Interactive robotics to aid physically disabled people in manufacturing tasks

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Automation is commonly considered for application in manufacturing industry as a means of increasing productivity on repetitive assembly tasks. Attempts to automate production processes fully have been hindered by the relatively slow development of suitable technology that is cost-effective in comparison with human labour. It is known that automation is successful for high volume, rigidly structured tasks that require little decision-making. It is not so successful in the less structured tasks where human decision-making plays an important role. It is in manufacturing scenarios that rely on human decision-making that people with impaired motor function may use appropriate handling devices to carry out limited manual tasks within a more complex job activity. Demographic changes are resulting in an ageing population, a shrinking labour force and, as a result, a need for industry to consider alternative sources of labour. Most previous attempts to use robots in vocational rehabilitation have been made on an individual basis where a person possessing a desired skill becomes disabled and is able to continue in the job with robot assistance. Since many people with severe physical disability from birth have a restricted primary and secondary education, it is unlikely that there will be widespread prospects in jobs such as computer programming or accounting. This is not to say that computer-oriented jobs are not ideal for some disabled people, particularly those who have attained a high level of job qualification prior to becoming disabled. The research described in this paper, however, aims to identify generic job activities that require human decision-making ability and that have a minimum of prerequisite educational qualifications. This scenario is typical of many of the jobs within the manufacturing sector that allow the worker to acquire the necessary job skills through on-the-job training.

1 INTRODUCTION

Rehabilitation robotics research, which is concerned with the provision of assistance to people with motor disabilities, has concentrated on three primary application areas—daily living activities, educational activities and vocational activities. The success of such research projects has been mixed and has been influenced by many factors. In the vocational applications, the success has largely been restricted to projects involving highly motivated individuals who have acquired a physical disability after becoming skilled at a particular job. This has been true of the successful application of interactive robotics in Seattle (**1**) and Palo Alto (**2**) in the USA and Malmo (**3**) in Sweden where robotic devices have been used to support computer-oriented vocational activities. The application of simple robot systems has made it possible for a small number of people to return to their original place of employment. Associated with each of these successful applications has been the desire of the employer and co-workers to assist a colleague who had become disabled to the point of being incapable of vocational activity without assistance. This motivation to employ and assist a highly skilled colleague in need is exceptional and cannot be taken for granted by the many physically disabled people who are unable to take advantage of employment opportunities.

The research described in this paper attempts to look beyond these exceptional cases and identify generic activities within manufacturing industry where human decision-making ability is required and the person may be trained on-the-job. In this sense, the approach is closer to that taken at the Cerebral Palsy Research Foundation (**4**) in Kansas and the IRV (**5**) in Holland where robots have been used to enable physically disabled people to participate in light manufacturing activities.

The key to the success of this approach is the identification of activities that improve the general production process while providing access for people with physical disabilities. This will provide the greatest motivation for companies to take an interest in the project and to commit time and money to the development of a system. Further incentives for corporate participation include good publicity associated with participating in such a project and government assistance toward the purchase of equipment that aids in the employment of people with disabilities. The latter incentives for participation cannot be relied upon in the long-term as they are highly dependent on the state of the economy and the policy of the government. The former incentive, that of increasing the general product quality by a method that also allows for the employment of a person with physical disability, is most desirable.

2 RESEARCH SUMMARY

This research project represents a collaboration between engineers interested in interactive robotics, engineers interested in manufacturing methods, Papworth's vocational placement specialists interested in the assessment and placement of people with physical disabilities, and industries involved in manufacturing (including The Papworth Group). To date the research

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has focused on two aspects of the general problem. From an engineering perspective, a survey of industry was carried out in order to identify interested manufacturing industries, the employment needs of the industries, and jobs within the industries that require a high level of human decision-making and limited manual dexterity. Conceptual models of robot systems that facilitate the employment of a disabled person in promising job activities have been developed and more detailed system design is underway. In addition to the survey and design work, current assessment procedures are under consideration with a view to developing worksamples to evaluate the performance of a human using an interactive robot to carry out selected manufacturing activities.

3 EXPLORATION OF PRODUCTION PROCESSES

The search for possible manufacturing activities began with a general mailshot to the managing directors or, where appropriate, the technical directors of 247 companies within the Cambridgeshire area. This mailshot spanned the manufacturing industry and included companies involved in the manufacture of perfume fragrances, the manufacture of electronic components, and the research and development of improved plant breeding techniques for the agricultural industry, to name but a few.

The initial mailshot took the form of a letter soliciting the help of the company in generating ideas that would enable severely disabled individuals to become productive in industry. It was stressed that no commitment was expected from the company with regard to employing disabled people. The mailshot asked the industrial contact to consider job activities in which the cognitive skills may not be replaced by machines on an economic basis and in which the manipulative requirement is modest. It was felt that the amount of manipulation within an activity must be low in comparison with the cognitive function in order for the activity to be successful. The domination of an activity by manipulation would likely open the activity to total automation or result in the human/robot operating at a much slower rate than a person with normal hand function. In either case, it is unlikely that industry would see a benefit in such a system.

Descriptions of two hypothetical human/robot production activities, which were agreed by the research group to reflect the types of activity that could be implemented using current technology, were included in the mailshot. The first of these described the use of a robot arm by a disabled person in placing silicon wafers on a microscope stage during the visual inspection of the wafers. The second described the use of an arm to manipulate castings during a polishing operation. Both of these activities are highly dependant on the visual acuity and skill of the human operator.

From this initial mailshot, replies were received from 50 companies with 25 favourable responses offering support to the project in the form of suggestions for activities or offers of site visits in order to identify suitable tasks. Given the nature of the mailshot, the response was very encouraging. In hindsight, the industrial interest may be attributed to both altruistic and economic considerations. The economic consideration is particularly encouraging since it indicates the growing need for certain industries to consider wider sources of labour.

After a review of the initial industrial response, 13 site visits were carried out in a search for practical applications. Based on these initial visits, prospective applications were identified primarily in quality control activities that involved some simple materials handling. The activities fell into one of the following categories: electronics production/inspection, inspection of machined parts, bench-top chemistry activities, specialized quality control, and general materials handling and inspection. Examples of promising activities included the inspection/testing of electronic circuit boards, the inspection of the dimensions and surfaces of machined parts, the inspection of seed samples and plant clippings, the inspection of fabrics in the textile industry, and the evaluation of the base chemicals used in fragrance production. The prospective applications were reviewed with regard to the suitability of the activity to a person with severe physical disability, to the extent of the activity in industry, and to the feasibility of introducing interactive robotics into the existing production process. As a result of this initial survey it was concluded that there are potentially many quality control-related activities that could be opened up to people with severe physical disability. Many of these require one-off robot systems to be integrated with existing manufacturing equipment, while others require a more generic, stand-alone system with some customization to the individual user. In view of the aims of the research project, it was decided to concentrate on the development of a generic system rather than a one-off system.

Based on the apparent wide base of employment in the electronics industry, it was decided to concentrate the search to companies involved in such production. Correspondence with a further 30 companies involved in various aspects of electronics production led to a number of site visits and discussions with quality assurance managers. In addition, input from automation consultants, umbrella organizations for the electronics industry, and manufacturers of quality assurance equipment was solicited in order to obtain a general view of the industry. During the course of this more detailed survey of the electronics industry it became apparent that the processes by which quality is assured vary dramatically between companies. Much of this variation depends on the nature of the production and the extent to which industry has implemented just-in-time (JIT) manufacturing methods and total quality management (TQM). These approaches to manufacture require employees to perform a range of activities within the manufacturing process with quality forming an integral part of each activity. While this complicates the process by which disabled people may take up employment in manufacturing industry, it does not rule out the possibility given a suitably flexible system. Modern approaches to manufacturing view visual inspection as undesirable since it does not add value to the product. As such, there is a desire to reduce the amount of visual inspection as the process is refined and to eliminate it when the process is perfected. Inspection, however, is not eliminated, and it becomes a general process control rather than a distinct stage in the production process. Having said this, much of the elec-

tronics production is carried out by companies who do batch production of circuit boards under contract to larger manufacturers of consumer products such as computers or automobiles. Within such facilities, the complete automation of a process, including the inspection and test, is not practical since the automated equipment does not support the flexibility required within such a facility. Furthermore, if such flexible automation existed, it would probably be considerably more expensive than labour.

The investigation of the electronics industry indicates that, although exceptions may be cited, the bulk of the electronics industry continues to rely on the flexibility of humans within the production process. While there are advances in the stabilization of production processes, there are even more rapid advances in the technology associated with the products. Just as conventional through-hole circuit boards have given way to surface-mount technology, this will soon be replaced by complete circuits on silicon. Although it may be possible to develop and apply automatic inspection systems that can detect flaws associated with manufacture using current technology, by the time these systems came into production they would be suited to obsolete manufacturing methods. While the testing of circuits may be done using automatic test equipment (ATE), it is concluded that such equipment will continue to require a human operator. In more intricate processes, such as hybrid manufacture, the use of ATE is not practical, and there is an even greater reliance on human inspection and test. In view of this, it is likely that for the foreseeable future there will remain a need for human sensing facilities and the ability to adapt to different inspection and testing tasks.

The introduction of robot assistance has some potential benefits to the general production process. An improved method for handling circuits that contain delicate connections could lead to an increase in the overall circuit yield. Wire-bonded hybrid circuits are an example of a product that is difficult to test automatically, is prone to damage as a result of human handling, and may be very expensive depending on the circuit. Since the production process for hybrid circuits is not easily stabilized, the need for handling and visual inspection remains. A similar argument may be applied for the processing of silicon and quartz wafers. There is also the possibility that the accuracy of inspection and test activities could be improved by optimizing the sequence of circuit board manipulations to eliminate redundant testing of the board and to lower operator fatigue.

4 ASSESSMENT

An assessment procedure focuses on evaluating an individual's aptitudes, skills and abilities, so that the optimum employment placement can be provided. Within the assessment, emphasis is placed on evaluating the following abilities: (a) manual and finger dexterity and co-ordination, (b) decision-making ability, (c) visual acuity and accuracy, and (d) spatial and abstract reasoning. If limitations associated with these abilities can be overcome, a person who is viewed as unproductive may be able to work within a chosen field, providing them with increased self-esteem, dignity and the economic benefits of work. The extent to which a work situation can be adapted to include a robot system depends largely on the value to the industry of the adaption, in addition to the person's ability and the available robot technology.

In any application of a robot system to vocational rehabilitation, the task must require a high degree of input from the person. The robot should be applied to redress the problems in physical manipulation, while allowing the person to have ultimate control over the selection, initiation and termination of any robot operations. Furthermore, the person should be able to undertake the task with a minimum of training or support related to robot use.

Assessment is important when introducing the robot system to a particular disabled candidate, and there must exist some formal procedure for measuring a person's ability to use the robot efficiently. This procedure must ensure that the person will benefit from the robot assistance, not only by widening the range of vocational tasks, but by providing the person with all of the economic and social benefits of work.

The initial assessment task was the VALPAR Tri-level Measurement worksample which was modified to enable a person with very poor hand control to carry out the task with robot assistance (**6**). This worksample, which is illustrated in Fig. 1, measures a person's ability to perform precise inspection and measurement tasks and to make decisions based on certain criteria. These abilities are considered to be significant worker characteristics for certain activities within the manufacturing industry. Example work activities related to this worksample include mechanical measurement and inspection, general visual inspection, planning and organization, and manual fabrication and assembly. The worksample requires visual acuity, discrimination, decision-making, manual dexterity, forward reach, and hand–eye co-ordination. The robot-assisted worksample allows the person to make the decisions necessary to complete the inspection and measurement tasks and instruct the robot to carry out the manipulation required.

While the Tri-level Measurement worksample has been carried out by a number of disabled people, there is a considerable amount of manipulation within the

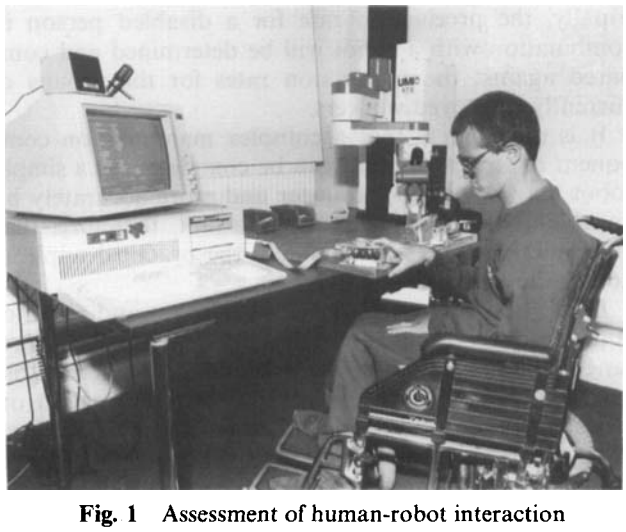

Fig. 1 Assessment of human-robot interaction

task and human–robot performance is slow in comparison with able-bodied human performance. A simpler assessment task is under development which focuses on the elements of performing a task with a robot and investigates the types and levels of robot assistance required. The task will be performed with a number of levels of user control, and it will assess the functionality of the robot and the users' interaction. Methods Time Measurement (MTM-1), which facilitates the analysis of motions and actions of operations in production into standardized time units, will be adopted to analyse the performance of the task (7). Any deviation from a given time allowance can be explained in terms of the time taken to perform a motion in relation to a standard, or in terms of the extra motions added to complete the task.

The procedure to assess interactive aptitude must include an introduction to the robot interface and a familiarization with the task to be performed. It may be necessary to repeat the assessment procedure with a variety of interfaces before a suitable interface is found. The most appropriate interface must be suited to the user and facilitate efficient execution of the job activity.

It is proposed that a person who, having been identified as a prospective candidate for the interactive robot approach, performs badly at the assessment activity may do so for two reasons. First, the person may not be motivated to carry out the particular job function. Second, the human–robot interface may not be appropriate for the person and may be confusing or difficult to access. The former result indicates a mismatch between the job and the person, while the latter requires modification to the system. Both of these results, in addition to feedback from people who achieve good performance at the activity, will provide valuable insight for subsequent system development and potential application areas.

In view of this, the assessment activity has a two-fold purpose. In the short-term, information will be gathered from within Papworth's base of able-bodied and disabled employees in order to compare performance at simple quality control activities. The average productivity rate for representative operations will be determined from a broad spectrum of able-bodied workers in the industries. Similarly, the average rate for a worker with impaired hand/arm function who is currently employed in an industry will be determined. Finally, the production rate for a disabled person in combination with a robot will be determined and compared against the production rates for the groups of currently employed workers.

It is quite likely that a complex manipulation component of an activity that can be completed by a simple robot may be completed faster and more accurately by an able-bodied person. It is important, therefore, that manipulation does not dominate the practical application or the assessment activity.

Parity between a disabled worker/robot and an able-bodied worker is unlikely although it is possible that a range of activities exists which fall within an acceptable productivity level. The range of tasks will depend on whether the comparison is with the able-bodied workers or those with some manipulation impairment. The long-term aim of the project is to enable a disabled worker to reach a relatively high-level of productivity in comparison with able-bodied workers over a range of suitable manufacturing activities. While an acceptable productivity level within a sheltered workshop setting may be lower than in mainstream industry, it must compare favourably with the baseline for current employment within such a workshop.

5 SYSTEM DESIGN AND DEVELOPMENT

Broadly speaking, engineering design involves the application of knowledge to the solution of technical problems within the constraints imposed by available technology and economic considerations. In rehabilitation, the design process must be expanded to consider the impact of the technology on the fundamental problem of improving the domestic, educational, or vocational situation for people with physical disabilities.

Design within research differs from design for manufacture since the problems are often only vaguely defined. For design problems such as those addressed in this project, the sources of knowledge are diverse and in many cases the communication between the knowledge sources is limited. Depending on the domain of the application and the immediacy of the development, the problem may be compounded further. For example, the development of a robot system that allows disabled people to take employment in the electronics industry may be thought to be (a) far removed from the immediate daily living needs of the many disabled people, and (b) far removed from the immediate needs of the target industries. Viewed at a higher level, such a project could hold considerable benefit for a segment of the disabled population and a segment of manufacturing industry. Once this perspective has been established by the organizations and companies involved in the design and development, useful knowledge emerges. The nature of such research-based design projects leads to the system designer becoming the centre of knowledge of both the problem and the solution. Without a careful design approach, there is a risk that the problem may be misinterpreted, thereby rendering the solution useless. The design approach taken in this project loosely follows that of Pahl and Beitz (8) and includes the following design phases—clarification of the task, conceptual design, embodiment design, and final design.

The 'clarification of the task' phase involves collecting information pertaining to the task requirements and identifying design constraints. The output of this initial design phase is the 'design specification' which may take the form of a requirements 'check-list'. In the case of the development of robot system for aiding in the employment of physically disabled people in industry, this initial phase also includes the 'identification of the task' which must occur before the task may be clarified. This results in even more widely distributed sources of knowledge, further increasing the complexity of the initial design phase.

Once the task has been clearly defined, the 'conceptual design' phase commences to develop a design that meets the task requirements. At this stage of design, the problem is viewed at an abstract level in order to reveal the general aspects and essential features of the problem. Functional structures can be generated and solution principles can be applied in order to generate

solution variants. Competing solution variants must be scored against the basic design specification.

Once the concept has evolved, the process shifts to the design specifics and a definitive layout is developed such that function, durability, production, assembly, operation, and cost can be examined. At this 'embodiment design' phase, the process moves abstract conceptual designs to more detailed designs. The spatial constraints are incorporated into detailed drawings and preliminary layouts and form designs of the main functional structures are developed.

The final design phase, that of 'detailed design', sees the specification of the arrangement, form, etc. of the system components and a confirmation of the technical and economic feasibility.

The total design process is merely a guideline and the divisions between the design phases are not clear-cut. Design projects within more research-oriented programmes such as rehabilitation engineering will see a great deal of feedback within the design cycle, particularly between the 'clarification of the task' phase and the 'conceptual design' phase.

Within this research project, the motivation for the exploration of robot applications in vocational settings was a logical extension to previous work in educational settings (**9**, **10**). The starting point for the project was the desire to transfer the technology associated with an interactive robot system, or at least the underlying concepts of the system, into an economically viable application. Economic viability of rehabilitation robot systems, and in particular justification based on cost-ceilings or cost/benefit, has been debated within the robotics community. In applications involving industry, the rules regarding economic viability are more rigid and must be considered from the outset of the design.

The design work to date has largely been confined to the 'clarification of the task' phase, and the requirements to be embodied in the final solution and the constraints of the problem are being identified through the industrial survey and assessment activities ongoing at the Papworth Assessment Centre. The 'conceptual design' phase has been entered, but this has primarily been to develop models that reflect the information and needs identified in determining the task requirements. Conceptual models using CAD have been generated and applied within the 'clarification of the task' stage in order to define further the task specification and design constraints.

Throughout the design process care is taken to ensure that the knowledge sources communicate in order to provide a unified body of information from which to make design decisions. These knowledge sources include people with expertise in the vocational assessment and training of people with physical disabilities, technical directors of industry who are able to present a long-term view of the needs of their industry, robotic consultants familiar with state-of-the-art automation technology, and researchers with a broad interest in applications of interactive robotics in rehabilitation. As the design proceeds beyond the 'identification of task' phase, the potential users of such systems will provide information critical to the design process.

Based on extensive discussions between the groups mentioned above, the following criteria have been identified for tasks involving an interactive robot workstation operating in a manufacturing environment:

1. The chosen tasks must be within the manufacturing industry and require human decision-making and modest manual dexterity.
2. The tasks must have a high decision-making to manipulation requirement.
3. The semi-automation of the tasks must provide a benefit to the target industries.
4. The introduction of automation will not eliminate the requirement for human decision-making.
5. The disabled individual should be able to interact with the robot in order to perform the tasks with minimal assistance from fellow employees.
6. The introduction of the robot hardware should involve minimum disturbance to the existing industrial practice and plant set-up.

Once the group discussions related to the industrial survey have been completed and the target industrial task specified, the information from both the survey and the assessment activities will be used to proceed with the design process outlined above.

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