Development of a Cleaning and Deburring Workstation for the AMRF

Harry G. McCain*
Roger D. Kilmer*
Karl N. Murphy*

*Robot Systems Division
Center for Manufacturing Engineering
National Bureau of Standards
Gaithersburg, MD 20899

Abstract

The National Bureau of Standards (NBS) is currently developing a facility for conducting research on automated manufacturing. This facility, called the Automated Manufacturing Research Facility, or AMRF, is concentrating on the manufacture of machined metal parts in small batches. One aspect of this overall manufacturing process is the deburring and cleaning of parts. These problems are being addressed in the AMRF in the Cleaning and Deburring Workstation. This paper presents the design philosophy of this workstation and the approaches to be used in developing an automated cleaning and deburring system. The near-term solution of utilizing conventional mass deburring and buff-brush-polish techniques is described. Future approaches involving the use of industrial robots to automatically deburr parts is also discussed, including research that is necessary to develop this technology. This research includes force servoing of robots and control of two robots working cooperatively.

1. Introduction

The National Bureau of Standards, Center for Manufacturing Engineering is implementing an experimental factory called the Automated Manufacturing Research Facility [1]. The research being conducted in this facility is concentrating on the problems of manufacturing machined metal parts in small batch sizes.

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(2) Commercial equipment is identified in this paper in order to adequately describe the systems under development. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply that this equipment was necessarily the best for the purpose.

Attention is directed to issues of flexibility and adaptability to varying work set-ups. The facility is designed in a modular fashion with a hierarchically structured control system which coordinates the activities of a wide variety of machine tools, robots, sensors, and computer systems produced by many different manufacturers. These are linked together by control and data base structures which utilize a system of standardized interfaces currently under development. One of the primary objectives of the AMRF is to provide a testbed that researchers from NBS, industry, universities and other government agencies can use to study questions of standardization, measurement, and quality control in the automated factory.

The AMRF will operate as a small batch machine shop. It is currently configured with six workstations: three machining workstations, a cleaning and deburring workstation, an inspection workstation and a materials handling workstation.

In a typical small batch machine shop, parts may be machined on sophisticated NC machine tools which require little or no human intervention, once set up. However, deburring operations are generally still performed manually [2]. Since the AMRF is working toward an understanding of total automation, these cleaning and deburring processes must be automated as well. The Cleaning and Deburring Workstation (emphasis on deburring despite workstation name) has therefore been included as one of the major components in the AMRF in an attempt to satisfy this requirement.

During the research and development of the AMRF it has become clear that cleaning and deburring is one of at least two shop floor functions with requirements which are beyond the current state-of-the-art in automation and robotics for the general case. (The other major problem area is automatic workpiece fixturing.) With this in mind, this paper describes the initial philosophy and implementation of the AMRF Cleaning and Deburring Workstation (CDWS) with no illusion that the general solution to the problem of automatic deburring will be found in the near future.

2. AMRF Description

The three machining workstations in the AMRF are: (1) the Horizontal Wokstation which contains a CNC horizontal spindle machining center, (2) the Vertical Workstation which contains a CNC vertical spindle machining center and (3) the Turning Workstation which contains a CNC turning center. Additionally, there is the Automatic Inspection Workstation which contains an automatic coordinate measuring machine, the Cleaning and Deburring Workstation which will contain both robotic and mass deburring and cleaning equipment and the Materials Handling Workstation which employs an automatic guided vehicle system for materials transfer. The three machining workstations and the inspection workstation each employ an industrial robot to perform parts handling and machine loading and unloading. At present, the CDWS contains two industrial robots. Figure 1 shows the floor plan of the AMRF indicating the locations of the five workstations and the equipment currently contained therein.

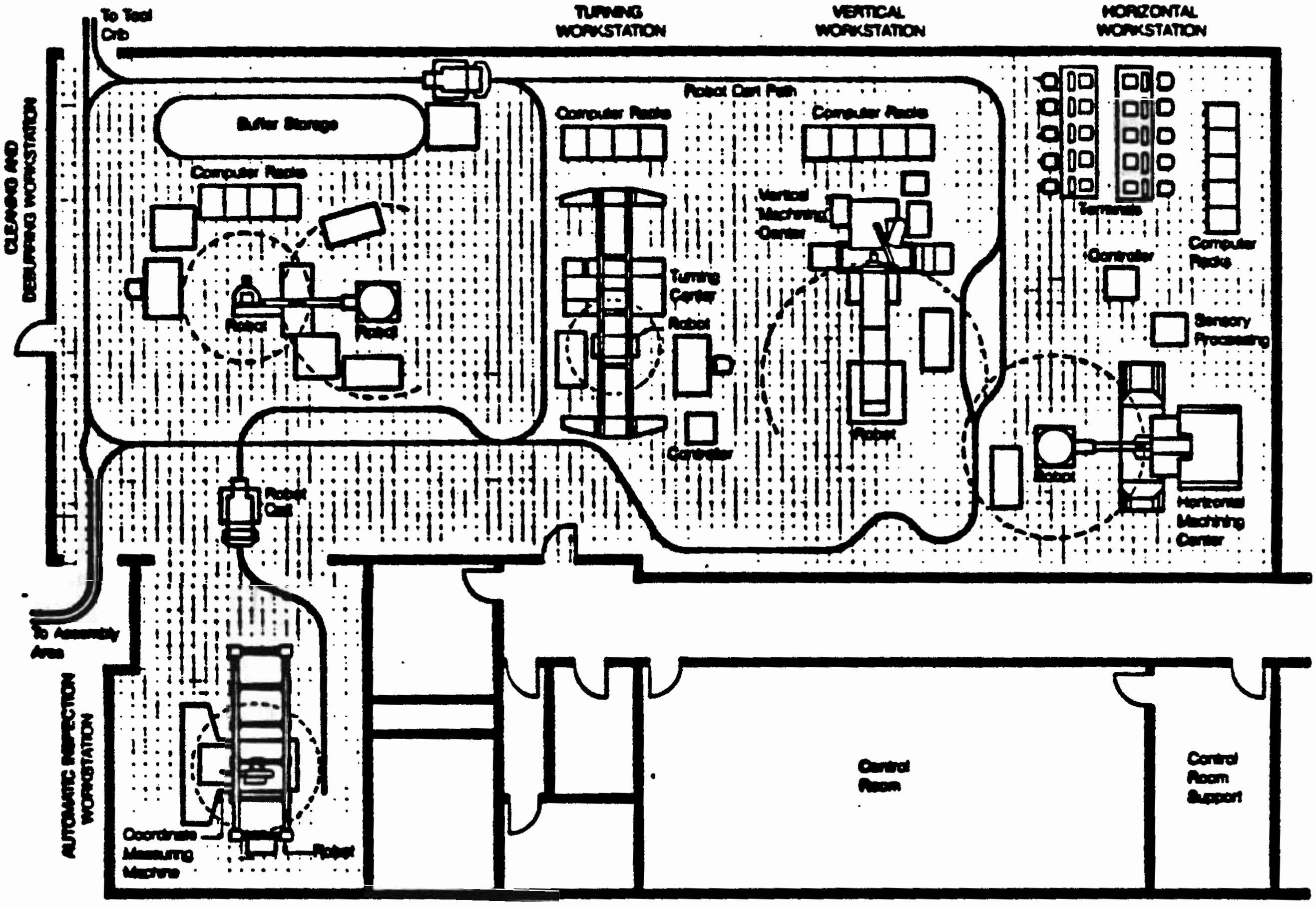

Figure 1. Automated Manufacturing Research Facility (AMRF) layout.

The concept of hierarchical control is extremely important in the AMRF and forms the basis for the whole system architecture [3]. Figure 2 depicts the hierarchical control structure of the AMRF. The highest level of the system is the Facility Level with the hierarchy forming an inverted tree structure as it works its way down to the control of the actual equipment on the shop floor. Communications between the various levels are accomplished via a local network which is being developed specifically to accomodate the needs of this type of facility. Additionally, there are sophisticated data management and process planning systems being developed to support the facility. At this writing, the Shop and Facility Levels have not been implemented. That is, the highest level currently operational is the Cell Level. The Cell Level schedules and coordinates the activities of the various workstations.

The ultimate goal of the AMRF is to automate the design and manufacture of any part that the current complement of machines is capable of physically producing. In the future, a designer will be able to sit down at a CAD system and produce a part design which can be fed into the system. The Process Planning System will then produce

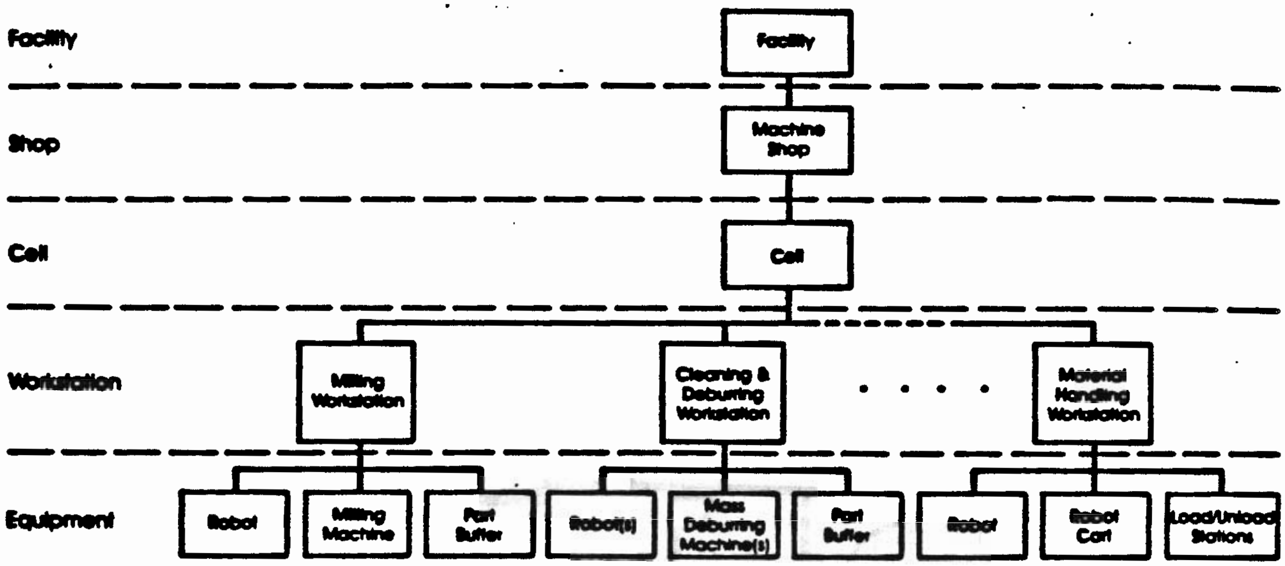

Figure 2. AMRF hierarchical control structure.

a process plan for the part. This process plan will then be "executed" according to batch size and schedule requirements supplied by the production control elements of the AMRF.

Although we are still far from accomplishing these ambitious goals in the AMRF, many of the required elements have been developed, implemented and tested in limited applications.

3. Cleaning and Deburring Process Planning

One of the research areas in the AMRF is automated process planning. Since deburring is primarily done manually, process planning is at present fairly ad hoc. As more automated methods for cleaning and deburring come into use, it will become necessary to include these steps and processes with the other manufacturing steps and processes. The following are some observations on this subject pertinent to the AMRF.

Cleaning and deburring steps are generally interleaved with the machining steps and should therefore be considered integral to the machining process. The Cleaning and Deburring Workstation in the AMRF, as currently configured, is a separate entity from the machining workstations and hence, resides in a separate physical location on the shop floor. It is not at all clear that it makes sense to transport a part from the machining workstation to the CDWS for each intermediate cleaning and/or deburring operation required during the machining of that part. It is also unlikely that the CDWS will ever have the capabilities to handle each and every cleaning and deburring problem presented by parts being manufactured in the AMRF. Therefore, it will be necessary to develop other methods and processes to complement the capabilities of the CDWS.

This dictates that a conscious effort be made to include cleaning and deburring processes into the overall process plan for the manufacture of a given part. This probably implies avoiding burrs when possible by designing the machining process with that in mind and/or using special deburring tools on the machine tool itself. These methods take advantage of the fixturing already in place on the machine tool, avoiding redesign or duplication in the CDWS. This would represent a major efficiency in both time and dollars. Finally, it should be noted, that in the near future the cleaning and deburring process plan may well have to include some manual steps on many part types. These steps should be anticipated and integrated into the process plan for the part as smoothly as possible.

4. CDWS Development Approach

The approach to the development and implementation of the Cleaning and Deburring Workstation will have two major thrusts. The first will concentrate on mass cleaning, deburring and finishing techniques currently in use in industry today. The second will address some of the research and development issues needed to further the state-of-the-art in automatic deburring using robotic techniques.

There is mass deburring equipment on the market today which produces good results for many part types. Also, it is possible to configure this equipment so that it can be robotically loaded and unloaded and can be readily interfaced with higher levels of control. Thus, the CDWS will be initially configured similarly to the machining workstations. That is, a general purpose machine(s) being tended by a robot(s) all under the control of a workstation controller. The criteria for selection of the specific equipment to be installed in the CDWS will be discussed later in the paper.

In parallel with the above approach, it is desirable to begin investigation of deburring methods using robotic techniques. These methods would more closely emulate the actions taken by a human in deburring a part and would permit a much more specialized treatment of a given part than would the mass deburring methods. There are already commercial robot systems available which can perform deburring tasks, but these systems are very limited in flexibility and often require many man-hours to program. They are therefore ill-suited to small batch production.

In order to achieve the needed additional flexibility in robotic deburring, advances in certain areas of robot control and sensing techniques will be required. There are four general areas where further research and development are needed. They are: (1) the ability to employ CAD data to develop robot trajectories accurate enough for deburring applications, (2) remote measurement of robot position to enhance positional accuracy,(3) high speed servo control using force feedback, and (4) control methods for cooperative actions of two or more robots. Work in each of these areas is planned as part of the CDWS development and implementation. Some initial thinking on these subjects has already begun and will be described later in the paper.

5. CDWS System Design

The system design and equipment selection for the CDWS is a function of the part and burr characteristics. It would therefore be desirable to completely define these characteristics. However, since the AMRF is a research facility, the types of material, part types, batch sizes, production rates, specific machining processes, etc., are not fixed and are not easily predicted. Therefore, the system has not been designed to clean and deburr all parts that could be produced in the AMRF, but rather a reasonable subset of possible parts. There are also other constraints, such as floor space, processing time and cost which were determining factors in the selection of equipment.

The general characteristics of the types of parts to be deburred and cleaned are:

a) Weight--40 lbs. (maximum),

b) Size,Prismatic -- 5"x5"x5" (maximum),

c) Size, Rotational -- 2" diameter, 4" long (maximum),

d) Batch Size -- 1 to 1,000 pieces,

e) Part Complexity -- up to 4 axes prismatic, and

f) Materials -- steel (mild), aluminum, brass, and bronze.

The parts may be machined on any of three machines: a White-Sunstrand Series 20 Omnimil CNC Horizontal Spindle Machining Center, a Monarch Cortland VMC 75 Vertical Spindle Machining Center, and/or a Hardinge Brothers, Inc. Superslant CNC Turning Center. In addition, it may be desirable to deburr and clean part blanks before machining takes place.

Based upon a review of technical literature, specifications of commercially available equipment and discussions with technical experts, a system design was developed. The major elements of the system will be: (1) a centrifugal disk deburring machine, (2) a buffing wheel system composed of four individual buffing wheels and a dust collector, (3) a washer/dryer parts cleaner, (4) two industrial robots and (5) associated conveyors with various devices for material handling, storage and media separation. The general layout of equipment is illustrated in Figure 3. Also shown in this figure are the controllers for the robots, the automatic guided vehicle (AGV) load/unload stations and associated computer systems, controllers and operator stations.

5.1 Centrifugal Disk Machine

Although alternate designs were given consideration, the centrifugal disk-type of mass deburring machine was the preferred design because of shorter process cycles (than vibratory bowl) and inherent capabilities of achieving better finishes and of handling more delicate parts. The centrifugal disk machine will have a capacity of approximately six cubic feet. It will be capable of running process

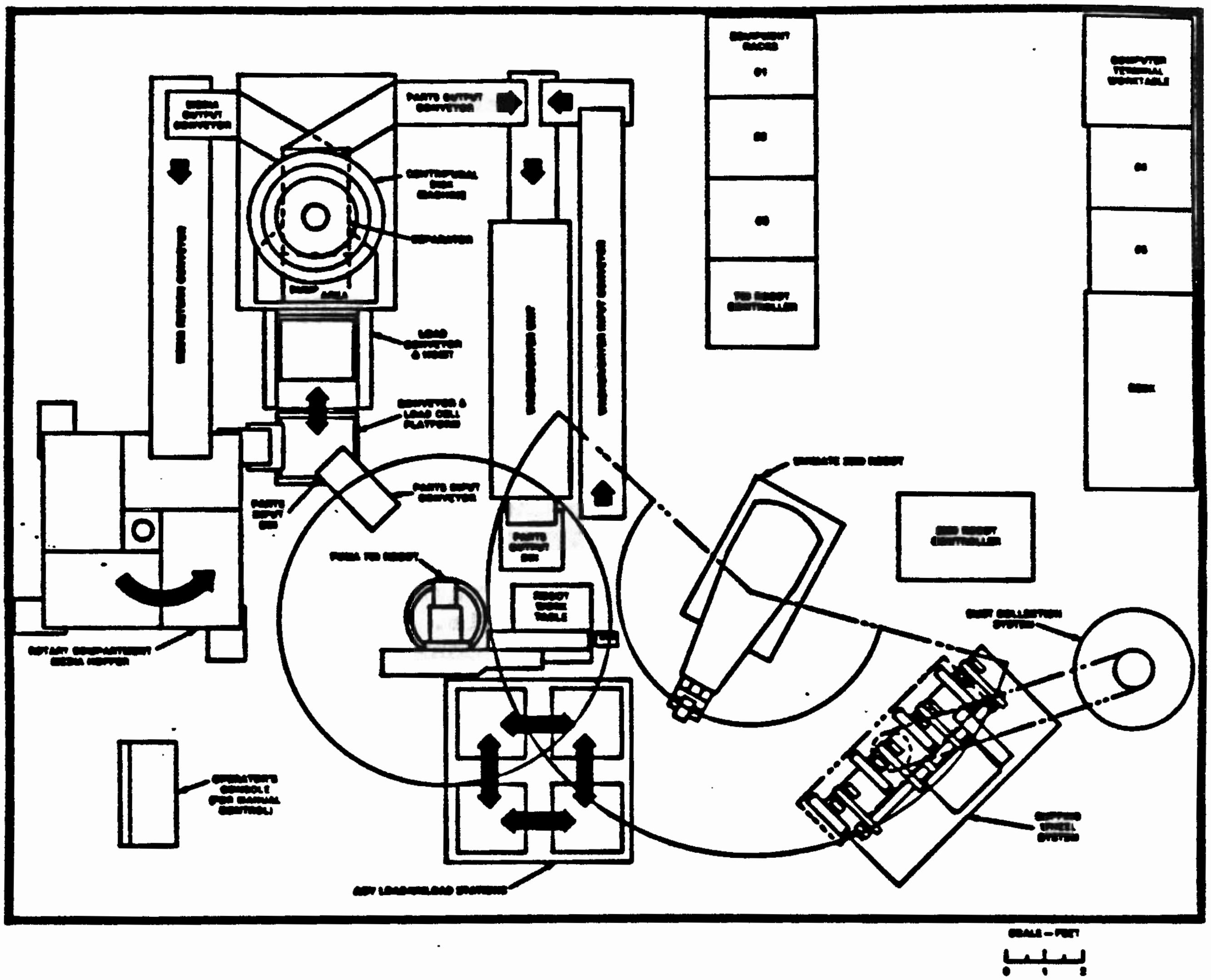

Figure 3. Proposed Cleaning and Deburring Workstation layout.

cycles as short as one minute and in excess of one hour at high speeds. Construction of the machine will be suitable for deburring with plastic media, steel media, ceramic media and other random materials, and will provide precise compound solution control. The machine will be robotically loaded and unloaded.

Associated with the mass deburring machine is a rotary hopper for media storage and dispensing. It will consist of four compartments with a capacity of approximately eight cubic feet each. The rotary hopper will be capable of automatically rotating and dispensing media from any one of the four compartments into the input parts bin.

5.2 Buffing Wheel System

The buffing wheel system was chosen to handle parts which are too large, or for some other reason, cannot be deburred by the centrifugal disk machine. This system will consist of four wheels: two buffing wheels, one abrasive filament brush and one flexible wire brush. Parts will be applied to the wheels by a robot using a predefined sequence of motions to achieve the desired results. Wheel speed will be infinitely variable and there will be automated compound application on the two buffing wheels. Because of a potential problem of compound spray and dust, the buffing wheel system will be totally enclosed, with a vinyl curtain in the front to permit access by the robot. The system will also be equipped with a dust collection system.

5.3 Washer/Dryer Unit

The washer/dryer unit will provide the capability of hot cleaning and blow drying of parts. The types of material that will typically be cleaned from these parts are cutting fluids, oils, and buffing compounds. It is planned that the washer/dryer unit will operate in a discrete rather than continuous cycle. That is, heaters may be left on to maintain temperatures, but the conveyor, washing action and blow drying will not be operating unless parts are actually being processed.

5.4 Robots

The two robots currently in the workstation and depicted in Figure 3 are a Puma 760 and a Unimate 2000, both manufactured by Unimation Inc. These robots were procured earlier, before the current workstation design was envisioned, and may or may not be the ideal robots for this workstation. However, they are adequate for the experimental research currently planned.

The Puma 760 is an electrically actuated six degree of freedom arm with a payload of approximately 22 lbs. This robot will be equipped with a vision system and will load and unload the centrifugal disk machine. The vision system is required because the robot must acquire disoriented parts [4]. The parts will be delivered to the workstation on trays by an automatic guided vehicle (AGV). The parts will not be precisely oriented in these trays. Also when parts are returned from the mass deburring and cleaning process, their orientation will have been lost and must be reacquired.

The Unimate 2000 is a hydraulically actuated five degree of freedom arm with a payload of approximately 100 lbs. This robot will be used to apply parts to the buffing wheel system and will have access to the washer/dryer unit.

As shown in Figure 3, the robots will be installed with overlapping work volumes to allow hand-off of parts and other more complex operations which will be part of the robot deburring operations.

5.5 Conveyors

There will be a system of parts conveyors in the workstation. Each of these, with its respective function, are shown in Figure 3.

6. CDWS Operational Scenerio

The general scenario for operation of the CDWS is as follows:

1) Parts to be deburred and cleaned are delivered on a tray by the AGV.

2) The parts are removed from the tray by the Puma 760 Robot.

3) If the parts are to be deburred in the centrifugal disk machine, the Puma 760 robot places the parts on the parts input conveyor. This conveyor feeds the parts into a parts bin which is sitting on the load cell platform.

4) Deburring media from the compartment rotary hopper is added to the parts bin along with the parts. The amount of media is measured by weight. The parts bin is conveyed to the hoist assembly where it is raised and the entire contents dumped into the centrifugal disk machine.

5) The centrifugal disk machine processes the media and parts for a prescribed time. After this processing is completed, the contents are dumped into the separator located beneath the centrifugal disk machine.

6) The parts and media are separated in the vibratory separator. The parts come out on the parts output conveyor and go to the washer/dryer unit. The media comes out on the media return conveyor and is returned to the rotary hopper to be used again.

7) The parts are washed, dryed, and deposited in the parts output bin. The Puma 760 robot picks up the parts individually and places them in a tray in one of the AGV load/unload stations, or in a location where the Unimate 2000 robot can take each part for further processing on the buffing wheel system.

8) If the parts are to be processed by the buffing wheel system, the Unimate 2000 robot takes the part to the buffing wheel system from one of two locations: from a work table common to the two robots, where the Puma 760 robot has previously placed it, or directly from the Puma 760 robot itself.

9) The Unimate places the part against the appropriate wheel(s) and moves the part in some prescribed pattern. If required, the Unimate 2000 robot can set the part down, regrip it, and return it to the buffing wheel system for further processing.

10) Following the buffing process, the Unimate 2000 robot places the part on the conveyor leading to the washer/dryer unit where the part is cleaned.

11) The part is washed, dryed and deposited in the parts output bin. The Puma 760 robot picks up the part and places it in a tray in one of the AGV load/unload stations.

12) The finished parts are transported to another workstation for further processing or inspection.

This scenario does not include any robotic deburring processes. These will be discussed later in the paper.

7. CDWS Hierarchical Control Structure

The entire AMRF is designed in a modular fashion with a hierarchically structured control system. Hierarchical control methods have been under study at the National Bureau of Standards for several years and the results of this work will hopefully lead to the formation of standard interfaces between the various control levels. This, in turn, could allow the design and implementation of automated manufacturing facilities where major components are bought from different vendors and plugged together much as we assemble a stereo or personal computer system today. This would facilitate the implementation of optimum facility designs at significantly lower cost than are currently possible.

Figure 2 depicts the hierarchical control structure of the AMRF. This structure also extends into the control structure of each workstation and, in fact, into the the control structure of the robots [5]. Figure 4 depicts the hierarchical control structure of the CDWS.

The Workstation Controller is at the highest level. There are three intermediate levels, and the actual equipment is on the lowest level. Each device or controller serves only one master, but may control one or more subsystems below it. That is, a controller receives commands only from the controller immediately above it, but may send commands to several devices or controllers below it. Each controller reports its status to the controller above it.

Commands from the higher levels are more complex and therefore take longer to complete. These commands are decomposed into simpler commands as they work their way down through the hierarchy of controllers. As the commands become simpler, they are executed more and more frequently. An example of this might be that the Cell tells the Workstation to deburr a given part. This action may take several minutes to complete and may require a robot to move the part. The original command to deburr the part is thus decomposed into many commands some of which control the robot. The robot commands are eventually decomposed all the way down to the servo control level at the robot joints where control cycles are in the order of milliseconds.

In this control scheme, "intelligence" is always pushed as far down the hierarchy as possible. This means that each controller must have the "intelligence" to decompose relatively complex commands as long as these commands do not require the coordination of activities with other systems at the same control level. This coordination is handled

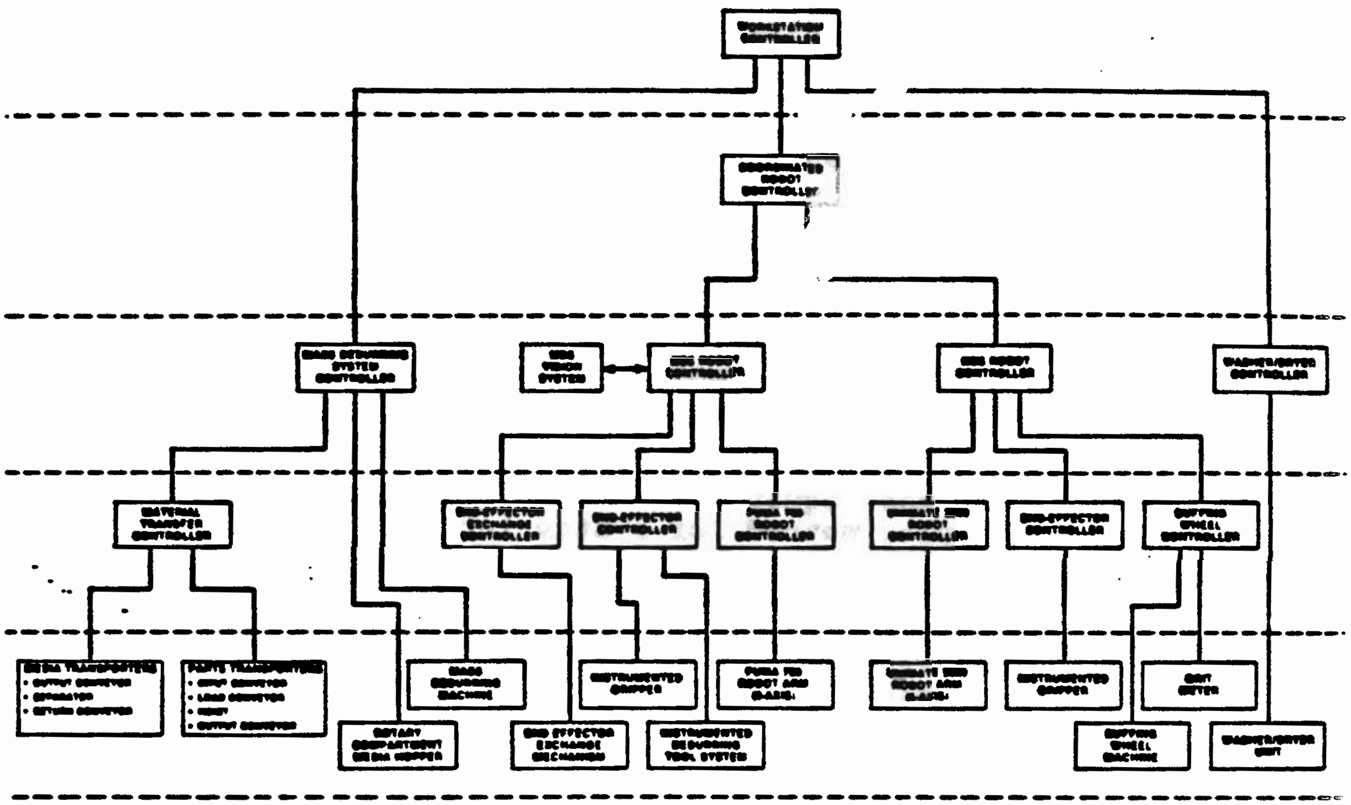

Figure 4. Cleaning and Deburring Workstation hierarchical control diagram.

at the next higher control level. The following is a brief description of each of the control levels shown in Figure 4.

The Workstation Controller coordinates the activities of the major components of the workstation; namely, the mass deburring equipment, the cleaning equipment, and the robots. When the Workstation Controller receives a command from the Cell Controller to perform a certain deburring task, it must decompose this command into the required tasks for the systems below it and plan the required sequence of events.

The next level down is the Coordinated Robot Control Level which is required because there are two robots in the workstation. This controller allows the Workstation Controller to issue complex commands that require both robots to work in concert. If the command from the Workstation Controller only requires the action of one robot, the command would be passed directly through this control level to the controller of the appropriate robot.

The next level down consists of four high-level equipment controllers. The function of these controllers is fairly obvious from the diagram, with only the robot controllers requiring further explanation. These high level robot controllers have been developed at NBS and are the product of extensive research. They are designed to interface with the commercial robot manufacturer's low-level servo controller as shown at the next lower level. These robot controllers are also designed to control other devices associated with the robot such as end-effectors or other complex subsystems which may also have their own servo controllers [5].

The next level down consists basically of the servo controllers for the various devices at the equipment level. The equipment level consists of commercial hardware which has been interfaced with the next higher level of control. This equipment may be operated in either manual or fully automatic mode. For the manual mode, the system will be configured so that each piece of equipment can be operated individually. This allows each subsystem to be used when the full AMRF is not operating. It also allows the development of a working knowledge of the equipment and its performance capabilities, and provides a simpler method for system integration and test.

Almost all of the high level controllers in the CDWS have been or will be designed and implemented at NBS. As interface standards evolve, these controllers should be able to be replaceable with functionally equivalent commercial products.

8. Robotic Deburring

The development of robotic deburring techniques will be one of the major thrusts of the CDWS research. One of the primary research areas in the AMRF has been the development of sensory interactive robot control techniques, and we, at NBS, have already developed a significant experience base in this field. It is, therefore, our intention to combine some of our experience in sensory interactive control with current robotic deburring techniques in the hopes of developing some new and innovative approaches to the deburring problem. We hope to work closely with industry on this problem, taking advantage of prior developments and experience to insure that the applications we attempt are practical and realistic. There are several robotic research areas that we plan to pursue: off-line programming, non-colocated sensing, force control, and cooperative robotic deburring.

8.1 Off-Line Programming

The bulk of current robotic deburring applications are accomplished through teach programming of the robot. This is very time-consuming and is only economically feasible for parts that are going to be produced in large quantities or where quality and uniformity are of utmost importance. It would be extremely desirable to be able to generate robot deburring trajectories off-line using CAD developed part data. This, unfortunately, places stringent requirements on the accuracy of the robot (the ability of the robot to go to a specified point in space) rather than the repeatability of the robot (the ability of the robot to return to a previously recorded point) required for the teach programming method [6]. This is a major problem because the accuracy of a given commercial robot may be orders of magnitude poorer than its repeatability. Therefore, a robot suitable for robotic deburring tasks using teach mode programming of trajectories may not adequately perform the required deburring trajectories if programmed off-line.

There are numerous potential methods for the improvement of robot accuracy. The most obvious one is to develop a robot that is mechanically superior to today's machines that will perform trajectories to the required accuracy. Although considerable work continues in the area of mechanical robot performance improvement, this is probably not going to be the most economical approach to the problem. Instead, we at NBS as well as many others, believe that the answer to the problem is through the use of sensory feedback control.

8.1 Non-Colocated Sensing

One method for improving robot performance is through the use of "non-colocated" sensing. This means that the position of the robot is not deduced from the joint angle information, but is sensed directly by an external sensing device which can measure the position of the robot in absolute space to the required degree of accuracy. If the robot control loop is closed through this external measuring system, all uncertainty created by mechanical and computational errors having to do with the robot itself can be eliminated. The sensing systems that have thus far been used experimentally for non-colocated closed loop control have been optical in nature.

Cannon at Stanford University has done some excellent work using non-colocated sensing for the control of flexible structures. At NBS we have developed a three dimensional tracking system [7] which, when integrated into the robot control system, should enable trajectory accuracies sufficient for deburring applications. The system is currently used for robot performance measurements.

8.2 Force Control

Another approach to achieving the desired deburring trajectories is to have the robot "feel" its way along the contour of the part using passive compliance, some form of closed loop force feedback control or a combination of both. The basis of this method is that the robot is given a trajectory to follow and that this trajectory is modified/refined as required in real-time.

End-of-arm tooling incorporating passive (spring loaded) compliance has been developed [8] which performs nicely for many deburring applications. The next apparent step in improving this capability is to combine these compliant devices with active force control at the tool tip allowing more sophisticated edge tracking tasks to be performed.

Current force feedback systems do not have sufficient bandwidth to track edges at high feed rates. One method of avoiding this problem and still taking advantage of the force feedback system is to let the robot traverse the path slowly, being guided by the force control. During this traversal, many trajectory points can be recorded and the robot can thereby "teach" itself the desired accurate trajectory. The recorded trajectory can then be followed at the desired higher speeds for actual deburring. This method can be employed to greatly decrease the number of man-hours required to teach program the robot for a given part.

Force control experimentation is now currently underway in the CDWS. The system is being implemented on the Puma 760 robot using the NBS Robot Control System [4,5]. The current configuration employs a wrist-mounted, six-axis force and torque sensor and a remote center of compliance device. The hardware configuration is shown in Figure 5. The system allows each axis to be controlled separately. The force and torque sensor measures forces in X,Y, and Z, as well as the torques about these axes. With the current force algorithm, only the linear axes are controlled, with the rotational axes to be included later. The system works in two modes which can be commanded separately for each axis: (1) command a force and limit the position, or (2) command a position and limit the force. This is still a relatively primitive system, but it has already shown promise for some selected deburring applications. More detail on this system will be supplied in a future publication.

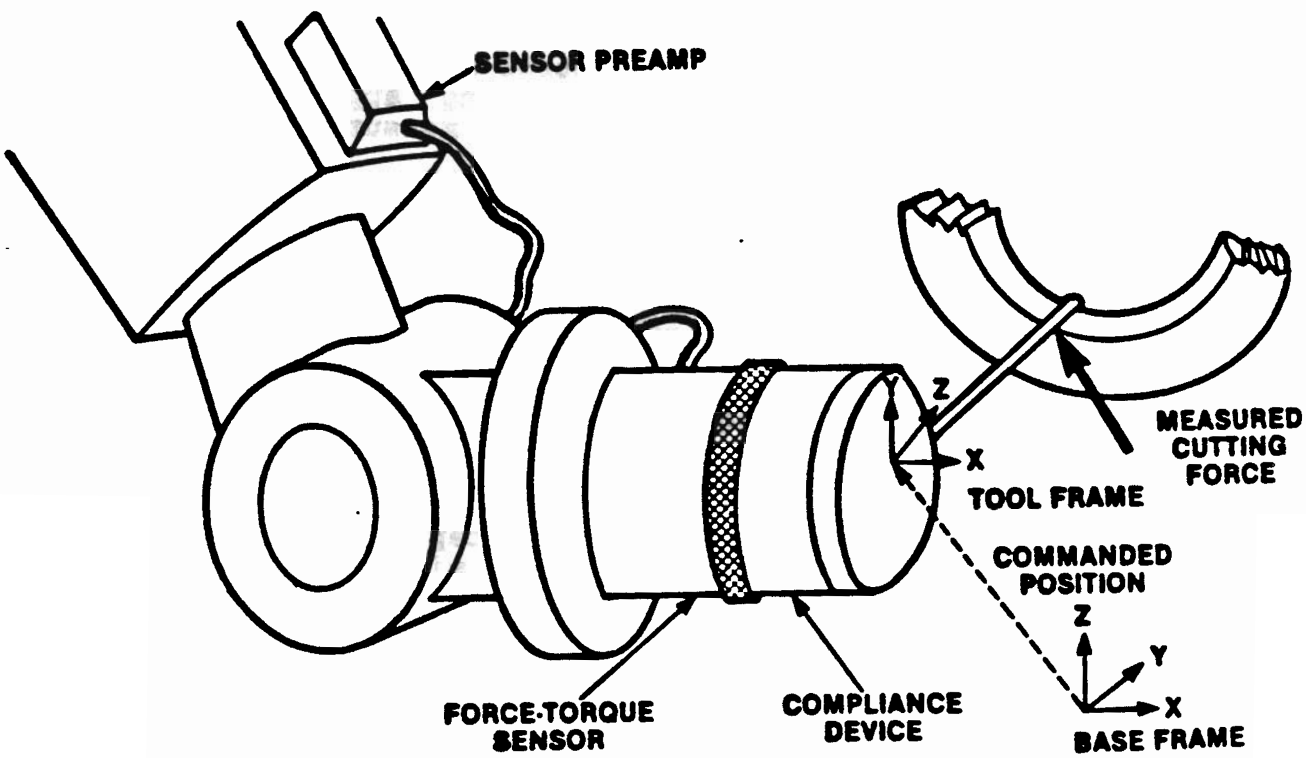

Figure 5. Puma 760 end-of-arm configuration.

8.3 Cooperative Robot Deburring

Robotic deburring applications which employ a single robot arm must use one of two methods: either the robot as the tool carrier or the robot as the workpiece carrier. In the former case, the tool is mounted on the robot wrist or held in some form of gripper. The tool is then applied to the fixtured part. If more than one tool is required, a tool change mechanism of some sort must be incorporated. In the latter case, the robot grips the workpiece and applies it to the tool which is fix-mounted. In this case, multiple tools can be fix-mounted within access of the robot. There are advantages and disadvantages to each of these methods which are discussed by Gustafson [8].

In the CDWS we are experimenting with a combination of both methods. That is, we are employing two robots: one to carry the workpiece, while a second robot carries the tool. This has a major advantage if a real-time force feedback system is to be employed. In the real-time (as opposed to the self-teaching scheme) system described earlier, a predetermined, but possibly inaccurate, trajectory is refined by closed loop force control. This requires that the robot control system simultaneously guide the arm through the prescribed trajectory while modifying this trajectory to achieve the desired forces. This type of robot control system can be implemented; however, it would be much simpler if the force and position commands to the robot could be completely decoupled. One way of accomplishing this is to have the two functions reside on different robots; one robot moves the workpiece through the trajectory while the other robot remains in a relatively static position and applies the tool, with the desired forces, to the workpiece. Our current configuration has the Puma 760 robot working under force control while the Unimate 2000 robot presents and moves the part. Using this method we were able to bring up a relatively simple demonstration in a very short time. Figures 6 and 7 show the system in operation.

9. Summary

The objective of the Cleaning and Deburring Workstation is to automatically clean and deburr parts manufactured in the AMRF. The initial planning phase has been completed, with the decision being made to incorporate both conventional and mass deburring equipment and advanced robotic deburring techniques. The conventional deburring equipment will consist of a centrifugal disk type mass deburring machine and a buffing wheel system. Both the centrifugal disk machine and the buffing wheel system will be robotically tended. A parallel effort will be the study of robotic deburring methods. These will include force control and cooperative robot control.

10. Acknowledgments

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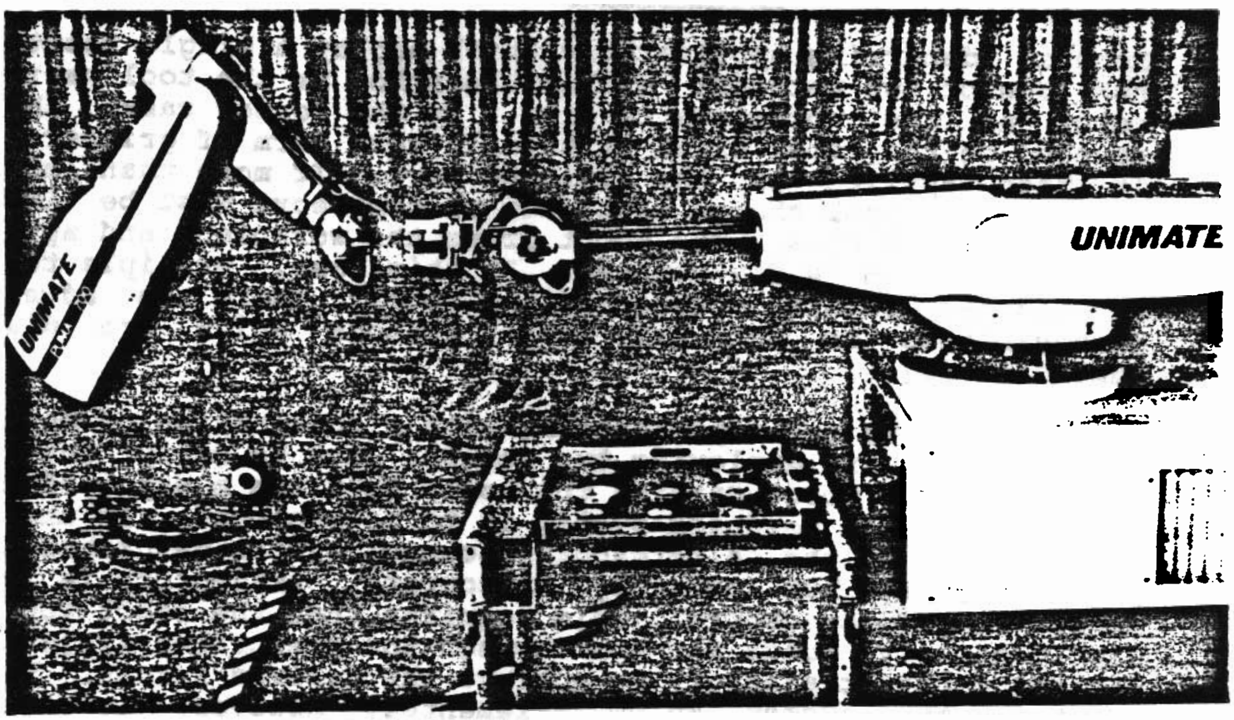

Figure 6. View of the Cleaning and Deburring Workstation showing the Puma 760 and Unimate 2000 robots.

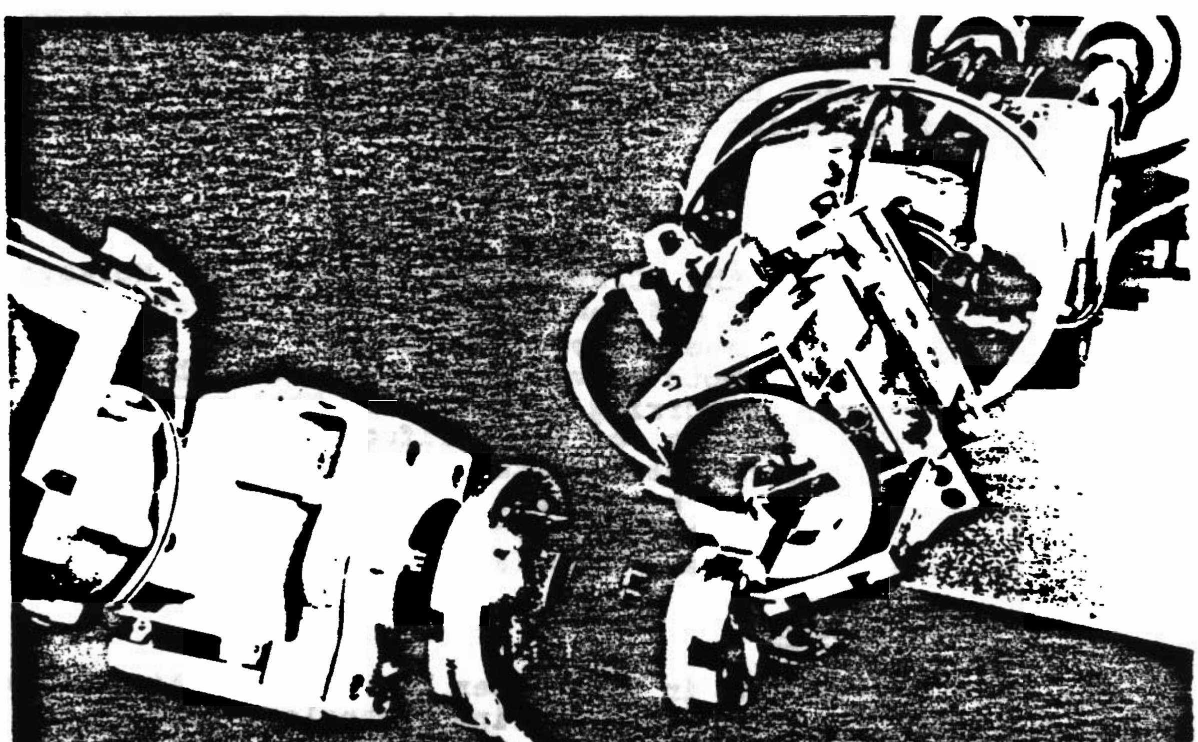

Figure 7. View of the end-of-arm tooling of the two robots showing the simulated deburring tool inserted in the part.

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