The Application of an Intersectoral Reconfigurable Manufacturing Automation Testbed to provide an Automation Solution to Industry

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ABSTRACT

In this work, we present the latest results in the development of a generic manufacturing automation testbed, that is being carried out in our laboratory. The testbed is highly reconfigurable in nature, and, unlike other reconfigurable automation systems found in the literature, is able to cater for the development of automation solutions for a wide variety of parts that do not belong to the same part family, or even to the same manufacturing sector. The testbed is intended to be used as a shared resource by a geographically-close cluster of diverse manufacturing companies. We present new detailed results on the design, selection, construction and/or procurement of specific off-the-shelf, reconfigurable and/or flexible components that form part of the system. We then focus on the application of our testbed to provide an automation solution in a real industrial test case, with an emphasis on how the generic resources of the testbed can be applied to the development of a very specific solution, and on how the specific solution itself contributes to the continued development and upgrading of the testbed.

1. INTRODUCTION

Many manufacturing companies today are experiencing ever more stringent challenges, with consumer products continuously changing to reflect increasing customer demands for variety and to incorporate new technologies and ideas. Manufacturing systems and processes are also being directly affected by the development of new technologies, processes and equipment. Introduction of new regulations affecting manufacturing processes as well as products are also leaving an effect on manufacturing systems. In addition, the shift towards globalisation means that manufacturing companies are required to compete on a wider scale.

From our previous study [1], based on the current situation in the Maltese Islands as a case study, it has been identified that further specific problems exist for manufacturing companies that operate in a small, cluster economy that consists of a variety of manufacturing sectors. Many of the specific challenges and problems that these companies face stem from the fact that most employ only a small number of people, and thus often do not have the time and resources to investigate potential improvements in their manufacturing strategy. These companies do not afford to employ personnel dedicated solely to the development of manufacturing systems. Another factor is that local automation suppliers and developers are often quite limited in number, resulting in a lack of local exposure to new manufacturing approaches and equipment. An added setback for the companies involved in our study is that their product manufacturing portfolio typically consists of numerous small volume batches. This results in the use of extensive manual labour. Although this gives the company a vast amount of flexibility, most of these companies are still seeing their production volumes decreasing, with manufacturing shifting to cheaper manual labour countries.

Our overall study aims to provide the necessary help to local manufacturing companies experiencing the above problems that stem out of the identified lack of resources. This has led to the development of a generic intersectoral reconfigurable manufacturing automation testbed, introduced in [2], to facilitate the development and implementation of manufacturing solutions.

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2. Intersectoral Manufacturing Automation Testbed

The development of a physical manufacturing testbed as a means to share resources is not in itself a new approach. In literature, various other cases of such an approach are documented [3]-[11]. Each of these testbeds however was targeted at a particular manufacturing sector, for example for the automotive industry or for light mechanical applications. In our work, the testbed is aimed to cater for a wide range of manufacturing industries, and it will provide equipment, personnel and expertise, as a direct resource to companies to embark on specific manufacturing projects. It is expected that some clients of the testbed will request turn-key manufacturing projects ready to be installed and integrated on their existing shopfloor. Other projects are expected to be more of a conceptual nature, with companies wanting to investigate a particular concept prior to investing in the resources and equipment. This may entail proving that a particular solution achieves the desired cycle time, quality, repeatability, and ultimately profitability. An added benefit of the testbed will be the demonstration of specific manufacturing equipment to particular companies that might never have had the chance to experience, and thus possibly implement, such manufacturing approaches. For these targets to be achieved, it is essential for the testbed to operate sustainably and at an economical cost.

On the testbed, different forms of manufacturing solutions are expected to be developed, since both Dedicated Manufacturing Systems (DMSs) and Reconfigurable Manufacturing Systems (RMSs) are currently very much applied in industry. The core potential of the testbed is the ability to allow ease of change and reconfigurability of the testbed to develop different solutions to different companies. These changes, however, will be made using, to a large extent, the same overall resources, as illustrated in Figure 1 with various solutions developed at the system level from the overall system. It has to be pointed out that in our context, the concept of reconfigurability is quite different from what is commonly referred to in RMSs. RMSs are normally developed to be reconfigured for a part family and therefore there would be a certain level of functional similarity between the different system configurations. On the other hand, changes on our testbed are expected to range from slight modifications and reconfigurations of already developed setups, up to significant reconfigurations, changes, or even redevelopment of the testbed to develop unrelated manufacturing solutions.

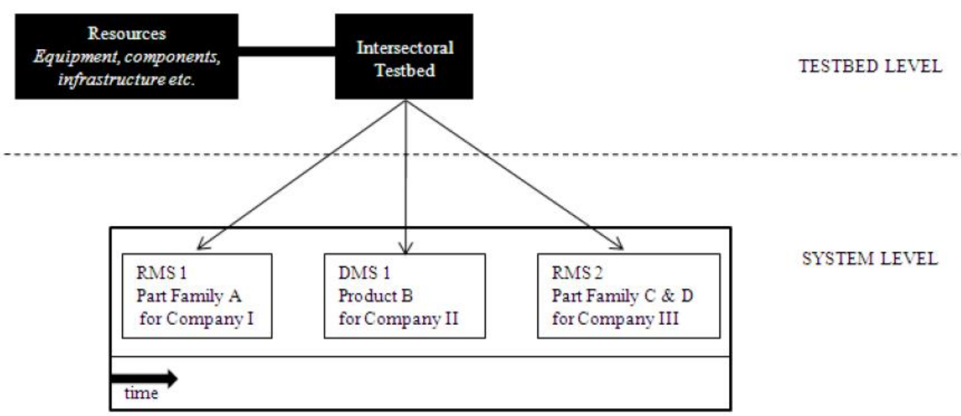

Figure 1 - Architecture of the reconfigurable manufacturing testbed

In this paper, we are reporting our progress in the development of the reconfigurable manufacturing testbed, and on specific approaches being taken in the setting up of an inventory for the testbed. The second part of this paper is focused on the application of the testbed to the development of a manufacturing solution for a local company.

3. Testbed Resources

To maximise the reusability of the testbed, the various resources of the testbed have been grouped into four basic categories [2]:

- The physical facility together with infrastructure,
- Equipment and components,

- System developmental guidelines, and
- Relevant personnel, so as to set up and make use of the above three resource categories.

Having different solutions stemming from the same overall resources results in each of the solutions having a certain degree of generic commonality with respect to the components or to the general approaches used. Each developed solution should therefore adhere to specific system developmental guidelines to maximise the reusability of equipment. In [2], it was discussed that developed solutions should wherever possible be broken down into simple functions and sub-functions, and then technical solutions are identified for these simple sub-functions. It was also emphasized that during the implementation and development of any equipment on the testbed, it is important to take into account the reusability of the same equipment for other solutions later on in the lifetime of the testbed.

A particular challenge therefore is the selection of equipment and components for the testbed. In order to set up an inventory of equipment promoting reusability and sustainability of the testbed, typical manufacturing automation systems were investigated to determine typical processing steps and subsequently the related automation equipment. Typical manufacturing steps include part handling, material transformation, material transportation, motion of tools and equipment, control and inspection. The testbed should have equipment that can be applied to the above manufacturing steps in different specific solutions. Certain trade-offs are clearly required to invest in equipment promoting versatility of the testbed. If one were to opt to have a vast amount of different components so that a vast number of different solutions could be developed rapidly on the testbed, this would increase the investment cost and the physical space for storage required, both of which are relatively limited. In [4], the authors point out that in high-volume automation systems, the trend is to make use of and develop components for specific parts only, with these components resulting in higher speeds and possibly even at a lower cost and complexity than if using completely general and reusable equipment. The authors then suggest various approaches for various manufacturing equipment, with agility in manufacturing being the primary target. These issues clearly have to be taken into consideration, especially since the testbed will be used partly for the development of turn-key production solutions. However, in the development of conceptual solutions and even in the evaluation of detailed solutions, more generic equipment can be adequate.

In our work, equipment and components have been categorized into four distinct groups in the setting up of a suitable inventory for the testbed. The first category consists of instantly purchasable specific off-the-shelf components, with these being added to the inventory on a “buy what is necessary, when necessary” philosophy. Components in this category include various actuators, specific sensors etc. Such equipment, apart from being quite readily available, as discussed above usually require to be applied to a specific solution according to the characteristics of each component in order to obtain high-speed, accurate and repeatable performance. The second and third categories include reconfigurable and flexible components respectively, both of which enable the reuse of the same equipment for different manufacturing solutions. In this case, the equipment is more generic, and it would be ideal if certain equipment and components in this category are included in the inventory of the testbed at the onset, giving the possibility for rapid use when required. The fourth category refers to specialized equipment which is used to obtain a manufacturing solution for a particular field and/or application. Such equipment would normally be very limited in its function, and would in general not be applicable for a different solution. Therefore, from the point of view of the testbed, it would not be justifiable to invest in such equipment. In such a case, if the equipment were required for the development of a solution, one option would be for the client to provide the equipment himself, and the rest of the solution would then be developed with this equipment.

In the next section, we are outlining the specific decisions taken in setting up of the inventory of the testbed as per the above guidelines.

4. Further Development of the Testbed

As discussed in section 1, local companies are experiencing lower production volumes due to competition from countries offering cheaper labour. One of the targets of the testbed is to aid such companies to reduce the production cost through automation. Currently, many of the operations that could potentially be automated, especially the assembly operations, are performed by human workers. One way of automating such operations is through an industrial robot, and thus, we determined that an industrial robot would be an important flexible component within our testbed. A human operator's arm reach typically is around 50-75cm, and handled parts during such assembly operations generally have a mass of less than 3kgs. Thus we needed a robot that would satisfy these minimal requirements. There are quite a number of robots in the market that satisfy the above general specifications. For our testbed, we selected the Mitsubishi RV-6SL six-degree of freedom revolute industrial robot with a reach of 93cm and a payload capacity of 6kgs. This makes this particular robot highly applicable for the test economy, in which the transition is to automate the human worker. Reprogramming of such robots is relatively easy and rapid, and apart from assembly and pick-and-place applications, they can also be applied to actual work processing such as soldering. Our robot is also in the process of being equipped with a tracking card to enable product tracking on a moving conveyor. This gives the possibility for products to be picked up from a moving conveyor without having to stop the conveyor or the object itself.

To enhance the reconfigurability of the testbed, the robot was mounted on a central moveable pedestal with a reconfigurable table surrounding this central pedestal, as illustrated in Figure 2. The idea of mounting a robot on a pedestal is quite a common approach and is already pointed out in [4] and in various implementations in industry. In our work, the pedestal is not anchored to the ground, and this provides the ability to move the robot where required with relative ease. The pedestal is also high enough for the robot to use nearly all the reachable space, both above and below the base of the robot. Additionally, in this work, the pedestal can also be dismantled and the robot attached solely to the base of the pedestal. In such a configuration, the robot can be implemented for lower reach applications such as next to a Computer Numerically Controlled (CNC) machine. The base of the pedestal had to be is designed to have a large mass, and is equipped with high friction, height-adjustable legs so as to prevent both toppling over and even any slight mobility to retain high accuracies and repeatability during high-speed operations. The reconfigurable table built around the robot consists of three two-level separate tables that "wrap" around the pedestal of the robot. The reconfigurable table is particularly useful for the placement of any jigs and other equipment, and allows the robot to be applied to several developmental projects concurrently. Two levels of surfaces provide the possibility to remove an upper level section, so that the lower level can instead be used as a working surface.

With regard to end effectors for material handling, two very commonly applied approaches in industry are two-jaw parallel grippers and vacuum suction grippers. The two-jaw parallel gripper is relatively quite simple but highly effective to grasp a wide range of objects. The authors in [4] propose a simple yet effective method to develop custom fingers for two jaw grippers based on a product's geometrical features. For our testbed, the pneumatic two-jaw parallel gripper purchased was selected based on the maximum force exerted, the stroke length, as well as the recommended maximum finger length. It was considered useful that the gripper would withstand the force exerted to lift products of 6kgs, the maximum payload of our robot, at the tip of standard flat surface fingers of 10cm in length with a low coefficient of friction. To increase the friction when no form closure is applied, the standard fingers were then coated with rubber. With the chosen gripper not having a variable stroke length, the distance between the fingers was also designed to be easily reconfigured by having fixed location holes to which the fingers can be mounted. This reduced the need of having to develop new fingers for different applications. Although not being

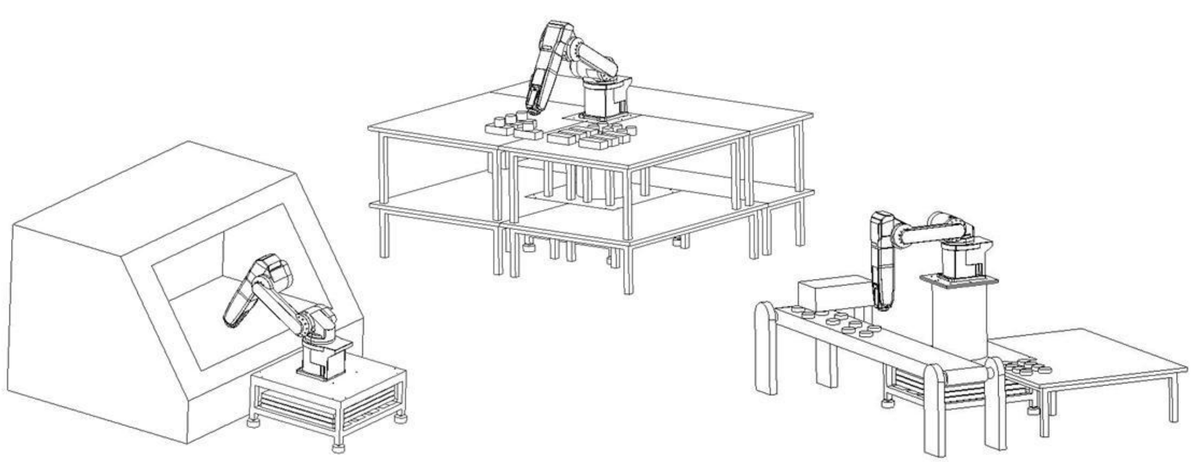

Figure 2 - (left) The robot on the base of the pedestal next to a CNC machine; (middle) The robot on the pedestal with the whole table set up; (right) The robot on the pedestal performing pick-and-place from a conveyor to a lower table

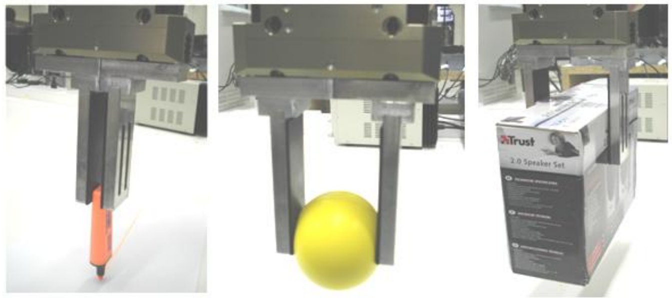

Figure 3 - (left) Robot gripping a highlighter pen; (middle) Robot gripping a ball; (right) Robot gripping a cardboard box

continuously incremental, these fixed discrete locations still allow the gripping of a wide range of different objects, as illustrated in Figure 3. Work is currently also being done to develop a continuous adjustment mechanism to be used in conjunction with the two-jaw parallel gripper. For vacuum suction gripping, a standard vacuum generator was purchased, together with a range of suction cups with various diameters and end-types. Interchanging between the grippers is rapidly achieved through a common adapter plate that allows interfacing of both grippers to the ISO flange of the robot.

The testbed is further equipped with a variety of generic sensory components such as through-beam and reflective photoelectric sensors, proximity sensors, magnetic sensors etc. Components such as these are quite commonly applied in manufacturing solutions and are not specific to a particular application only. With machine vision increasingly being applied in various manufacturing shopfloors, this was also identified as a critical flexible component of our testbed. The testbed currently has available two Cognex CCD cameras, one colour and another monochrome. Illumination is generally critical to successful machine vision implementation. Backlighting, strobe, diffuse, low-angle ring light and coaxial lighting have been identified as important components to form part of our testbed inventory.

Other critical equipment for the development of manufacturing solutions includes control and supervisory equipment. In this respect several computers, Data Acquisition Cards and Programmable Logic Controllers are available in the inventory of the testbed. CAD software is also essential in the development of a system and to provide conceptual drawings to clients, and as such forms part of our inventory.

Equipment of the testbed is expected to be continuously added and developed. Currently, a reconfigurable conveyor, capable of being reconfigured for different length, width and height, as well as for different belt types and rollers is being developed. Conveyors are a very common unit found in various manufacturing sectors, although often with different properties and setups. It has also been identified that such a conveyor should have provision for easy integration of a variety of peripheral equipment along its length, such as sensors, lighting for machine vision including backlighting, and pick-and-place devices. This reconfigurable conveyor is expected to be a valuable asset of the testbed and is expected to be applied to various solutions.

In this paper we are further reporting on the first application of the testbed to develop a manufacturing production solution to a local manufacturing company.

5. Application Example – A Case Study

5.1. Current Process and Objectives

This case study stems from a medium-sized company and involves automating the assembly of small plastic cases/containers, where aesthetics is of utmost importance. Currently, the part family under consideration is made up of ten different plastic cases, each consisting of a base container and a lid, which are then pinned or clipped together. Differences between the bases and lids include their size, geometry, colour, as well as their reflectivity index as, illustrated in Figure 4. The current assembly of these products is performed manually. The base and lid arrive from

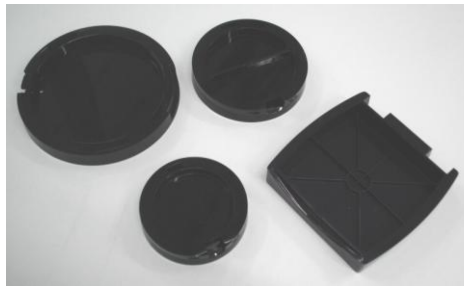

Figure 4 - A range of the different shapes and sizes of base containers to be handled. Colour and reflectivity also vary.

their previous stations from opposite directions in random positions and orientations on a dual flat-belt conveyor. The worker proceeds to pick up a base and lid, and places these on top of each other in a jig where they are assembled together. The operator then picks up the assembled product and places it onto another conveyor for further processing steps. This process is highly repetitive, and the manufacturing company is interested in analysing the benefits resulting from automating it.

Apart from being flexible in terms of the product within the part family, the solution should ideally be flexible also in terms of the overall process. In this case it is to be applied for the assembly of cases, however the client expressed the desire to investigate whether the approach could later also be developed for implementation in other processes requiring pick-and-place operations such as packaging. Changeover times are highly critical, with manufacturing consisting of a high variety of small volume product batches. Additionally, any developed solution on the testbed should be accurate and repeatable as well as cost effective both with respect to the testbed as well as to the customer.

5.2. APPLICATION OF THE TESTBED TO THE CASE STUDY

The overall objective of this automation case study is that of an orienting and pick-and-place application. The first step is to clearly analyse all the current and future variations, and their effects on the manufacturing steps. In this case, variations result from different products as well as from the possibility of the system to be implemented in other manufacturing lines and process tasks. This may result in different object localisation approaches, different gripping mechanisms, and different jigs. These variations are typical in the manufacturing of a high variety of small volume batches, and are experienced by various local manufacturing companies. Flexibility and reconfigurability are essential in the solution development. A flexible solution will minimize the variation effects resulting from different products, whilst a modular approach will reduce and simplify the reconfigurations required.

Currently, the human worker easily adapts to the large amount of variations. As explained above, the testbed is especially equipped for cases such as this transition from a manual to an automated system. The six-axis revolute robot can replace the human arm, and in this specific case, to further replicate the human worker, it was decided to integrate this robot with a machine vision system. At this stage it should be highlighted that although a six degree of freedom revolute robot is being used in the testbed, the client may later choose to implement a cheaper SCARA configuration robot if the necessary motions are still achieved.

For product transfer, the company currently makes use of a specific model of conveyor throughout its operations, with a dual-belt setup to allow two separate parts to arrive to the station from two opposite directions. Since the company showed the desire not to shift from this approach, a conveyor was transferred from the company to the testbed for use in the solution development. By removing one of the sections of the reconfigurable robot table as discussed in section 4 above, it was easy to place the conveyor within the working range of the robot.

For object localisation colour is not essential, and therefore a monochrome Cognex 5403 CCD camera was used. Due to the high reflectivity of the parts, the images captured by a camera are highly affected by any stray lighting from external factors as illustrated in Figure 5 (left). To eliminate these effects the images are captured when the part is passing through an enclosed region along the conveyor. The high reflectivity, and with some of the parts being perfectly circular in shape as illustrated in Figure 5 (middle), the choice of illumination is critical in order to consistently extract two locations on the part from which to determine the orientation. The possibility to obtain

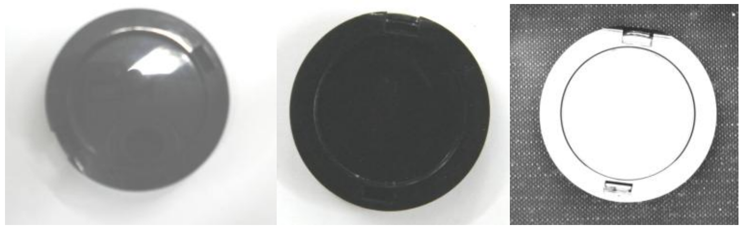

Figure 5 (left) - High reflectivity in one of the bases; (middle) - Certain parts are perfectly circular when seen from above; (right) - Part illuminated from above with coaxial lighting

adequate images of as many different plastic products from the same illumination approach is ideal since this would reduce the setup time of the system when changing the production batch, and possibly also the investment cost. After several experiments, coaxial lighting was chosen to be a suitable approach, as illustrated by the image in Figure 5 (right), from which the orientation can be determined.

In order to decrease the processing time and possibly the solution cost, it would be ideal if the Region of Interest (ROI) is as small as possible. This also results in the possibility that a smaller lighting unit can be used. To achieve these benefits, passive orienting guides were developed to guide the parts to a specific area under the camera. To be able to be used for all of the different products, the guides were designed to have continuous adjustment capability.

When a part is localised, the camera transmits the calculated pose of the part over Ethernet to the robot, which is multitasking several programs. The pose coordinates, are then fed into a FIFO buffer, and are then read by the movement program of the robot. The part is stopped on the conveyor by a fixture that prevents any further movement and is then picked up by the robot using a vacuum gripper. This approach is adequate to prove that the concept works, and determine the cycle time and the accuracy of the system, which were primary concerns for the client. Further development to finalise the system include the possible implementation of conveyor tracking following the localisation of a part. Figure 6 shows a schematic of the overall general system and the integration of the different equipment.

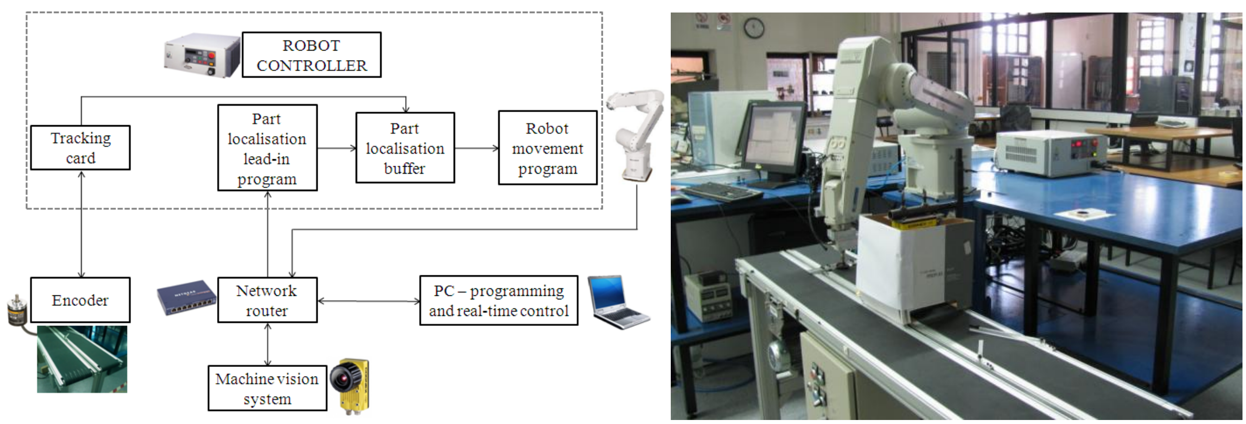

Figure 6 – (left) The overall developed system and the communication between the separate devices; (right) A photo of the physical system

5.3. *INTRODUCTION OF NEW PARTS*

As discussed, the system will require reconfiguration for different batches quite frequently. Having developed the system on a flexible and modular approach, this will only require changing and/or reconfiguring a few well defined tasks and components, with changeover generally requiring only a few minutes. Different programs for the robot and machine vision algorithms will be required to be loaded in the system. The passive orienting guides will require to be adjusted so that the parts are routed to the correct location beneath the camera. Whenever a new part is added to the product line-up of the company, a new pose localisation algorithm is required to be developed. If necessary, a new program would also need to be developed for the movement of the robot.

6. OUTCOMES OF THE STUDY

The solution of this case study using the testbed proves to the client that the process can in fact be automated without the client running the risk of investing in equipment without a guarantee of success. Further to this, the testbed has also provided the client with nearly a turn-key solution, with only a few changes required to implement for production on the shopfloor. The solution was developed without the client needing to divert resources from his production (with the exception, in this case, of the conveyor) while work was being carried out. From the point of view of the testbed, such test cases provide fundamental additional experience to personnel as well as additional items of equipment. As mentioned previously, further equipment, especially generic components, will be added to the inventory. Each test case will further provide more guidance on equipment that should be included in the testbed for the sustainable development of a wide range of solutions.

7. CONCLUSION

In this overall study, we have further emphasized the need of a reconfigurable intersectoral manufacturing automation testbed to improve the competitiveness of manufacturing companies operating within a small, cluster economy. The testbed is aimed at being readily available to companies to develop automation solutions. In this particular work, we have outlined specific new guidelines in the setting up of such a testbed, and the approaches taken with the main focus being the reusability of the testbed for different manufacturing solutions. Further to this, we have illustrated how generic, flexible and reconfigurable equipment can be applied to develop a production solution to a local manufacturing company. In continuing work, the testbed will be expanded by the addition of further resources, both hardware and software, and new technologies to be able to aid more manufacturing companies to address several new challenges.

ACKNOWLEDGEMENTS

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