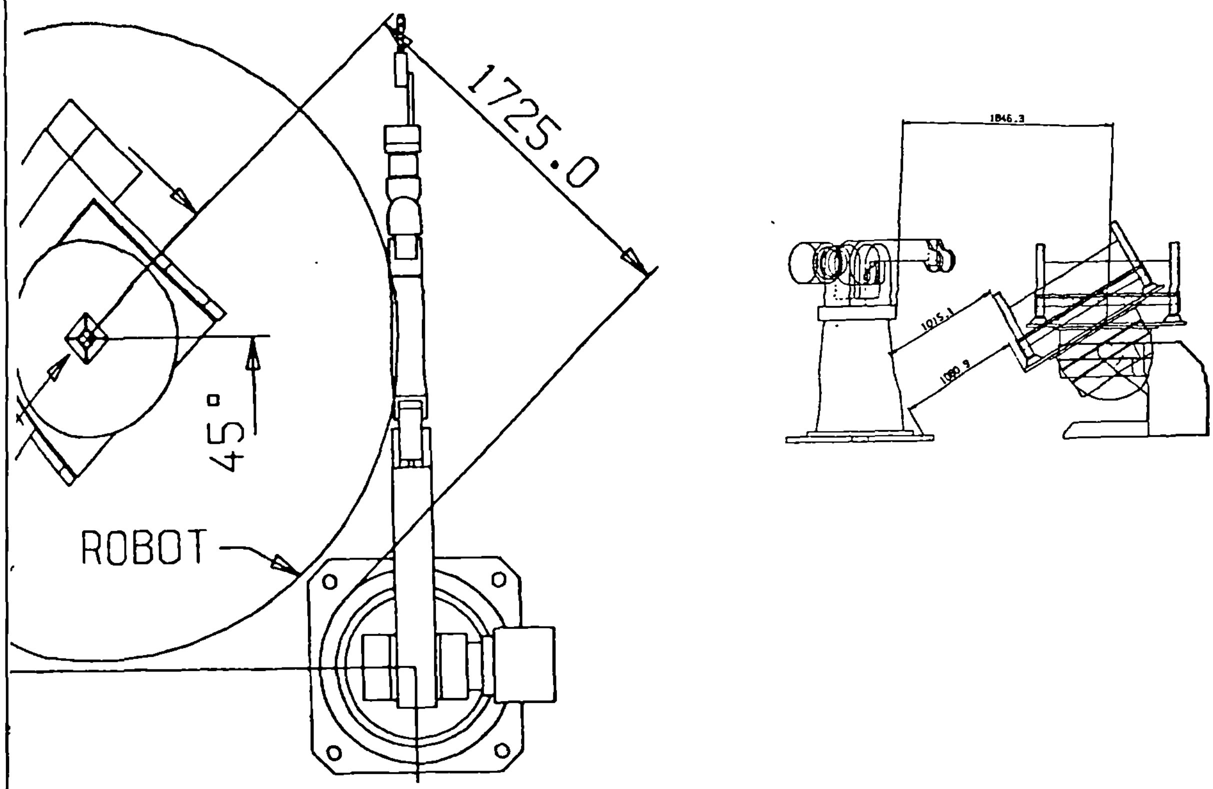
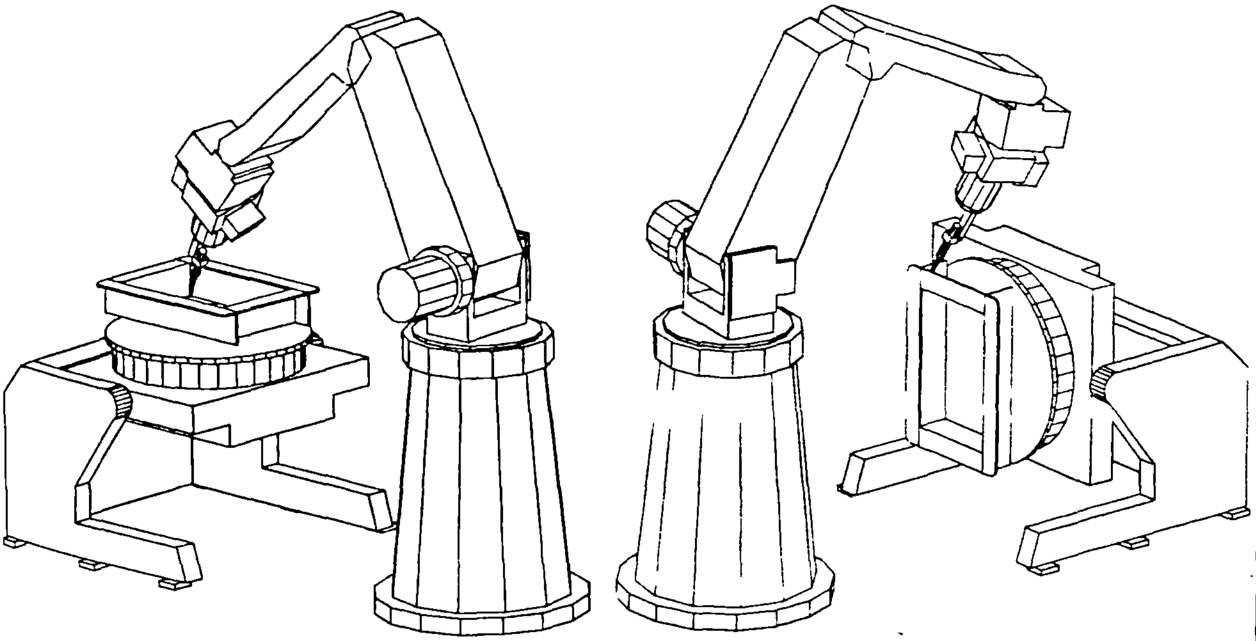


FIGURE 9 TYPICAL ROBOT O.L.P. INSTALLATION



a. Checking the clearances for welding the pallet.
(As simulated on the IBM CADAM system)



b. Welding a manhole coaming (As simulated on GRASP).

FIGURE 10. SIMULATION OF THE SHS ROBOT

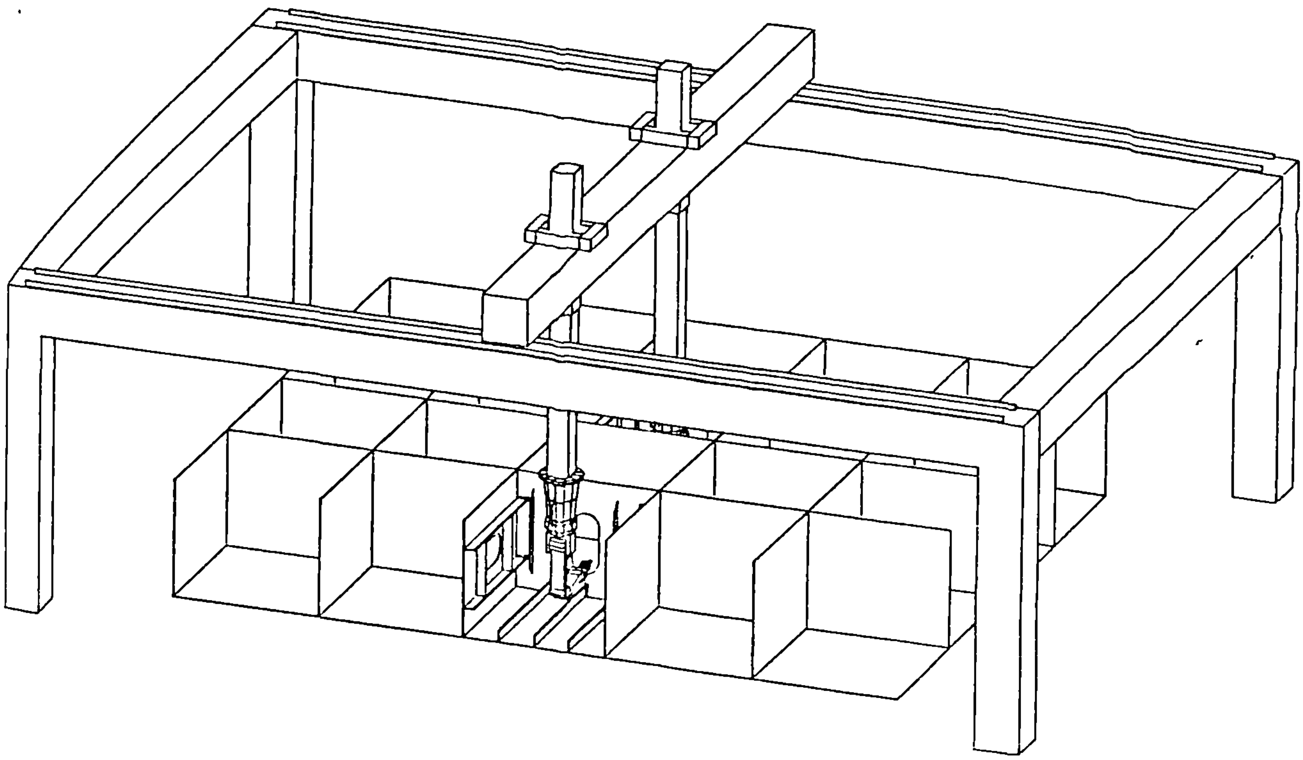


FIGURE 11 A HYPOTHETICAL ROBOT GANTRY STRUCTURE MODELLED IN THE G.R.A.S.P. SYSTEM (GRAPHICAL ROBOT APPLICATION SIMULATIONS PACKAGE) (16)

7.8 SKILL REQUIREMENTS

It was found during the course of the investigations, that certain robot teaching skills need to be developed, which are currently alien to traditional skills within the shipbuilding industry. Familiarity with computerised machinery is an important aspect of an operator's comfort in a robotic environment. The advent of the home computer has provided computer-literacy and familiarity across a significant proportion of the workforce which can be exploited as robotics are introduced. Workers have not found robot programming as difficult as they feared. It has been found that they climb very rapidly the learning curve associated with robot programming. A considerable amount of skill and knowledge is acquired by practice and experience in operating the robot.

Control functions and pendant design have been found simple and comprehensive and so has the interaction of the software. That does not mean however that there is not room for further improvements in the user friendliness of the system.

For welding applications it has been found that traditional welding skills are not necessary, while a technical understanding of the process is. The selection of a knowledgeable welder to train as robot programmer has been found necessary to preserve the integrity of the welding process while allowing the operator to concentrate on the programming functions. At a subsequent stage two more non-welders were trained on how to programme the robot and despite the extra training course on welding which they had subsequently undergone, in order to avoid trial and error welding programmes, they still require the assistance of a welding engineer.

In maintenance, the skills required to support robotic installations are beyond those normally required in a shipyard. Traditionally, even NC installations have been fairly robust and an acceptable operation was performed even if equipment was not in pristine condition. This situation is different for the generation of robots that we are currently experiencing and which require checking and correction to maintain uniform operating characteristics.

Preventive maintenance has also proved to be of paramount importance in any robotic installation.

Fixture design is another new skill function. Here again, skill is acquired by practice and experience. Numerous factors of traditional jig and fixture design, now jump up in level of importance. The designer is now faced with robot accessibility, 'jigging-out', welding distortion, etc. The use of 3-D computer graphics and animation techniques has also been found an indispensable tool for jig and fixture designers for robotic work.

7.9 INDUSTRIAL RELATIONS AND WORKFORCE ACCEPTANCE

Prior to the installation of the cell at SHS, representatives of all sections of the workforce were consulted. Far from being against investigatory work of the nature to be undertaken, representatives supported the initiative and were keen to learn. Throughout the development, representatives were kept informed and acceptance of the equipment for production work was reached without discontent. This process was assisted by an agreement reached in February 1984, to a far-reaching review of working practices which provided a mechanism for the introduction of new technology. Regular features appeared in the SHS newspaper informing the workforce about the progress.

It was found that taking the initiative to inform the work force and their representatives gave them an understanding of the reasons why we were looking at robotics. Generally the representatives of the workforce expressed their support for the introduction of new technology and were keen that their members should play a full and active part in its use at all levels.

However, the shipbuilding industry in general, must take a greater initiative in informing the workforce about robots, in order to gain a general understanding, acceptance and realistic enthusiasm. This will help avoid being put in a position of having to defend the use of industrial robots against attacks and criticism based on what might be sincere fears; fears of the unknown.

Until now, industrial robot informational activities have mainly been directed to specialist by specialists. Now, a totally new and different 'audience' must be approached and informed - the workforce. The success of industrial robots in any industry, and more so in shipbuilding, being a highly labour intensive one, depends on workforce support and acceptance.

The workforce should be assured that robot justification will come mainly from increased productivity and not from savings in labour costs by making workers redundant. They should also be made to understand that the development of this country's economy and competivity must pass through the use of advanced manufacturing techniques. Robotics will slowly necessitate a 'shift of skills' from manual to information technology ones. For this they must be prepared to be trained, retrained and in general be flexible and adaptive to the needs of the industry. As FAST should take years to be implemented, no sudden explosion in employment or skill levels is expected.

Involvement with robotics is currently seen as an opportunity for advancement and a significant enrichment to the normal job of the shipyard worker, rather than a threat for a job loss.

However, to achieve and maintain good industrial relations, a partnership must be formed with all those involved to encourage their ideas and suggestions. Such involvement must start from the very early project stages and be continuous. No development plans should be kept secret.

7.10 HEALTH AND SAFETY

Safety was considered a few years ago as the main reason for exploring robots for shipyard use. Although nowadays and in the future, increased productivity, reduced manufacturing costs and CIM play the prime role, safety will always be an important consideration.

By introducing robots on the shop floor, a safer environment can be created for the workers. For example, the welding robot now releases the worker from the vicinity of the dangerous welding arc. On the other hand, if safety regulations are not observed, workers may damage equipment and themselves. However, the same argument holds for any piece of machinery, not just robots.

Today there are more than 100,000 industrial robots used in manufacturing industries around the world and still the percentage of accidents is very low. This is due to the responsible attitude of the workers, proper training and an awareness that people are working with 'robots'. There are now safety regulations set up in the USA, the UK, Japan, etc that dictate certain procedures for safe robot operation.

However, it has been found that 'too many' safety precautions can interfere with the efficient use of the robotic workcell. A happy medium cannot be reached easily and safety precautions must be implemented, sometimes at the expense of efficient production work, due to the legislation involved.

Since the commissioning of the SHS robotic installation, there have been no accidents. Safety requirements, guidance and legislation were considered from the conceptual development of the installation. A number of 'emergency stop' buttons have been installed, and all access gates into the robot enclosure have been wired to an 'interrupt button' that freeze the robot, should a gate be opened. (See Figure 2).

7.11 PRODUCT REDESIGN FOR ROBOTIC PRODUCTION

It was recognised at an early date that product redesign was an important element in maximising robot application potential. The reasons for this are as follows:

- robot cycles can be greatly simplified and teach difficulties overcome by simple product redesign.

- the fixturing of products is linked intrinsically to the design of the product.

- the operational tolerances of component manufacturing processes must be considered if repeatability of weld seam positions and adequacy of fixtures is to be guaranteed.

- product redesign also contributes significantly to the development of larger batch sizes and creates potential for flexible jigging which enables more than one product to be produced by re-setting a fixture rather than replacing it.

- robot friendly processors can be introduced.

However, it is anticipated that with the advent of sensors and their incorporation on the robot end effector, the requirements for product redesign will reduce.

7.12 TURNTABLES

In robotic welding (or turntables) positioner tables carry the necessary fixtures which locate the different workpieces and present them for robot welding with the best possible orientation. 'Best' implies avoiding awkward welding positions, maximising duty cycle, allowing for robot access, optimising robot path, etc.

Double turntables can be fixed in such a position that when one end is inside the working envelope (for robot welding) the other end is outside the working envelope (for loading-unloading the workpieces). After welding and loading is complete the whole configuration is rotated and the end which was inside the working envelope carrying the finished part, is outside and ready to be safely unloaded, while the newly loaded workpiece is now inside the working envelope ready for welding.

In selecting turntables, the following factors are of prime importance:

a) VOLUME, SIZE AND WEIGHT OF WORKPIECES

- number of batches
- numbers within a batch
- maximum size and weight of workpiece

b) HIGH ROBOT UTILISATION WITH MINIMUM FLOOR-TO-FLOOR TIME FOR EACH COMPONENT AND MINIMUM BATCH PRODUCTION TIME

- workpiece loading/unloading time
- fixture loading/unloading time
- robot arc and cycle time
- component floor-to-floor time
- batch production time

c) ABILITY OF ROBOT CONTROLLER TURNTABLES

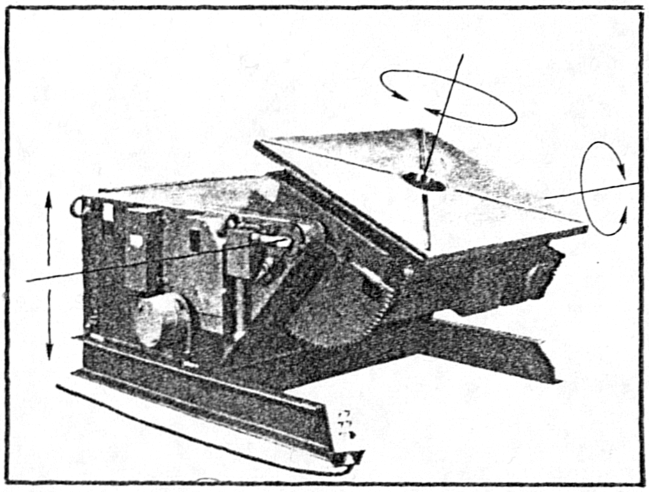
The Cincinnati Milacron Acramatic Robot Controller can control up to 12 axes or up to four positioner tables with a maximum of three axe's each.

d) SAFETY

- the operator must be kept out of the working envelope during the automatic mode of operation.

- adequate means of stopping the robot at any time must be provided.

Illustrations of double and single turntables are shown in Figure 11a and an illustration of time saved as a result of certain combinations of turntables is shown in Figure 12.



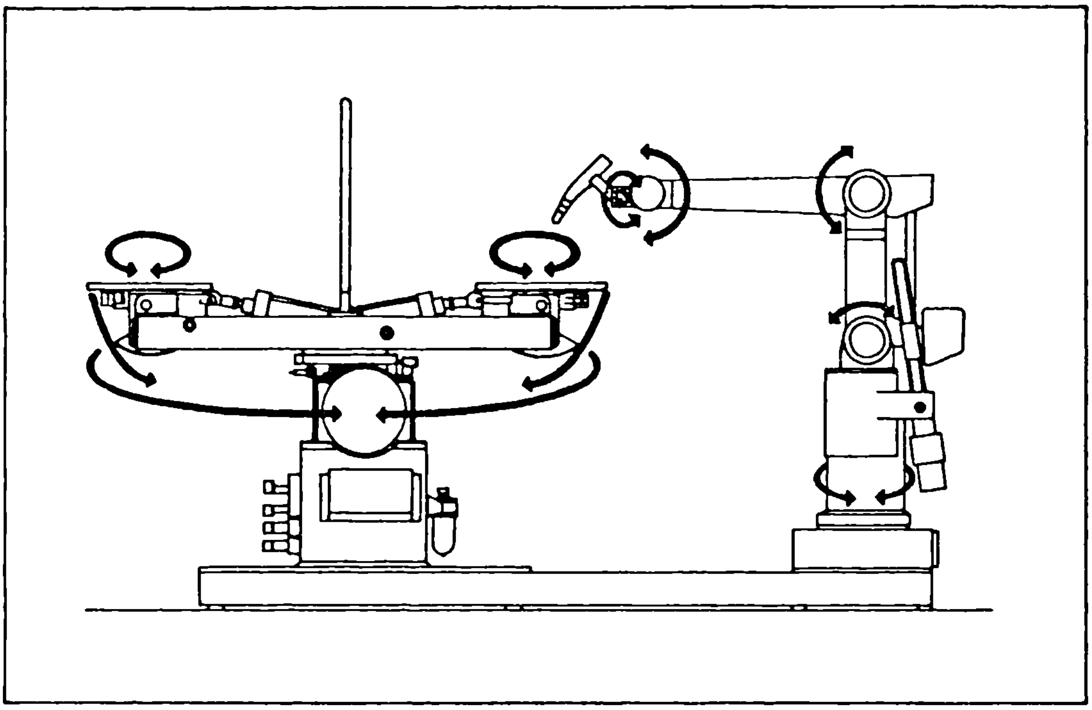
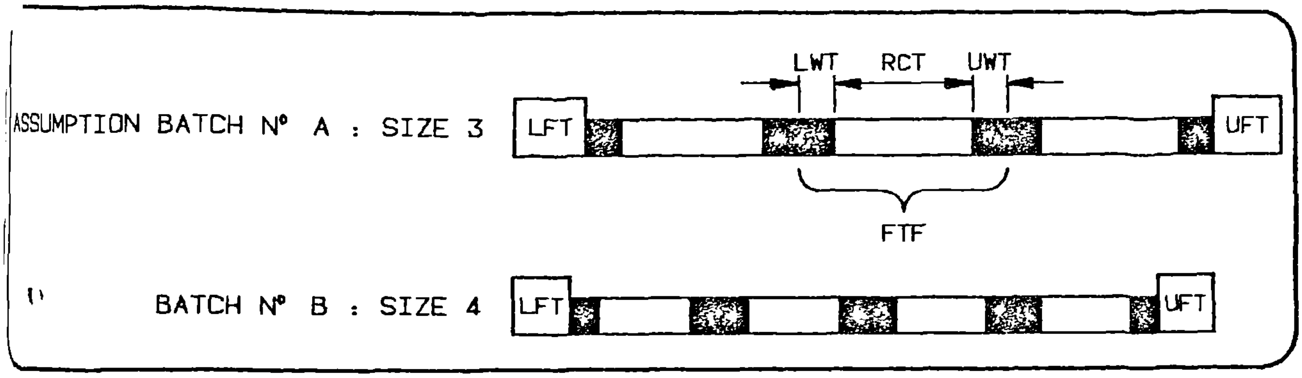


FIGURE 11a SINGLE AND DOUBLE TURNTABLES



For an explanation of symbols, see FIG 3

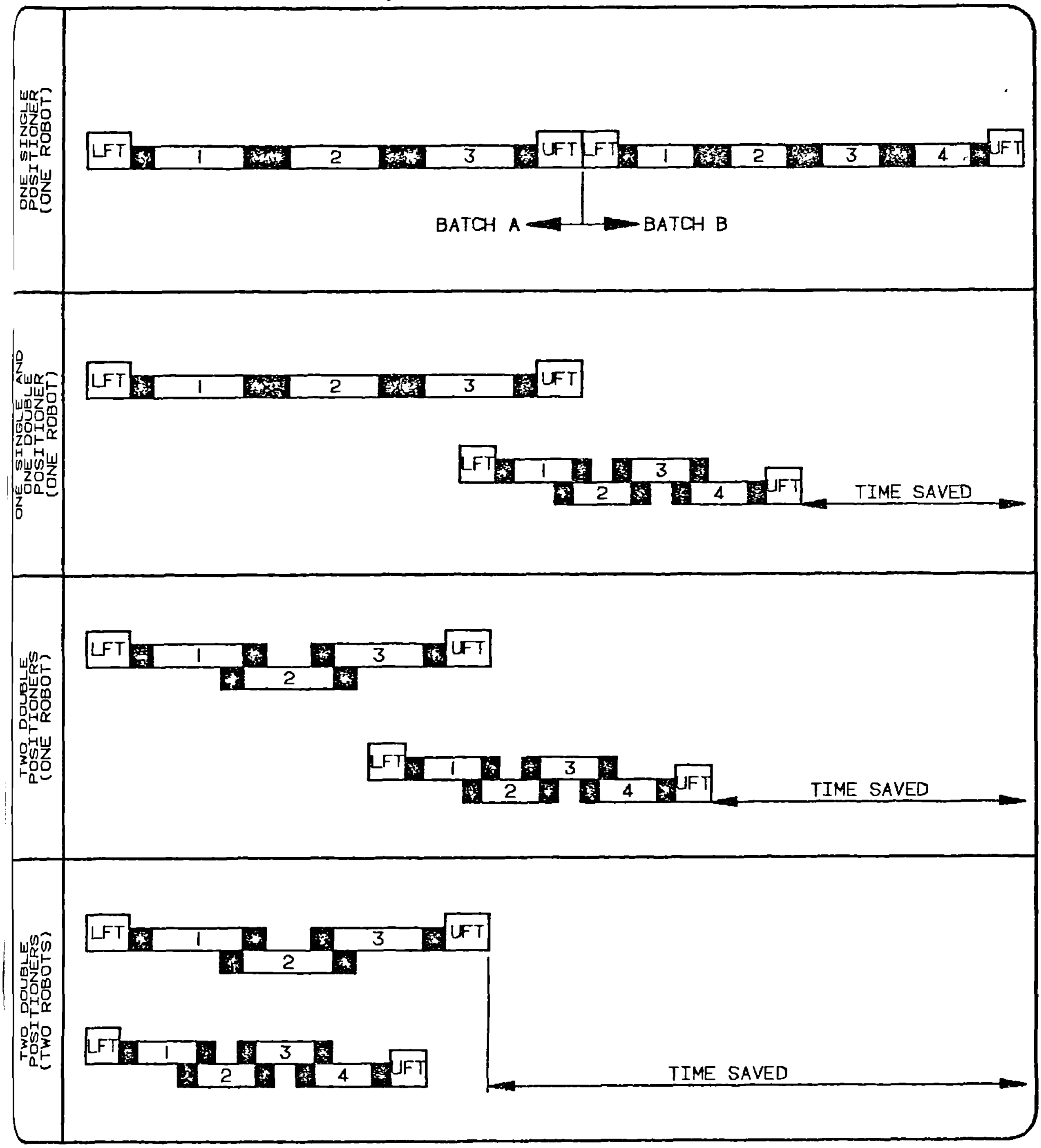


FIG 12 EXAMPLE ON USE OF TURNTABLES

8. ECONOMIC CONSIDERATIONS

Robots have been actively proving their worth since the first ever robot was installed in the manufacturing industry, to unload a die casting machine in 1961 (19). At that time, the main justification for robots was the performance of very dangerous and hazardous tasks. The immense economic benefit obtained due to increased productivity was a spin-off.

However, times have changed. Labour costs have risen dramatically without a corresponding increase in productivity. Today industry needs to plan ahead, set high goals and have such tools to achieve these goals. Recognising that robotics is a well proven tool, the battle is on to find a financial justification method that would take into account all facts and justify new technology with its long term benefits.

8.1 TANGIBLE AND INTANGIBLE BENEFITS

The use of robots on the shop floor offers numerous benefits some of which could be easily quantified (tangible) such as:

- direct labour savings
- reduced manufacturing times
- increased productivity (higher production rates, etc)

However, benefits can be very difficult to quantify (intangible) or include in an economic justification such as:

- quality improvement
- increased safety of employees and quality of working life
- better consistency of finished parts
- increased flexibility when compared to conventional machines

- reduced inventory requirements
- increased ability to face the future skilled labour shortage
- increased material savings with reduced scrap and rework
- increased technological development of employees
- enhanced company image
- increased ability to plan and schedule work with the provision of accurate manufacturing times
- ability to communicate with other manufacturing machines for the provision of computer based integrated systems, etc.

All such benefits ultimately increase the company's viability. However, the inability to include them (together with all hidden costs both quantifiable and unquantifiable) in a financial justification method, forces the use of traditional methods that have been proved inadequate for new technology as they are geared for the 'quick return' on money solution. Companies must stop looking for the 'quick' return on their investments, neglecting that their competitors are planning for long term viability.

8.2 REASONS FOR FAILING TO JUSTIFY ROBOTS

On the other hand, however, during the last few years a number of failures have been reported of companies investing 'blindly' in advanced manufacturing technology, without being adequately prepared first. Ironically, such case studies have served significantly in the wider understanding of the difficulties present when companies reach the stage of financial evaluation. The main difficulties are:

1) The lack of an overall corporate strategy in advanced manufacturing technology.

2) The lack of adequate information to make sound estimates of future net returns.

3) The inability to quantify the numerous intangible benefits flowing from flexibility and other spin offs of advanced manufacturing technologies.

4) The absence of satisfactory accounting procedures capable of tackling new technology assessments.

Certain local, national and international authoritative bodies have realised the difficulties associated with justifying new technology with traditional methods and also the need to increase the commercial viability of their area of concern. As a result they offer numerous grants (in the form of Regional Development Grants, Department of Trade and Industry grants, EEC grants with programmes like ESPRIT, EUREKA, BRITE, RACE etc). Such grants certainly help the financial justification, but do not necessarily give solutions to the problem.

8.3 CAPITAL APPRAISAL METHODS

There are many methods of evaluating expenditure. (See Table 8). However, all capital appraisal techniques in existence are subject to a company screening process to see if the proposals are financially acceptable or not by that particular company. There are tremendous variations in how vigorous these screening processes may be. It is also important to realise that management's choice of what it considers to be the most appropriate approach can restrict or even distort expenditure programmes.

8.4 THE JUSTIFICATION OF ROBOTIC WELDING FOR S.B.M. AT S.H.S. LTD.

Although no method is particularly suited to evaluating advanced manufacturing technologies such as robotics, CIM, etc, an attempt was made to evaluate with available data the use of a welding robot for (S.B.M.) small batch manufacturing of minor steelwork and outfit items in a shipyard, using the payback and RoI methods. Based on the welding requirements of the minor steelwork and outfit items of the last four ships built at SHS Ltd, two welding robots with one double and one single turntable each, will yield a return on investment of 47% and a pay back period of 1.81 years. For the detailed calculations of the economic justification, see Appendix 8 & Ref 10. (Ref. 10 is an economic justification project which utilised data offered by the author and was performed under his close supervision).

The above justification was based on the following ten assumptions:

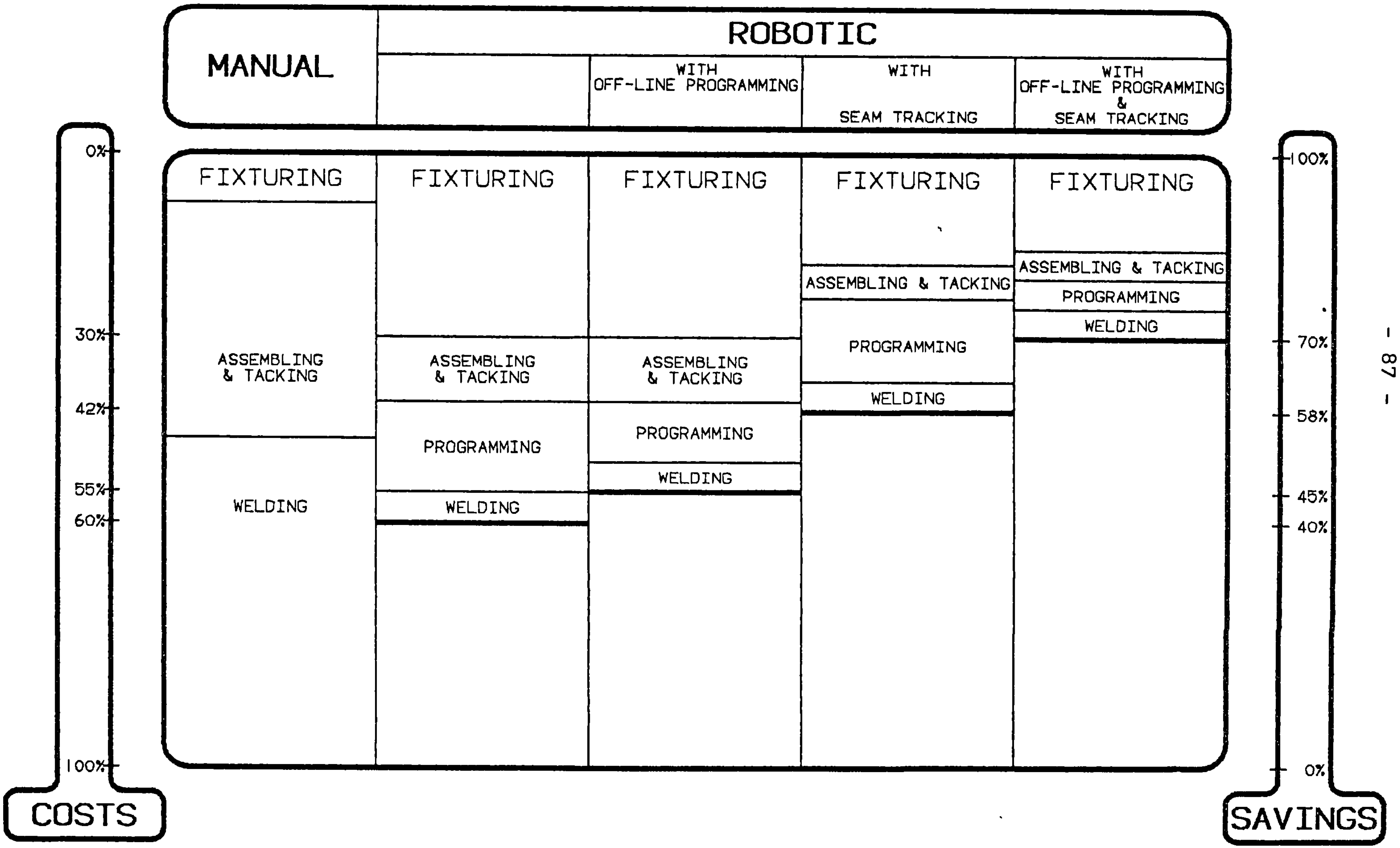
- Manual arc welding efficiency: 30%
- Robotic arc welding efficiency: 80%
- Fixturing costs: 30% of the robot cost
- Manual weld material (excess, consumables etc.) 20% more than the robotic cost
- Company profit tax: 40% for the first year & 35% for subsequent years
- Increased speed of operation (welding speed, manual endurance limits etc.) 30% due to robot
- Labour rate of skilled manual welder equal to the robot operator
- For the N.P.V. calculation, a 14% discount value was used
- No robot salvage value

Also, as technology develops further, the efficiency of the equipment increases and as such the labour cost can decrease. Table 9 illustrates the reduction in labour costs by simply adding certain technological innovations into the robot system. The cost of the hardware used was not taken into account for producing that particular table too.

TABLE 8 **BRIEF COMPARISON OF FOUR CAPITAL APPRAISAL METHODS**

	The Method		Advantages	Disadvantages
1	PAY-BACK METHOD	This method involves demonstrating the time taken to recover initial capital outlay, and is normally expressed in years, i.e. the pay-back period. Such assessements normally examine the robot as a non-integrated stand-alone investment capable of offering short pay-back periods	* Simple (most commonly used) * Demonstrates clearly short-term benefits	* It Ignores income after pay-back point * It cannot indicate the relative profitability of projects * It tends to concentrate on limited variables (e.g. labour savings) and can ignore significant less tangible benefits. * It is biased against investments which do not yield their highest returns in their early years.
2	ROI OR ACCOUNTING RATE OF RETURN	It uses the ratio of profit/capital employed. Profit is normally averaged out over the anticipated life of the installation	* Relatively simple method * Useful as a selling tool * It can provide a useful analysis to judge past performance	* No account is taken of the time value of money * It tends to discriminate against projects of less than 10 years * Unsuitable for the task of optimising investment decisions
3	DISCOUNTED CASH-FLOW TECHNIQUES (IRR, NPV)	<u>I.R.R.</u> is closely related to ROI, but is an attempt to determine a "real" discounted rate of return (taking into account the time value of money) and this rate can be assessed to see if it is acceptable within corporate objectives. <u>N.P.V.</u> is more realistic. The calculations are used to assess whether a project will provide a negative or positive return (in £). The flows of money are discounted during the period, using a rate specified by the Company. (Such rate normally equates to the Company's cost of capital.)	* They take into account the time value of money	* Data indicated is limited to certain aspects of capital projects
4	LIFE CYCLE COST ANALYSIS (L.C.C.A.)	This method takes into account <u>all</u> cost factors from the date of the decision to acquire the asset fight through to its disposal	* Full life cycle cost investigations are more capable of revealing the the financial advantages offered by the Advanced Manufacturing Technologies * Much more thorough approach to project appraisal * Presents management with a greater comparative understanding of the economics of alternative proposals	* Makes great demands upon the resources of a Company * Costly system to set up

TABLE 9 COMPARATIVE LABOUR COSTS



9. THE FUTURE USE OF ROBOTS IN SHIPBUILDING

9.1 SHIPYARD AREAS AND PROCESSES FOR ROBOTISATION

The robotics industry currently offers a large variety of industrial robots with different configurations and specifications from large gantry mounted to small portable. However, most of these models were designed with a particular industry and/or application in mind. Standard off-the-shelf industrial robots designed for shipyard use have only recently started to appear on the market, mainly from Japan, the USA, Finland and France. The situation still remains, however, that shipbuilding robots will need to be specially designed, or standard robots will need to be modified to suit the particular shipyard area they are being applied for. Nevertheless, a number of standard industrial robots will also find their way in shipyards for the more 'conventional' applications.

Shipbuilding robots in general could be of fixed base, sliding base, gantry mounted, small portable and autonomously travelling/climbing. All types of robots could be split into material handling robots, tool handling robots and hybrid robots (that is material and tool handling combined). Most, if not all shipyard areas and processes should be catered for by these categories.

Tool handling robots could perform processes such as flame or plasma cutting, grinding, welding, drilling, painting, blasting, NDT testing/inspection, heat line bending or even manipulate a laser beam for a multitude of processes (eg welding, cutting, machining, drilling, heat treating, etc).

Shipyard processes for robotisation were examined by the author in his MSc thesis (1) with an update on his paper to ROBOTS 9 Conference (5) and BRA 10 reference (20). Material handling robots could be used in a variety of ways such as: transport material, load and unload material onto and from, NC machines, jigs and fixtures, conveyors, pallets, AGV's (Automated Guided Vehicles) or even act as 'flexible fixtures' themselves by assembling and locating material, or even manipulate material against fixed tools such as a grinding wheel, etc.

A third category includes the hybrid robots, where they could perform both tool and material handling either with a multiple arm construction or with a single arm and a tool changing station containing different tools such as grippers, drills, torches, spraying guns, etc. (See Figure 7).

Table 10 summarises the above mentioned categories of shipbuilding robots. There is virtually no limit to the processes that robots can carry out ranging from waterjet cutting of woodwork in the joinery shops to the NDT testing and inspection at berth or even underwater! (5)(6)

There are many areas in a shipyard where existing robotics technology could be applied today and in the near future. Judging by the current interest and rate of applications by shipbuilders worldwide, it is expected that by the end of this decade, most shipyard areas and processes will have seen the introduction of robotics technology to different extents. The creation of 'islands of flexible automation' should also have occurred in some of these areas.

The following shipyard areas are given as an example of the use of robots:

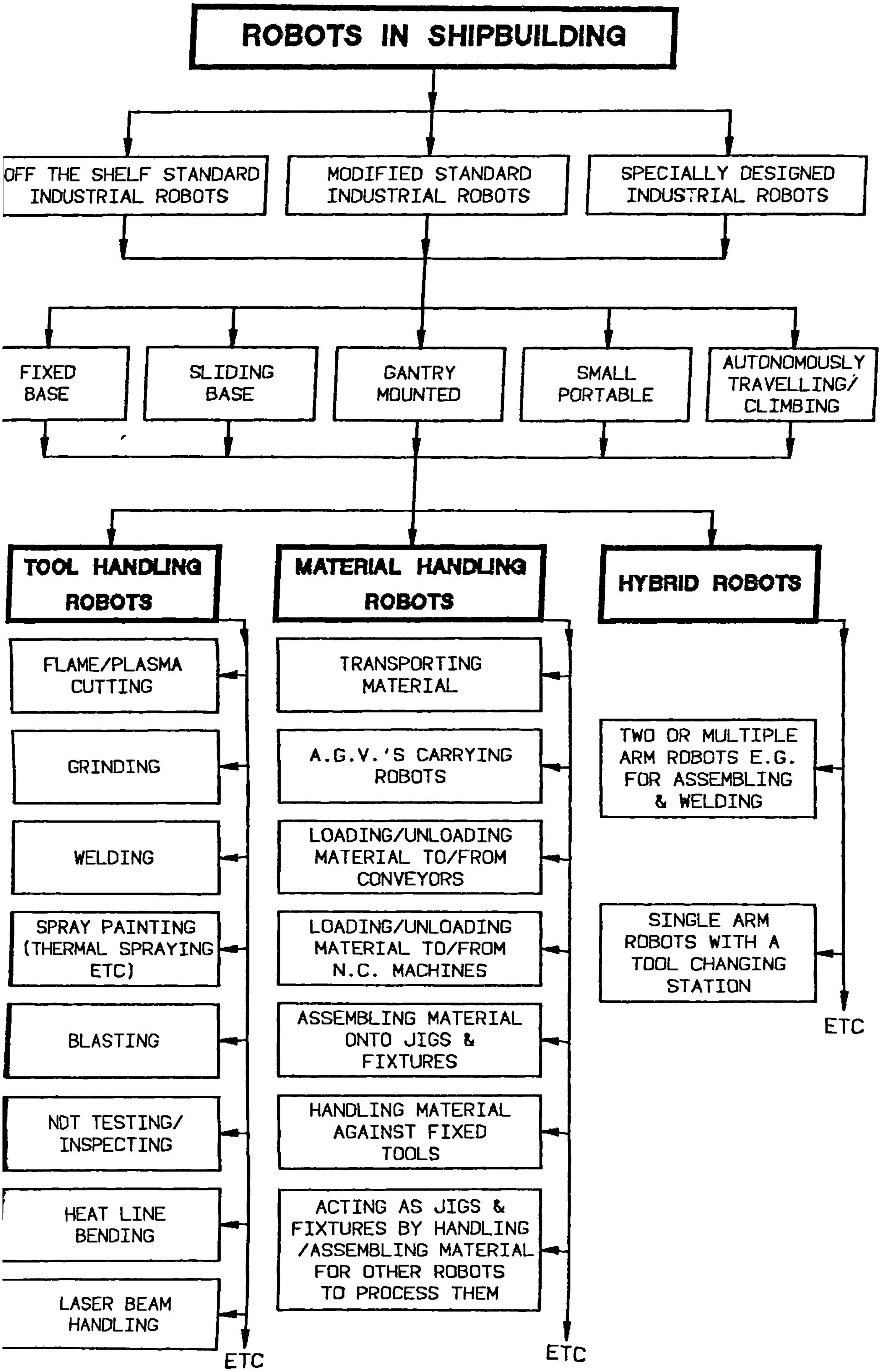

ROBOTS IN SHIPBUILDING
OFF THE SHELF STANDARD INDUSTRIAL ROBOTS
MODIFIED STANDARD INDUSTRIAL ROBOTS
SPECIALLY DESIGNED INDUSTRIAL ROBOTS
FIXED BASE
SLIDING BASE
GANTRY MOUNTED
SMALL PORTABLE
AUTONOMOUSLY TRAVELLING/ CLIMBING
TOOL HANDLING ROBOTS
MATERIAL HANDLING ROBOTS
HYBRID ROBOTS
FLAME/PLASMA CUTTING
GRINDING
WELDING
SPRAY PAINTING (THERMAL SPRAYING ETC)
BLASTING
NDT TESTING/ INSPECTING
HEAT LINE BENDING
LASER BEAM HANDLING
ETC
TRANSPORTING MATERIAL
A.G.V.'S CARRYING ROBOTS
LOADING/UNLOADING MATERIAL TO/FROM CONVEYORS
LOADING/UNLOADING MATERIAL TO/FROM N.C. MACHINES
ASSEMBLING MATERIAL ONTO JIGS & FIXTURES
HANDLING MATERIAL AGAINST FIXED TOOLS
ACTING AS JIGS & FIXTURES BY HANDLING /ASSEMBLING MATERIAL FOR OTHER ROBOTS TO PROCESS THEM
ETC
TWO OR MULTIPLE ARM ROBOTS E.G. FOR ASSEMBLING & WELDING
SINGLE ARM ROBOTS WITH A TOOL CHANGING STATION
ETC

TABLE 10

a) Steel Plate and Section Stockyards

Gantry type robots could be used here to unload incoming loads of plates and sections and store them to pre-defined areas in the stockyard ground. Similarly, the same robots will be used to load plates and sections onto conveyors, AGV's etc for transportation to the surface treatment and preparation lines which should be 'hard-automated' lines.

b) Cutting of Steel Plates

As 'hard-automation' will again be used here ie NC flame/plasma cutting machines to cut the plates to required shapes, the robots will be used only for unloading the plates from the steel treatment lines and storing them or loading them to the flame/plasma cutting NC machines. They will again be used for unloading the cut pieces for transportation to the sub-assembly bays, panel lines, etc.

c) Cutting and Preparation of Steel Sections

Here, both material and tool handling robots could be used. The material handling ones will be transporting material to and from the tool handling robotic workstations where cutting will be performed on the 3-dimensional sections. Such robotised workcells have now started appearing on the market for shipyard use. (15)

d) Fabrication of Minor Steel and Outfit Items

A number of material, tool handling and hybrid robots could be used in a variety of configurations. Although work in this area is complex, most of the workpieces produced are of relatively small size and can be handled by current available off-the-shelf industrial robots. An example of a robot working in this area is given in Section 6 of this thesis.

Many shipyards have now started looking in this area for gaining first hand experience of robots.

e) Sub-assembly and Panel Line Areas

Large gantry type, material and tool handling, portable and hybrid robots could be used here. Some of the most remarkable advances on robots in shipbuilding have been made in these areas by the Japanese, Finns and French. Robotic systems in these areas are now well underway.

f) Assembly and Main Block Fabrication Areas

Here, only the Japanese have made some progress by using large robots on sliding bases. Large gantry type portable and self travelling robots could also be used in conjunction with large material handling ones.

g) Pre-outfitting and Module Shops

Again, large gantry types, of the hybrid type, are expected to dominate these areas.

h) Main Berth Erection Areas

Although these are the most labour intensive areas in shipbuilding it will be one of the last areas to be robotised as more advanced robotics technology is required and this will first be proved in the shops before the birth is attempted. However, it is expected that in the not too distant future a number of portable tool handling robots should be working alongside with men performing a variety of tasks. After that stage, very large gantry types of robots could be lowering smaller portable robots and then self-travelling/ climbing robots should appear. Work is already underway in these areas by the Japanese and Americans. [5],[9],[22]

i) Pipe Shops

Tool and material handling of robots of a variety of types in conjunction with NC machines are expected to bring nearer the realisation of the flexible and automatic pipe shop. Pipe shops should be excellent examples of islands of flexible automation in shipyards.

j) Machine Shops

Machine shops are further examples of islands of flexible automation in shipyards, utilising a number of NC machines served by material handling robots. The technology for such an 'island' has already been proven in a number of other industries, where they have been termed FMS (Flexible Manufacturing Systems). In a typical FMS robots unload and store incoming material for subsequent loading as required, to automatic conveyors and AGV's. Robots are again used to pick material from conveyors or AGV's and place it on a variety of NC lathes etc where specific programmes are executed, that have been written off-line at the design and planning stage.

k) Sheetmetal Shops

Again, here the solution is similar to the Machine Shops and is leading to an 'island'. Material handling robots should load and unload the plates to numerous NC machines. Tool handling robots (eg performing welding) should also form numerous other supporting workcells.

l) Paint Shops

A variety of types and sizes of robots should also be used in the paint shops. They could range from large gantry ones to small portable and autonomously travelling/ climbing. Painting in shipbuilding was one of the first areas to be addressed by the Japanese, the British, etc and ongoing work should reveal certain robot applications in the near future. [5],[19],[22]

m) Joinery Shops

As with pre-outfitting, joinery work will be addressed on a longer term. However, a variety of types of robots is again expected to form here too another island of flexible automation. A lot of the work should be produced in modular form and transported to the outfitting areas.

n) Blacksmiths

It is highly unlikely that the future shipyard will utilise blacksmith operations, but for the medium term a number of fires and presses could be arranged inside the working area of a material handling fixed base robot for the production of odd items. Such arrangements could be part of the island that will eventually be formed in the fabrication of minor steel and outfit items area.

Table 11 summarises the possible shipyard use of different categories of robots.

9.2 THE FAST CONCEPT

The FAST concept (Flexible Automation in Shipbuilding Technology) is a concept devised by the author in order to basically establish the way in which the shipbuilding industry must move in order to achieve CIM. Three discrete and critical phases are identified in increasing order in terms of integration and technological growth (see Figure 12a).

Phase 1 The 'stand alone' phase
Phase 2 The 'island' phase
Phase 3 The 'total system integration' phase

Any new technology entering the shipbuilding environment must pass through these three phases. These are explained below.

Although the FAST concept applies equally to all areas in shipbuilding, in this thesis, its relation to manufacturing automation is given as an example.

Phase 1

When a shipbuilder is making the decision to invest in robotics it is the stand alone applications that are considered first. (Although stand alone applications are now termed as 'systems' by various robot suppliers). It is considered too risky to invest in large systems before the small ones 'prove' themselves. This is not unwise as there are certain advantages when the robotics plunge is taken with stand alone applications such as: the lower investment and operational costs, the relatively small downtime input on other operations, etc.

Some shipyard areas \ Categories of robots & applications	Off the shelf	Specially designed	Fixed base	Sliding base	Gantry mounted	Small portable	Autonomously travelling climbing	Materials handling	Tool handling	Hybrid	Application for the: Short term	Medium term	Long term
a) Steel plate & section stockyard	Possibly	Possibly	Unlikely	Unlikely	Most likely	Unlikely	Unlikely	Most likely	Unlikely	Unlikely	Unlikely	Most likely	Possibly
b) Cutting of steel plates area	Possibly	Possibly	Unlikely	Possibly	Most likely	Possibly	Unlikely	Most likely	Unlikely	Unlikely	Unlikely	Most likely	Possibly
c) Cutting of steel section area	Most likely	Unlikely	Most likely	Possibly	Possibly	Unlikely	Unlikely	Unlikely	Most likely	Unlikely	Most likely	Possibly	Unlikely
d) Fabrication of MS & outfit items	Most likely	Unlikely	Most likely	Possibly	Possibly	Unlikely	Unlikely	Possibly	Most likely	Possibly	Most likely	Possibly	Unlikely
e) Sub assy & panel line areas	Possibly	Possibly	Unlikely	Unlikely	Most likely	Possibly	Unlikely	Possibly	Most likely	Possibly	Most likely	Possibly	Unlikely
f) Assy & main fab areas	Unlikely	Possibly	Unlikely	Unlikely	Possibly	Most likely	Possibly	Possibly	Most likely	Possibly	Unlikely	Possibly	Most likely
g) Pre-outfitting & module shops	Unlikely	Most likely	Unlikely	Possibly	Most likely	Possibly	Possibly	Possibly	Possibly	Most likely	Unlikely	Possibly	Most likely
h) Main berth & erection areas	Unlikely	Most likely	Unlikely	Unlikely	Possibly	Most likely	Most likely	Possibly	Most likely	Possibly	Unlikely	Possibly	Most likely
i) Pipe shops	Most likely	Possibly	Possibly	Possibly	Possibly	Unlikely	Unlikely	Possibly	Most likely	Possibly	Most likely	Possibly	Unlikely
j) Machine shops	Most likely	Unlikely	Possibly	Possibly	Possibly	Unlikely	Unlikely	Most likely	Possibly	Unlikely	Most likely	Possibly	Unlikely
k) Sheet metal shops	Possibly	Possibly	Possibly	Possibly	Possibly	Unlikely	Unlikely	Most likely	Possibly	Unlikely	Unlikely	Most likely	Unlikely
l) Paint shops	Possibly	Possibly	Unlikely	Possibly	Most likely	Most likely	Most likely	Unlikely	Most likely	Unlikely	Most likely	Possibly	Unlikely
m) Joinery shops	Possibly	Possibly	Possibly	Possibly	Possibly	Unlikely	Unlikely	Most likely	Possibly	Possibly	Unlikely	Unlikely	Most likely
n) Blacksmiths	Possibly	Unlikely	Possibly	Possibly	Possibly	Unlikely	Unlikely	Most likely	Unlikely	Unlikely	Unlikely	Possibly	Unlikely

MOST LIKELY (stippled) POSSIBLY (hatched) UNLIKELY (blank)

TABLE II ROBOTIC SHIPYARD USE

Most important of all perhaps is that Phase 1 offers an understanding of this new technology, an understanding which should spread from the people on the shop floor, to the engineers, managers and directors. In general terms, shipbuilders begin to climb the learning curve associated with robotics and other new technologies. However, stand alone new technology is relatively inefficient when compared with the next phase which is the systems or 'island' phase.

Today we stand at Phase 1 which is also the most critical phase, as stand alone new technology can be misused to the point where it is very difficult or impossible to integrate later on, thus failing to reach CIM.Stand alone new technology such as robotics, various NC machines, CAD, CAM etc must be chosen so as to include such features which will allow for integration at a later stage.

Phase 2

Once initial operating experience and feedback has been obtained, shipyards must capitalise on this experience and move to the second phase of FAST which is the systems phase and create a number of 'islands' of flexible automation in different areas of the shipyard.

A typical island would be programmed off-line and would be capable of producing a number of different products within a significant period - perhaps over a shift. During this period it would not be dependant on manual intervention for normal operation of the robot or for materials handling. A buffer of material would of course be prepared for automatic in-feed.

At this stage the true flexibility, as opposed to flexibility through convertability of robots, will be exploited. One-off products within the process capabilities of the installation, will be capable of being manufactured automatically.

A number of significant improvements in production efficiency will be gained by the installation of 'islands' of this type, such as:

- cycle times and product costs will be predictable
- cycle times will be reduced
- work-in-progress will be reduced
- quality and consistency will be improved
- 'communication errors' will be eliminated by the automatic transfer of technical information from CAD to CAM
- 'paper-pushing' will be reduced

The main thrust of robotic application investment is now in this level of technology. There is indeed great potential for 'islands' in shipbuilding.

Phase 3

A number of 'islands' integrated together may be loosely termed as CIM. For the goal of CIM it is greater than that, it is the integration of all the islands within the production facility, together with all other functions of the shipyard, design, business administration etc, under one main computer sharing a large common data base.

However, as opposed to the technology needed for Phases 1 and 2, Phase 3 requires the further development of certain technological aspects, which coupled with the fact that Phase 2 might last for quite some time, it is difficult to predict when CIM in shipbuilding will start being implemented.

CIM for shipbuilding is not utopia. The Japanese are working hard towards it and as revealed recently to the author, they expect to have started implementing it by the end of this decade!

However, there is a lot of work to be done by computer and robot manufacturers, let alone the shipbuilders. It is through a phased implementation that shipyards will get there. There is also a trap associated with the 'piece-meal' approach, that is sub-optimising the pieces of the system to a point where they are not integratable. One cannot lose sight of the final goal: CIM.

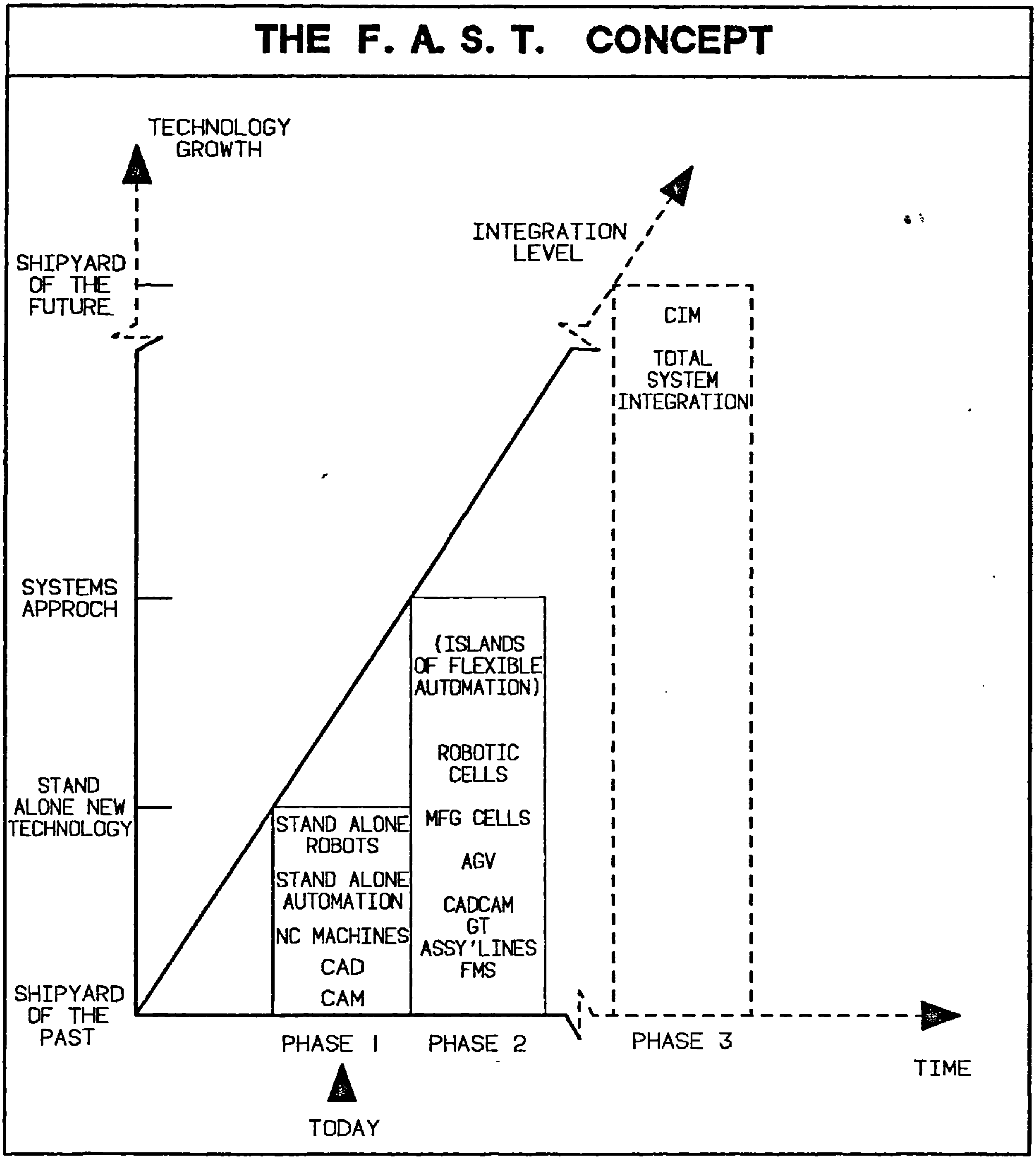


FIG 12a THE THREE MAJOR PHASES OF F.A.S.T.

10. DISCUSSION

10.1 General observations

The success of the shipbuilding industry depends on a number of issues. World economy, new markets, politics, marketing, management, organisation, workforce, technology, all play very important roles. This thesis has addressed a technological issue. The academic and technical challenge of the robotics field is undeniable.

Shipbuilding has always been associated with low technology and machinery. This image is now rapidly changing, not only with the introduction of CAD/CAM, but also by giving the workforce new and technologically advanced tools to work with. Effective computer use becomes the key issue for the future of the industry.

However, technological change must not just happen, or in particular only happen in response to competitive or market pressures, but it must be planned. A successful shipyard is one which considers technology as a strategic issue, which requires medium to long term planning and the setting of tactics towards accomplishment of a strategic goal of technological change.

Unfortunately, shipbuilding research and development, until now, was often involved in duplicating technological changes or advances made in other sectors of the industry, or even invented in one country's shipyard or research establishment, but developed, applied and practiced elsewhere, and then subsequently borrowed back! Even worse than that is the slow rate of technology transfer. Here again, other sectors of the industry appear to be more alert to the transfer of technological innovations. They would also devote more researches to the discovery of such opportunities.

Shipbuilders have learnt enough lessons. The future success in shipbuilding will depend on the use of high technology applications, requiring a considerable amount of investment. The computer and its 'associates' are expected to automate, to a great extent, ship production, when compared with today's practices.

A narrow look into the possibilities and capabilities of the robotisation of the welding process is convincing that a breakthrough is expected in the late eighties, early nineties. Maybe this is not yet realised by people with a very pessimistic attitude to the competitiveness of European shipyards, relative to the shipyards in low cost countries. Perhaps European shipbuilding does not need such people!

By developing and employing new technology, shipbuilding in Britain should have at least the same possibilities for survival as any other advanced modern industry in today's economic crisis. In the years ahead and with hard work from all those involved, the prosperity and pioneering status of shipbuilding in Great Britain, can most certainly be restored.

It must also be stressed that in the near future a successful industry will not be one which employs a high number of robots, but rather one which has achieved a good and smooth relationship between high technology, workforce and management.

10.2 New Ship or New Robot Designs?

There are two different schools of thought here:

a) DESIGN FOR AUTOMATIC PRODUCTION

Design ship structures to be easily fabricated by robots. Standardisation, modularisation, ease of access (eg one sided welding) etc, feature prominently here.

b) INNOVATE, FOR DESIGN PRODUCTION

Design robotic structures to cope with the complications of the designs produced. Robot designers are expected to come up with sophisticated autonomously driven robots, multi-axis long armed, large gantry structure robots, etc.

Both schools will soon realise that neither can stand alone, Naval Architects and Robot Designers must work together. Although Naval Architects will influence the design of robots and Robot Designers the design of ship structures, none of these should be done in isolation.

However, the Naval Architects are at a disadvantage in this race. Ship design has taken centuries to evolve and tradition has, unfortunately, a great influence on the way of thinking, while the formalisation of designing for production rules has only recently started to make some advances. For centuries, Naval Architects relied on their skilled (and motivated) manpower to cope with the complications of the designs produced.

Robot designs, on the other hand, have taken only a few years to evolve, and are continuing to do so at an impressive speed. Today we can witness whole robot production lines designed specifically to suite the work done. An example of this is the automobile industry which had robots tailored to meet their needs. Robot designers were expected and have indeed come up with some very innovative robot structures.

Today, Robot Designers and Naval Architects must both sit in front of the 3-D colour graphics computer terminal and interactively design, test and simulate ship structures that can be produced by robots, and robots that can produce such structures. Ship designs will most certainly change to the 'better' but that will not be solely due to production requirements.

There is every indication that Naval Architects can think in terms of design for automatic production, as the recent thinking of design for production has indeed produced some simplification in ship designs. However, in designing new ships, amongst other problems they are faced with the difficulty of quantifying exactly what is tolerable for a human worker and what is not. With robotic devices however, certain rules and limits of reach etc can be built as constraints, with greater confidence. Then with the aid of computer graphics and simulation, ship designs can be evaluated for productibility.

One such early example of co-operation is the Wartsila robot. This is a custom made shipbuilding robot which resulted from the collaboration of the Wartsila shipyard with KEMPPI (welding experts). Today a large number of minor modifications have been made to certain parts of the ship structure, while the robot design itself also has certain unique features not to be found on robots operating in other industries (e.g. It is very long and thin (14)).

10.3 Some useful lessons

a) WELDING FIXTURES

During the research period only a limited number of welding fixtures were constructed for the execution of experiments. However, small batch manufacturing necessitates by principle, the availability of a large number of jigs and fixtures.As manufacturing costs for jigs and fixtures can be expensive, it is also recommended that more flexible and universal fixture designs are explored.

b) ADAPTIVE CONTROL

Although it has been demonstrated that robotic welding can be cost effective, further savings can be realised in a production situation with the provision of adaptive control systems. For the full exploitation of welding robots in shipbuilding, it is recommended that such systems are used.

c) TYPES OF ROBOTS FOR WELDING

The hydraulic robot used demonstrated a poorer accuracy and repeatability (than that of its sister electric robot), a sensitivity to environmental fluctuations, an inability of software in certain situations. It is recommended that electric robots are used for welding applications.

d) TURNTABLES

For the application of robots in small batch manufacturing and also for safety reasons, the use of double turntables is recommended.

e) ACCURACY OF COMPONENTS

It is recommended that the accuracy of the different manufacturing processes is brought down to ±1mm. With such accuracy on component parts the potential of robotic workcells will be enhanced further.

f) OFF-LINE PROGRAMMING

The use of on-line programming of robots necessitates that only components with a higher percentage of arc time and/or large batches are used. Off-line programming frees the robot for more productive work and allows very small batches to be produced.

g) 3-D COMPUTER GRAPHICS FOR WORKCELL EVALUATION/SIMULATION

There is an endless number of combinations for workcell layout. It has been found that computer graphics is the most effective way of optimising the workcell layout. Also by simulating robot operations on the computer terminal, valuable time is gained on the shop floor.

It is also preferable that off-line programming and workcell evaluation/simulation is integrated into the yard's CAD/CAM system, for maximum benefits. In the future, robot programmes should be created at the design stage.

h) SAFETY AND PRODUCTION REQUIREMENTS

The 'absolutely safe' robotic workcell might be possible but will be created at the expense of production efficiency. Safety precautions must be weighed against any production trade-offs. With careful consideration a 'balanced & practicable' situation can be achieved. 'Caging' must be kept as close as possible to the robot's working envelope.

10.4 Own Contribution

a) To provide an example whereby a facility in the shipyard can be used as a "laboratory" equipment to verify the assumptions and hypothesis formulated at the University.

b) Overcoming shipyard tradition, a hostile workforce and doubts of technical staff to use the facilities for the verification of concepts and identifying an opportunity to produce usable products.

c) Pioneering the use of a standard robot as a "stand alone" facility in the shipyard production line while demonstrating that in small batch production the robot can be cost effective.

d) To have selected a topic, use of a welding robot to improve shipyard production, which could not attract the interest of production engineers and made a significant contribution.

e) The research results achieved and experience gained have allowed a total range of new ideas to be generated for possible advanced robot production in shipbuilding.

f) Identification of entire product range for small batch production suitable for robot welding.

11. CONCLUSIONS

Based on the research, the following conclusions are drawn:

a) A commercially available industrial robot can serve as a 'useful tool' for the production of minor steelwork outfit items in shipbuilding.

b) Robotic workcells for small batch manufacturing of minor steelwork and outfit items can offer increased productivity, reduced manufacturing costs, high quality and consistency, not previously available.

c) Considerable scope is still available for the application of robots in other areas of the ship production process, but that must only happen as a response to specifically identified inefficient areas.

d) Shipyards must now plan the application of robots on a strategic basis, bearing in mind the transition expected from standalone applications to islands of flexible automation, to eventually reach the ultimate goal of CIM.

ACKNOWLEDGEMENTS

The author is indebted to the Board of Swan Hunter Shipbuilders Limited for sponsoring him to carry out this research. Appreciative acknowledgements are especially due to Messrs A J Marsh, J S MacDougall, P D Forrest and D Maccoy for their continuing support and to the workforce of SHS Limited who helped the author to carry out his experiments.

The author also wishes to express special appreciation to his supervisor, Professor Chengi Kuo, for his invaluable guidance, continued interest and comments during the research period, and to all members of the lecturing staff associated with the Ship Production Technology Course at the University of Strathclyde.

Thanks are also due to Mrs. Christine Avery for her meticulous attention and speedy typing of the thesis.

Finally, the author would like to express his sincere gratitude to numerous industrialists and researchers in the shipbuilding, manufacturing and robotics industries from all over the world, who freely discussed the author's ideas, and helped to guide his efforts.

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APPENDICES

APPENDIX 1. GLOSSARY OF ROBOTIC & COMPUTER RELATED TERMS

ACCURACY	The difference between the point that a robot is trying to achieve the actual resultant position.
ADA	General computer programming language intended to be the primary language used in U.S. defence applications.
ADAPTABLE	Capable of making self-directed corrections. In a robot, this is often accomplished with vision or tactile sensors.
ADAPTABLE CONTROL	A control method in which control parameters are continuously and automatically adjusted in response to measured process variables to achieve better performance.
AGV (AUTOMATED GUIDED VEHICLE)	A mobile self-propelled and self-guiding (though not necessarily robotic) platform.
ARTIFICIAL INTELLIGENCE	The ability of a device to perform functions that are normally associated with human intelligence such as reasoning, planning, problem solving, pattern recognition, perception, cognition, understanding and learning.
AUTOMATION	The science and practice of machinery or mechanisms which are so self-controlled and automatic that manual input is not necessary during operation. The technique of making a process automatic or self controlling.
BATCH MANUFACTURING	A process in which a facility produces different parts by manufacturing them in groups, lots, or batches in which each part in the batch is identical.
BIN-PICKING PROBLEM	Selection by robot of an individual component from a jumbled collection stored in a bin.
BUG	Errors in computer programmes (see also DEBUGGING).
CAD (COMPUTER AIDED DESIGN)	The use of a computer to develop the design of a product to be manufactured.
CADCAM	A methodology of linking CAD and CAM systems into a single integrated computerised design and manufacture set-up.
CADMAT	Computer-aided design manufacture and testing. As with CADCAM but with additional automatic testing.
CAE (COMPUTER AIDED ENGINEERING)	Testing by computer of a proposed engineering design without actually building it.
CAM (COMPUTER AIDED MANUFACTURING)	The use of computers and computer technology to control, manage, operate, and monitor manufacturing processes.
CELL	A self contained manufacturing unit with at least one robot and other manufacturing devices.
CHIP	An integrated circuit.
CIM (COMPUTER INTEGRATED MANUFACTURE)	Use of interlinked computer-based technology throughout a whole factory.
CIRCULAR INTERPULATION	Automatic filling in of intermediate points of a circle uniquely specified by only three points.
CNC (COMPUTER NUMERICAL CONTROL)	The use of a dedicated mini or microcomputer to implement the numerical control function. Uses local data input from devices such as paper tape, magnetic tape cassette or floppy disc.
COMPUTER	A device capable of accepting information applying prescribed processes to the information and supplying the results of these processes.
CONTINUOUS PATH CONTROL	A control scheme whereby the inputs or commands specify every point along a desired path of motion.
CONTROL	The process of making a variable or system of variables conform to what is desired.
CONTROLLER	An information processing device whose inputs are both desired and measured position velocity, or other pertinent variables in a process and whose outputs are drive signals to a controlling motor or actuator. A communication device through which a person introduces commands to a control system.
CYBERNETICS	Study of the theory of control systems.
CYCLE	A sequence of operations that is repeated regularly.
CYCLE TIME	The period of time from starting one machine operation to starting another (in a pattern of continuous repetition). (A sequence of patterns that is repeated regularly).
DATABASE	A collection of data which is organised in a systematic structure. A structured computer storage and retrieval system designed as an 'electronic filing cabinet' for data.

DEBUGGING	The process of validating a computer routine, locating any errors and correcting them. Also the detection of malfunctions in the computer itself.
DOWNLINE LOADING	Procedure of one computer sending a programme down data lines for another to subsequently process.
DOWN TIME	Proportion of its potential running time that a given robot is actually not available usually due to a breakdown.
DNC (DIRECT NUMERICAL CONTROL)	The use of a central computer to store piece part programmes and provide these to one or more remotely located NC machines via a communications link.
DUTY CYCLE	The fraction of time during which a device or system will be active, or at full power.
END-EFFECTOR	An actuator or mechanical device attached to the wrist of a manipulator by which objects can be grasped or otherwise acted upon.
EXPERT SYSTEM	System that performs a task that normally requires human experience. Most expert systems are rule-based systems. Most are able to solve simple problems quickly and to explain their own reasoning, but few are able to break their own rules, to run simulations, to take a different perspective or to learn.
FACTORY	A complete manufacturing unit consisting of a number of manufacturing centres with the materials, transport, storage buffers and communications that interconnect them.
FEEDBACK	The signal or data fed back to a commanding unit form a controlled machine or process to denote its response to the command signal. The signal representing the difference between actual response and desired response that is used by the commanding unit to improve performance of the controlled machine or process.
FIFTH GENERATION	Label used by the Japanese for their ambitious programme to achieve supremacy in the computer business. Separated from previous generations by higher speed and by employment of artificial intelligence.
FIXED AUTOMATION	Machines without the flexibility to perform more than one task unless physically readjusted.
FLEXIBLE	Multipurpose; adaptable, capable of being redirected, retained or used for new purposes. Refers to the reprogrammability or multi-task capability of robots.
FLEXIBLE MANUFACTURING SYSTEM (FMS)	A manufacturing system whereby a group of machines, usually numerically controlled, is interconnected by a system of conveyors and part transport devices so that a variety of similar but different products can be manufactured automatically.
FIXTURE	A device that accurately and repeatedly locates the components of a workpiece to be processed by the robot.
FLOOR-TO-FLOOR TIME	The total time elapsed for picking up a part (manually or by robot) loading it to a machine, (jig, fixture etc.) carrying out the required robotic operations and unloading it (back to the floor, or bin or pallet etc.)
GRIPPER	A device by which a robot may grasp, hold, manipulate and release the part or object being handled.
GROUP TECHNOLOGY	A technique for grouping various parts into families based on their geometric shapes, processing requirements or other manufacturing characteristics of the parts, so that these families may be processed together.
HAND	A device attached to the wrist having a mechanism with closing jaws or other means to grasp objects.
HARDWARE	The actual physical parts of an electronic control system, such as the printed circuit boards, electronic components, wiring, enclosures etc.
IC (INTEGRATED CIRCUIT)	An electronic circuit consisting of a chunk of semi-conducting material on which many electronic devices have been simultaneously fabricated, containing tens of thousands of transistors.
INDUSTRIAL ROBOT	An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tods, or specialised manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks.
INFORMATION TECHNOLOGY	Nebulous term originally referring to data processing, but expanded to include robotics etc.
INTELLIGENT ROBOT	A category of robots that have sensory perception, making them capable of performing complex tasks which may vary from cycle to cycle. Intelligent robots are capable of making decisions and modifications to each cycle.
INTERACTIVE	A type of computer control system in which an interaction occurs between the system operators and the system throughput processing. The computer asks various questions or provides choices to which the operator must react.
INTERFACE	The name given to the method, procedure, or hardware which allows one system or part of a system to communicate with or work with another.
JIG	A device that accurately and repeatedly guides a tool onto a component for processing.

LASER	Light amplification by stimulated emission of radiation. A coherent light source of variable intensity with a wide range of applications (i.e. cutting, welding, data transmission etc.)
LEVEL OF AUTOMATION	The degree to which a task or process operates automatically. This degree must take into account the ability of the system to diagnose problems in its operation, the ability of a system to recover from an error or fault, the ability of a system to start up and shut down without human intervention and the like.
MASS PRODUCTION	The large scale production of parts in a continuous process uninterrupted by the production of other parts.
MISTER SLAVE MANIPULATOR	A type of teleoperator consisting of a master arm held, moved and positioned by a person and a slave arm which simultaneously duplicates the motions of the person. There is normally a scale factor between the master and slave arm so that the slave arm can be larger, reach farther, or carry more than the master arm.
MATERIAL HANDLING ROBOT	A robot designed to grasp, move, transport or otherwise handle parts of materials in a manufacturing operation.
MATERIAL PROCESSING ROBOT	A robot designed and programmed so that it can machine, cut, form, or in some way change the shape, function, or properties of the materials it handles between the time the materials are first grasped and the time they are released in a manufacturing process.
MEMORY	Any device into which data can be input, retained, and later retrieved for use. That part of a computer which retains data or programme information.
MICROCOMPUTER	A type of computer which utilises a single chip micro-processor as its basic operating element. A system comprised of a micro-processor plus other necessary electronic elements to provide the input, processing, memory and output necessary for computing.
MICRO-PROCESSOR	The basic element of a central processing unit devleoped on a single integrated circuit chip. A single integrated chip provides the basic core of a central processing unit, even though it may require additional components to operate as a central processing unit.
MINI-COMPUTER	A class of computer in which the basic element of the central processing unit is constructed of a number of discreet components and integrated circuits rather than being comprised of a single integrated circuit as in the micro-processor.
MODERN (MODULATOR - DEMODULATOR)	An electronic device that sends and receives digital data using telecommunication lines. To transmit data, the digital signals are used to vary (modulate), an electronic signal that is coupled into the telecommunication lines. To receive data, electronic signals are converted (demodulated) to digital data.
MOUSE	Hand-held device that is rolled about on a table to move a terminal's cursor.
N.C. (NUMERICAL CONTROL)	A system for controlling machines in which the pre-recorded information necessary for operating the machine is provided often through the use of paper tape or magnetic tape in coded form. The machine reads the numeric instructions and operates accordingly.
OFF-LINE	Processor not at that time connected to the robot.
OFF-LINE PROGRAMMING	Computer programme development on a system separate from the computer onboard a robot.
ONE-PASS SYSTEM	Form of seamtracking which senses the seam during welding so dynamically adjusts to follow it.
ON-LINE	Processor in direct control of the robot.
ON-LINE PROGRAMMING	Computer programme development on the system included in a robot.
OPERATIONAL RESEARCH	Quantification of a management problem in mathematical terms in order to find an optimal solution.
PARALLEL PROCESSING	Concurrent or simultaneous execution of two or more operations in devices such as multiple arithmetic or logic units.
PATTERN RECOGNITION	Area of artificial intelligence involved with the computerised interpretation of images.
PAYLOAD	The maximum weight or mass of a material that can be handled satisfactorily by a robot or process in normal and continuous operation.
PC (PERSONAL COMPUTER)	A computer that is powerful enough to be user friendly and inexpensive enough to be nonshared.
POST PROCESSOR	The interface between an independant computer and the robot's controller.
PROGRAMMABLE	Capable of being instructed to operate in a specified manner or of accepting setpoints or other commands from a remote source.
PROTOCOL	The procedural rules for controlling data communications between devices in computer systems.
PRODUCTION LINE	Production system with a continuous stream of units sequentially built up to their final form.

RAIL	Modern programming for robot programming. A product of Automatix Incorporated of Billerica, Massachusetts.
REALTIME	Computation performed in synchrony with the physical process with which it is associated.
REPEATABILITY	The ability of a system or mechanism to repeat the same motion or achieve the same points when presented with the same control signals.
ROBOT	A mechanical device which can be programmed to perform some task of manipulation or locomotion, under automatic control. (See also INDUSTRIAL ROBOT).
RS 232	A standard computer interface for connecting peripheral devices to computers. Maximum range 40 feet and a maxium speed of 20,000 baud.
ROBOT ACCURACY	Degree to which the actual position of a robot corresponds to the desired or commanded position.
ROBOT REPEATABILITY	Closeness of agreement of repeated movements to the same location under the same conditions.
SEAM TRAFING	Continuous position control of the welding torch, with respect to any changes of the welding seams from the programmed path.
SENSOR	A transducer whose input is a physical phenomenon and whose output is a quantitative measure of that physical phenomenon.
SERVO-CONTROLLED ROBOT	A robot driven by servomechanisms, i.e. motors whose driving signal is a function of the difference between commanded position and/or rate and measured actual position and/or rate. Such a robot is capable of stopping at or moving through a practically unlimited number of points in executing a programmed trajectory.
SOFTWARE	A name given to instructions, programmes, mathematical formulea, and the like utilised in the computer system which instructs the operations of the computer.
SOLID STATE CAMERA	A television camera that uses a solid state integrated circuit to change the incoming light image into electronic signals.
STATE OF THE ART	Fully up to date technology.
SYSTEM	A collection of parts or devices that forms and operates as an organised whole through some form of regulated interaction.
TEACH	To programme a robot by guiding it through a series of points or in a motion pattern that is recorded for subsequent automatic action by the robot.
THROUGH-THE-ARC SENSING	Analysing arc current and voltage while weaving as a form of seam tracking during welding.
TOOL	A term used loosely to define something mounted on the end of the robot arm; for example, a hand, a simple gripper, an arc welding torch, etc.
TRACKING	Continuous position control response to a continuously changing input.
TURNKEY SYSTEM	System ready for immediate use on purchase.
TWO PASS SYSTEM	Form of seam tracking involving a 'trial run' with sensing followed by a welding run without sensing.
UNMANNED FACTORY	Currently unrealised design of automated factory incorporating no human workers on the shop floor.
VAL (VARIABLE ASSEMBLY LANGUAGE)	Manipulator-orientated programming language for robot programming. A product of Unimation Inc., U.S.A.
VAX	Line of powerful computers manufactured by Digital Equipment Corporation (DEC).
VISION SYSTEM	A device that collects data and forms an image that can be interpreted by a robot computer to determine the position, the orientation, etc., or to see an object.
WORKCELL	See CELL.
WORKING ENVELOPE	The set of points representing the maximum extent or reach of the robot hand or working tool in all directions.
WORKSTATION	A discrete manufacturing area, in which predefined processes take place. Small processing area within the working envelope of a robot.
WORLD MODEL	Computerised symbolic representation of the robot arm, workspace, and objects involved in a given task.

APPENDIX 2

ROBOT POPULATION AND DEFINITIONS

DEFINITIONS

- BRITISH ROBOT ASSOCIATION (UK):
  "An Industrial Robot is a programmable device designed to both manipulate and transport parts, tools, or specialised manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks".

- ROBOT INSTITUTE OF AMERICA (USA):
  An industrial Robot is a programmable, multi-functional manipulator designed to move material, parts, tools or specialised devices through variable programmed motions for the performance of a variety of tasks".

- JAPANESE INDUSTRIAL ROBOT ASSOCIATION (JAPAN):
  JIRA classifies industrial robots for the method input information. However, their 'wide' definition of 'robot' includes machines that are not classed as robots elsewhere (eg nos 1 and 2 below).

  1) Manual Manipulator - manipulator that is worked by an operator.

  2) Fixed Sequence Robot - a manipulator which repeatedly performs successive steps of a given operation according to a pre-determined sequence, condition and position and whose set information cannot be easily changed.

  3) Variable Sequence Robot - a manipulator which repeatedly performs successive steps of a given operation according to a pre-determined sequence,

condition and position and whose set information can be easily changed.

4) Playback Robot - a manipulator which can produce, from memory, operations originally executed under human control. A human operator initially operates the robot in order to input instructions. All the information relevant to the operations (sequence, conditions and positions) is put into the memory. When needed this information is recalled (or played back - hence its name) and the operations are repeatedly executed automatically from memory.

5) NC (Numerical Control) Robot - a manipulator that can perform a given task according to the sequence, conditions and position, as commanded via numerical data. The software used for these robots includes punched tapes, cards and digital switches. This robot has the same control mode as an NC machine.

6) Intelligent Robot - this robot with sensory perception (visual and/or tactile) can detect changes in the work environment or work condition, and using its own decision-making faculty can proceed with its operation accordingly.

OTHER DEFINITIONS

- "A mechanical device which can be programmed to perform some task of manipulation or locomotion under automatic control".

- "Any automated machine programmed to perform a specific mechanical function in a manner of a man".

- "A programmed manipulator designed to perform useful work automatically without human assistance".

- "A commercially available mechanical programmable device that independently performs manipulative job functions".

- "A machine that can duplicate human skills and flexibility
with accuracy and precision".

ROBOT POPULATION

World industrial robot population is growing rapidly. The robotics industry has come a long way since Unimation (U.S.A.) installed the first robot at a forging plant in 1960. In 1982, Japan employed 13,000 robots, in 1983 they were increased to 16,5000 and in 1984. they reached a staggering 64,600!! (Far more than the whole of the world put together) See Figure 14. The use of robots in UK has been growing too, but at a far lower rate than Japan, U.S.A. W. Germany, France and Italy. See Figure 15. The British Robot Association published in the beginning of 1986 a UK 'Robot Industry Analysis'. In it, the shipbuilding and the aerospace industries together account for 105 installations out of the 3,208 in the country. See Figure 16a & 16b. It has been predicted however, that shipbuilding and heavy fabrication industries are growth areas for robotics, while the automobile industry is approaching saturation point.

BRITISH ROBOT ASSOCIATION
25-30 HIGH STREET,
KEMPSTON, BEDFORD MK42 7AJ, ENGLAND
TEL. BEDFORD (0234) 854477 TELEX 825489

ROBOT FACTS – December 1984

Definition

An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tools, or specialized manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks.

64800

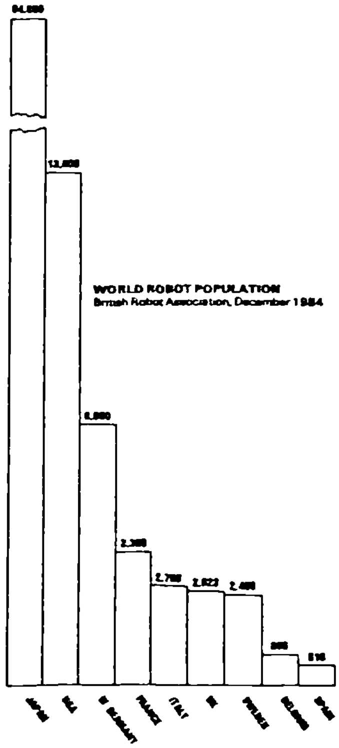


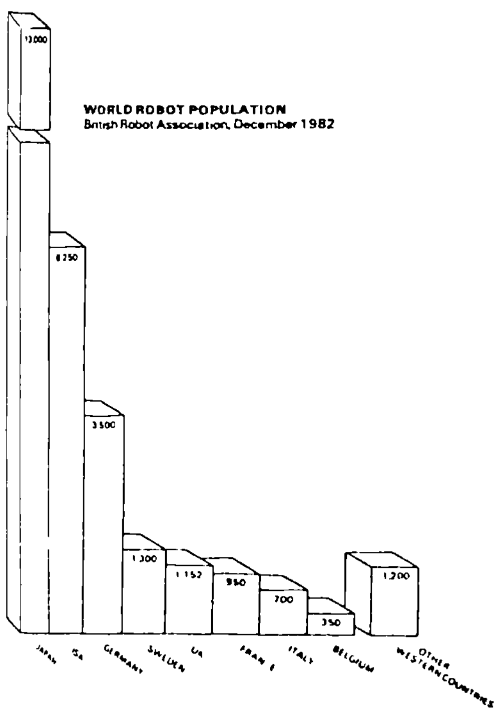
FIGURE 14

BRITISH ROBOT ASSOCIATION
35 39 HIGH STREET,
KEMPSTON, BEDFORD MK42 7BT, ENGLAND
TEL: BEDFORD (0234) 853605 & 856271 TELEX 825489

ROBOT FACTS – December 1982

Definition

An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tools, or specialised manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks.

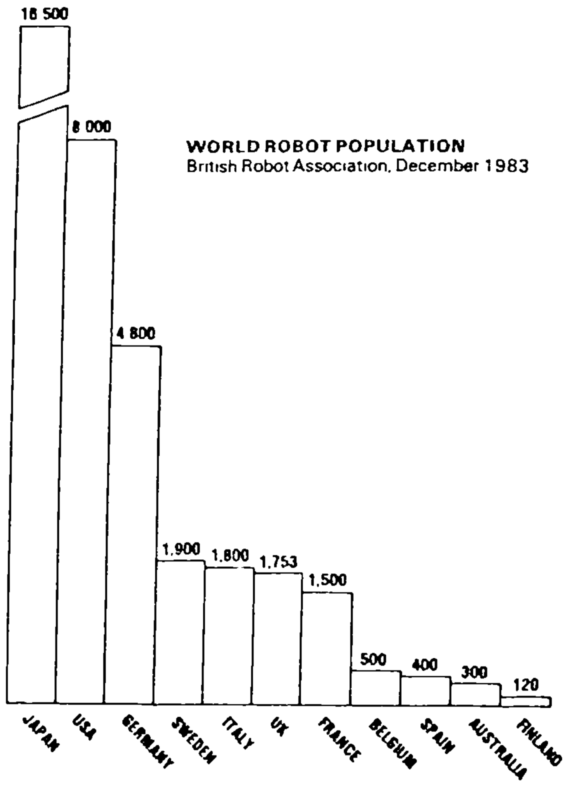


BRITISH ROBOT ASSOCIATION
28 30 HIGH STREET,
KEMPSTON, BEDFORD MK42 7AJ, ENGLAND
TEL BEDFORD (0234) 854477 TELEX 825489

ROBOT FACTS – December 1983

Definition

An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tools or specialised manufacturing implements through variable programmed motions for the performance or specific manufacturing tasks



BRITISH ROBOT ASSOCIATION

28-30 HIGH STREET,
KEMPSTON, BEDFORD MK42 7AJ, ENGLAND
TEL. BEDFORD (0234) 854477 TELEX: 825489

ROBOTS FACTS – December 1985

Definition

An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tools, or specialised manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks.

POPULATION GROWTH – UK/WEST GERMANY/USA
British Robot Association, December 1985

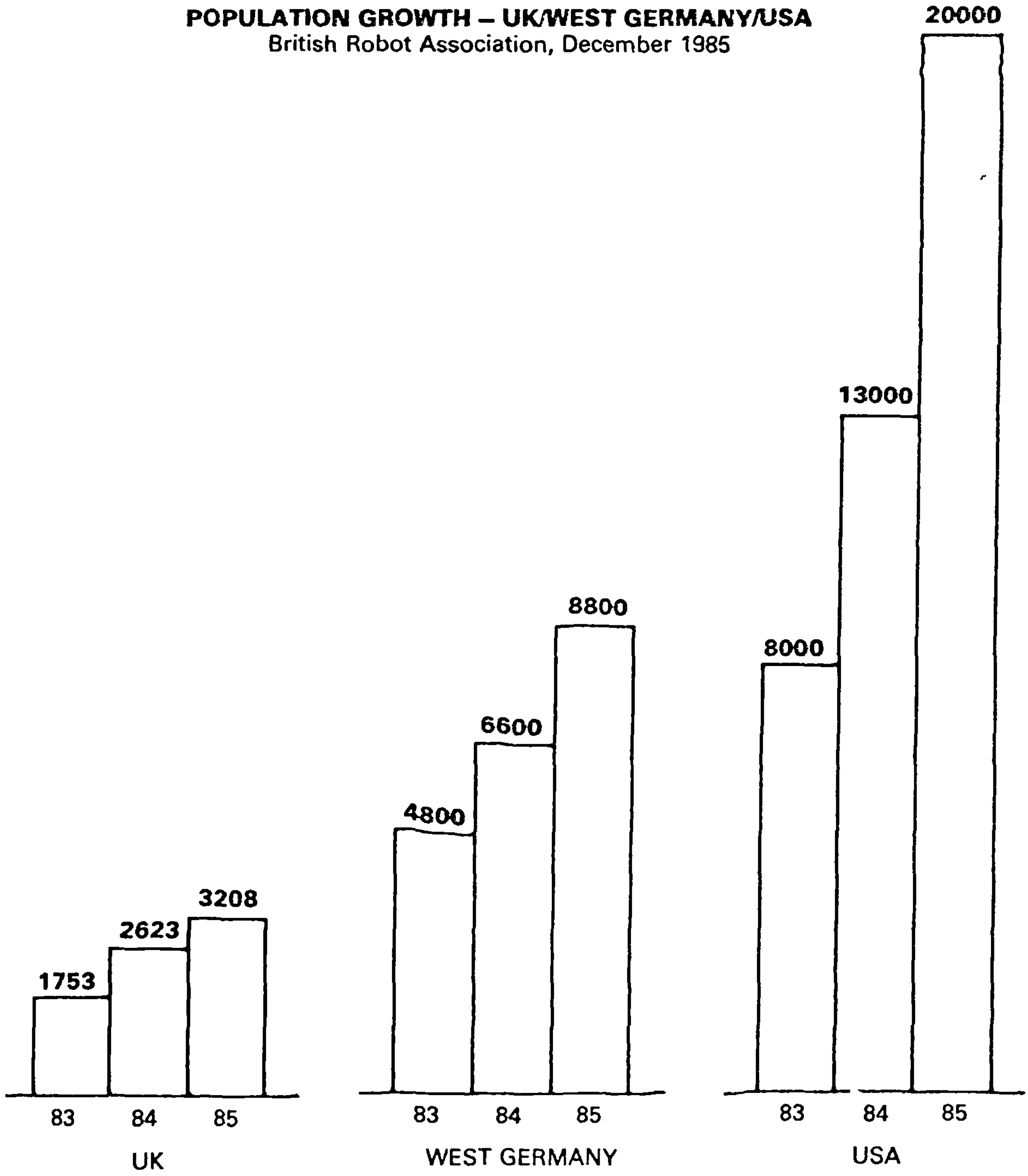
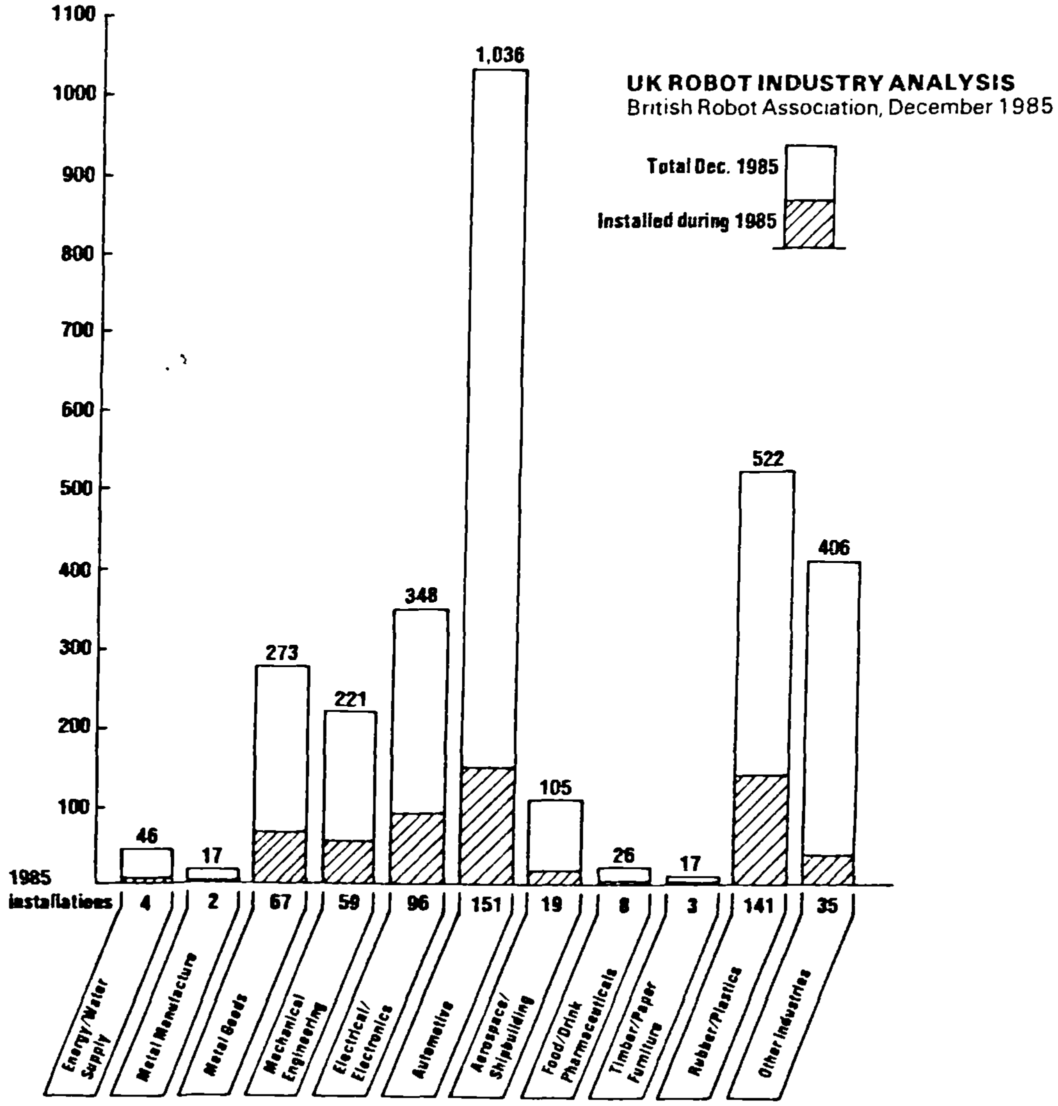
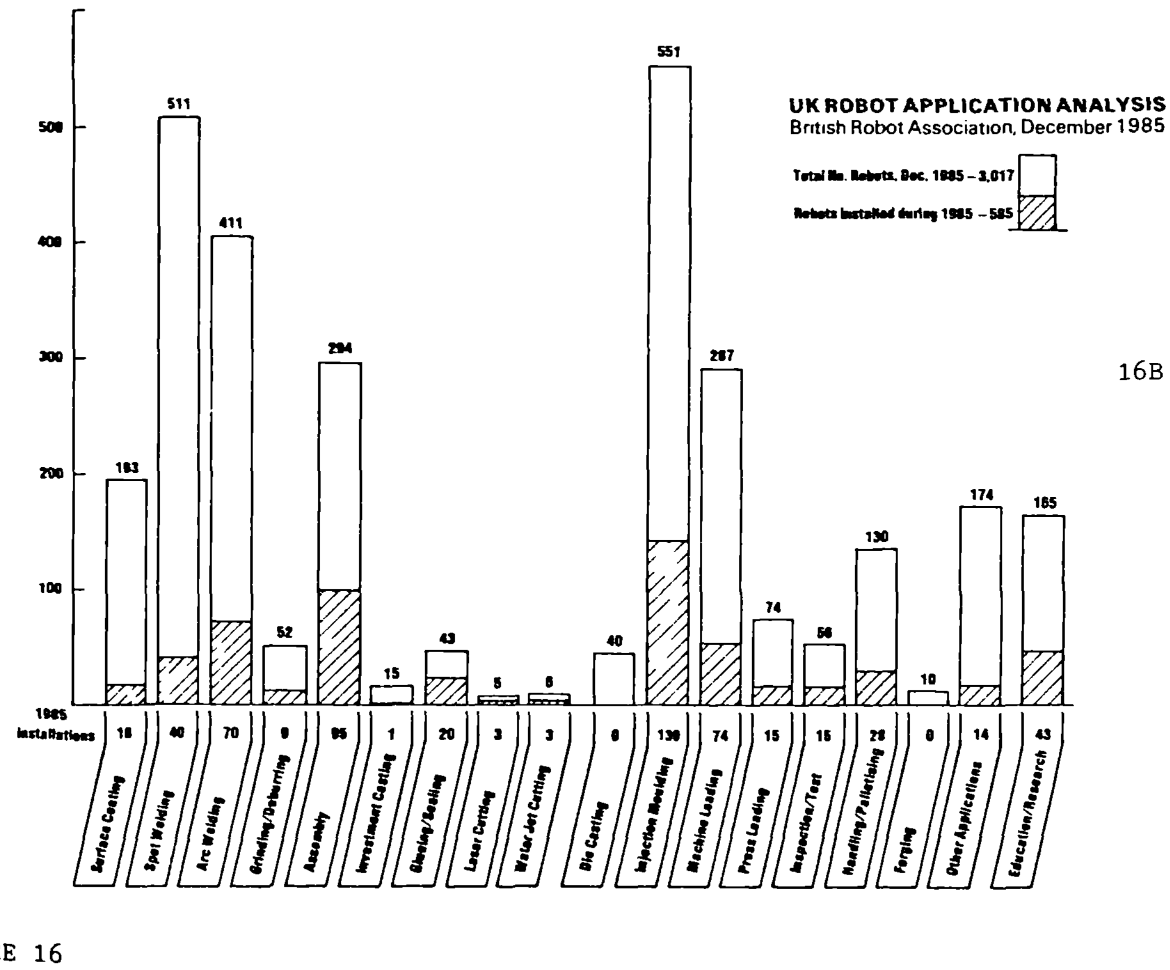


FIGURE 15



16B



16B

FIGURE 16

APPENDIX 3

THE GLOBAL SOCIAL ASPECTS

Fears that automation will inevitably lead to higher unemployment are not new. In 1811 the Luddites rioted and destroyed the textile machinery which they saw as a direct threat to their jobs. Yet employment in the textile industry proceeded to grow during most of the 19th Century. In the same century the fastest growing industries, in terms of employment, were those based on new technology. The last century demonstrates clearly that despite the fears to which new technology gave rise, technology promoted employment. More recent history repeats the lesson. The facts do not support any casual relationship between automation, higher productivity and unemployment.

Undoubtedly, concern about the impact of robots and other microelectronic based production equipment, has been exacerbated by the depressed world economy and the current high levels of unemployment. However, the unemployed cannot blame automation. There is too little equipment installed to account for the levels of unemployment. Even when such equipment has been installed, it would be wrong to conclude that the overall impact on jobs has been negative. The overall impact on jobs is indeed positive. A typical industrial robot costs from £30,000 to £80,000 and sometimes more by the time it is installed and operating. This cost means that creating every robot requires from two to four persons - years of work somewhere in the economy, and this requirement will grow with the growing robotics industry. Robot production will add jobs to the economy possibly as fast as robot installation will force such changes in jobs. Today, the countries with the highest level of robots per employee (eg Japan, Sweden, etc) have very low rates of unemployment.

Many years, perhaps even centuries will pass before 'robots' can design, manufacture, market, install, programme, repair, maintain and supervise themselves with no human intervention. In the meantime, the manufacture and servicing of robots will produce an enormous demand for mechanical engineers, technicians, computer programmers, electronic designers and robot installation and repair persons. However, one can argue that all of the above jobs could one day be computerised or robotised for the sake of higher efficiency! Of course they will. (One day!). This is the changing nature of our society. Today we stand at the edge of another great social revolution. During the decades ahead, just as agricultural jobs were eliminated by the tractor and the population migrated from farm to factory work, robots and computers will eliminate factory work and the population will migrate to information work and the service industry.

During the next century most manual workers should be free to do what they do best: creative planning and decision making functions. The quality of working life and productivity will improve. Jobs in the shipyard of the future will be more challenging and satisfying. According to Joseph Engelberger (the father of the industrial robot) robots will improve the self-worth and dignity of workers as 'the guy looking after five robots becomes a boss'. (19)

Today it is clearly recognised that it is not automation but the failure to automate that risks jobs. Secure employment and healthy economies will come from embracing new technology, not from pretending it does not exist. What is needed however, is the right training and re-training and governments therefore have a duty to inform people and provide a wide range of training schemes and courses.

It is believed by certain sociologists that CIM and robotics will result in people with more satisfying jobs where they are using their heads more than their hands. People might also have to learn that being more versatile, performing different functions, migrating to different jobs, might just come to be the new way of life!

There is a (mistaken) belief shared by many people that trade unions are opposed to new technology, including the introduction of robots. Resistance to the introduction of new technology will damage our opportunity to create the wealth that is needed to improve society, not only in the industrialised countries but in the third world. In order to survive trade unions need to progress technologically and become multi-national in their perspective. They must support programmes to give their workers the further training or retraining which is necessary for the new technology. Sophisticated research departments must be created to help unions analyse new technological developments and assess their potential impact.

Trade unions should also become multinational, in order to co-ordinate action. This would be particularly important in respect of social policies such as reducing working time where a not unreasonable target would be 15% reduction every five years. The working week would thus become 33 hours in 1991, 28 hours in 1996 and 24 hours in the year 2001. This could mean a six hour day and a four day working week. Added to this there would be paid study for further training and retraining. By 2001 a great change in the skills needed will have occurred.

Unions must understand that, in a robot era, employment patterns must obviously favour the information operatives rather than the machine and manual operatives. An ill thought out response can only delay progress and make the situation more difficult for everyone. British Unions also need a wider demarcation line than that which exists at present between unions and crafts, if this nation wishes to be as efficient and productive as overseas competitors.

The challenge for the future of ship production technology is to design the production system in such a way that the most effective use is made of all the resources available. The resource which has largely been taken for granted in the past, is the human resource. Production systems have been designed in spite of, rather than for, the manpower which is till their most significant

part. The limitation of human involvement to simple, repetitive, physical strength requiring tasks is the most dramatic disregard of human potential.
Often the robot is seen as a rival to the worker but in reality it is the rival of other forms of automation called 'hard automation' or 'dedicated machinery'. The reason for this is that the trend in any industry is for increased automation, whether robots are used or not.

To increase competitiveness the shipbuilding industry must increase productivity and reduce many costs; there is no alternative.

Cheap labour is abundant in many countries that are hungry to industrialise and this pattern of newly industrialised nations taking over in some of the manufacturing sector will continue. However, as time goes on, so these countries will want higher levels of technology, so there will be more and more competition for industries in developing nations. In that battle to increase productivity while maintaining the flexibility needed to react to forces of the market and competition, there is no doubt that the robot is a valuable and powerful tool.

The widening of the application base and hence the quantitative growth of the industrial robots used, depends on two developments with different time horizons.

Firstly, it is necessary to open up further fields of application for the existing industrial robot technology, in such industries as shipbuilding, which have so far made little or hardly any use of industrial robots. This is a problem of diffusion where innovation barriers must be broken down and where new technologies are always opposed. Strictly speaking, however, industrial robots are not 'new technologies' and although innovation resistance, which cannot be underestimated is present in the word 'robot', NC technology by comparison, has never had to fight against such emotional innovation barriers, although evidence can be produced in this field that an enormous increase in productivity has been achieved with NC machinery.

However, one additional problem, difficult to overcome with industrial robots, is the fact that their use represents from the beginning a big jump in automation, compared with the introduction of NC technology. The size of this overall jump in automation is demonstrated by the fact that the use of an industrial robot, even on attending an NC machine (eg loading and unloading parts) once again increases the degree of automation of the whole system.

There is worry expressed about possible adverse effects which the robotisation of the shipbuilding process would have on the morale of the shipyard workers who find satisfaction and pride in acquiring skill through years of experience and practice.

However, when other industries are being modernised through reduction in labour consuming operations and by providing a safe working environment, it is doubtful that young people would prefer working in the shipbuilding industry than in other industries if it alone, continues to remain a labour intensive industry.

They would rather enjoy operating automated or mechanised systems in modernised shipyards, become interested in their mechanisms and receive technical training to improve themselves. They would also be attracted by the speed at which vessels are built in a short period, thanks to improved productivity. If shipbuilders then secure capable employees and try to raise their morale in a favourable working environment then we can say that they have made excellent progress towards securing prosperous business.

However, new technology inevitably relies on research and development and we must not forget that the real wealth of any nation lies in the skills and education of its people.

FAST is not expected to have a different impact in shipbuilding in terms of employment levels, that any other industry has felt due to the introduction of new technology. Due to the tight economic environment, shipyard workers are decreasing in numbers in many countries around the world already. The focus must not be on retaining workers to do what they have always done. The shift of skills is occurring now and the sooner shipyards realise this the better they will be able to react and start the training and re-training of employees according to the needs of the changing methods, shipbuilding techniques and equipment.

In any case, FAST needs capital and requires time, so an explosive situation will not occur.

APPENDIX 4

CIM IN SHIPBUILDING

a) The Concept

CIM involves the integration and co-ordination of all design, manufacturing and management functions, using computer based systems with centralised and commonly shared databases. CIM is not yet a specific technology that can be purchased, but rather an approach to factory organisation and management.

The shipbuilding industry has a lot of catching up to do with new technology, advanced manufacturing systems and computer integration. Most importantly for CIM shipbuilders must understand that 'information-era' technology cannot be applied with 'industrial-era' thinking.

Industrial-era thinking signifies the concept of breaking each manufacturing process down to its most basic elements in order to address them most effectively. Unfortunately the flexible automation systems, typical of the information-era, demand exactly the opposite approach. The nature of these systems is that they integrate manufacturing processes rather than break them down. Industrial-era thinking is typified by manual process, polarised departments and rigid work roles. It is also declarative in nature. Orders are passed down to workers from top management, but management receives little feedback as to the success with which these orders are performed or if any problems are encountered along the way.

The information-era organisation, on the other hand, can be characterised as using computer-aided systems to perform a variety of manufacturing and other processes. The computer allows the information-era organisation to be integrative as well as interactive. When changes need to be made they can be implemented quickly and accurately because the information is readily available. The information-era organisation supplies management with many more channels through which to stay informed. Thus, if problems occur, they are detected and changes can be made more easily.

It is expected to be quite difficult to implement CIM in shipbuilding. The most progressive and far sighted manufacturing companies worldwide are addressing these issues today and these companies will be far ahead of the competitors in the future. The Japanese shipbuilders, for example, have already started addressing CIM for use in their shipyards. (8),(12)

There is no leap frogging in CIM. Implementation takes careful planning and step-by-step strategy. For shipbuilders to sit back and wait for the technology to 'stabilise' is a mistake, because an organisation will never catch up with the competitor who is thrashing out the problems today. Every company wants to be a significant worldwide competitor in the future, must be willing to make investments in money, time and people to ensure successful CIM implementation.

The free market system in shipbuilding, with all its pluses and minuses, does ensure that 'only the strongest competitors survive'. Change of this magnitude can be disturbing since it involves facing the unknown and the unfamiliar, but worldwide competition will ultimately force shipbuilders to either exploit these changes or find they can no longer compete in the market place.

CIM needs a strategic approach and for is successful implementation it is required to be well understood, by all those who are going to implement it.

One should be able to visualise that the amount of control data required by a CIM system is tremendous. That holds especially true for such a work intensive industry as shipbuilding. For example, it has been estimated (7) that for a 40,000 DWT class bulk carrier, the volume of control data is approximately 80 MB (see Table 12). However, computer technology has advanced dramatically and is continuing to do so towards higher transmission speeds and capacities. Speeds of a few million bits per second can now be achieved.

In most shipyards, the computerisation of single processes or functions, has resulted in a productivity enhancing solution for a particular manufacturing area, process or departmental function. Linking various automated processes or departments however, is not as well thought out. As a result, facilities are left with a multitude of disjointed systems and applications. When one application completes its function, it cannot pass the results along to the next function. The concept of CIM implies the existence of communications between systems in such a way that information generated by any one system can be used by all other systems.

To clarify the subject of integration the following example, involving Department A and Department B, is used. (See Figure 16). (The philosophy is the same for production areas A and B on the shopfloor).

Each department functions through a number of sub-systems, which may receive their input data from within the department, or from other departments. Likewise some sub-systems within each department will produce output data to be used within the department and by other departments.

Although certain sub-systems may be computerised and although their output could be in a form of a magnetic tape, disc etc this does not necessarily imply that the output can be readily used as an input to other systems. It usually has to undergo a pre-process which converts the information to a format that can be interpreted by the next system. For non computerised systems the output is in the form of listings or drawings that again need to be 'translated' (manually this time) before it can be used as useful input for another system.

Table 12 ESTIMATED AMOUNT OF DATA

(Unit: kB)

	Model Block	40,000 DWT Class Bulk Carrier
1. Geometrical Data	120	54,000
2. Properties	80	12,000
3. Schedule Data	70	10,500
4. Others	200	200
TOTAL	470	76,700

Whether such pre-process of translation is carried out manually or by running specifically designed computer programmes, a considerable amount of time is required and an important source of errors is introduced in this transformation of information.

This situation can be avoided by 'bridging' the various systems together via the use of common interfaces. Such integration of systems will transfer departments into 'islands' which in turn would be capable of direct communication between departments. (See Figure 17). This is the basic principle of CIM which will eventually integrate all functions of the business enterprise.

b) The Basic Sub-divisions of CIM

CIM in shipbuilding can be sub-divided into four basic areas to be integrated:

1) Computer aided design
2) Computer aided manufacture
3) Computer aided production management, and
4) Computer aided business administration

All four of which are supported via a processing strategy, a communications strategy and a data strategy (see Figure 18).

Computer Aided Design

This area covers the use of a computer based system to assist all those tasks involved in the process of developing a concept for a product into a full engineering design, described in sufficient detail to enable it to be manufactured. The process starts with a functional specification, ie a statement of the owner's requirements, within which the design must be constrained.

The process ends with the release of information from

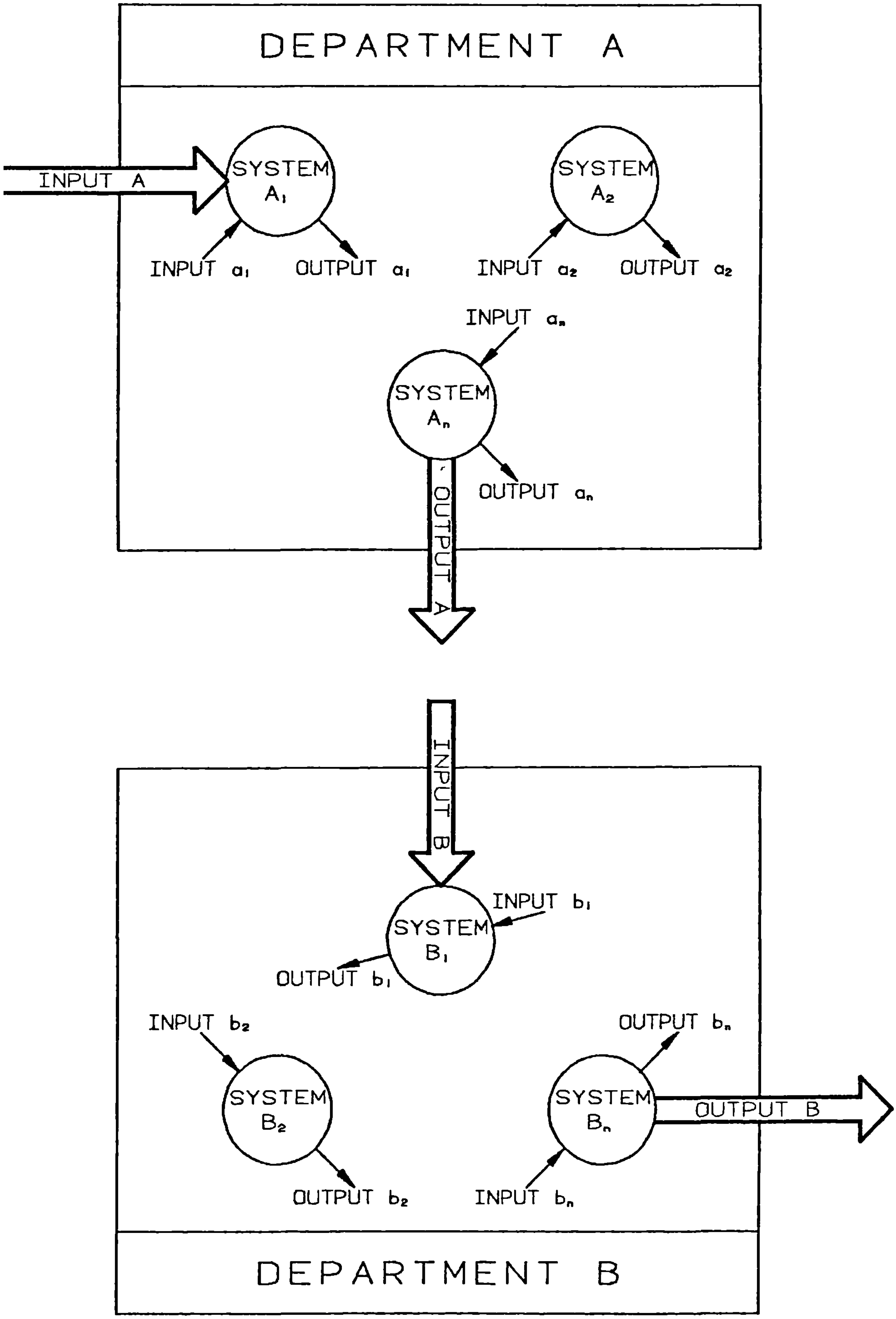


FIG 16a SCHEMATIC OF NON INTEGRATED INFORMATION FLOW BETWEEN DEPARTMENTS AND SYSTEMS WITHIN DEPARTMENTS.

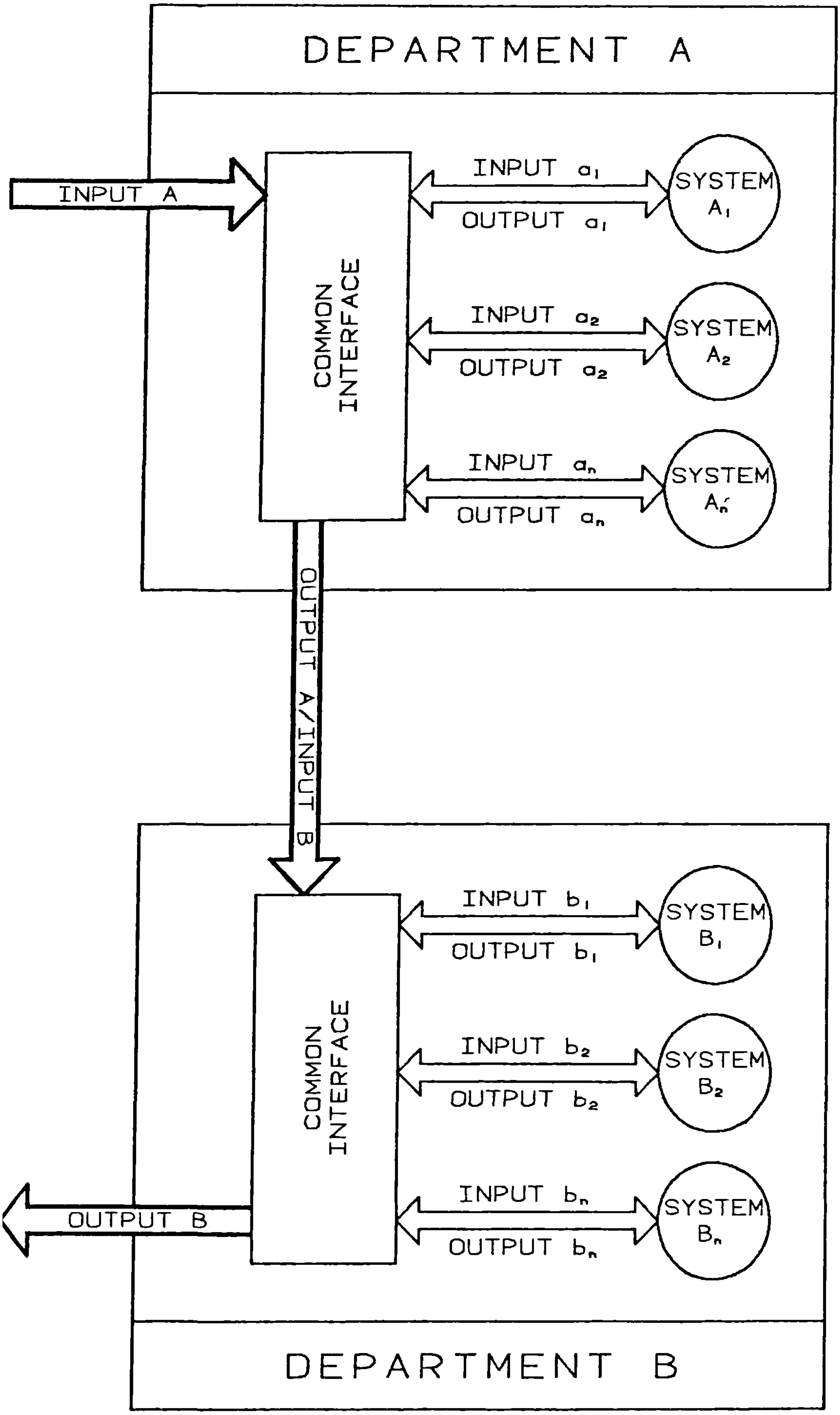


FIG 17 SCHEMATIC OF INTEGRATED INFORMATION FLOW BETWEEN DEPARTMENTS AND SYSTEMS WITHIN DEPARTMENTS.

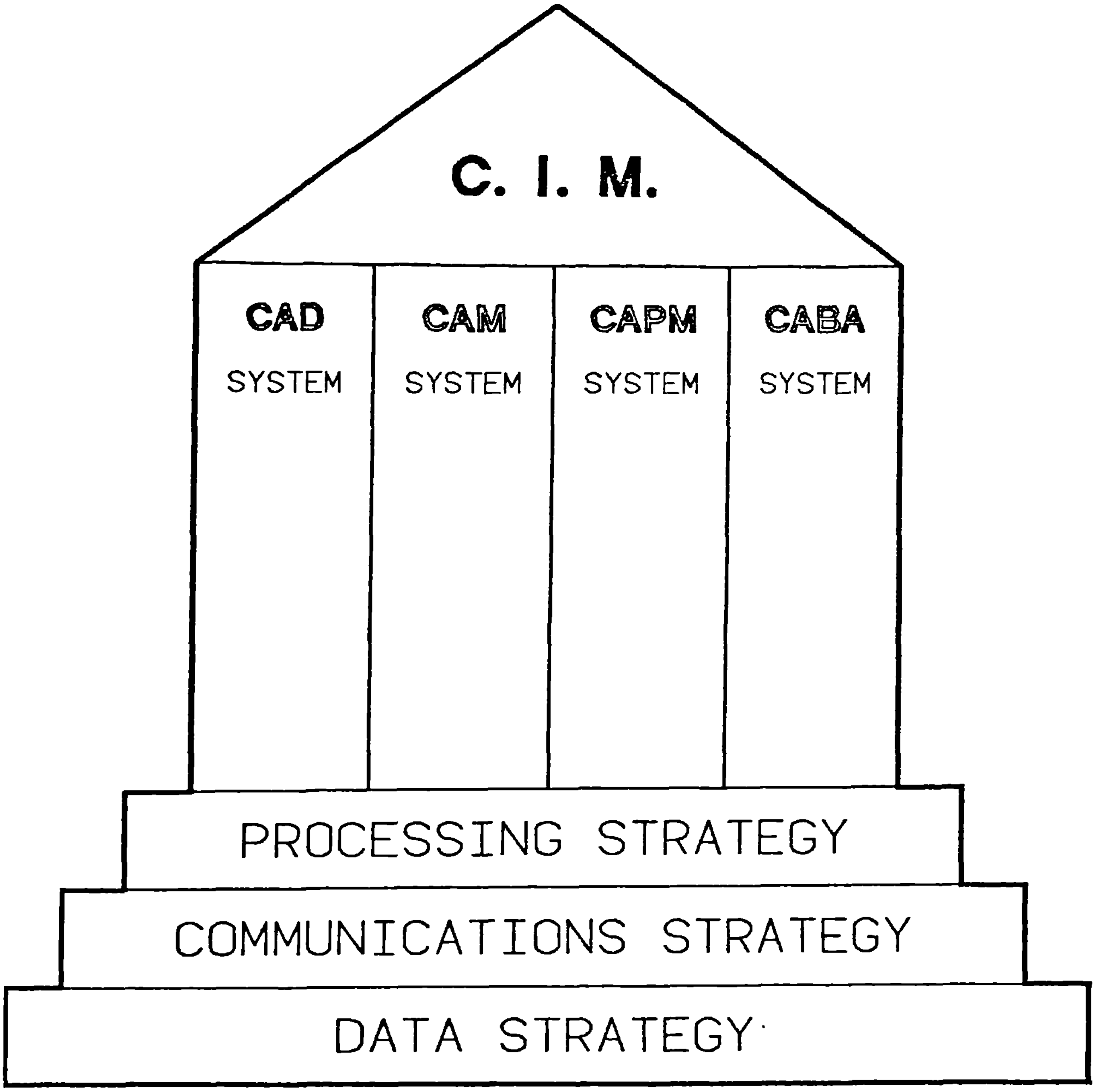


FIG 18 THE FOUR BASIC SUBDIVISIONS OF C.I.M.
AND THE SUPPORTING STRATEGIES.

engineering to manufacturing, describing the shapes of the constituent parts of the product, the materials from which they are to be made, and the manufacturing processes and assembly instruction which may be mandatory to ensure the integrity of the design.

Computer Aided Manufacturing

CAM receives numerical control programmes generated at the design stage to drive a variety of NC machinery at the shop floor such as robotics, AGV's etc. It includes all machine tool control systems, component inspection and testing, support services such as factory maintenance and computer aided storage and transportation.

Computer Aided Production Management

This includes computer aided production planning which covers the forecasting of long term resource demands involving simulations of the manufacturing processes, the planning of production requirements based on the dated demands for end products according to current order book, the short term scheduling of orders for manufacture using associated material and resource constraint profiles and the real time activity of selection and sequencing of the next manufacturing process when a required manufacturing resource becomes available.

It also includes Computer Aided Production Engineering which covers Computer Aided Process Planning and process selection, plan layout and workpiece modelling with an interface to computer simulation of plant operations.

Computer Aided Business Administration

This includes areas such as finance, purchasing, administration, accounts, payroll, personnel, marketing and corporate planning.

c) The Three Critical Strategies

The Processing Strategy

The processing strategy concerns the manner in which processing is to be distributed between a large number of different processing devices. Such processing devices will almost certainly include a 'centralised' mainframe computer, a large number of mini and micro computers of greatly varying size and type, programmable logic control units and a large number of 'intelligent' and 'non-intelligent' devices from robots to simple relays.

The Communications Strategy

The communications network for a computerised manufacturing system must be such that all transmissions can take place within the required time frame.

Between both processes communicating using the network, a protocol must be chosen. For an integrated manufacturing system, all processes communicate at least conceptually, over the same net. A communications protocol has two aspects: the general formal, which may exist on each level and the particular format that two processes have agreed upon.

In addition to these two aspects, tools are needed to map a particular format onto a general format, so that designers need to worry only about application formats.

The Data Strategy

The data strategy concerns the design and distribution of the total database, such that all processors and procedures have access to consistent and authorative data values - particularly in reference to items of data that are of common interest to many different manufacturing functions and activities.

Due to substantial differences in the way in which man sub-systems will need to process basic data, certain data will have to be replicated in several different files, of different kinds. The design rules must ensure that all copies of each data item are consistently maintained to correspond with the 'master' occurrence, eg 'latest' modification level, 'current' stock level, 'current' prices, etc.

d) The FAST Pyramid

Within the working envelope of a robot exist a number of workstations where discrete operation processes are performed, possibly on different products. A number of workstations where the robot may be travelling to and from, are termed the workcell. A number of workcells integrated together constitute an 'island of flexible automation'. A number of islands constitute the plant. This sequence also illustrates the hierarchy of control which needs to be applied to achieve CIM in shipbuilding. (See Figure 19). It divides the complete control system into levels corresponding to the tasks performed at each level.

Machinery/Process Level

The first level at the base of the pyramid focuses on machinery and processes. This is where the controls directly interface to the elements of production. This first level deals with the direct interface to the actual elements of production. Interface devices at this level include such simple elements as limit switches, push buttons, conveyor sensors, temperature sensors, etc. Control devices may include relays, starters, remote input/output (I/O) modules, etc. Output devices can include such things as pilot lights, alarm contacts, actuators, etc.

Devices used at this level of control have similar characteristics. They are designed to be highly reliable in the rugged shipyard environment.

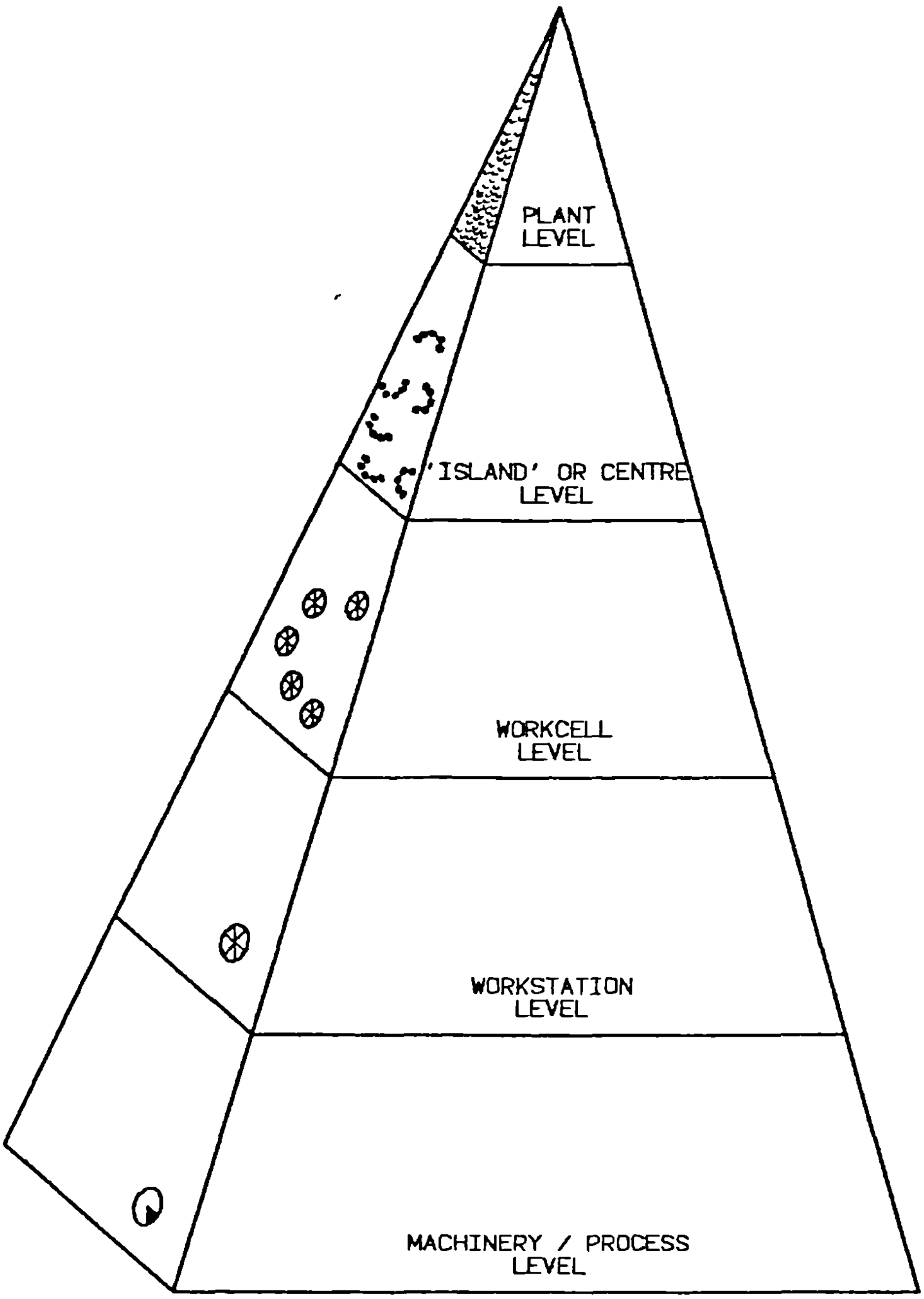


FIG 19 THE F.A.S.T. PYRAMID APPROACH TO AUTOMATION CONTROL

They are usually single-purpose devices with little or no intelligence and have a very narrow span of control.Functions performed at this level include simple on-off control, simple indicator output and other minor interface functions.

Workstation Level

The workstation level accounts for real-time equipment controllers usually dedicated to controlling the activities of a single station device such as a machine tool, or a small process device like an inspection station, and so on.

This is the domain of programmable controllers, computer numerical controls and other intelligent devices which interface to the sensors and output devices of the first level and co-ordinate their operations. From a functional point of view the workstation level includes capabilities to sequence, monitor, collect, compile and store limited data; to position mechanical devices and control their speed, acceleration, torque, etc and to control analog process variables such as pressure, temperature, etc.

For example: start grinding wheel motor if the sensor at the robot's gripper has been activated, or start robot programme if all sensors at the tip of the hydraulic clamps have been activated.

Or if sensor at robot's gripper reaches a set level, they perform a certain part of the robot's programme, a pre-set amount of times and so on. Operator interfaces may also be included such as CRT screens, printers, operator panels, etc.

Workcell Level

At the workcell level, co-ordination of multiple stations is taking place. At this level, large programmable controllers

(PC's) act as supervisors. Back-up becomes important and a back-up PC continuously monitors the input status. If the primary unit should fail, provision should be made for automatic transfer to a standby control system. Another feature of such large PC systems should be its report generation capability. Through report generation, an operator can be prompted for response. Based on the response, the system can change parts, programmes, take alternative action or other modifications to the process.

'Island' or Work Centre Level

The island level is concerned mainly with scheduling, production and management information. Multiple cells are controlled and scheduled production is balanced with available capacity. The man/machine interface here is basically a supervisory device. Report generating capability will be another role where for example data and its changing relation with time can be accessed and graphs are made.

Both at the workcell and island level the user is no longer involved in the control of real time devices or in operator interface to the shop floor. Rather he is concerned with the scheduling of production and management information for decision support systems.

Plant Level

The plant level is the domain of the plant MIS function. At this level management directs overall planning, execution and control of operations according to current order books.

Although planning in the FAST pyramid of control takes place from top to bottom, implementation is going the opposite way starting from the bottom level and reaching the top (see Figure 20).

The FAST pyramid of control superimposed on the 'CIM for shipbuilding' idea, is illustrated in Figure 21 with the CAM system of CIM used as an example.

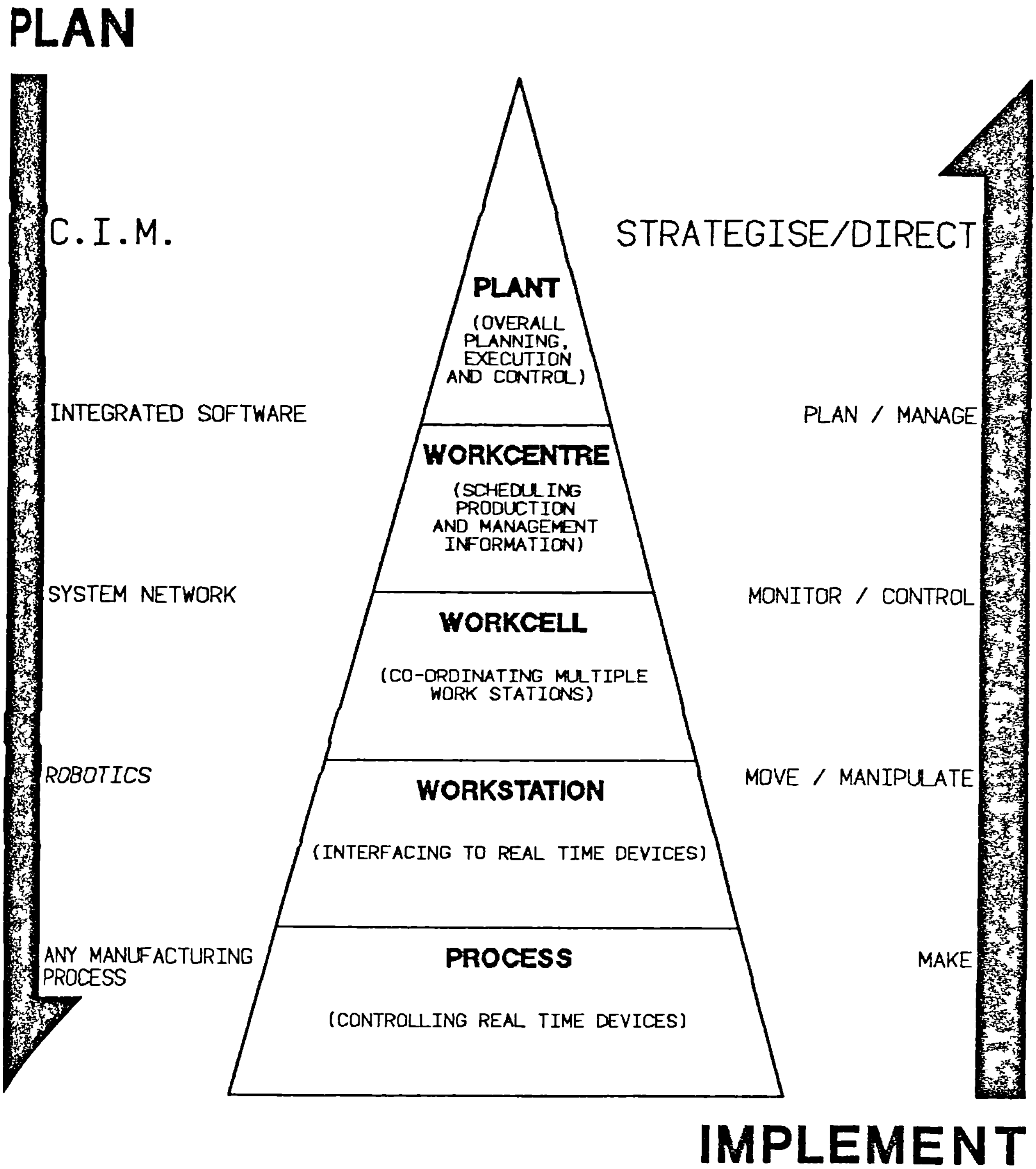


FIG 20. PLANNING AND IMPLEMENTATION OF THE FAST PYRAMID OF CONTROL

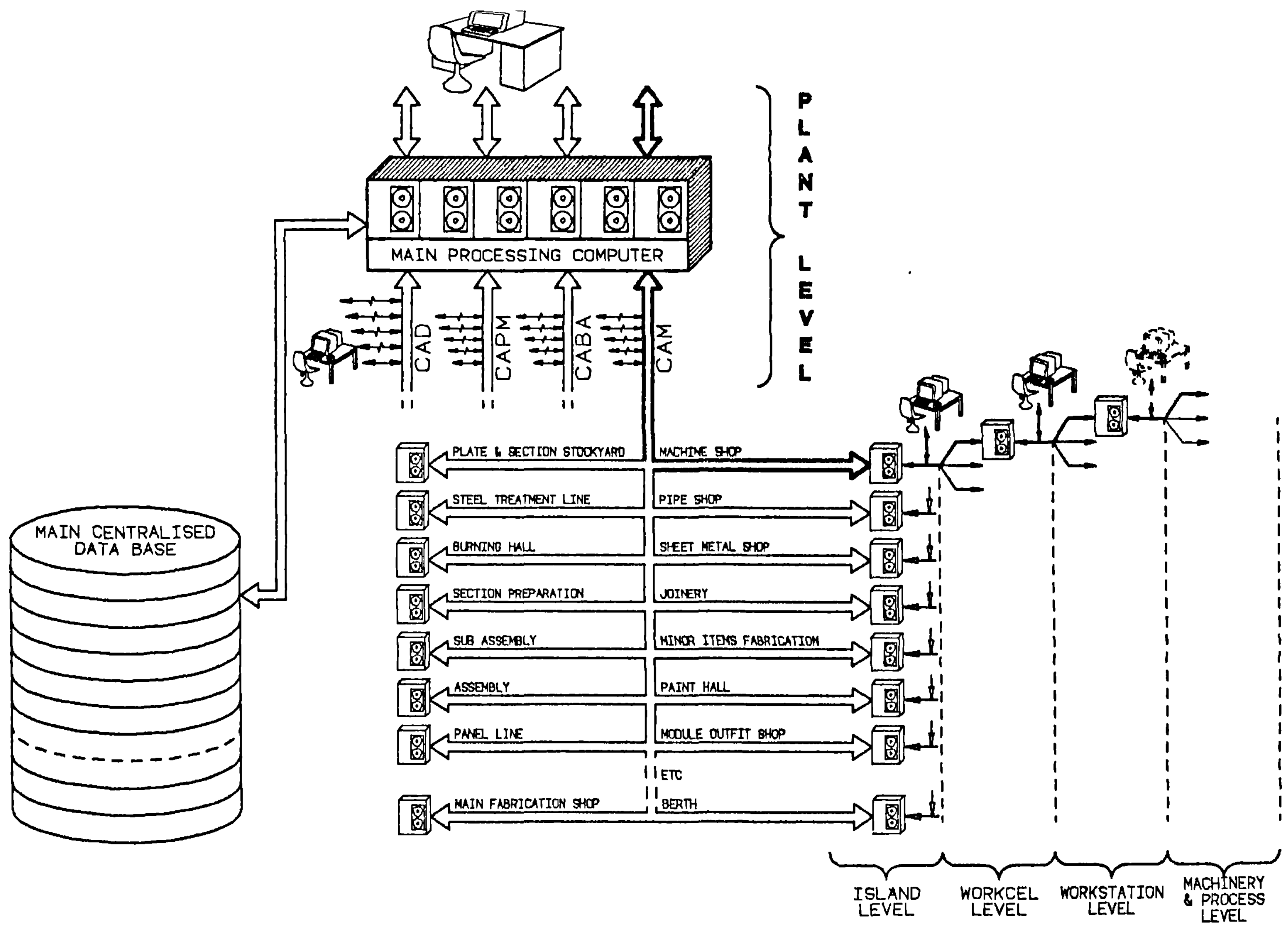
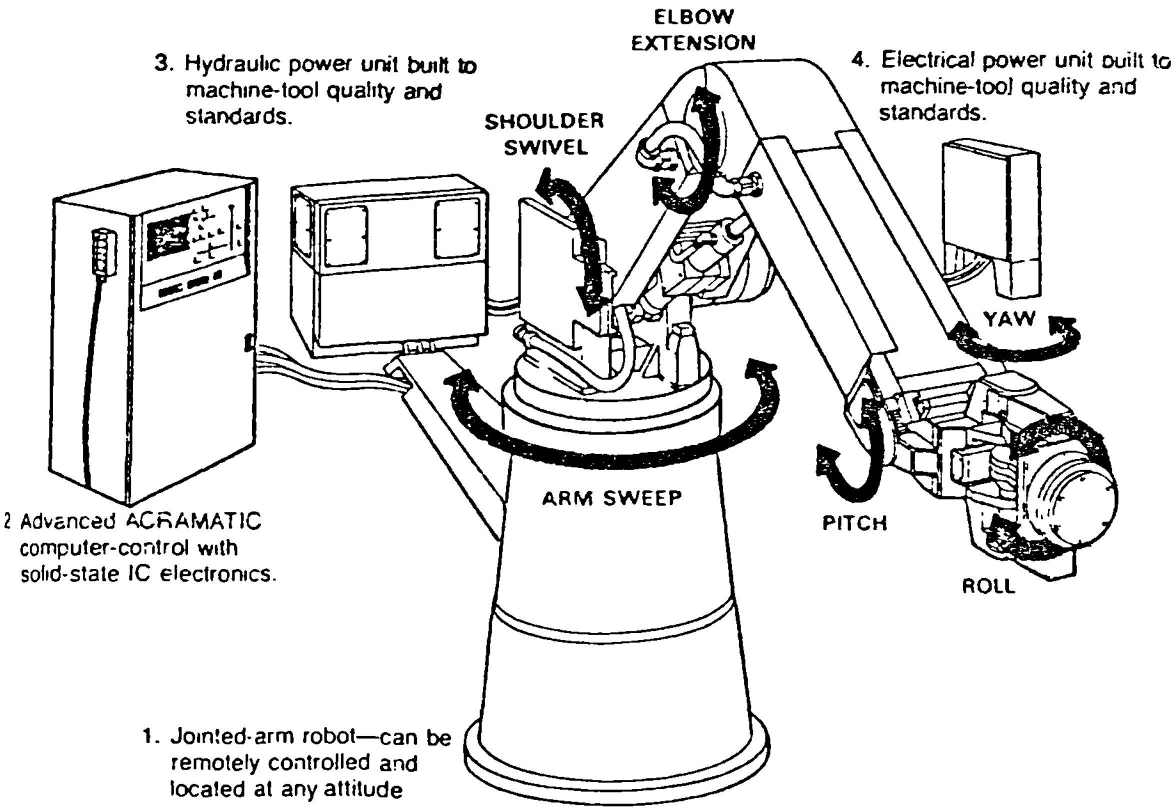
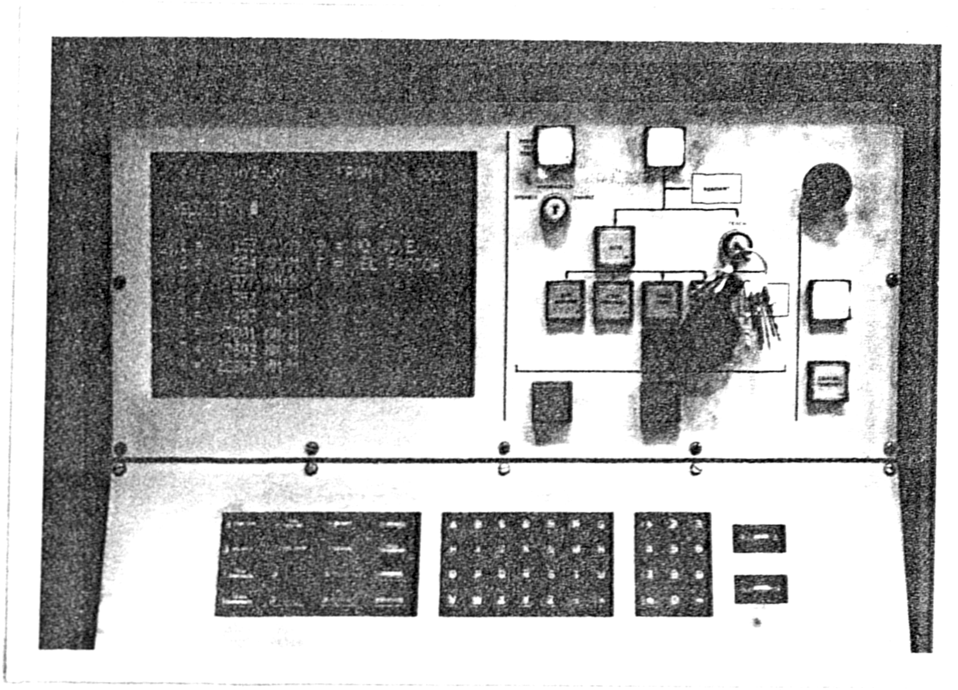


FIG 21 C.I.M. IN SHIPBUILDING (WITH THE FAST PYRAMID APPROACH TO AUTOMATION CONTROL)

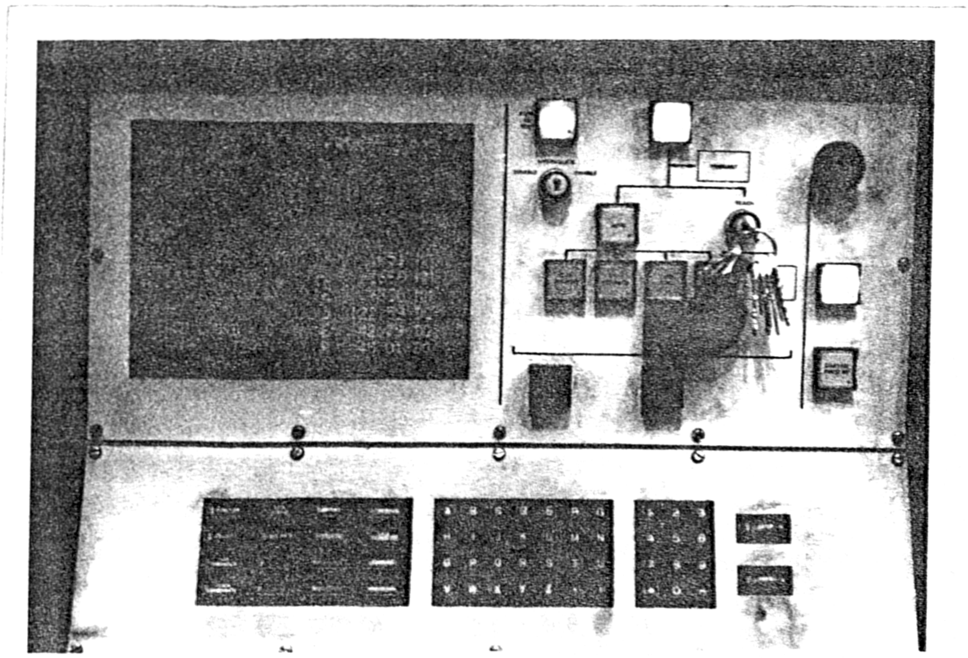
APPENDIX 5 THE CM-T3-566 ROBOT AT SHS LTD

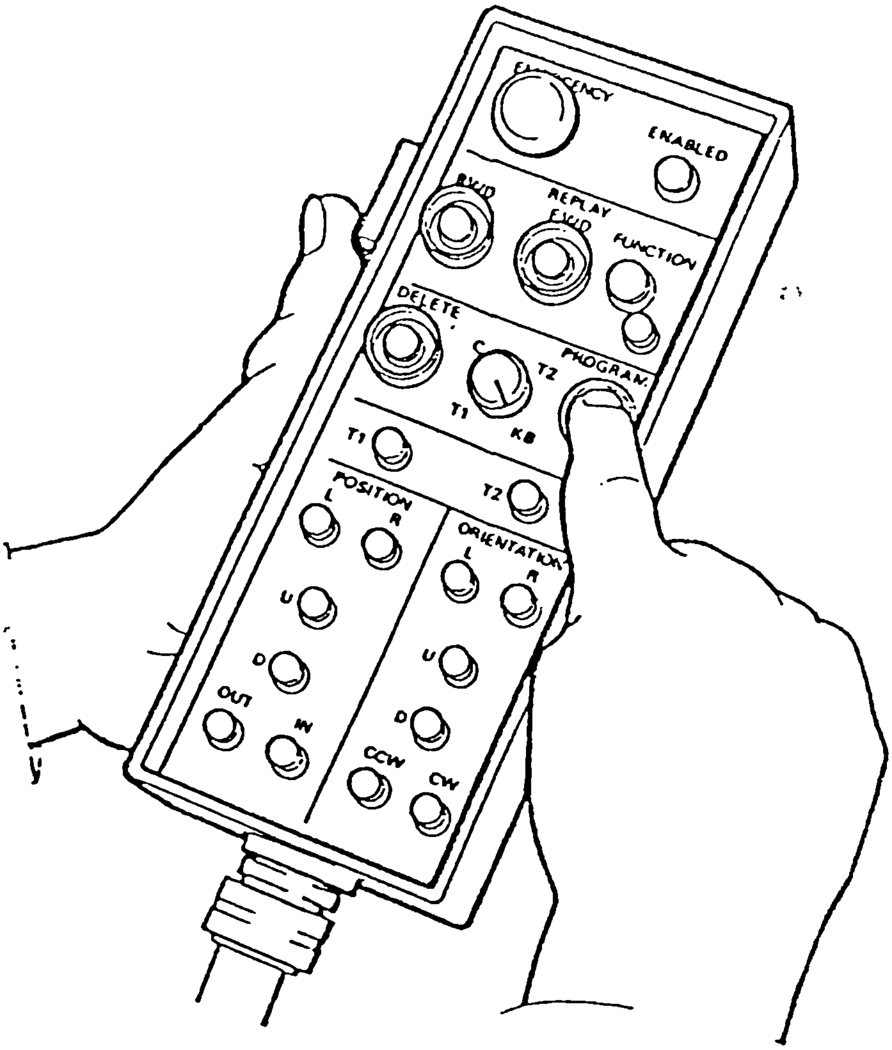
The following pages illustrate the CM-T3-566 robot as used at SHS Ltd with few photographs and a manufacture information leaflet.



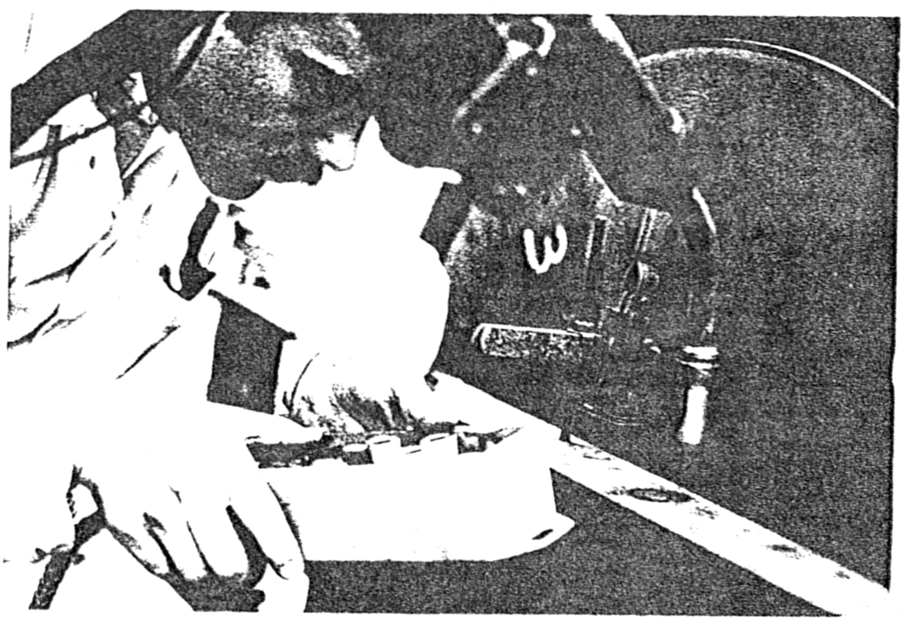


THE KEYBOARD AND CRT OF THE
COMPUTER CONTROLLED ROBOT CONSOLE
SHOWING THE RANGE OF VELOCITIES (ABOVE), AND THE COORDINATES AND WELDING PARAMETERS OF A POINT IN SPACE (BELOW)

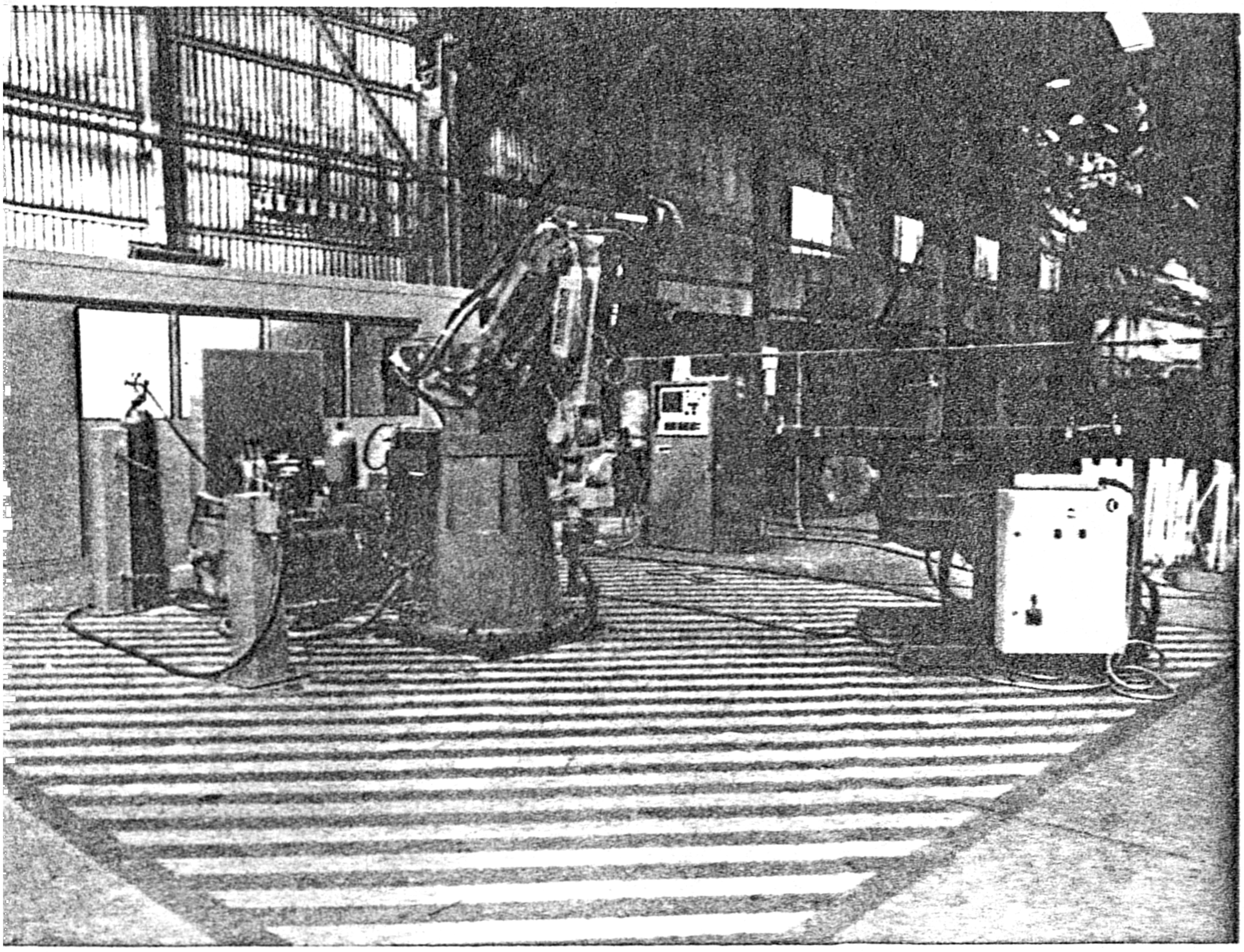




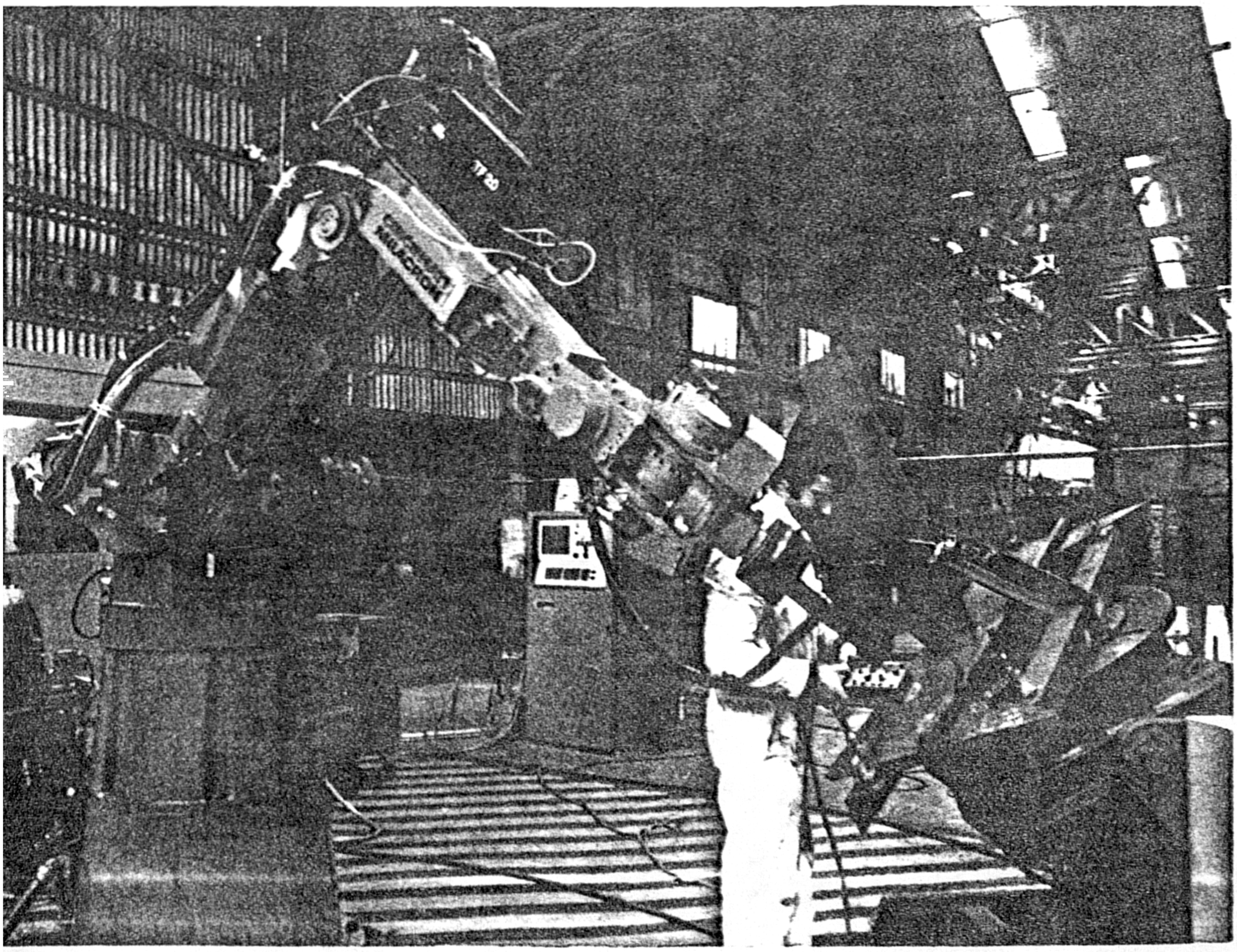
T3 teach pendant control.



Robot operator programming the correct
torch orientation with the teach pendant.



The CM-T3-566 robot with associated equipment at Swan Hunter Shipbuilders - Wallsend shipyard.

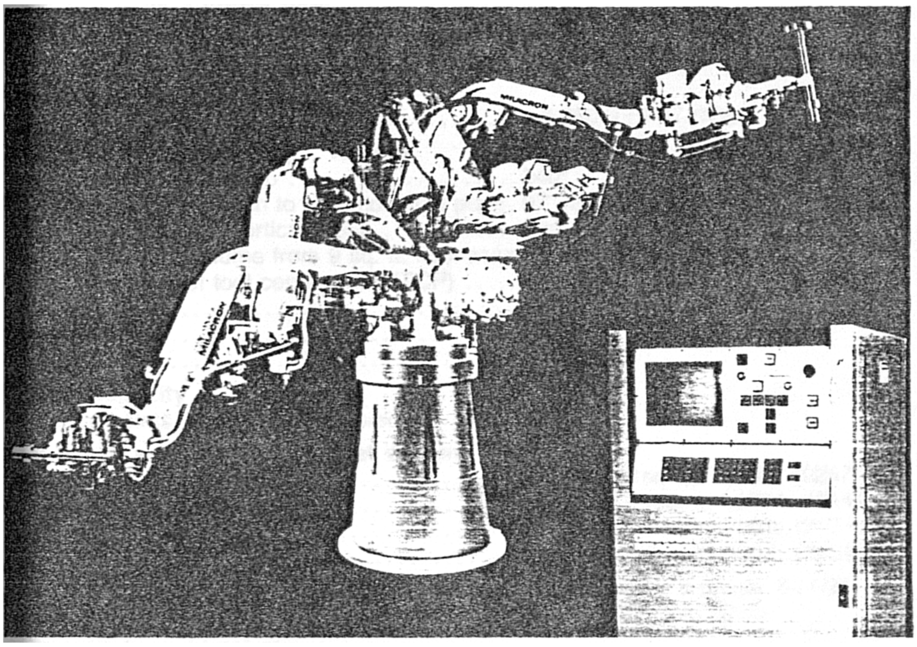


Programming a welding sequence.

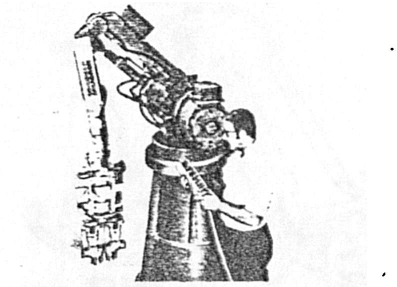
CINCINNATI
MILACRON

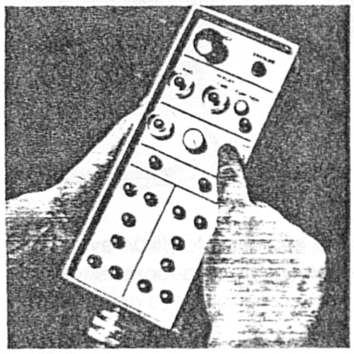
T³ Computer-Controlled Industrial Robot (Standard Model)

Offers the durability, reach, freedom of motion and strength to do the most grueling job around the clock no matter how hazardous the working conditions.



T³ Computer-Controlled Industrial Robot ... THE TOMORROW TOOL. Today. ... with Cincinnati Milacron ACRAMATIC Computer Robot Control ... Stacks—Tracks—Packs—Picks—Puts—Searches—Feels—Finds—Reasons





Portable, light-weight, hand-held teach unit provides convenient means of programming the robot

The T³ is a simple, solidly built 6-axis computer-controlled industrial robot. It combines a heavy base casting with strong shoulder, upper arm, and forearm fabrications for total structure ruggedness and stability.

Unique Jointed Arm Construction

Exclusive with T³ this unique 6-axis jointed-arm construction provides the added flexibility the robot needs to get down into difficult-to-reach places. Duplicating much of the dexterity of the human arm/hand, T³'s jointed arm is tougher by far, well able to withstand the most hostile industrial environment to get the job done...day in, day out ...with astonishing reliability. Sealed-for-life lubrication and rotary joints with large anti-friction bearings result in minimal wear and virtually maintenance-free operation.

Powerful Direct Drives

Each of the six jointed-arm axes of the T³ is direct driven by its own powerful and independent electro-hydraulic servo system. Five of the axes use compact rotary actuators built-into each joint and one axis is driven by a pivoted cylinder. This construction gives the robot a backlash-free system capable of the high torque, speed and flexibility needed to handle hefty payloads with up to 240° of movement. Tests prove that T³ can easily lift 100-lb. loads three shifts a day at speeds up to 50 ips.

Precise Position Feedback

Each axis also has its own position feedback device consisting of a resolver and tachometer to assure repeatable and precise arm positioning. Repeatability to any programmed point is $\pm 0.050''$.

Cost-Effective Straight-Line Motion

The powerful logic of the robot's reliable ACRAMATIC minicomputer-based control provides infinitely variable 6-axis positioning and controlled path (straight-line) motion between programmed points. All of T³'s jointed-arm motion is referenced to the Tool Center Point (TCP) ... a discrete point at a selectable distance from the arm where the tool meets the work. All TCP moves are made in a cost-effective straight-line.

"Teaching" T³ Is Fast and Easy

No computer experience is needed; no calculations are involved — just knowledge of the physical job to be performed. A lightweight, hand-held unit lets the operator program the T³ from the best vantage point. Optional offset branching further simplifies the teaching function in that a series of repetitive moves can be "taught" as a subroutine just once. Jobs requiring lengthy teaching sessions or recurring jobs can be easily committed to the robot's semiconductor memory and stored on the optional tape cassette for future use.

Wide Application Flexibility

Easy to program ... to tool ... to use with pallet-oriented work ... the T³ can smoothly track moving lines, and while tracking, put welds in precisely the right spots, or pluck an assembly out of a moving welding jig and hang it high overhead on a moving conveyor, tracking the two continuously moving lines independently of one another. T³ can reach with ease into tight places at multiple levels, with one hand or two, at virtually any angle, anywhere within 1000 cu. ft. of volume—inside an auto chassis, under a hood, down deep into boxes, or straight out 97" to load one or more machine tools, forging presses or injection molding machines.

Industrial Robot Division,
Cincinnati Milacron Ltd.,
Caxton Road
Bedford MK 41 OHT, England.
Phone 0234-45221

THE TOMORROW TOOL (T^3) Computer-Controlled Industrial Robot

Reliable ... smart ... swift ... strong ... spacesaving ... it offers unique application flexibility

Specs for basic T^3

Load Capacity
Load 10" (254 mm) from tool mounting plate ..... 100 lb. (45 kg)*

Number of Axes, Control Type
Number of seroved axes (hydraulically powered) . 6
Control type .... Controlled path at tool center point

Positioning Repeatability
Repeatability to any programmed point .... ±0.050" (±1.27 mm)

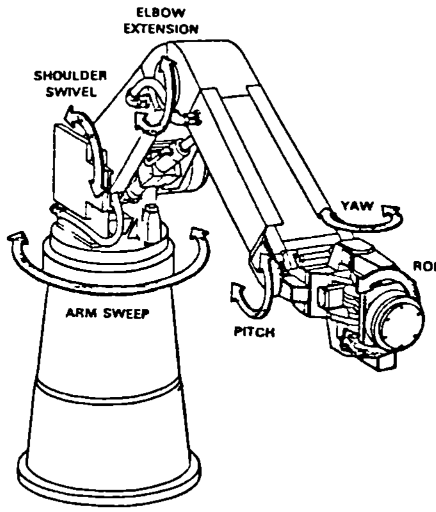
Jointed-arm Motions, Range, Velocity
Maximum horizontal sweep .... 240°
Maximum horizontal reach to tool mounting plate . 97" (2464 mm)
Minimum to maximum vertical reach .... 0 to 154" (0 to 3911 mm)
Maximum working volume from 9 sq. ft. floor area 1000 cu. ft. (28.32 cu. m.)
Maximum velocity of tool center point (TCP) ..... 50 ips (1270 mmps)
Pitch .... 180°
Yaw .... 180°
Roll .... 270°

Memory Capacity
Number of points which may be stored 450**

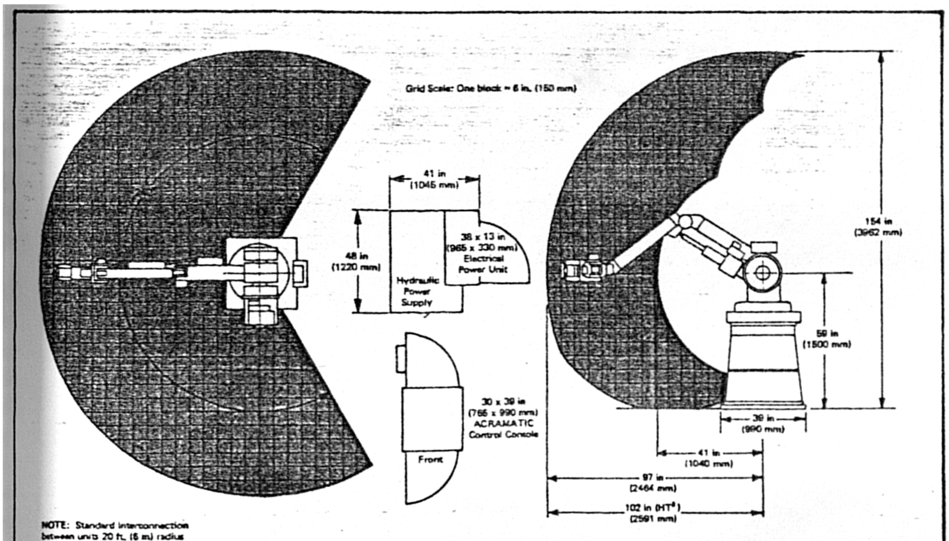
Floor Space and Approximate Net Weight
Robot .... 9 sq. ft. (0.8 sqm); 5,000 lb. (2267 kg)
Hydraulic power supply .... 17 sq. ft. (1.5 sqm); 1,200 lb. (544 kg)
Electric power unit .... 3.4 sq. ft. (0.3 sqm); 700 lb. (317 kg)
ACRAMATIC control console .... 8.3 sq. ft. (0.8 sqm); 800 lb. (365 kg)

Power Requirements .... 230/460 volts, 3 phase, 60 Hz†
Environmental Temperature* .... 40 to 120°F (5 to 50°C)

*Consult factory for special application
**Additional memory available
†50 Hz available



Maneuverability of the 6-axis jointed-arm increases productivity of all stationary-base line tracking operations



Basic range and floor space drawings

Check These T^3 Advantages

- ✓ Strong, Highly-Maneuverable 6-Axis Jointed Arm
- ✓ Easy-to-Use Hand-Portable Teach Unit
- ✓ Simple to Interface with Peripheral Equipment or External Computer
- ✓ Unique Arc Welding and Tracking Options
- ✓ Infinitely Variable 6-Axis Positioning with Coordinated Straight-Line Motion
- ✓ Built-in Diagnostics with CRT Display
- ✓ Superior Software Flexibility
- ✓ Computer Stored Program
- ✓ Superior Turnkey Adaptability

All illustrations and specifications contained in this literature are based on the latest product information available at the time of publication. The right is reserved to make changes at any time without notice in prices, materials, equipment, specifications, and models, and to discontinue models. In addition, all nominal dimensions are subject to an allowable variation of ±0.25-in. (6 mm), unless otherwise specified.

WARNING. In order to clearly show details of this machine, some covers, shields, doors, guards or other protective devices have either been removed or shown in an "open" position. All such protective devices shall be installed in position before operating this machine. Failure to follow this instruction may result in damage to machine components and/or personal injury.

CINCINNATI MILACRON

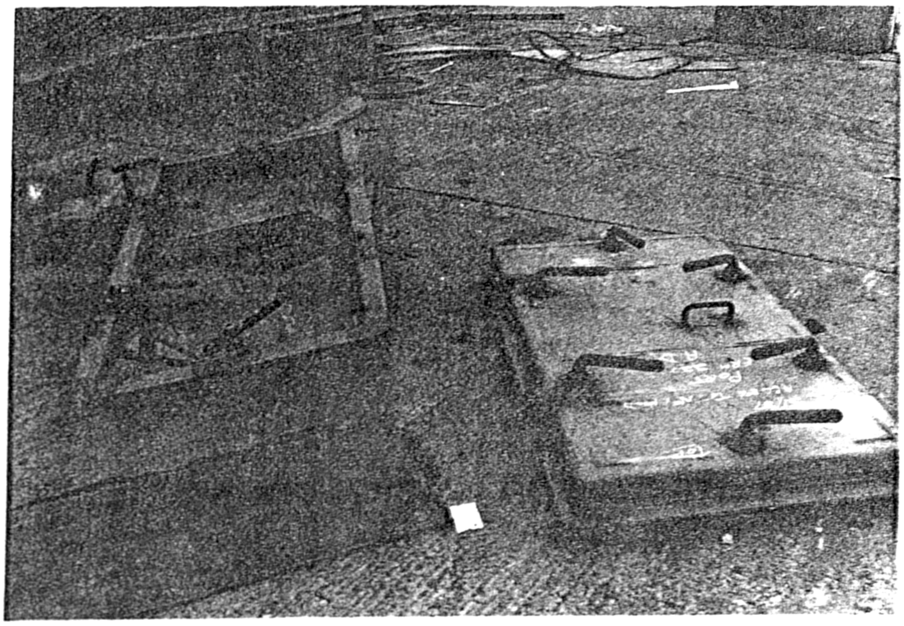
Publication No. A-255-6

Printed in U.S.A
10M 281 OZ

TYPICAL APPLICATION EXAMPLES

APPENDIX 6

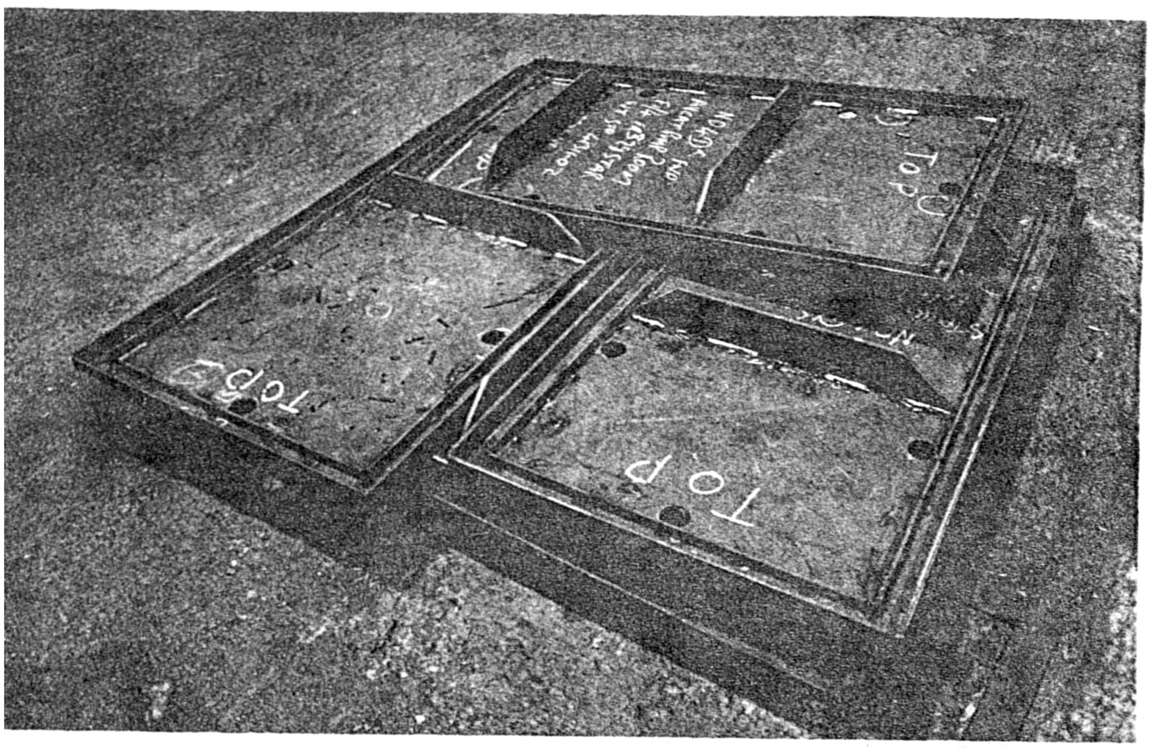
The following pages, few photographs are shown, to illustrate some of the typical applications for a minor steelwork and outfit items robotic welding workstation.

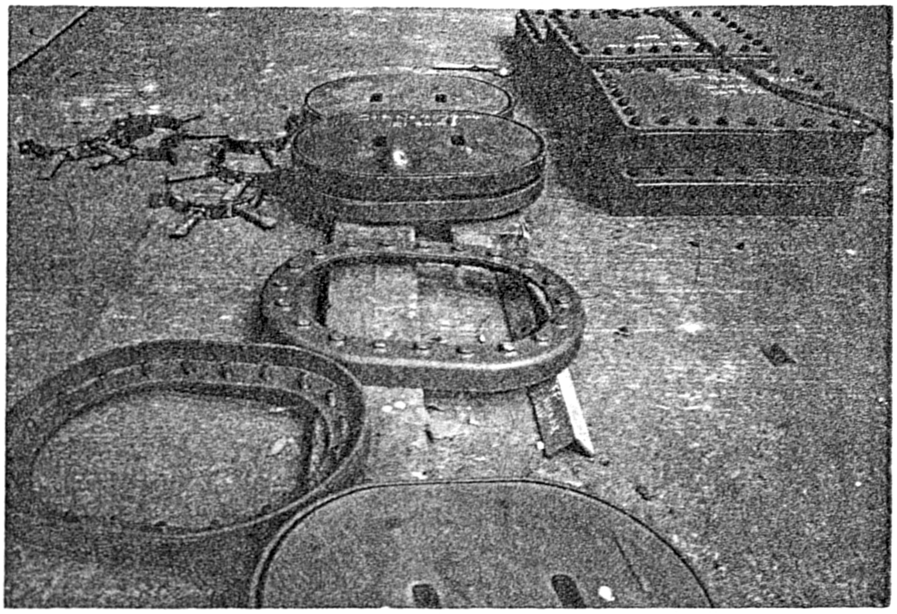


STEEL DOORS

Above: completed

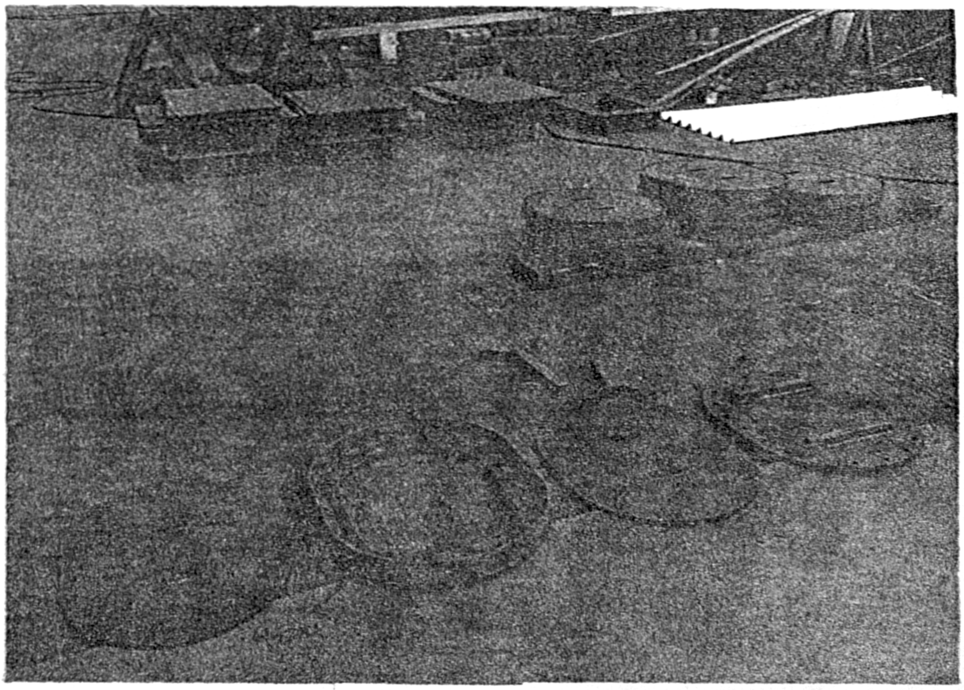
Below: covers

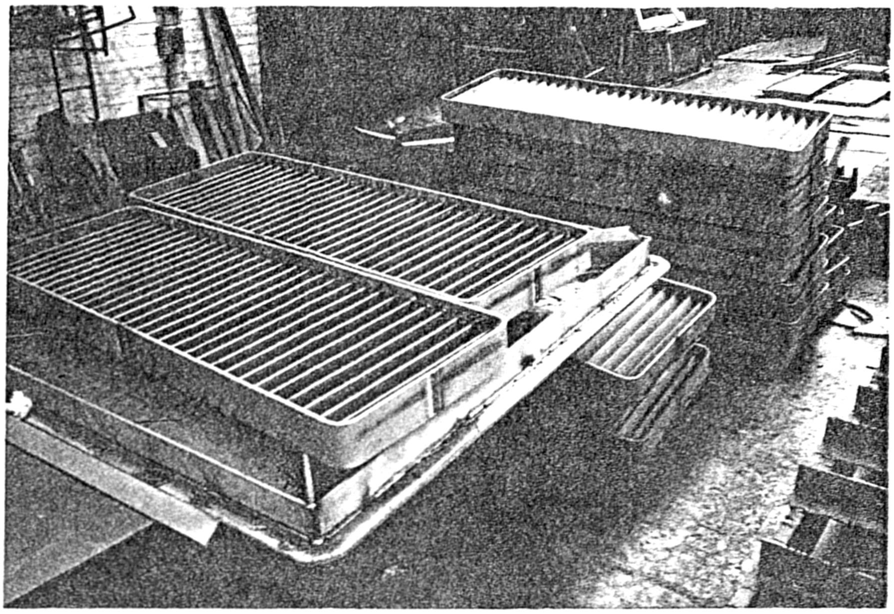




WATERTIGHT FLUSH MANHOLES
(in foreground of both photographs)

ANGLE BAR MANHOLE COAMINGS
(in background of both photographs)

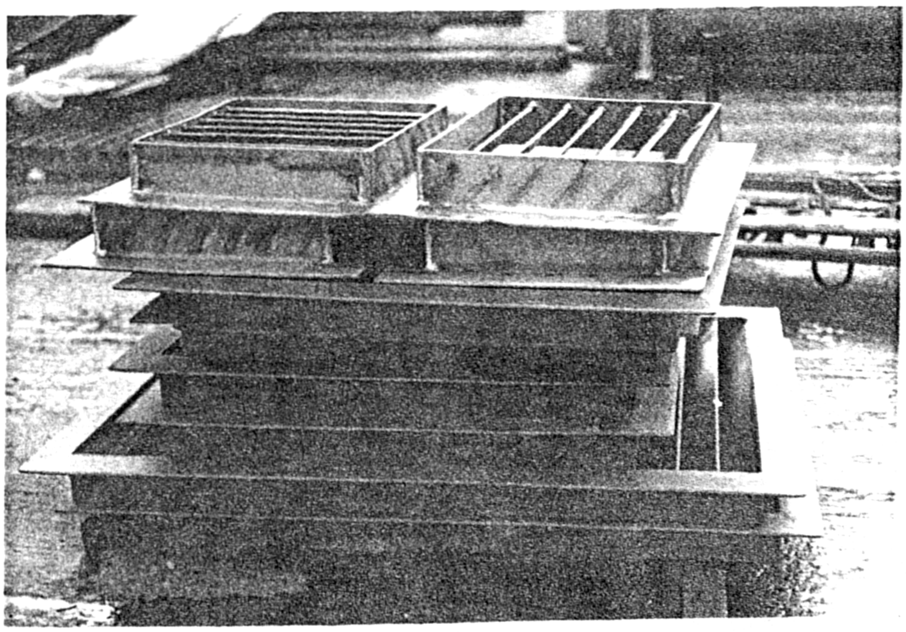


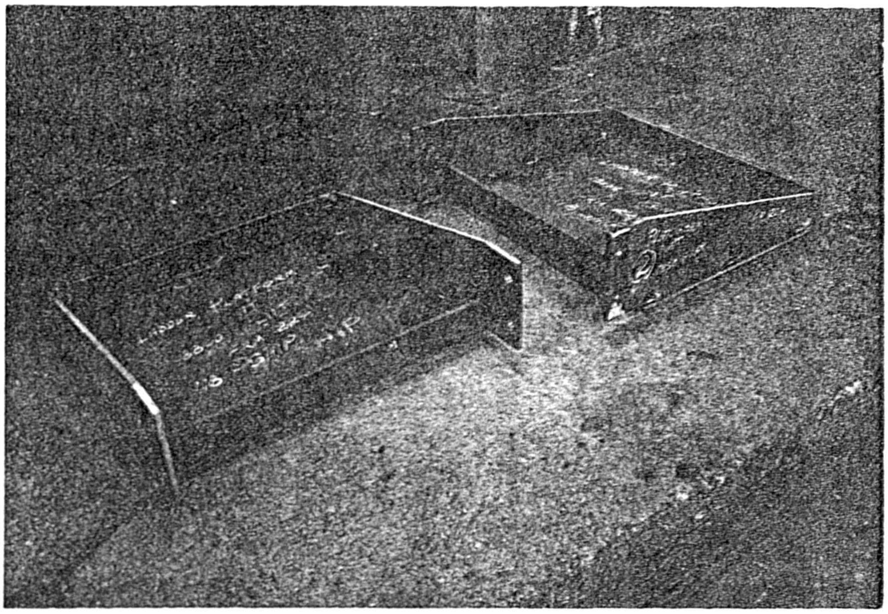


JALOUSIES

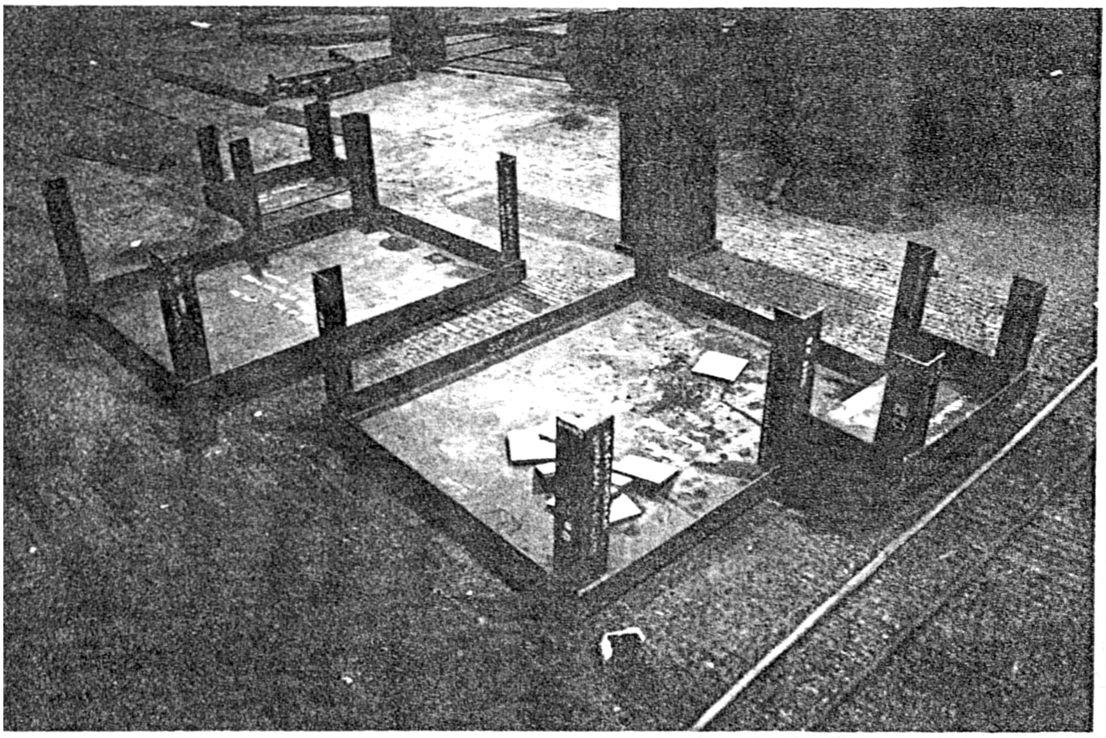
ABOVE: FLAT BAR COAMINGS

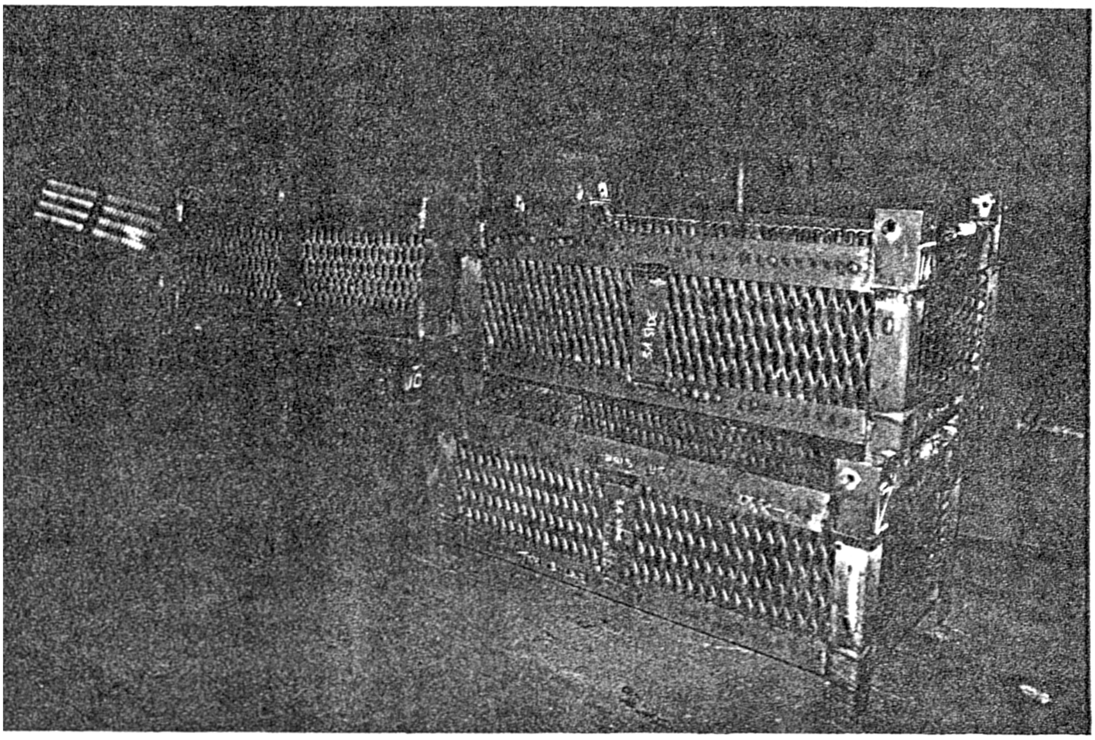
BELOW: ANGLE BAR COAMINGS



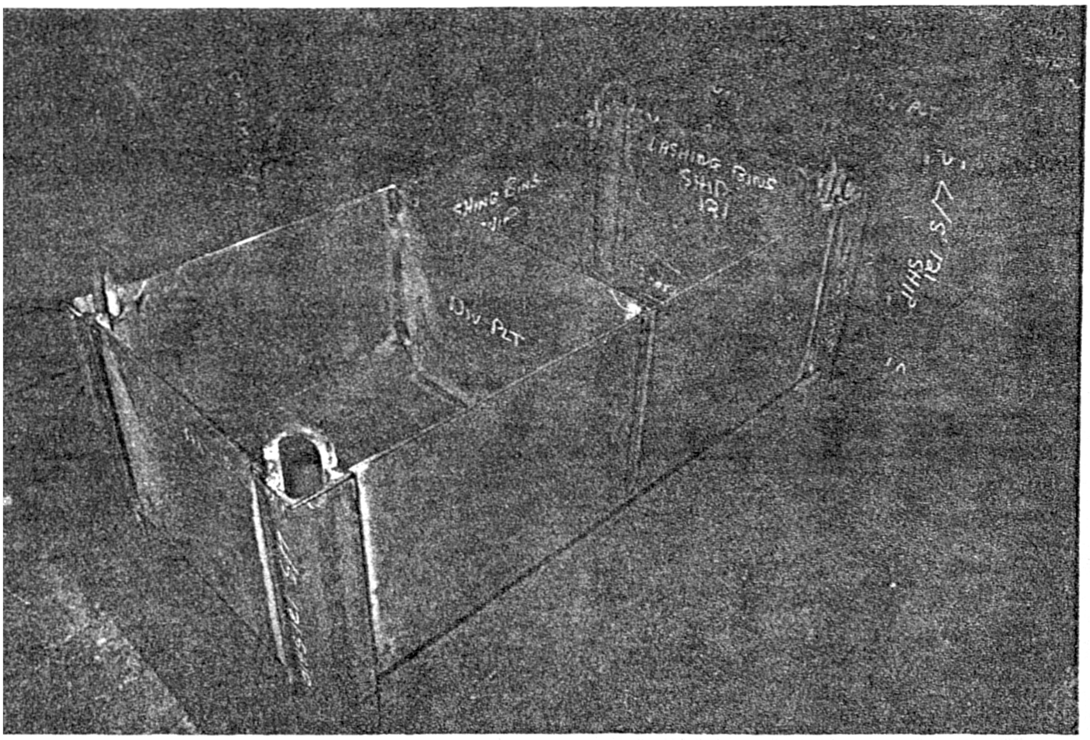


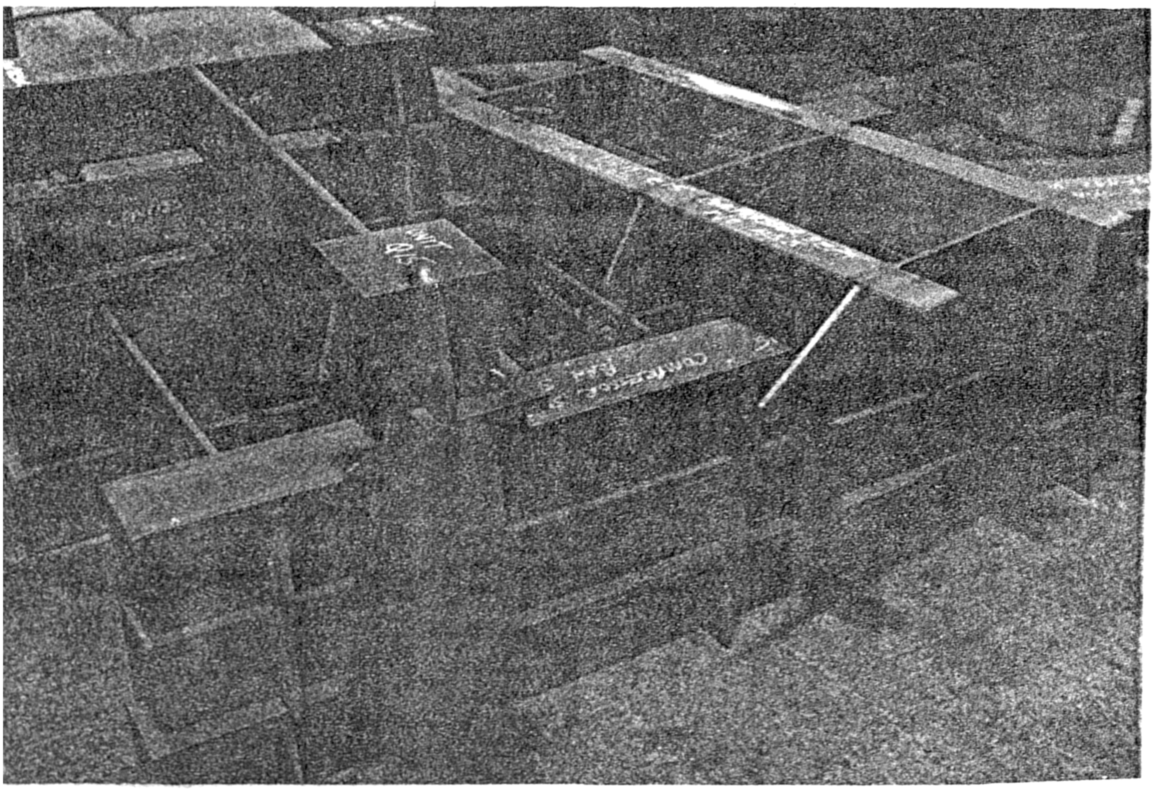
SMALL PLATFORMS



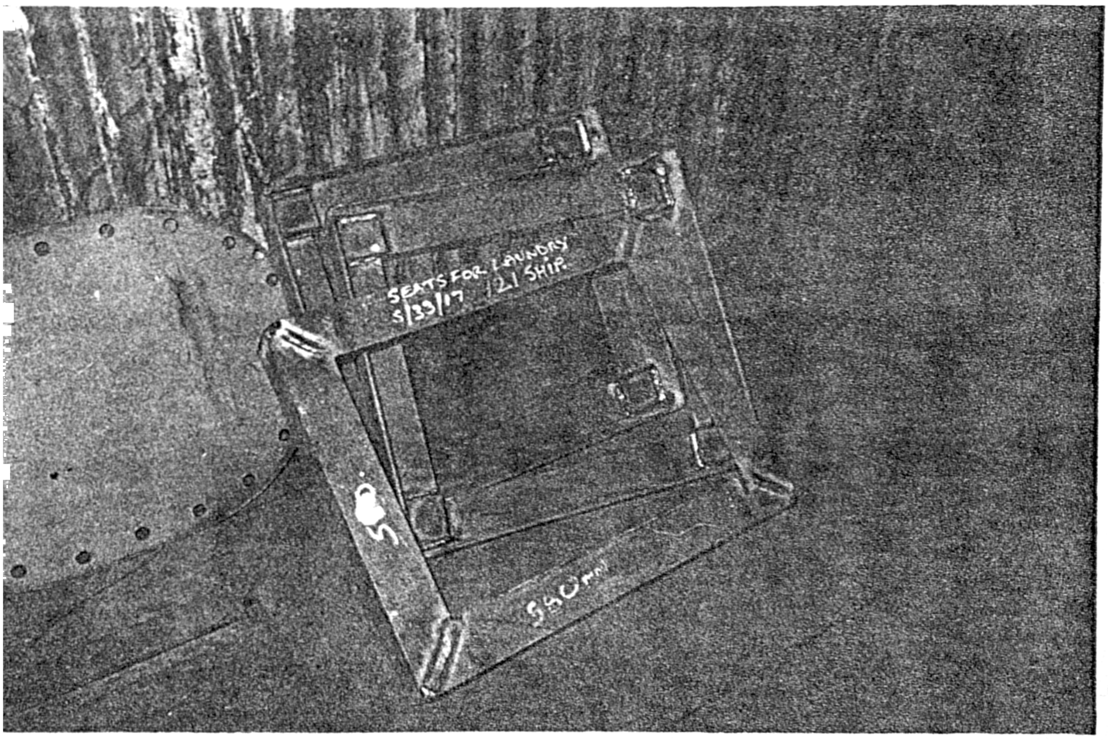


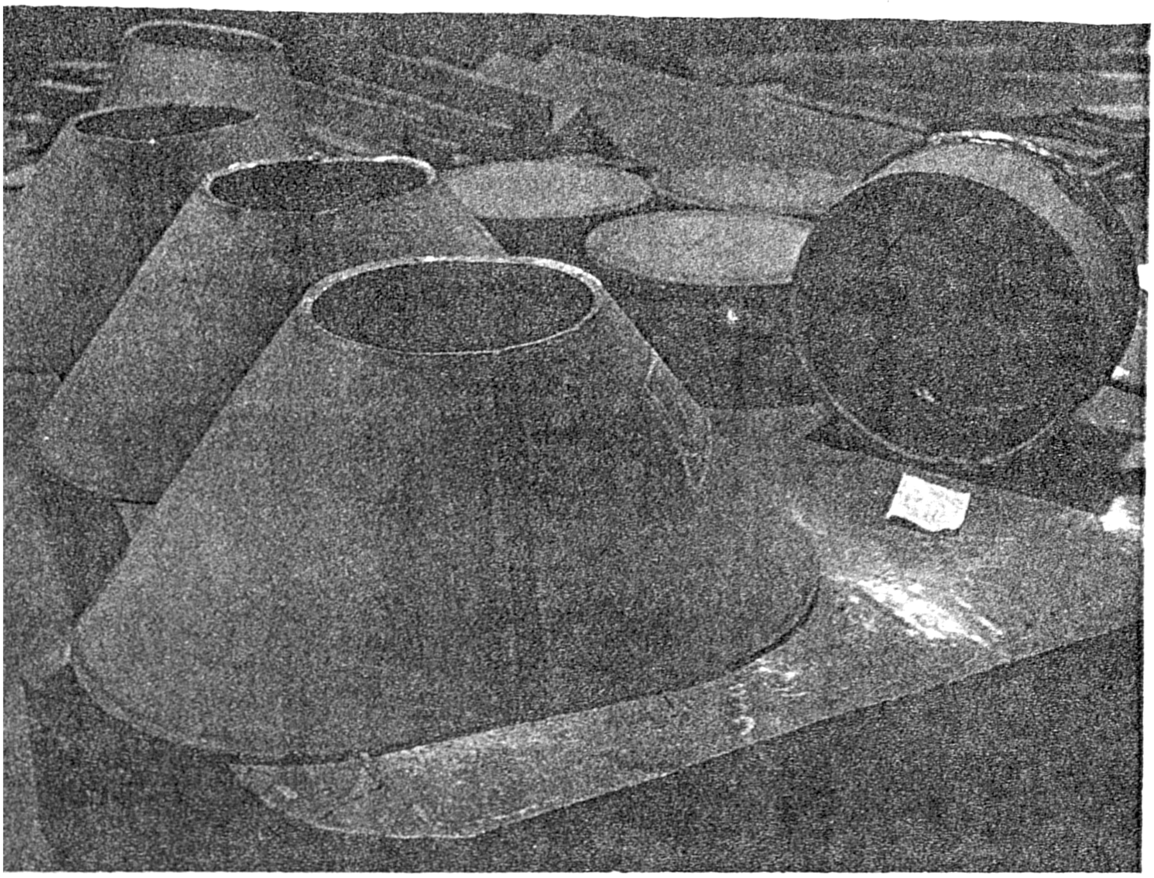
LASHING BINS





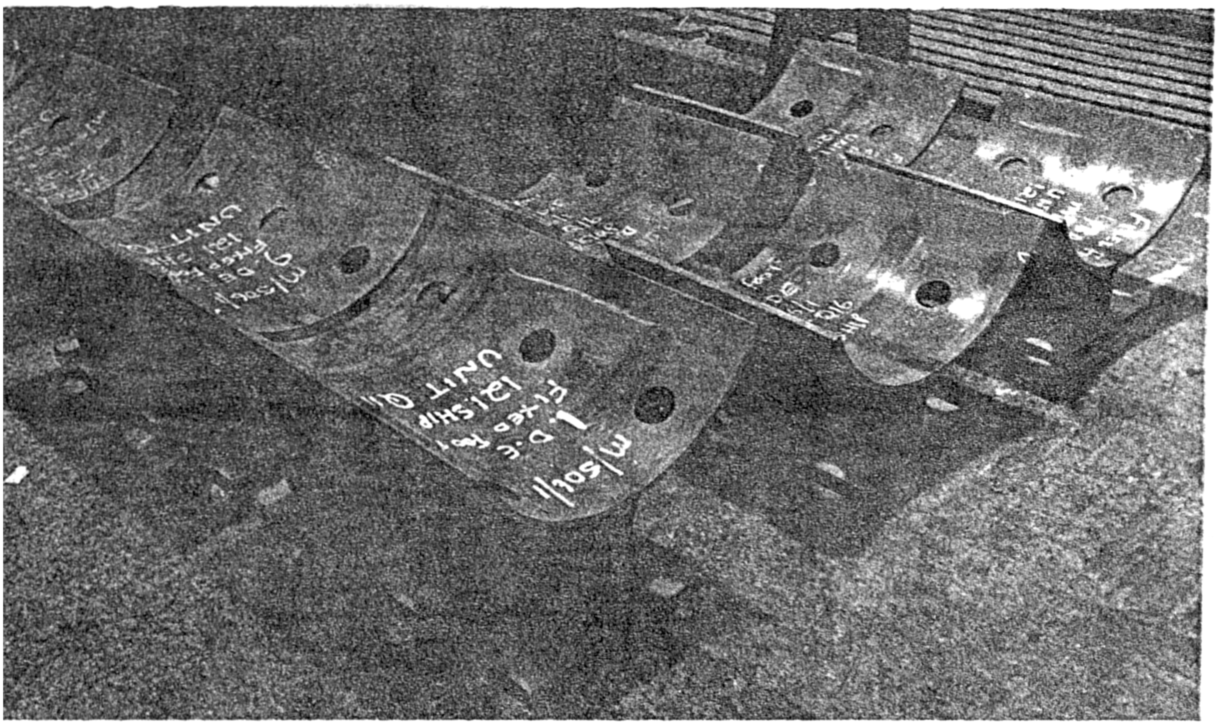
COMPRESSOR & LAUNDRY SEATINGS

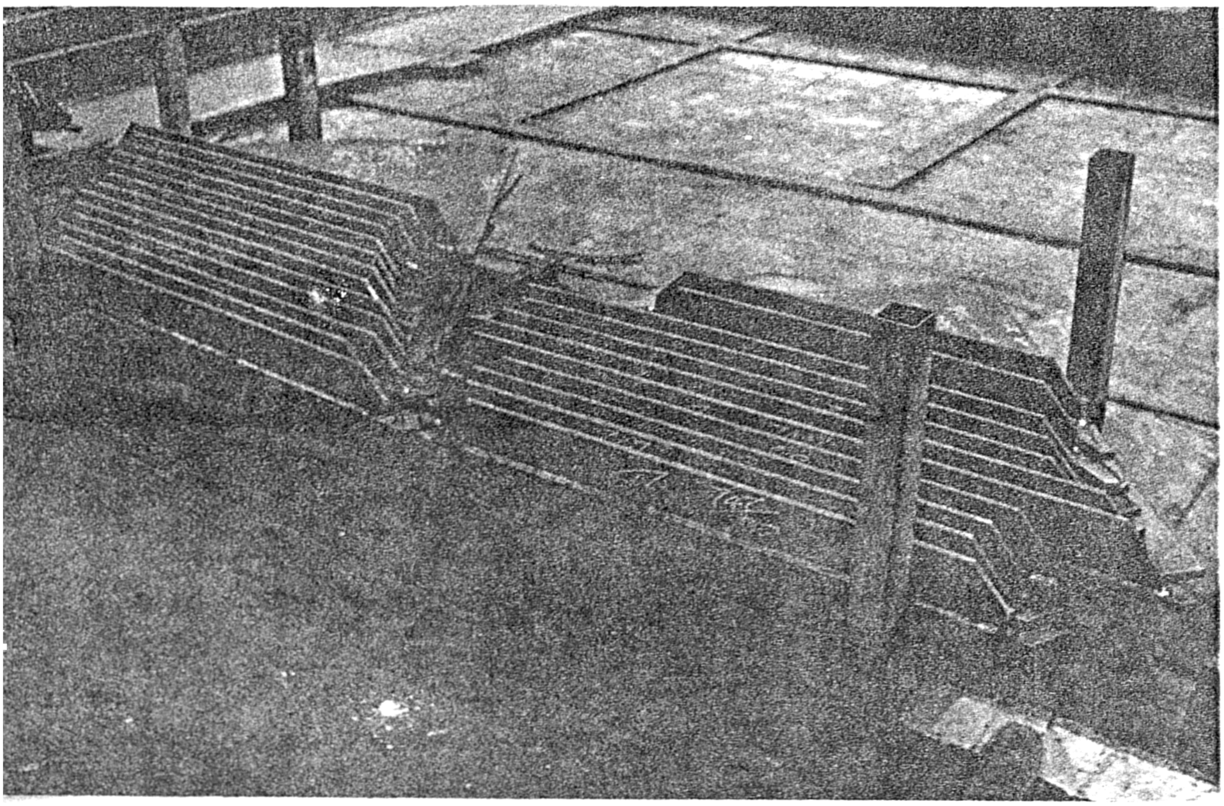




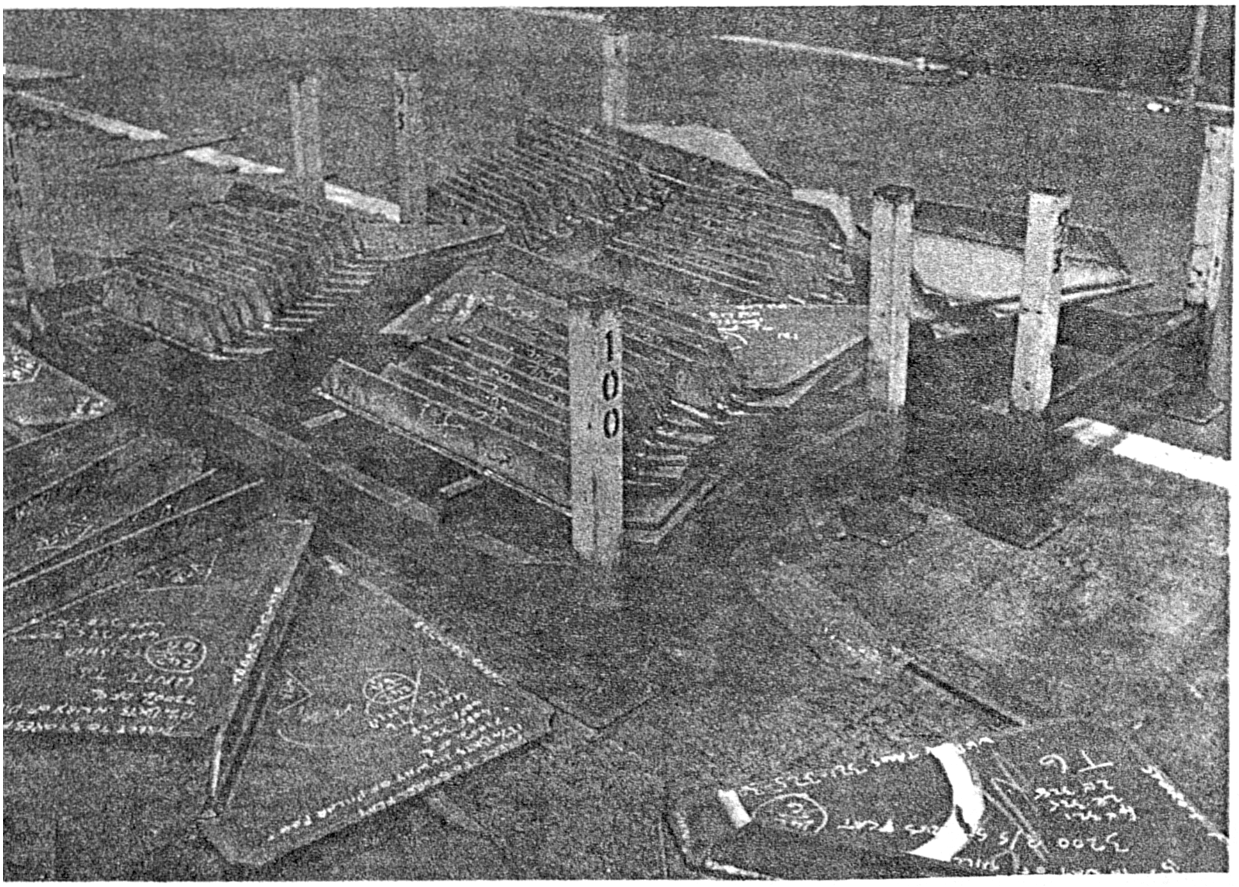
ABOVE: SUCTION MOUTHS/DRAIN HATS

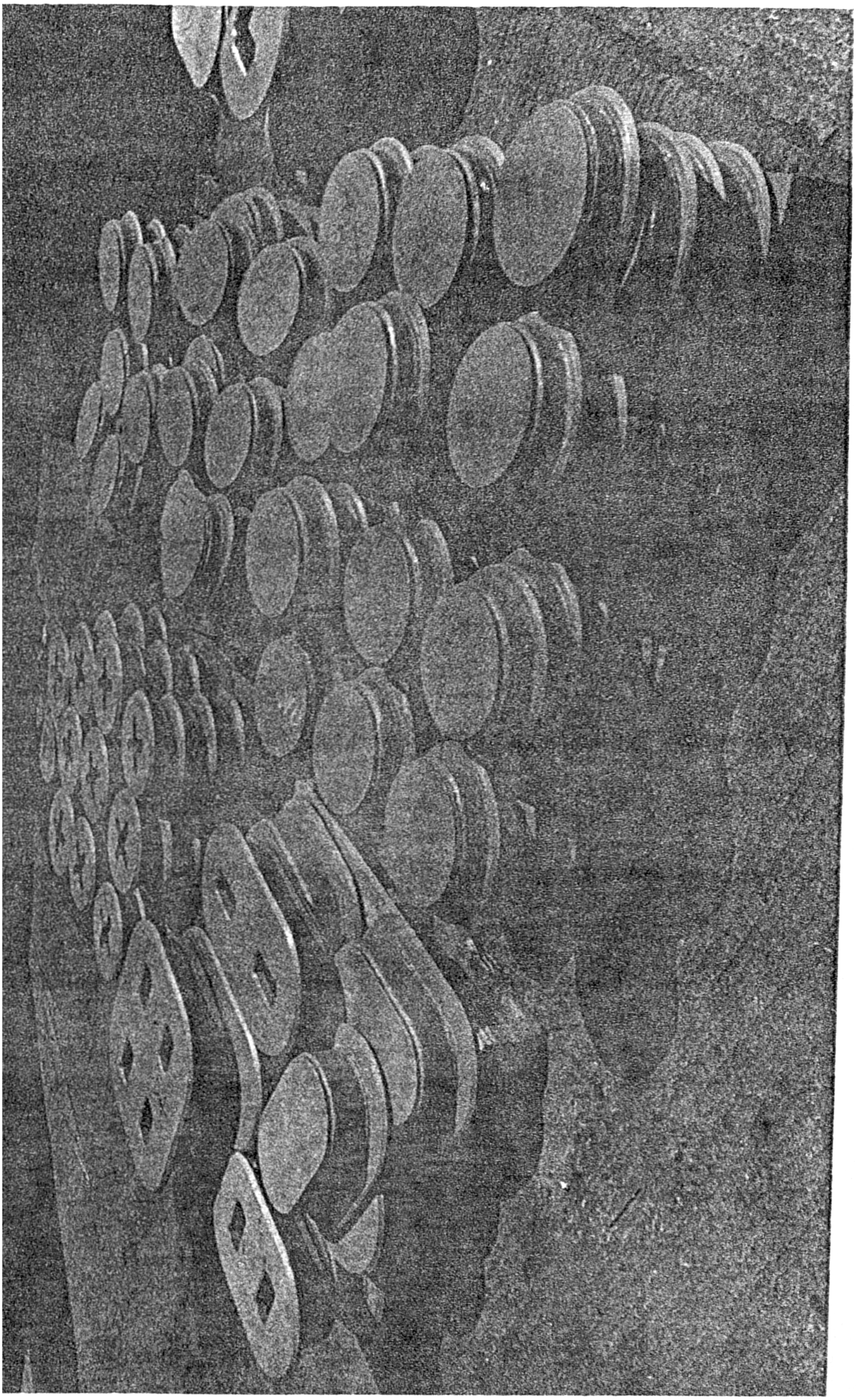
BELOW: FIXED FEET





BRACKETS





LASHING AND CONTAINER POTS

APPENDIX 7

A worked example - recessed lashing box

The item selected for this example is the recessed lashing box for use on a ship's bulkhead. For the ship in question 1633 lashing eyes had to be welded on to angle bars of different lengths in order to make up the required lashing boxes. Fig (3) illustrates the final format of these as installed on the ship.

There are three basic phases in developing the use of the robot for a specific welding task:

a) Planning

b) Implementation

c) Documentation

Each of these will now be examined in detail.

a) Planning Phase

Before the welding robot could be used for any small batch manufacturing application a procedure had to be devised whereby basic thinking could be done, prior to the actual implementation. This procedure comprises the following principal components:-

i) **Background Understanding.** Acquire an understanding of the basic function of the product, the existing methods of manufacture and their cost.

ii) **Comparative Studies.** Examine critically how the same product could be manufactured with the aid of the welding robot and propose some possible approaches; then select an approach which meets the production criteria in the most efficient way.

iii) **Manufacturing Procedure.** Devise a suitable manufacturing procedure using the welding robot. This might possibly involve some redesigning of the product and/or the support fixtures and material handling equipment.

iv) **Simulation.** Simulate the product and its production with the aid of either a physical model or computer graphics. The aim of this is to verify the procedure and find the best approach out of several possible alternatives.

v) **Robot Program.** Prepare a robot program for implementation of the welding sequences and check its correctness. Perform a trial production run of a typical batch to establish production times.

b) Implementation Phase

Implementation can involve six steps:

i) **Fixture Design.** Since in the case in question a fixture was required for accurate positioning and presentation to the welding robot of the lashing eyes and angle boxes, the first step was to design this and construct it. Fig. (A3-1) shows this fixture in use.

ii) **Materials Handling Equipment.** Suitable equipment may not be available for loading and unloading the workpieces for a specific item onto the fixture, and it may be necessary to design and construct dedicated handling equipment. For the case in question a set of rollers/conveyors and worktables was designed to assist in moving the angle bars in and out of the fixture. Figs. (A3-2) and (A3-3) show the loading and unloading of an angle bar.

iii) **Preparing the Robot Program.** Once the method of manufacturing has been selected a robot program has to be prepared using the T3 teach pendant control, see Fig. (A3-4). This is then stored in a cassette.

iv) **Test Runs.** The fixture and materials handling equipment are positioned round the welding robot, the program cassette is loaded into the controller and test runs are performed. The purpose of these is to check the production sequence, accuracy, etc. in a real production situation. During these tests the timing of the robot sequences is identified and possible improvements in the program are considered.

v) **Assessment of Costs.** Although this was a research project it was felt that the costs involved in using a robot must be determined before the production phase commenced, in order to establish the practice of evaluation every new production procedure on a cost benefit basis. This was in order to reduce the possibility of over-enthusiastic robot application ;without reference to cost and to help bring about optimum implementation of the welding robot.

vi) **Manufacturing.** Once the fixture, handling equipment and robot program are ready it takes between thirty and forty-five minutes to set up the facilities for manufacturing of the items in question, when required according to the total production plan of the shipyard.

c) <u>Documentation Phase</u>

Once a particular application is established, considerable effort is then devoted to preparing the relevant documentation. The importance of having good documentation cannot be over-emphasised, because it simplifies practical applications, and facilitates the training of robot operators and future us usage.

Documentation for each application of the robot involves the following ten items:

i) **Component Description, Illustrations and Alternative Designs:** Description of the component and its purpose, in both its traditional manufacturing location and its finished location aboard a unit, module of ship. Alternative designs of the component as used by other yards or as redesigned for robot production, with appropriate comments.

ii) **Component Technical Drawings:** Drawings of the component as produced by the Design Office and Standards Department, together with any British Standards of Classification Societies' regulations.

iii) **Present Manufacturing Process and Proposed Robotic Manufacturing Process:** Description and illustrations of the traditional and the robotic manufacturing processes.

iv) **Outline of Robotic Investigation:** Brief description of the steps taken during the investigation for robotic manufacture.

v) **Jigs and Fixtures:** Description and illustrations of the means of jigging and "fixturing" the workpieces.

vi) **Workstation Layout:** Description and illustrations of the robot workstation layout for the production of the component.

vii) **Weld Station Specifications and Lengths:** Breakdown of the welding specifications and the final weld volume for the components.

viii) **Robot Program:** Description of the robot program incorporating a list of table moves, and weld and weave schedules where applicable.

ix) **Timing:** The floor-to-floor time for the component, with the robot cycle time, arc cycle time, material handling time and programming time.

x) **Economic Considerations:** The cost of producing the component traditionally within the yard, with the robot within the yard, and by outside contractors if possible.

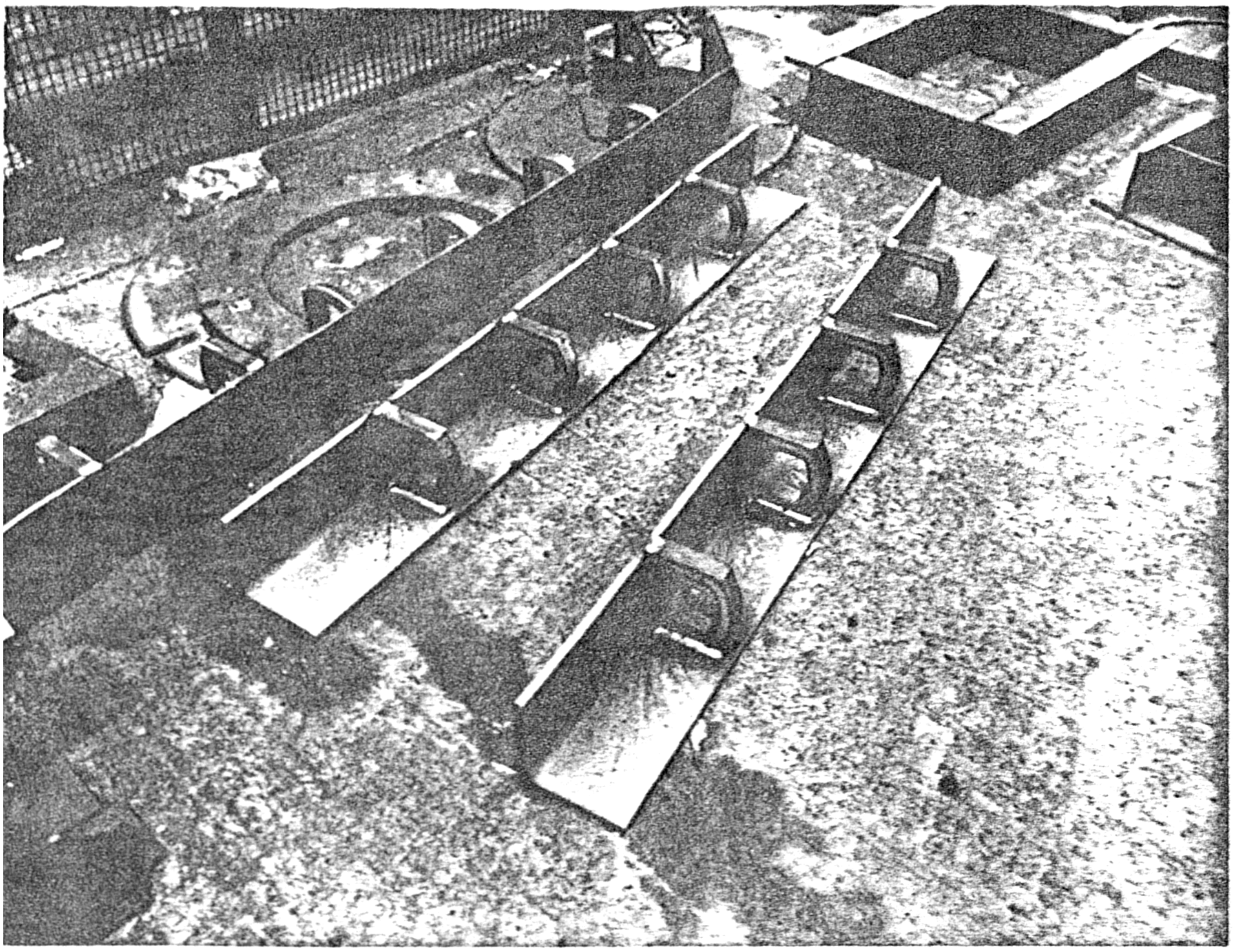


PHOTO 1. Complete workpieces.

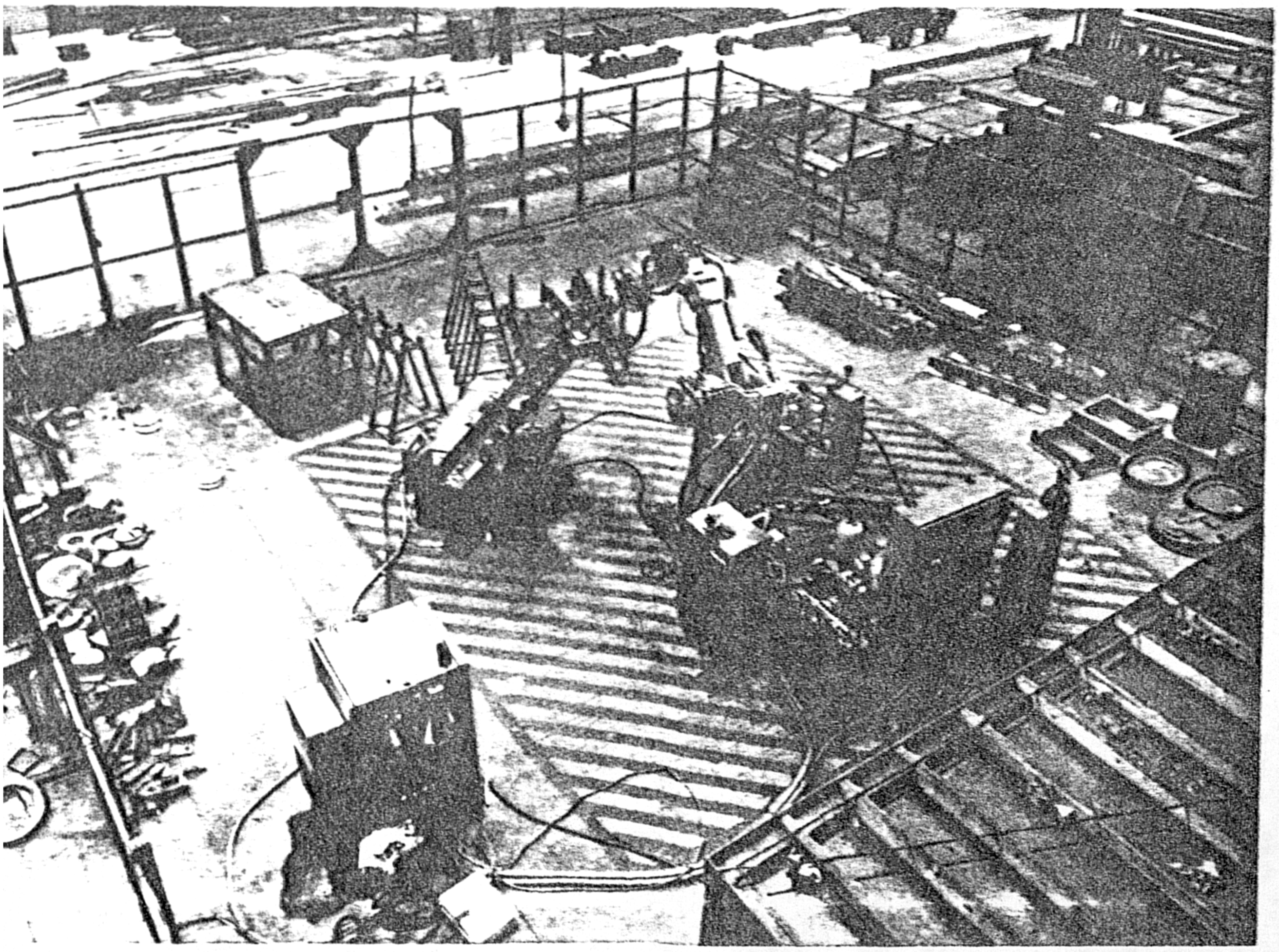


PHOTO 2. General view of the workstation layout.

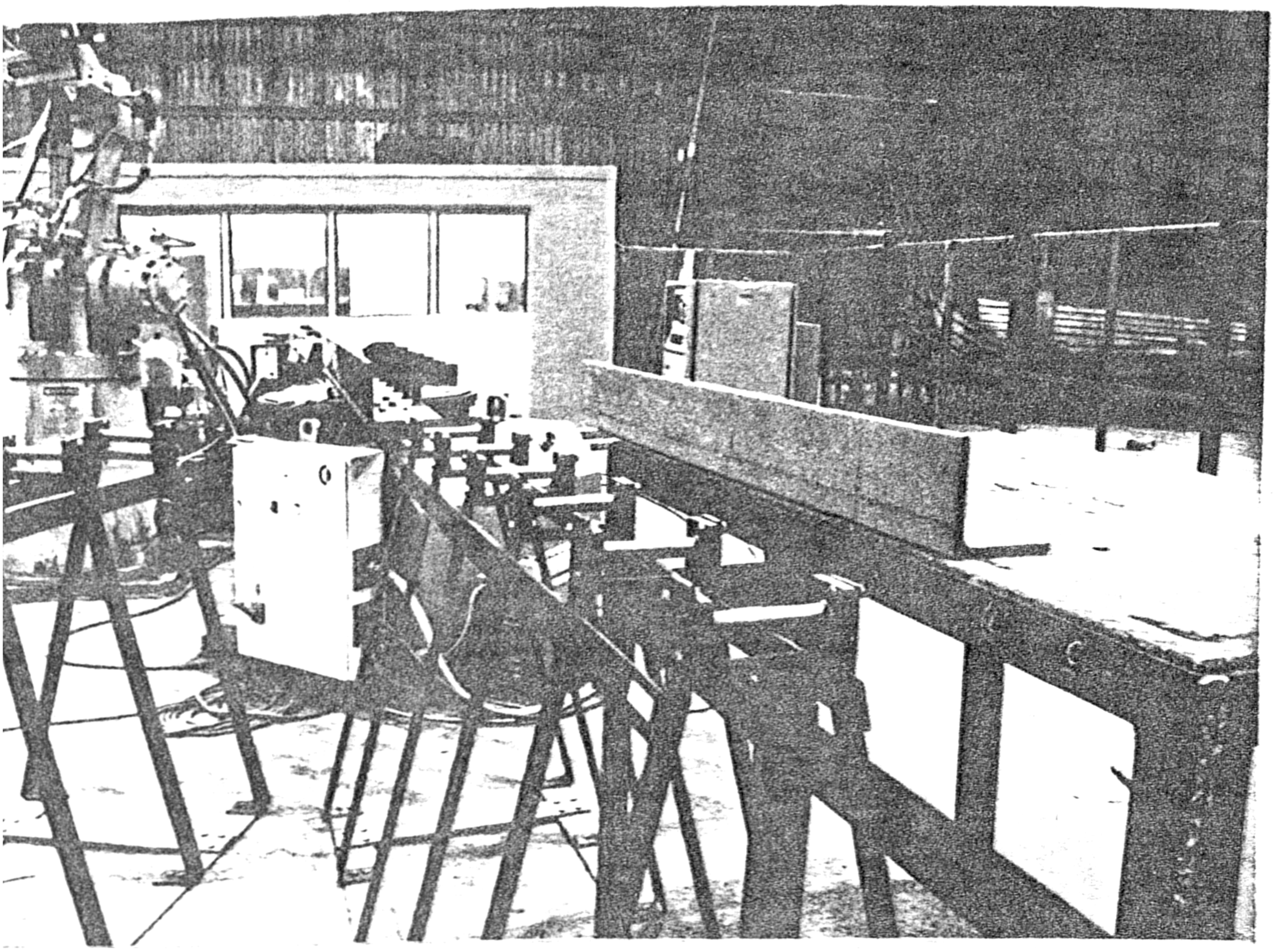


PHOTO 3. **Angle bar is loaded from the storage table onto the rollers.**

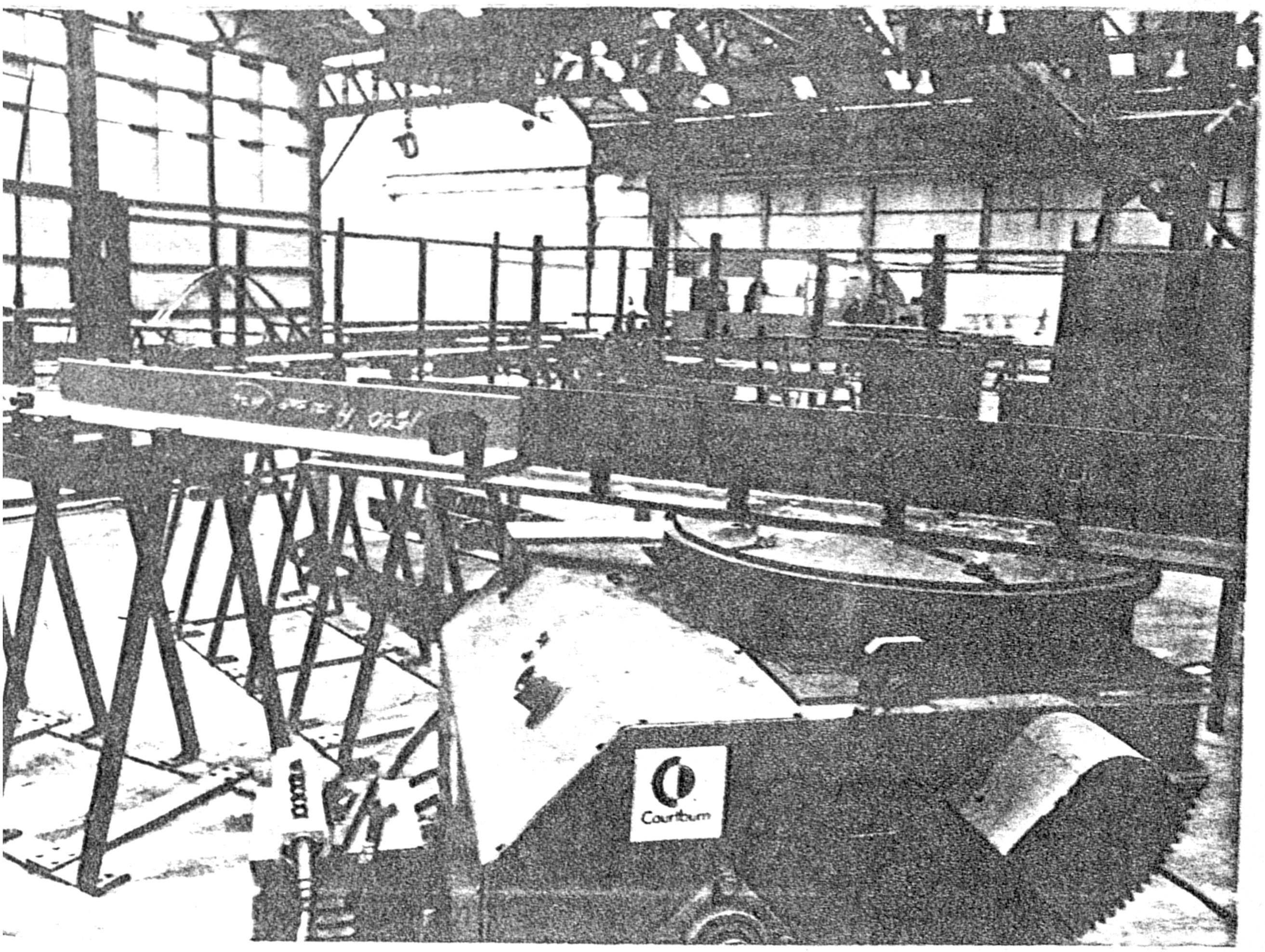


PHOTO 4. **Angle bar is slid from the rollers to the jig.**

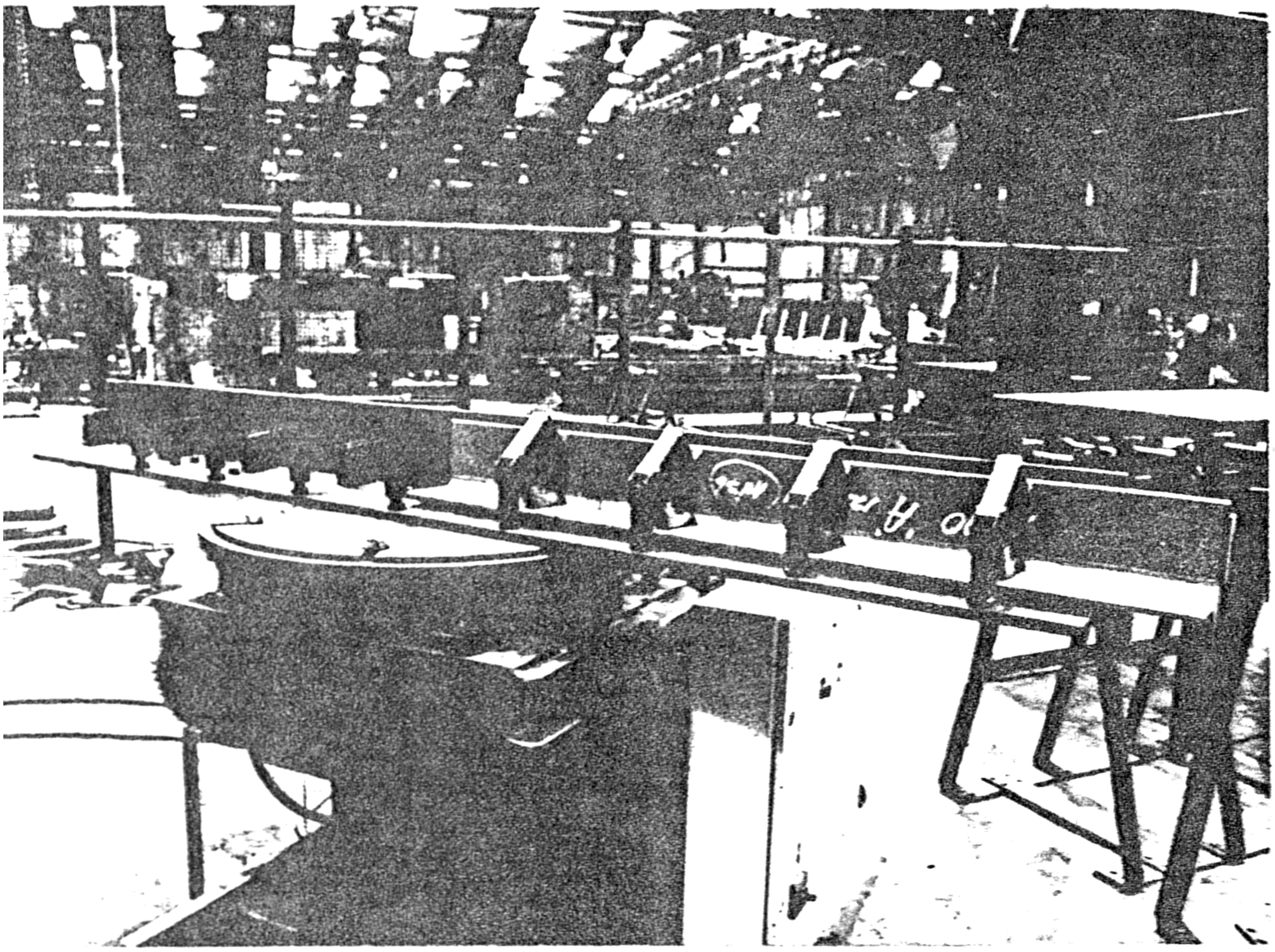


PHOTO 5. The lashing eyes are loaded onto the jig (Table turn)

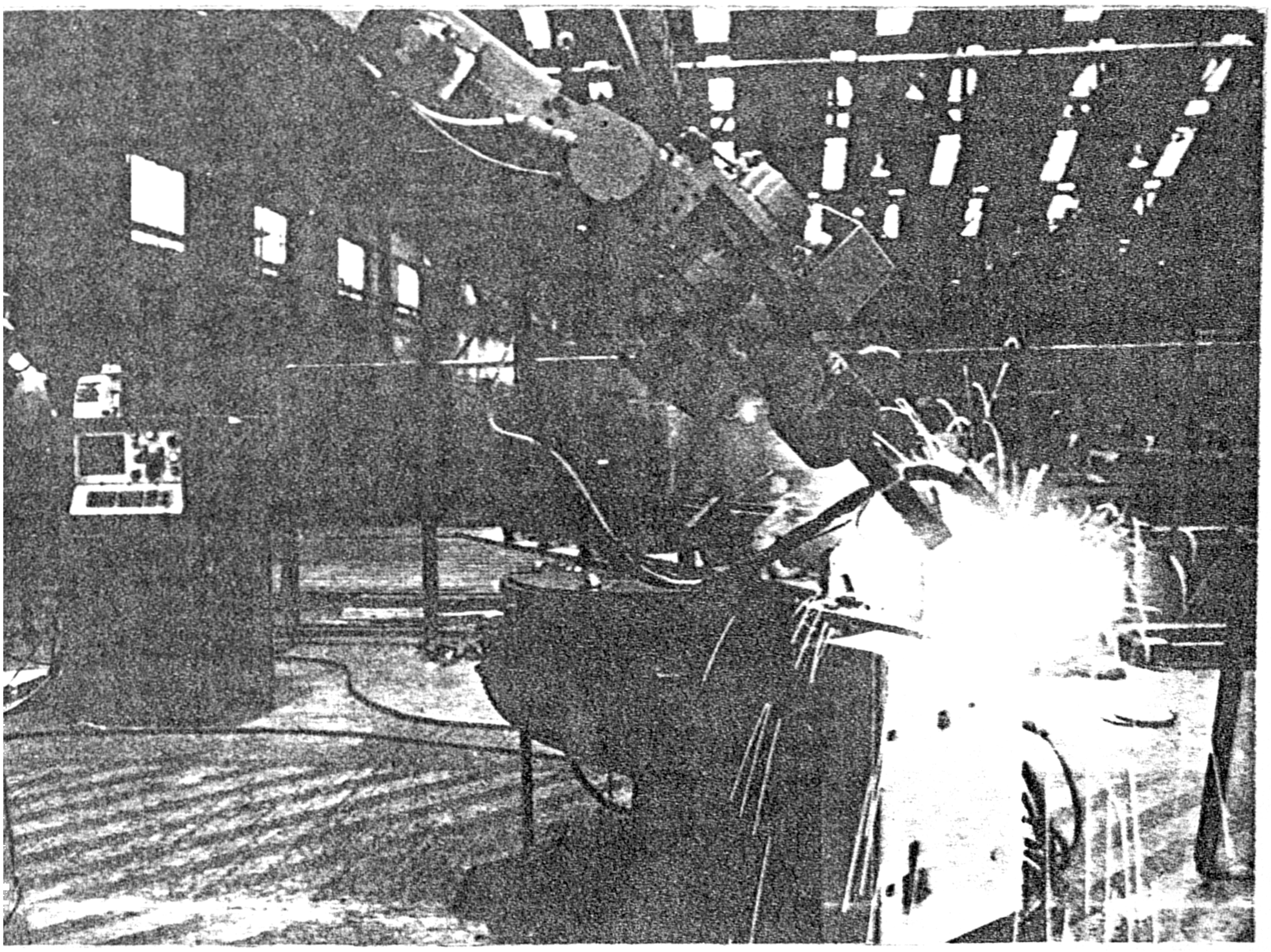


PHOTO 6. Robotic arc welding.

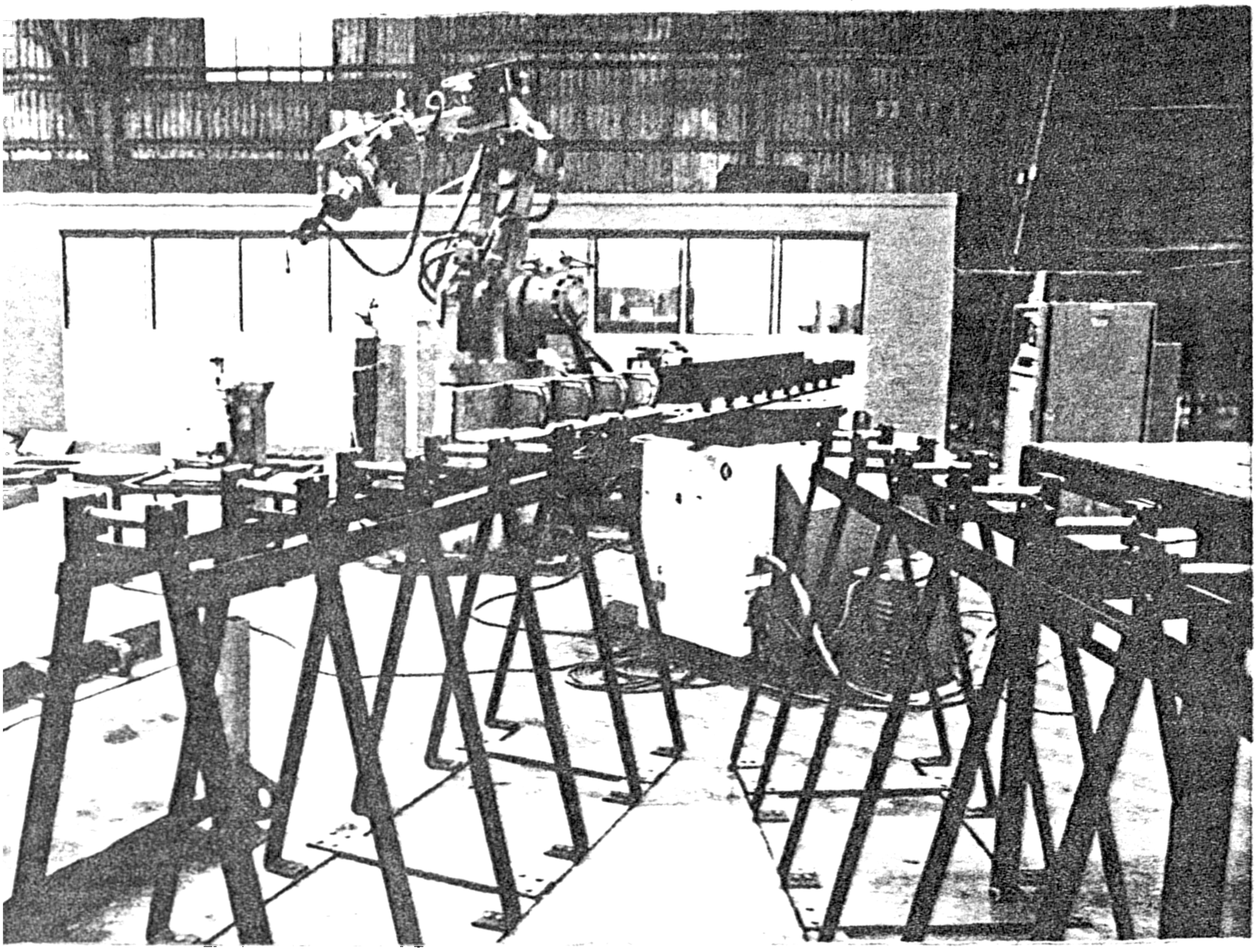


PHOTO 7. Complete workpiece is slid off the jig onto the rollers.

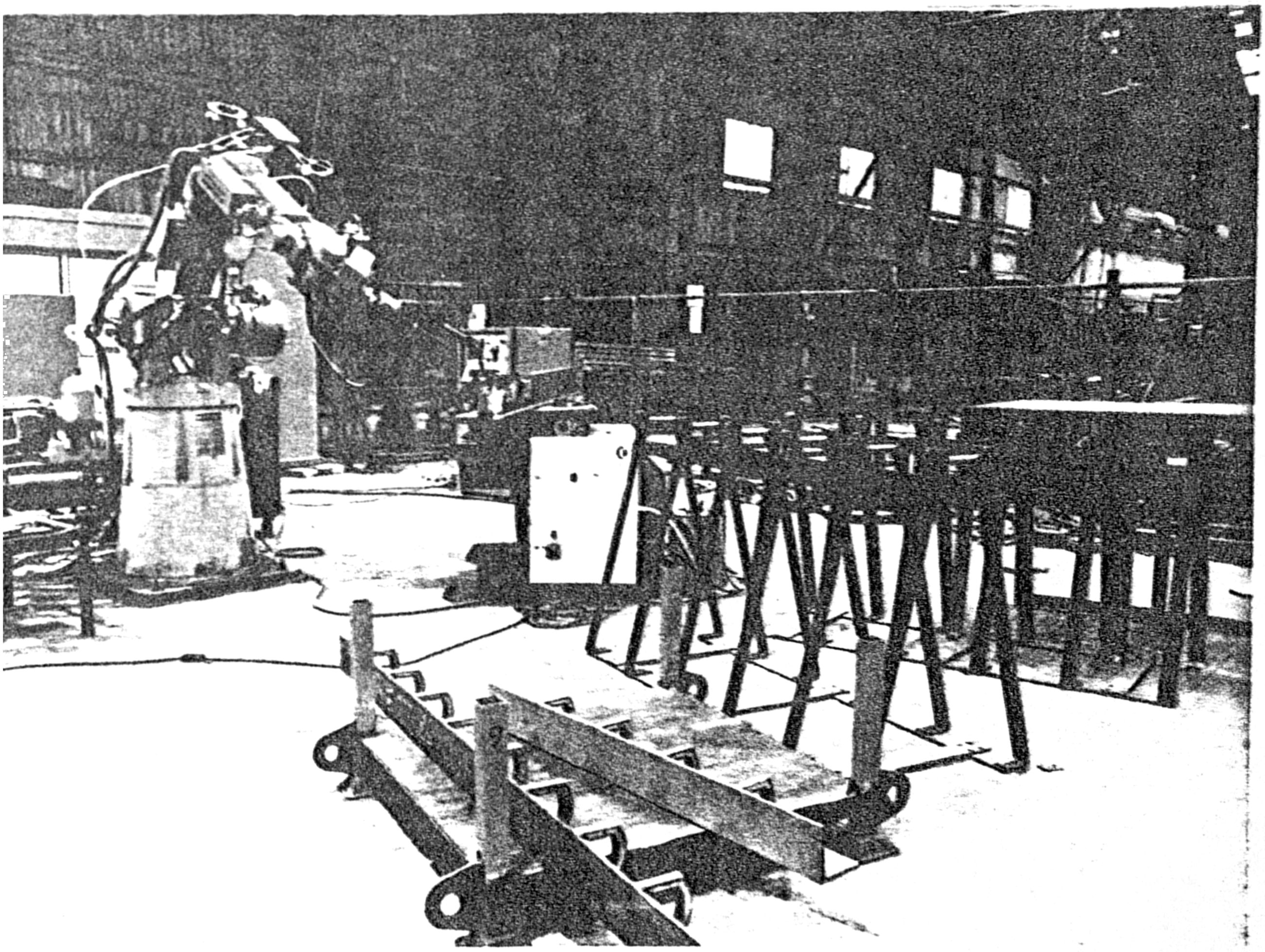


PHOTO 8.With the aid of the crane, the workpiece is placed onto the pallet, ready to go to the FAB. shed.

APPENDIX 8

CALCULATIONS FOR THE ECONOMIC JUSTIFICATION OF ROBOTIC WELDING FOR SMALL BATCH MANUFACTURING IN SHIPBUILDING

The economic justification, was based on the labour cost savings between manual and robotic welding.

The following twelve assumptions were used:-

Assumptions

1. Manual arc welding efficiency (arc time) varies from 20-35% depending upon the complexity of the product. For these calculations (for a mixed and complex group of products) an average figure of 30% was used. Similarly, arc efficiency of a robot welding, although it may reach as high as 95%, for this case it was assumed it to be 80%

2. When switching from manual welding to robot welding, welding travel speed and deposition rate can both be increased sometimes by a factor of two. This is not to say that a robot can make any one particular weld faster than an expert human welder, but that the robot can work under optimum conditions all day long. Such conditions would fatigue a human welder in a short period of time. It was assumed an increase of 30%

3. The most time-consuming activity for robotic welding is the initial time spent by the operator in programming an individual item. For a complex situation such as minor steelwork products, this time is usually high (perhaps two days per product), but when programming experience has been attained, this time usually falls (perhaps less than half a day). These calculations were based at a constant programming rate of one day per product.

4. Each item to be welded by a robot requires a fixture to hold the item on the positioner table. The aim is to design a fixture for a number or products, so as to minimise unproductive time associated with removal and remounting of fixtures. Investigating and designing such fixtures is an ongoing task, and therefore it is not possible to identify the range of products and the fixture design in the first place. However, in order to assess the cost with reasonable limits, fixturing costs were assumed to be 30% of robot cost.

5. The practice of over-designing weldments to compensate for variations from piece to piece and from welder to welder is not unusual. For example, a part may require a ¼ inch leg fillet weld for adequate strength. The designer, to assure getting a minimum ¼ inch fillet weld, may specify a 5/16 inch. This apparent insignificant increase in welds size increases the cross-sectional area of deposited filler metal by about 50%. In these calculations it was assumed a 20% increase in manual weld material cost as compared to robotic weld material.

6. It was assumed that yard work is equivalent to the construction of four ships, and it takes five years to complete the order book. This assumption was based on the order book and delivery schedule of the yard, at the time of the project.

7. It was assumed that the Company pays profit tax at the rate of 40% for the first year and at a uniform rate of 35% for subsequent years. These rates are currently in force for UK companies.

8. The labour rate of a skilled welder and the robot operator were assumed to be the same.

9. It was assumed that robot/positioner system efficiency is 50% arc time of manual floor to floor time. The actual robotic floor to floor time was evaluated on the basis of the number of positioners per robot. A two positioner per robot provides a highly efficient system. A single positioner system makes the robot unproductive for the time during which the job is being loaded and unloaded and therefore the robot would be less efficient. In this case it was assumed a two positioner robot work cell.

10. The net present value (NPV) was evaluated on the assumption of a 14% discount rate factor. Also, the salvage value of the robot system was not considered, because it was assumed that it does not affect the decision of introducing the new technology.

11. The total number of minor steelwork and outfit items identified amounted to 334 different products. (see table 13a - g). However, for the four ships under consideration an average of 240 minor steelwork products per ship were identified as products that could be pushed through the robotic workcell in question.

12. Real shipyard data was obtained for only 77 products, and such data was used as the basis for estimation of the average cost and manhours worked for the 240 products.

For the economic justification the following procedure was used:-

Step 1 Calculation of Average labour cost and hours
Step 2 Calculation of welding cost per metre (manual & robot)
Step 3 Calculation of weld length per ship
Step 4 Calculation of total floor to floor time (manual & robot)
Step 5 Calculation of the average cost savings per year
Step 6 Calculation of initial investment cost (manual & robot)
Step 7 Calculation of pay back period and return on investment, with discounted cash flow.

The calculations are as follows:-

Step 1

Average earnings for the four ships = £40561.5
(77 products) (shipyard data)

Average hours worked for the four ships = 12066 hours
(77 products) (shipyard data)

Estimated earnings for 240 products = 40561.5 x 240 / 77
= £126425 per ship

Estimated hours for 240 products = 12066 x 240 / 77
= 37609 hours per ship

Step 2

The cost of manual and robot welding per metre of welded lengths is:-

$CM = WM / (VM \times NM)$ - (1)
$CR = WR / (VR \times NR)$ - (2)

where

CM = cost of manual welding/metre
CR = cost of robot welding/metre
WM = labour rate for manual welding, £/hr
WR = labour rate for robot welding, £/hr
VM = manual weld velocity, m/hr (assumed to be 15m/hr)
VR = robot weld velocity, m/hr (assumed to be 20m/hr)
NM = manual percentage arc time (assumed to be 30%)
NR = robot percentage arc time (assumed to be 80%)

From Step 1, labour rate is $\frac{126425}{37609} = £3.36/hr$

with 127% labour overheads, it becomes £7.7/hour

So cost of manual welding/metre (CM) is £1.71=/m
and the cost of robotic welding/metre (CR) is £0.50/m

Step 3

$$\text{The weld length per ships} = \frac{\text{Total labour cost}}{\text{Labour cost per metre}} = \frac{126425}{1.71}$$

= 73932 metres/ship

Assuming an order book of 4 ships and that it takes five years to deliver them;

Total metres welded per year = 73932 x 4 / 5 = 59000 m/year

Step 4

The average floor to floor time for manual welding is 38000 hours (shipyard data). So the manual arc time @ 30% efficiency is 38000 x 0.3 = 11400 hours.

Assuming robot system efficiency as 80% arc time, then total robot floor to floor time = $\frac{11400}{0.80} = 14250$ hours

hence the robot arc duty time = 14250 hours.

In order to carry out the estimated work, two robots will be needed and therefore four positioners.

Step 5

Cost savings/year depends upon the savings of hours when switched from manual to robot welding. From Step 4 the difference between floor to floor time of manual and robotic welding is

37609 - 14250

= 23359 hrs.

Hence, cost savings/year = 178163/year, labour rate
at £3.36/hr plus 127% labour o/head

Step 6

Manual welding equipment cost per set = £15,000

Set includes - rectifiers/transformers
- cables
- electrode holders
- welder's supporting equipment;
gloves
brushes
glasses
flux removal hammer, etc.

Approximate cost of six sets = £100,000.

Robot welding investment:

Capital cost of robot installation

- robot complete with welding unit, interfacing, guarding, fume extraction etc. @ 60,000/set	= £120,000
- installation and service	= £10,000
- jigs, fixtures etc.	= £60,000
- positioner tables @ £3,000/table	= £12,000

Project cost

- development cost including programming @ 1 day/item (240 items)	= £20,000
- planning and training	= £10,000
TOTAL COST (Capital and Project)	£232,000

Step 7

The break even point is found graphically. See Figs.

Step 8

A - without recurring costs

Year	0	1	2	3	4	5	6
Investment (£)	(232,000)						
Savings before tax	-	178163	178163	178163	178163	178163	178163
Tax	-	-	40%	35%	35%	35%	35%
Savings after tax		178163	106898	115806	115806	115806	(62351)
PV Factor @ 14%	1	.8771	.7694	.6749	.5920	.5193	.4556
Net present value (£)	(232,000)	156267	82247	78157	68557	60138	(28409)

Pay back period = 1.5 years

Total of NP value = £146957.00

The NP value is greater than initial investment of 232,000, therefore the investment is viable.

Average saving (after tax) = £126495

Return on investment = 126495 + 232000 = 55%

B - with recurring costs

Assume recurring cost (for 1st year) = 30% of robot development cost

Now robot development cost = £90,000

Hence recurring cost = 90,000 x 0.3

= £27,000

The effect of the recurring cost is to increase the cost of robot welding per metre and is distributed over the first year.

Amount of welding done per year = 59000 metres

Hence, cost increase/metre = $\frac{27,000}{59,000}$

= £0.45/metre

Original cost/metre (as found in Step 2) = £0.5/metre

Therefore cost/metre welding (for 1st year only)

= 0.45 + 0.5

= £0.95/metre

This effect is shown in Fig. 7.3, line AB

Assuming initial investment as the sum of the robot system cost and the recurring cost, the payback period and return on investment is found as follows:-

Year	0	1	2	3	4	5	6
Investment (£)	(232,000)						
Savings before tax	-	178163	178163	178163	178163	178163	178163
Tax	-	-	40%	35%	35%	35%	35%
Savings after tax		178163	106898	115806	115806	115806	(62357)
PV Factor @ 14%	1	.8771	.7694	.6749	.5920	.5193	.4556
Net present value (£)	(265,000)	156267	82247	78157	68557	60138	(28409)

Pay back period = 1.81 years

Total of Np value = £416957.00

Np value is greater than the initial investment of 265,000, hence the
investment is viable.

Average savings after tax = 126495

Return on investment = $\frac{126495}{265,000}$

= 47%

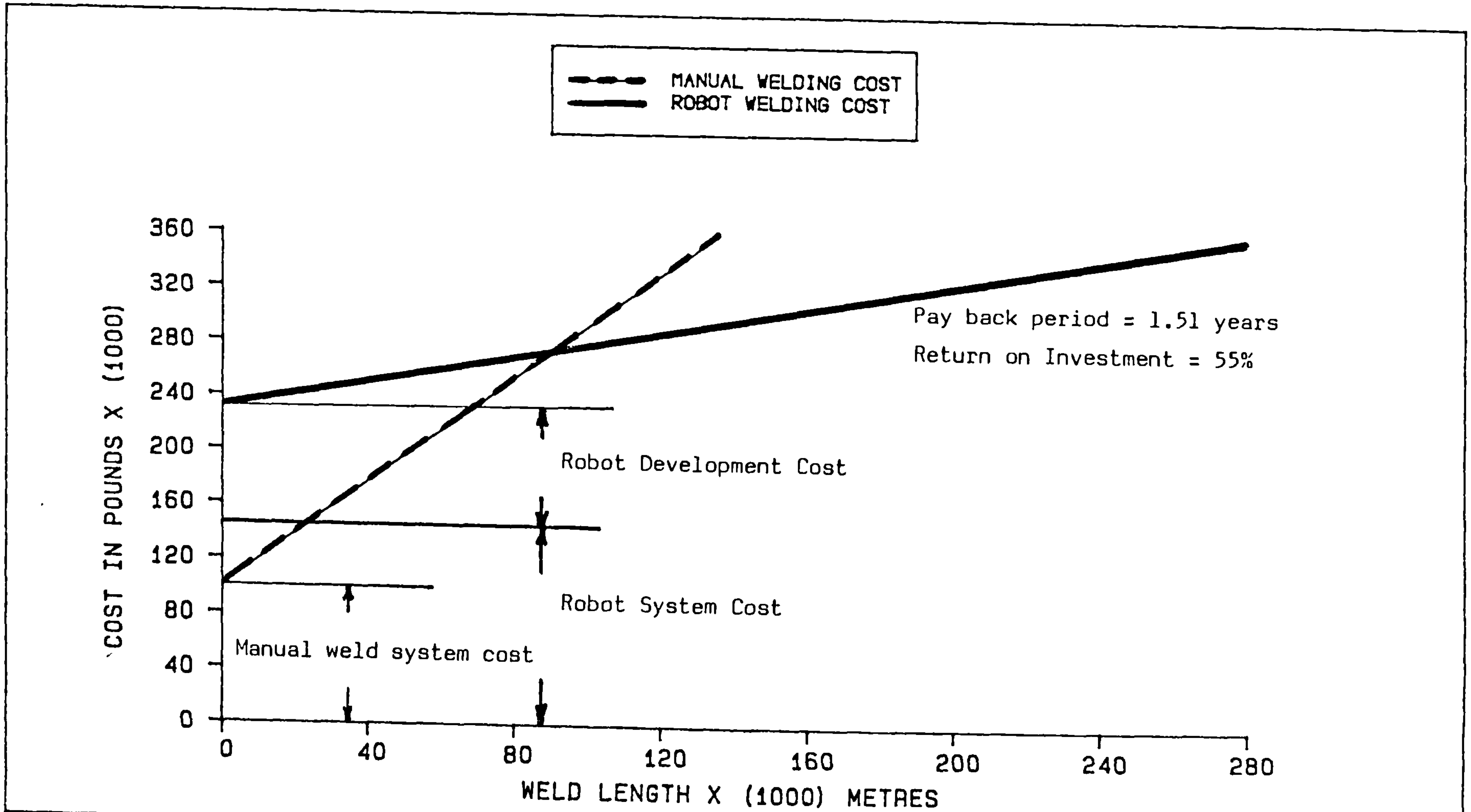


FIG 22 BREAK EVEN ANALYSIS (WITHOUT RECURRENT COST EFFECT)

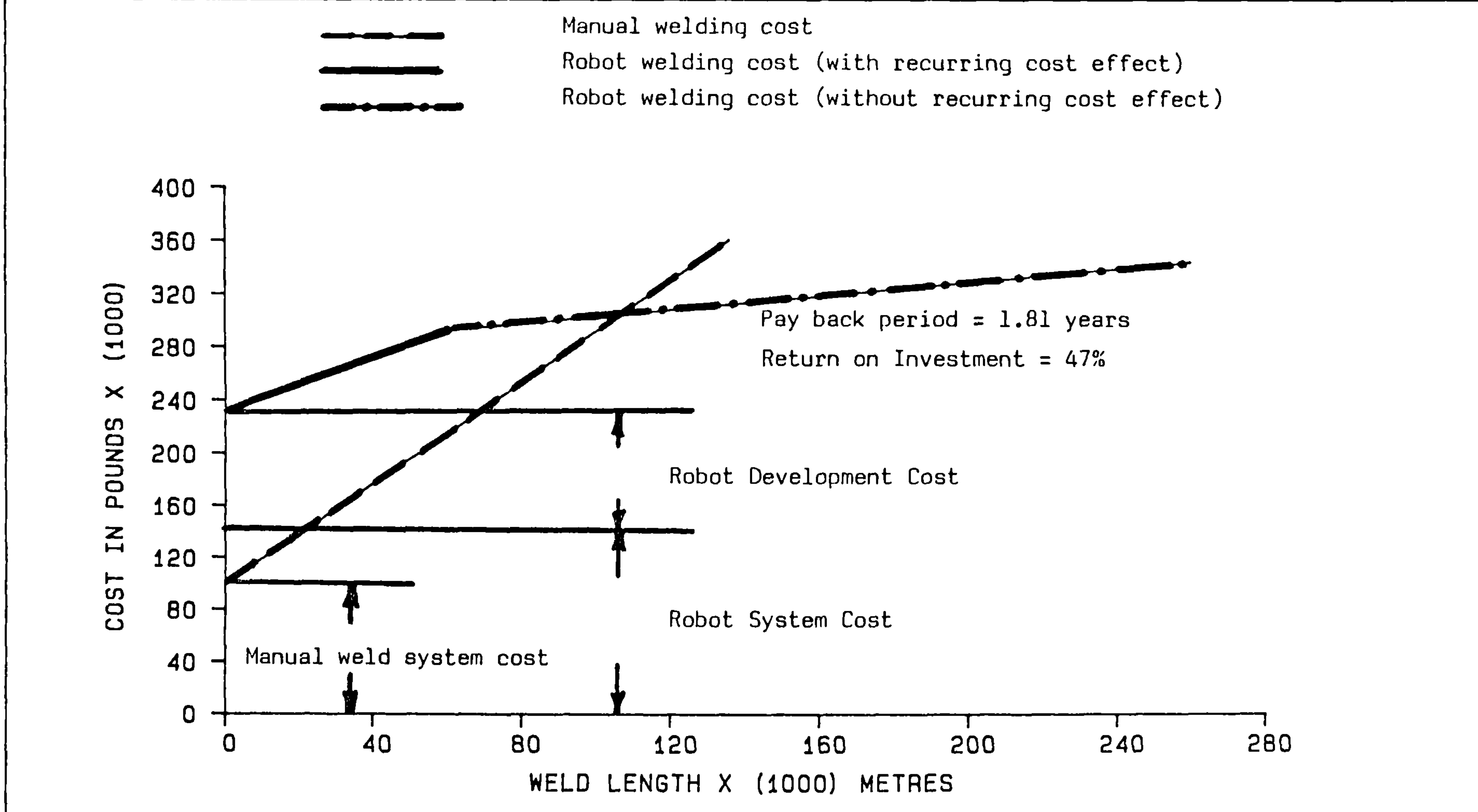


FIG. 23	BREAK EVEN ANALYSIS (WITH IN-PRODCTION COST EFFECT)

The following table (13a,b,c,d,e,f and g) shows the complete list of minor steelwork and outfit items for a commercial container ship and a Royal Navy destroyer.

Explanations of symbols used:

QTY = Quantity:	L = Low	1-10 items
	M = Medium	10-20 items
	H = High	Over 30 items

CLASS:
- S = Standard item
- M = Modular item
- U = Unique item
- N = Ministry of Defence item

MATL = Material
- S = section
- P = Plate
- T = Tube

Processes included in the table are:

Marking	Burning	Drilling	Forming
Sawing	Forging	Lathe (machining)	Assembling
Sharing	Welding	Milling	Coating
			Transporting

Under each process, the letter signifies the location area within the Swan Hunter group of shipyards.

- A = Wallsend Shipyard (North)
- B = Neptune Shipyard (Boiler Shop)
- C = Walker Shipyard (Blacksmiths)
- D = Neptune Shipyard (South)
- E = Neptune Shipyard (Machine Shop)
- F = Neptune Shipyard (Pipe Shop)
- G = Wallsend Shipyard (Joiners Shop)

Under COAT (Coating), P = Painting and G = Galvanising. Under TRANSP (transporting) the number signifies the number of moves made between the different locations.

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
1	ARMS BALANCE WEIGHT	L	S	P	C			C			C				C		
2	ARMS HINGE	H	S	P	C			C			C				C		
3	BALANCE WEIGHTS	S	S	S	C	C									C		
4	BALASTRADE	L	S	S	C	C			C	C					C		
5	BAR SUPPORT P.REFUSE CHTE	L	SN	P	E			E			E						
6	BARS BOTTLE STOWAGE	L	S	S	C	C			C		E						01
7	BARS CHAFING	H	S	S	C	C			C								
8	BARS PROTECTIVE	H	S	S	C	C			C						C		
9	BARS RETAINING	M	SN	S	C	C			C		E						01
10	BASEPLATES	M	S	P	C		C								C		
11	BATTENS CARGO	H	S	S	A			A			A			A	A		
12	BATTENS SUPPORT	M	S	S	A			A									
13	BEAMS LIFTING	L	S	S	A			A		A	AE	E		A	A		01
14	BEDPLATE	M	SN	P	B		B	B		B	E		E	B	B	P	01
15	BELLMOUTHS VENTING	M	SN	P	DE		D	E		D	E	E		D	D		01
16	BENDS	M	SN	P	D		D			D				D	D		
17	BILGE KEEL	L	S	S	A			A						A			
18	BINS LASHING	M	S	P	A		D	A		A	AD			A	A		
19	BINS MISCL.	M	S	P	A		D	A		A	AD			A	A		
20	BOARD GAUGE	H	SN	SP	DE		D			D	E			D	D		01
21	BOGIES TORPEDO	L	MN	SPT	DE	E	D			E	E	E		D	E		02
22	BOLLARDS	L	S	SPT	A	F		A		A		E		A	A		03
23	BOLT TUMBLER	H	SN	SP	C	C			C		E	E					01
24	BOLTS HINGE	H	S	S	C	C			C		C	E			C		02
25	BOLTS HOOK	L	S	S	C	C			C		C				C		
26	BOLTS LAUNCHING	H	S	S	C	C			C			E			E		01
27	BOLTS TOGGLE	H	S	S	C	C			C		E	E			C		02
28	BOLTS VENT	H	S	S	C	C			C		C	E			C		02
29	BONNET DOCKING	L	SN	P	B			B		B		E		B	B	P	01
30	BOOM STORES	L	MN	SPT	C	C			C		E	E			E		01
31	BOX BILGE STRAINER	L	MN	SP	DE		D			D	E			D	D		01
32	BOX COVER	M	SN	P	D		D			D				D	D		
33	BOX PROTECTIVE	M	SN	P	D		D			D				D	D		
34	BOX SALVAGE EDUCTOR STRNR	L	MN	SP	DE		D			D	E			D	D		01
35	BOXES BOWLIGHT	L	SN	P	B		B	B		B	B			B	B	P	
36	BOXES CABLE DUCT	M	S	P	A		A	A		A	AD			A	A		
37	BOXES CONTROL	M	S	P	A		A	A		A	AD			A	A		
38	BOXES CONTROL CH. WATER	M	MN	SP	D		D			D	D			D	D		
39	BOXES DRAW IN F.MAST	L	S	P	D		D			D	D			D	D		
40	BOXES ELECTRICAL	H	S	P	A		A			A	AD			A	A		
41	BOXES HELPTR.WINCH SUPPT.	L	MN	SP	E			E		E	E				E		
42	BOXES HYD. STARTER	L	S	P	A		A			A	AD			A	A		
43	BOXES MISCL.	M	S	P	A		A			A	AD			A	A		
44	BOXES STRAINER	L	M	SPT	A	F	A			A	AD			A	A		03
45	BRACE SWING	L	SN	SP	B	B		B		B	E			B	B	P	01
46	BRACING TOP MAIN ENG.	L	S	SP	A			E			E	E	E		E		
47	BRACKET MOUNTING	M	SN	SP	B			B		B	E			B	B	P	01
48	BRACKETS ASSY CABLE STOW.	H	SN	S	C	C			C		E						01
49	BRACKETS CABLE CLENCH	M	S	SP	C	C			C	C					C		

TABLE 13a

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
50	BRACKETS DAVIT	L	SN	P	B		B	B			B	E	E	B		P	01
51	BRACKETS DOOR	H	SN	P	D		D			D				D	D		
52	BRACKETS F.LIGHT MTGS.	M	SN	SP	DC		D	C	C		E	E		D	E		
53	BRACKETS FLANGED	H	S	P	A			A						A			
54	BRACKETS MTG ARRGT.	L	SN	SP	B			B		B	E			B	B	P	01
55	BRACKETS NAMEPLATE	M	S	S	C		C		C						C		
56	BRACKETS PIVOT	M	SN	P	DE		D				E			D			01
57	BRACKETS PIVOT TABLES	M	SN	P	DE		D				E			D			01
58	BRACKETS ROD GEARING	H	SN	SP	B		B	B		B	E			B	B	P	01
59	BRACKETS SEAT W.D.ENCLOS.	M	MN	SP	DE	E	D			D	E		E		E		01
60	BRACKETS SUPPT.LIGHT FTGS	M	SN	P	DE		D				E			D			01
61	BULKHEADS MESH	L	S	P	D		D			D				D	D		
62	BULKHEADS MINOR STIFFN.	M	S	SP	A			A		A					A	P	
63	BULKHEADS MINOR SWEDGED	M	S	P	A			A		A				A	A	P	
64	BULWARKS	L	S	SP	A			A		A	A			A	A	P	
65	CABLE GLANDS	H	MN	SPT	C	E		C	C	C	E	E	E		E		01
66	CABLE GLANDS A	M	S	SP	C	E		C	C	C	E	E			E		
67	CABLE GLANDS B	M	S	SP	C	E		C	C	C	E	E			E		
68	CABLE GLANDS C	M	S	SP	C	E		C	C	C	E	E			E		
69	CABLE GLANDS D	M	S	SP	C	E		C	C	C	E	E			E		
70	CABLE GLANDS SPECIAL	M	S	SP	C	E		C	C	C	E	E			E		
71	CANOPY	M	SN	P	D		D			D				D	D		
72	CARRIAGE F.LIFT	L	MN	SP	DE	E	D	E		D	E	E	E	D	E		01
73	CHOCKS SHOCK	M	SN	SP	B			B		B	E	E	E	B	E	P	01
74	CLAMP ANTENNA	L	SN	S	E	E		E			E	E	E		E		
75	CLAMP BEAM	M	SN	P	C			C	C		E				E		01
76	CLAMPS	M	S	SP	C	C			C	C	E						01
77	CLAMPS LIGHT	H	SN	S	C		C		C		E	E			E	G	01
78	CLEATS	H	S	S	C	C			C						C		
79	CLIPS	H	S	P	C		C		C		E						01
80	CLIPS CYLINDER LINER	L	S	P	C		C		C		E					P	01
81	CLIPS FASTENERS	M	S	P	C		C		C		E					P	01
82	CLIPS PISTON RODS	L	S	P	C		C		C		E					P	01
83	CLIPS SPARE PISTON	L	S	P	C		C		C		E					P	01
84	COAMING HATCH	M	S	SP	A			A		A					A	P	
85	COAMING MISCL.	L	S	SP	A			A		A					A	P	
86	COAMING VENT	M	S	SPT	A	F	D	A		A				AD		P	
87	COLLARS BOTTLE	M	SN	P	B			B		B	E			B	B	P	01
88	COLLARS MISCL.	H	S	P	A			A									
89	COUNTER WEIGHT F.LIFT	L	SN	SP	DE		D				E						01
90	COVERPLATE MESH GRILLES	L	SN	P	DE		D				E				E		01
91	COVERS CABLE	H	S	P	A		D	A		A	AD			A	A		
92	COVERS GASTIGHT	M	SN	P	DE		D				E						01
93	COVERS HATCH	M	S	SP	A		D	A		A	AD			A	A		
94	COVERS HATCH COAMING	M	SN	P	B		B	B		B	B			B	B	P	
95	COVERS HAWSE PIPES	L	SN	P	D		D			D				D	D		
96	COVERS HINGE	M	S	SP	A			A		A				A	A		
97	COVERS MANHOLE	H	M	SP	A	C		A	C	A	AE	E		A	A		
98	COVERS MISCL.	M	S	P	A		D	A		A				D	A		

TABLE 13b

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
99	COVERS MISCL.	M	SN	P	D		D			D				D	D		
100	COVERS NAVAL PIPE	L	SN	P	D		D			D				D	D		
101	COVERS PLATE	H	S	P	A		D	A		A	D			D	A		
102	COVERS S/STEEL	L	SN	P	E						E						
103	COWL MISCL.	L	SN	P	B		B	B		B	B			B	B	P	
104	CRADLE STORE S	L	M	SP	A			A		A	A			A	A		
105	CRUTCH CRANE	L	S	SP	A			A		A	E			A	A		
106	CRUTCH MISCL.	L	S	SP	A			A		A	E			A	A		
107	DAMPERS	M	SN	SP	DE		D				E			D			01
108	DAMPERS FIRE	L	M	SPT	DE	E	D			D	E	E			D		03
109	DAVIT	L	MN	SPT	FEC	F			C	C	E	E	E		C		02
110	DAVIT P.CANAL LIGHT	L	M	SPT	C	C			C	C	E	E	E	F	C		03
111	DOCKING PLUG KEYS	L	S	S	C	C			C	C	C				C		
112	DOG STEPS	H	S	S	C	C			C								
113	DOOR ACCESS F.O. FILL TRK	L	SN	P	E			E			E	E					
114	DOORS JALOUSIE	M	M	SP	A	C	D	A	C	A	D	E		AD	A		03
115	DOORS LIFT OFF	M	SN	SP	DE	C	D		C	D	E				D		02
116	DOORS SLIDING	L	M	SP	A			A		A				A	A		
117	DOORS STEEL	M	M	SP	A	C	D	A	C	A	D	E		AD	A		03
118	DOORS W.T.	M	M	SP	A	C		A	C	A	E	E		A	A		03
119	EDDY PLATES	L	S	P	A			A						A			
120	ENSIGN STAFF	L	SN	ST	C	C			C	C	E	E			C	P	01
121	EYEBOLT COVER PLATE	L	SN	P	E			E			E	E	E				
122	EYEBOLTS PROP.SHAFT	L	S	P	C			C	C						C		
123	EYEPLATES BOLLARD	M	S	P	C			C	C							C	
124	EYEPLATES LASHING	H	S	P	A			A	C					A			
125	EYEPLATES MISCL.	H	S	P	C			C	C								
126	EYEPLATES MTG. ARRGT.	L	SN	P	E			E			E						
127	EYEPLATES STANCHIONS	H	SN	P	E			E			E						
128	EYEPLATES STOPPER	H	SN	P	C			C	C		E						01
129	EYES CALIPER	H	S	S	C			C	C								
130	EYES PAINTING	M	S	P	C			C	C								
131	FAIRLEADS	M	S	P	A			A	C	A				A	A		
132	FEET FIXED & SLIDING	M	S	SP	A			A		E	E			A	E		01
133	FILTER ASSY	L	SN	SP	D		D			D				D	D		
134	FLANGES	M	SN	P	DE		D				E						01
135	FLANGES BLANK	H	S	P	A			A			AE			A			
136	FLANGES BULKHEAD	H	S	P	A			A				A					
137	FLAPS VENT GAS	CQ	SN	SP	DE	E	D				E	E	E	D	E		01
138	FLAPS VENTING	M	SN	SP	DE	E	D			D	E			D	E		01
139	FLOORPLATES & SUPPORTS	H	S	SP	B	B		B		B	B				B		
140	FLOORS FALSE	M	SN	SP	B	B	B	B		B	B				B	P	
141	FOREMAST	L	M	SP	A			A		A	E	E		A	A		01
142	FRAMES LIFTING	M	SN	SP	B	B	B	B		B	E			B	B	P	01
143	FUNNEL PIECE MISCL.	M	SN	SP	B	B	B	B		B	B			B	B	P	
144	GLANDS SHAFTING	L	SN	P	E			E			E		E		E		
145	GRABS BEAM	M	S	P	C	C			C	C					C		
146	GRATINGS	H	S	S	C	C				C					C		
147	GRATINGS SEA INLET	M	SN	SP	B		B	B		B	E			B	B	G	01

TABLE 13c

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
148	GRIDS WEED	M	S	SP	A	E		A		A	E			A	A		01
149	GRILLES MESH INTAKES	M	SN	SP	D		D			D				D	D		
150	GROUNDINGS JOINERS	H	S	S	G	G				G	G				G		
151	GUARD OIL UNIT	H	SN	P	D		D			D	D			D	D		
152	GUARD SHAFT	L	SN	P	D		D			D	D			D	D		
153	GUARDRAILS	M	SN	SP	C	C		C	C		E	E			C		02
154	GUARDS CABLE GLANDS	H	SN	P	D		D			D				D	D		
155	GUARDS COUPLING	L	S	P	E		D				E			D			01
156	GUARDS MESH	M	SN	P	D		D			D				D	D		
157	GUARDS ROPE	L	S	P	A			A				E	E	A			01
158	GUIDE CABLE	H	SN	P	D		D			D				D	D		
159	GUIDES CABLE	H	S	P	A			A		A					A		
160	GUIDES HATCH	H	S	S	A			A									
161	GUIDES ROPE	M	SN	S	C	C			C	C					C		
162	GUIDES STEEL DOORS	H	S	S	A			A									
163	GUSSETS	H	S	P	A			A									
164	HANDLES DOOR	H	S	S	C	C			C		E				C		02
165	HANDLES PULL	H	S	S	C	C			C								
166	HANDRAIL BENDS	M	S	T	C	C								C			
167	HANDRAIL RODS	M	S	S	C	C			C								
168	HANGERS U BOLTS	H	S	S	C	C			C			E			E		03
169	HANGERS 350 N.B.	M	S	P	C		C		C		E						01
170	HANGERS NON FERR PIPES	H	S	S	C		C		C		E				E		01
171	HANGERS PIPE	H	S	S	C		C		C		E			D			01
172	HANGERS TRAY PLATE	M	S	S	C		C		C		E			D			01
173	HASP & STAPLE ASSY.	M	M	SP	C	C	C		C		C				C		
174	HATCH DEVICE CTRE.	L	M	SP	A			A		A					A		
175	HATCHES MACGREGOR	L	M	P	A			A		A					A		
176	HATCHES ROPE	L	M	ST	A	F		A						A	A		
177	HATCHES SMALL	M	M	SP	A	C	D	A	C	A	D			D	A		01
178	HEEL FITTING ASSY	L	MN	SP	C	C		C	C	E	E	E	E		E		01
179	HINGES	H	M	S	C		C		C						C		
180	HINGES BREAKWATER	L	SN	SP	C	C		C	C		E	E			E		01
181	HOOD D.G. FILTER	L	SN	P	D		D			D				D	D		
182	HOOK PINS CARGO LASHING	H	S	S	C	C			C								
183	HOOKPLATES RAMS HORN	H	SN	SP	D		D				D			D			
184	HOOKS & EYES HANDRAILS	H	S	S	C	C			C						C		
185	HOOKS & EYES STEEL DOORS	H	S	S	C	C			C						C		
186	HOOKS LASHING	H	S	P	A			A									
187	HOOKS LIFEBELT CROSSES	M	S	S	C	C			C						C		
188	HOOKS MISCL.	M	S	S	C	C			C								
189	HOOKS SHIP'S NAMEBOARD	L	S	S	C	C			C								
190	HOUSING D.G. FILTER	L	MN	SP	D		D			D	D			D	D		
191	HOUSING LONG PROBE	L	SN	SP	B	B		B		B	E			B	B	P	01
192	HOUSING SONAR T.D.	L	MN	SP	B	B		B		B	E			B	B	P	01
193	INGRESS PLATE DG INTAKES	L	SN	P	DE		D				E			D			01
194	INSERTS DECK	H	SN	P	E			E					E				
195	INSERTS GOOSE NECK	L	SN	P	B			B			E			B		P	01
196	INSERTS PORTABLE DERRICK	L	SN	P	E			E					E				

TABLE 13d

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
197	INSERTS SEA INLET	M	SN	P	E			E			E	E					
198	INTAKES D.G. MAIN	M	SN	SP	B		B	B		B	E	E		B	B		01
199	JACKSTAFF	L	SN	ST	C	C		C	C	C		E			C	P	01
200	JALOUSIES	M	M	SP	A	C	D	A		A				AD	A		01
201	LADDER PILOT	L	M	S	A			A		A					A		
202	LADDERS	H	S	S	A	C		A		A	C				A		
203	LADDERS INTERNAL	M	S	P	D		D			D				D	D		
204	LASHING DECK	H	S	P	A			A		A					A		
205	LASHING POINTS	H	S	P	A			A		A					A		
206	LEVERS BRAKE F.LIFT	L	SN	S	E						E	E			E		
207	LIFTING BEAM	M	SN	SP	B	B	B	B		B	E			B	B	P	01
208	LIFTING GEAR	M	M	P	A			A			A			A			
209	LINKS HALYARD	M	SN	S	C	C			C								
210	LOUVRES RAIN	M	SN	SP	B	B	B	B		B	B			B	B	P	
211	LUGS FAIRING	H	S	SP	A			A									
212	LUGS HINGE	H	S	P	C	C			C		C				C		
213	LUGS LADDER	H	S	S	A			A			A			A	A		
214	LUGS LIFTING	H	S	SP	A			A	C		A			A			
215	LUGS PLATFORM	M	S	S	A			A			A			A			
216	LUGS TOGGLE	H	S	P	C	C			C		C				C		
217	MANHOLES	H	SN	SP	B			B		B	B	E		B	B	P	01
218	MAST SIGNAL	L	M	SP	A			A		A				A	A		
219	MOUNTINGS DRAIN TANK	L	M	PT	EF	F		E			E		E		A		02
220	MOUNTINGS GAUGE	M	S	PT	EF	F		E			E	E			A		02
221	NUTS MOORING ARRGT.	L	S	S	C	C			F		E	E					01
222	NUTS WING	H	S	S	C	C			C		C						
223	PADS BENCH MARK	M	SN	P	D		D										
224	PADS MISCL.	H	S	SP	A			A									
225	PADS PILLAR	H	S	P	A			A									
226	PADS TABLE	M	SN	P	DE		D				E						01
227	PANELS CONTROL	M	SN	SP	D		D			D				D	D		
228	PEDESTAL CRANE	M	S	P	A			A		A				A	A		
229	PEDESTAL MISCL.	M	S	P	A			A		A				A	A		
230	PINS & KEEL DRIVERS	H	S	S	C	C			C								
231	PINS CABLE CLENCH	L	S	S	C	C			C								
232	PINS HINGE	H	S	S	C	C					C				C		
233	PINS LOCKING D.NOSE	H	S	S	C	C			C		E				E		01
234	PIPE CHAIN	L	S	PT	A	F				A				A	A		01
235	PLATE BACK LIFEBOAT STOW	L	SN	P	D		D										
236	PLATE PORTABLE	M	SN	P	E			E			E	E					
237	PLATE SUPPORT ACC.LADDER	L	SN	P	D		D										
238	PLATES ADJUST ACC. LADDER	L	SN	P	C	E	C		C		E	E	E				01
239	PLATES BASE MTG.	M	SN	P	B			B		B	E		E	B	B	P	01
240	PLATES CLOSURE ACC. LADDR	L	SN	P	DC		D		C	D				D	D		
241	PLATES DATUM	M	SN	P	D		D										
242	PLATES HINGE ACC. LADDER	L	SN	SP	DC		D		C	D				D	D		
243	PLATES JALOUSIE COVER	M	M	P	A			A		A	A			A			
244	PLATES PIVOT FIRE DOOR	L	MN	SP	C	E	C		C		E	E					01
245	PLATES SADDLE	H	SN	P	D		D							D			

TABLE 13e

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
246	PLATES SLOTTED	M	SN	P	DE		D				E		E	D			01
247	PLATES SONAR	L	MN	SP	B			B		B	E	E	E	B	B	P	01
248	PLATES TOGGLE	H	S	P	C	C			C								
249	PLATES TOP	M	SN	P	B			B		B				B	B	P	
250	PLATFORM GANGWAY	L	M	SP	A			A		A					A		
251	PLATFORM HATCH	L	M	SP	A			A		A					A		
252	PLATFORM HINGED	L	M	SP	A	E		A		A	E	E			A		01
253	PLATFORM PANAMA	L	M	SP	A			A		A					A		
254	PLATFORM WINDLASS	L	M	SP	A			A		A					A		
255	PLATFORMS MISCL.	L	M	SP	A			A		A					A		
256	PLENUM VENT	M	M	SP	A		D	A		A	D			AD	A		01
257	RAFT MOUNTING	L	SN	SP	B			B		B	E			B	B	P	01
258	RAIL REMOVAL TYNE	M	SN	SP	B	B	B	B		B	B			B	B	P	
259	RAIL SAFETY	H	S	S	A			A									
260	RAMPS PORTABLE	M	M	P	A			A		A				A	A		
261	RECESS LIGHT	M	SN	P	B		B	B		B	E	E	E	B	B	P	01
262	REDUCERS MANIFOLD	M	SN	P	B			B		B				B	B	P	
263	REELS BOSUNS	L	SN	SP	DE	E	D			D		E		D	E		01
264	REELS HOSE	M	MN	SP	DE	E	D			D	E	E		D	D		01
265	RIDERS & COLLARS	H	SN	P	B			B								P	
266	RINGS CABLE GUIDES	M	S	S	C	C			C	C							
267	RINGS MISCL.	M	S	S	C	C			C	C							
268	RINGS SEA CHEST	M	S	S	C	C			C	C							
269	SAVEALLS	H	S	S	A		D	A		A				D			
270	SCREEN RATTAN	L	MN	SP	B	E		B			E	E	E		E		01
271	SCUPPER BODIES	H	SN	P	B			B	C	B				B		P	
272	SEAT WINCHES	L	M	SP	A			A		A			E		A		01
273	SEATS AUX.M/C	H	M	SP	A			A		A	E		E		A		01
274	SEATS DATUM PLATES	M	SN	P	B		B						E				01
275	SEATS FAN	M	M	SP	A		D	A		A					A		
276	SEATS FLOODLIGHT	L	M	S	C			C	C		C						
277	SEATS HATCH WINCH	L	M	SP	A			A		A					A		
278	SEATS MISCL.	M	M	SP	A		D	A		A					A		
279	SEATS WINDLASS	L	M	SP	A			A		A					A		
280	SEATUBES	M	M	PT	A			A		A		E		A	A		01
281	SHACKLES	M	SN	S	C	C			C		E	E					01
282	SHACKLES ROLLER	M	SN	S	C	C			C		E	E	E		E		01
283	SHAFT WITHDRAWAL	M	M	SP	A			A		A					A		
284	SLEEVES	H	S	P	C			C	C	C							
285	SOCKETS STANCHIONS	H	SN	S	E						E	E	E				
286	STAGING	H	S	S	A			A									
287	STAIRWAYS INT.	M	M	P	A		A	A		A				A	A		
288	STANCHIONS	H	S	S	A	C		A			ACE	E		A			01
289	STANCHIONS HATCH & M.HOLE	M	SN	SP	E			E			E	E	E		E		
290	STERNFRAME	L	M	SP	A			A		A				A	A		
291	STIFFENERS	H	S	S	A			A									
292	STOOLS	M	M	P	C	C			C		E						01
293	STOOLS	M	SN	SP	B		B	B		B	E		E	B	B	P	01
294	STOPS CRANE	M	S	P	A			A					E	A	A		02

TABLE 13f

MINOR STEELWORK BY MANUFACTURING PROCESS

REF	PRODUCT	QTY	CLASS	MATL	MARK	SAW	SHEAR	BURN	FORGE	WELD	DRILL	LATHE	MILL	FORM	ASSY	COAT	TRANSP
295	STOPS DOOR	H	SN	P	B			B			B		E		B	P	01
296	STOPS GAPAGE DOOR	M	S	SP	A			A		A			E		A		02
297	STOPS HATCH WHEEL	M	S	P	A			A									
298	STOWAGE CARGO	H	M	P	A			A		A					A		
299	STOWAGE HATCH	M	M	P	A			A		A					A		
300	STOWAGE SONAR	L	SN	SP	DE	C	D		C	D	E	E		D	D		02
301	STOWAGE SPARE PROP.	L	M	SP	A			A		A	E	E			A		02
302	STRAP BOOM C.LIGHT	L	SN	S	C			C	C		E	E			E	G	01
303	STRAP SUPPORT	M	SN	S	C		C		C		E	E			E	G	01
304	STRAPS HINGED	H	S	P	C	C			C		C				C		
305	STRAPS LAUNCHWAY	M	S	S	A			A			A			A			
306	STRAPS MISCL.	M	S	P	C	C			C		E						01
307	SUPPORT SEADART RAFT	L	MN	SP	B		B	B		B			E		B	P	01
308	SUPPORTS CABLE TRAY	H	S	P	C	C			C								
309	SUPPORTS F.FLOOR	H	SN	S	B			B		B	B				B	P	
310	SUPPORTS LASHING	H	S	SP	A			A		A					A		
311	SUPPORTS PIPE	H	S	SP	A			A	C	A	AE			A	A		01
312	SUPPORTS SNUBBER	L	SN	P	B			B		B	E			B	B	P	01
313	SWIMMING POOL	L	M	SP	A			A		A				A	A		
314	SWORDS & CLEATS H. BOARD	L	SN	SP	C	C			C		E					G	01
315	TANK DRAIN	L	M	SP	A		D	A		A				A	A		01
316	TANKS LOOSE	M	M	SP	A		D	A		A				D	A		01
317	TANKS LOOSE	M	MN	SP	B		B	B		B	E	E		D	B		01
318	TANKS OIL	L	M	SP	A		D	A		A				D	A		01
319	TIEBARS SONAR PLATE	L	SN	P	B	B		B			E		E				01
320	TRACK SLIDING DOOR	L	SN	S	DE	D							E				01
321	TRANSITION PIECE DG INTKE	L	SN	P	DE		D	E		D	E	E		D	D		01
322	TRANSITION PIECES	L	SN	P	B		B	B		B	B			B	B	P	
323	TRAY DRIP	M	SN	P	D		D			D				D	D		
324	TRAYS WIRE MESH	H	SN	P	D		D							D	D		
325	TRUNKING HINGED M.MAST	L	MN	SP	E	E		E			E	E	E		E		
326	UPTAKES	M	M	SP	A			A		A	E	E		ABD	A		01
327	UPTAKES AUX BOILER	M	SN	P	B		B	B		B	B			B	B	P	
328	VENTS	H	M	SP	A		D	A		A				AD	A		
329	VENTS BULKHEAD	H	M	SP	A	C	D	A	C	A	E	E		A	A		03
330	VENTS GOOSENECK	L	M	SPT	DE	E	D	E		E	E	E		F	E		02
331	VENTS MUSHROOM	L	M	SPT	A	E	D	A		E	E	E			E		03
332	WALKWAYS	M	M	SP	A			A		A					A		
333	WEATHER DECK ENCLOSURES	M	SN	SP	D		D			D				D	D		
334	WEDGES	H	S	S	C		C		C								

TABLE 13g