Assembly Automation

Emerald Article: A modular, reconfigurable end effector for the plastics industry

Michael A. Saliba, Andrew Vella Zarb, Jonathan C. Borg

A modular, reconfigurable end effector for the plastics industry

Michael A. Saliba, Andrew Vella Zarb and Jonathan C. Borg
Department of Industrial and Manufacturing Engineering, Faculty of Engineering, University of Malta, Msida, Malta

Abstract

Purpose – The purpose of this paper is to address a problem that is commonly faced by manufacturing companies in the plastics industry, where large and different batches of freshly produced units need to be unloaded from the injection-moulding machines and relocated, using automation.

Design/methodology/approach – The new solution is reached through a formal design approach, including a function analysis, a product design specification, a quality function deployment exercise, the generation of a number of conceptual solutions, and concept evaluation using morphological charts, failure mode and effect analysis and a decision matrix.

Findings – A single modular end effector that can be easily reconfigured for a large variety of moulds has been developed. The results are also extrapolated to more general applications where an end effector is required to carry out simultaneously several different but well-defined functions in the presence of high variety.

Research limitations/implications – The critical decision that often needs to be made in industry, between flexibility and reconfigurability, is discussed. It is shown that when batch sizes are large, the penalty incurred in reconfiguration time is well offset by gains in simplicity, reliability and lower cost.

Practical implications – The company involved in this case study will achieve significant savings in costs and in storage space, since it will no longer need dedicated gripping devices for its different products.

Originality/value – This paper demonstrates the application of a formal design and development approach to arrive at a novel reconfigurable solution to a common parts handling problem in industry.

Keywords Plastics industry, Design and development, Automation

Paper type Research paper

1. Introduction

Manufacturing automation systems have traditionally been categorised into three distinct types, these being fixed, programmable and flexible (Groover, 2001). Fixed automation refers to a system that is custom designed for the production of a particular product, and is indicated where the production volume is high but where the product has little or no variety. Such a system has a number of benefits due to its dedicated nature, including relatively low cost and simplicity, however it has the major potential drawback of becoming obsolete if and when the product is discontinued. Programmable automation refers to a system in which the sequence of operations and motion parameters can be changed to accommodate different product batches, and is indicated in situations where production volumes are low but where there is relatively high-product variety. Programmable automation systems are typically computerised numerically controlled machines or industrial robots. While offering the significant advantage of being applicable to a wide variety of products, these systems normally require a high-investment cost, and normally require a significant amount of set-up and programming time between batches of different products. Flexible automation refers to a system that can handle a variety of products without set-up or reprogramming. Such systems are widely regarded as representing an ultimate achievement in automation, however they are not without drawbacks. Generally, they are relatively complex systems that come at a substantial cost, and moreover the amount of product variety that they can process is often quite limited.

Recent market is characterised by tough competition that continually forces manufacturers to push down their costs, coupled with a discerning customer who constantly demands a higher level of variety. This scenario has led to the search for new automation systems that combine advantages of the three traditional approaches, while mitigating the disadvantages of each. The ideal automation system would be cheap and simple to implement, while at the same time would be able to handle a high degree of variety with minimal set-up time between batches of different products. This search has led to the development of a new paradigm in manufacturing automation, that of reconfigurable automation (Koren *et al.*, 1999; Mehrabi *et al.*, 2000; Chen, 2001; Denkena and Drabow, 2003; Chen *et al.*, 2004). The basic concept of this approach is to develop an automation system that is very modular in nature, and where the constituent modules can be quickly interchanged, exchanged, or otherwise reconfigured to handle different products. Once the two fundamental

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problems of module definition and of module interfacing have been solved, these systems can become quite inexpensive and simple to implement, have the capability to handle a significant amount of variety, and can be reconfigured (normally manually) relatively fast.

A very common requirement in manufacturing automation systems is that of grasping and handling objects, and as such, significant effort is very often made to maximise the effectiveness of this function within the automation system (Newman *et al.*, 2000; Causey, 2003). Where it is required to find a relatively low-cost solution to dealing with the gripping of objects in the presence of variety, the use of a reconfigurable gripping device may be indicated. This is often done by developing a gripper in which the positions of some or all of the fingers can be adjusted to accommodate each particular batch of objects before the start of each production run (Costo *et al.*, 2002; Yeung and Mills, 2004).

In this paper, we address a handling problem related to the plastics injection-moulding industry, namely the transfer of freshly produced parts from a mould to a conveyor, on which the parts later move for further processing. The issue is addressed in the context of an actual case study, in which a company is seeking to improve an already automated process. As shall be seen below, the problem at hand has a number of distinctive features. Apart from a high degree of variety in part size and shape (approximately 400 different products) that need to be handled, the number and positions of identical parts manufactured simultaneously within each mould also differs. Furthermore, in addition to grasping the parts, the parts handling device has to cut and dispose of the runners and sprues associated with the injection-moulding process. The grasped parts need to be released on to the conveyor in a highly ordered manner, in order to be ready for further automated processing. The main general objectives that need to be achieved are a reduction in the costs associated with the development and set-up of the gripping device whenever a new product is introduced by the company; and a reduction in the required storage space for the gripping devices and associated sub-components that are not in use. For the reasons indicated above, the approach selected to solve this problem is the design and development of a modular, reconfigurable end effector.

2. Problem definition

2.1 The company

The company involved in this work is privately owned and deals with the manufacture of high-quality plastic packaging. The plastic products go from raw material to the finished packaging product in-house. The cases and containers produced are then sold to client companies that complete the production process and distribute the products to retailers, for eventual sale to the end-users. All the cases produced by the company have to meet very high standards of quality on both an aesthetic and a functional basis. To produce such high-quality products, the production equipment used is centred on quality, and the margin of acceptable defects is very small.

To retain its competitive edge, the company is always seeking to improve its manufacturing system. These improvements can range from the installation of newer machinery to simply altering a sequence of production operations using the current installation. These changes can often work out to be costly and then become counterproductive as the product price may increase, thus reducing the economic competitiveness. However, product quality can be improved without increasing cost, by investing in automation and lean manufacturing techniques. These techniques strive to reduce waste and thus increase profitability by reducing the overall product cost.

In light of this, the company is constantly seeking to reduce waste (both material and time) in various stages of the production operations. This is what has led to the formulation of this project.

2.2 The current process

The operation under consideration involves the unloading of the injection-moulded parts from the open mould, the disposal of the runners, and the transfer of the parts to a conveyor system. This operation is already automated using Cartesian robots, but the company has a different end effector associated with each mould, to grasp and relocate the units and to cut and dispose of the runners. The number of identical units produced simultaneously by each single mould varies between two and 16. The company makes use of around 400 customized end effectors, with an associated penalty in storage, handling, and set-up costs. The company designs and develops a new end effector whenever a new product is commissioned. The maximum combined weight of the parts to be transferred is of about 3N.

An example of an end effector that is currently used for this operation is shown in Figure 1(a). The end effectors, or robot plates, make use of vacuum grippers (Figure 1(b)) to grasp the moulded parts, and jaw grippers (Figure 1(c)) to grasp and snap off the runners. For the example given, the mould produces four units per cycle, with the positions of the finished units within the open mould corresponding to the positions of the four vacuum grippers on the robot plate, which would have been custom built for this particular mould.

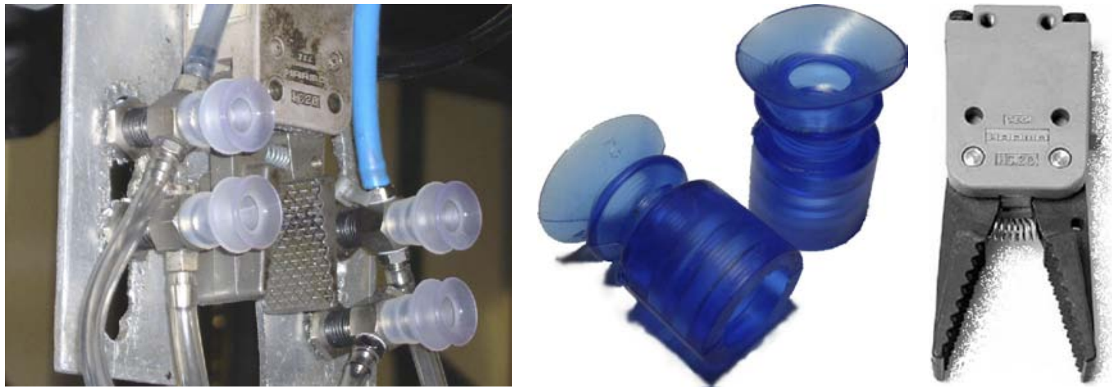
The work is batch oriented. This means that a particular product is produced for a limited period of time to fulfill a customer's needs. Once the pre-ordered number of products have been produced, the product is discontinued for an amount of time which may vary. Every time, a batch has been completed, the tooling used is removed from the injection machine, the particular robot plate is removed from the robot wrist-mounting plate, and the controller programs are saved and removed from the controller. Once the injection machine is needed for a new batch (of the same product or even different products), the tool is once again mounted on the injection machine platen if already manufactured, its respective robot plate is mounted or custom made, and the relevant controller program is either re-loaded or written from scratch.

Every mould tool requires a particular robot plate. The number of mould tools used already exceeds 400, and new products are continually developed. The customized robot plates are not only expensive to produce, but are also expensive to store due to the large number of plates kept.

2.3 Function analysis

The parts are gripped from the open mould, in the vertical position. In this position, the retaining force of the vacuum grippers is at its lowest, being exposed to a shearing force by the weight of the part. The robot plate is then raised above the

Figure 1



(a) (b) (c)

Notes: (a) Robot plate; (b) vacuum grippers; (c) jaw gripper

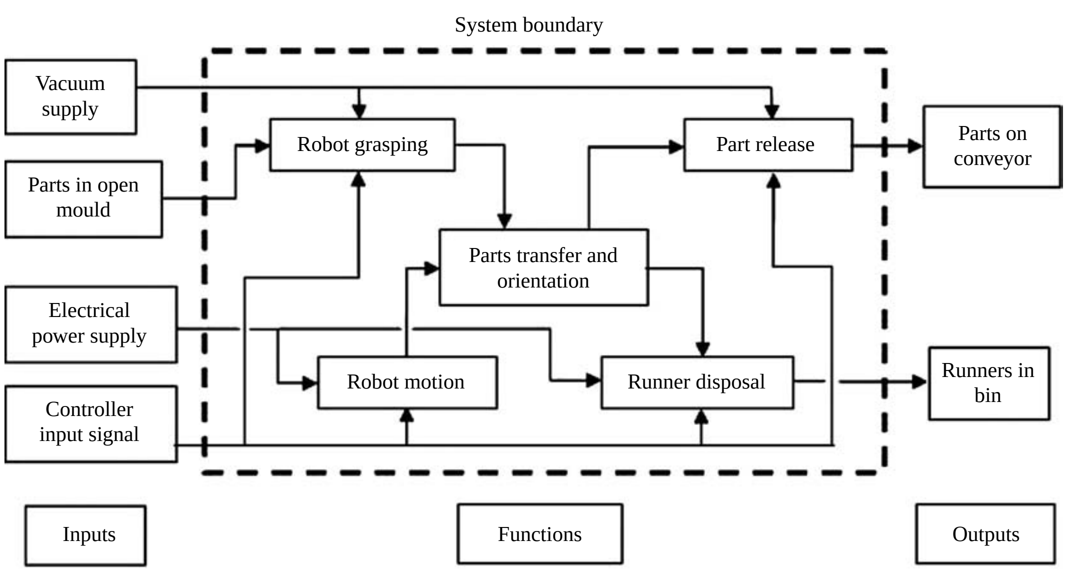
open mould, still in the vertical position. Once clear of the mould, the wrist-mounting plate then rotates downwards, thus positioning the gripped parts directly below the robot plate. Here, the vacuum gripper retaining force is higher since the weight of the parts is acting directly against the vacuum force applied. A vertical and horizontal translation by the robot then positions the robot plate over a disposal bin. Here, the jaw grippers are opened, releasing the runners which fall into a disposal bin. The robot plate is then moved over to the conveyor belt. Once in position, the robot plate is then lowered, gently placing the products onto the conveyor. The cycle time for this operation, including all mould and robot motion, is of 19 s. The problem boundary, based on the transparent box approach, is shown in Figure 2.

2.4 Product design specification and quality function deployment

A product design specification (PDS) for the end effector was drawn up, outlining the customer's requirements in terms of demands and wishes. With regard to the working environment, a demand was that the end effector needed to be able to work in proximity to hot mould tools. To satisfy performance requirements, the device needed to perform the basic part transfer operation; maintain the existing level of positioning accuracy; not damage the parts; be adequate for future products of the same part family; be able to handle hot, freshly moulded parts; and be easy to set-up or reconfigure. The device needed to have a service life that would allow it to process one entire batch (approximately 50,000 units) as an absolute minimum. The device also had to be compatible with the existing bulk machinery. With regard to kinematics, the device would have to withstand high accelerations. The device weight was limited to a maximum of 5 kg, and size to 250 mm, due to robot payload and open mould gap constraints. During the disposal phase, the device needed to be harmless to the environment. To satisfy materials requirements, the device needed to have no effect on the facilities and products; it had to be lightweight; it had to resist warping and deformation; and it had to be safe for workers to handle.

The design wishes included an ability to handle as large a number of batches as possible within its lifetime, and to have consistent performance characteristics throughout its life; to be inexpensive to develop and to have low-running costs; to make use of readily available forms of energy; to be small and

Figure 2 System boundary



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easy to store when not in use; to be easy and inexpensive to maintain; to be able to be fully or partially re-usable at the end of life; and to be made of readily available materials.

A quality function deployment (QFD) chart was drawn up to relate the requirements and preferences of the company to specific technical parameters. This chart is shown in Figure 3. In the QFD chart, the relative importance of each of the customer requirements is rated on a scale of one to ten, based on detailed discussions with the technical staff of the company. On the right-hand side of the chart, a score is given for the existing solution and for the expected solution, for each of the customer requirements.

3. Concept generation

A morphological chart of candidate subsystems that would perform each of the required functions of the device was drawn up. A number of alternative concepts were generated for each element in the morphological chart. The concepts that were generated for the working principle are shown in Figure 4.

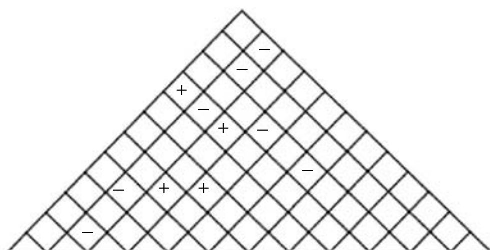
In the concept shown in Figure 4(a), the matrix of pins conforms to the object to be grasped, and the extended pins are then compressed against the objects by a surrounding inflatable bladder. The concept of Figure 4(b) consists of a matrix of suction grippers, which would be used in conjunction with a customized blanking plate. In both these concepts, the runners are disposed of in a separate process. In Figure 4(c), the conceptual solution consists of a flexible, soft polymer pad with perforations that can be connected to a vacuum pump. Runner removal can be performed using a high-powered air jet. The concept of Figure 4(d) consists of a reconfigurable plug board to which suction and jaw grippers can be attached as required for each mould. In Figure 4(e), the conceptual solution consists of individual suction and jaw grippers that can be inserted in various positions along horizontal rails. The rails themselves can be attached to cross-rails for further position setting.

4. Concept evaluation and selection

Concept evaluation was carried out using two design tools, namely failure mode and effect analysis (FMEA) in order to reveal potential failures of each conceptual solution, and a decision matrix to compare different solutions.

Figure 3 The QFD chart

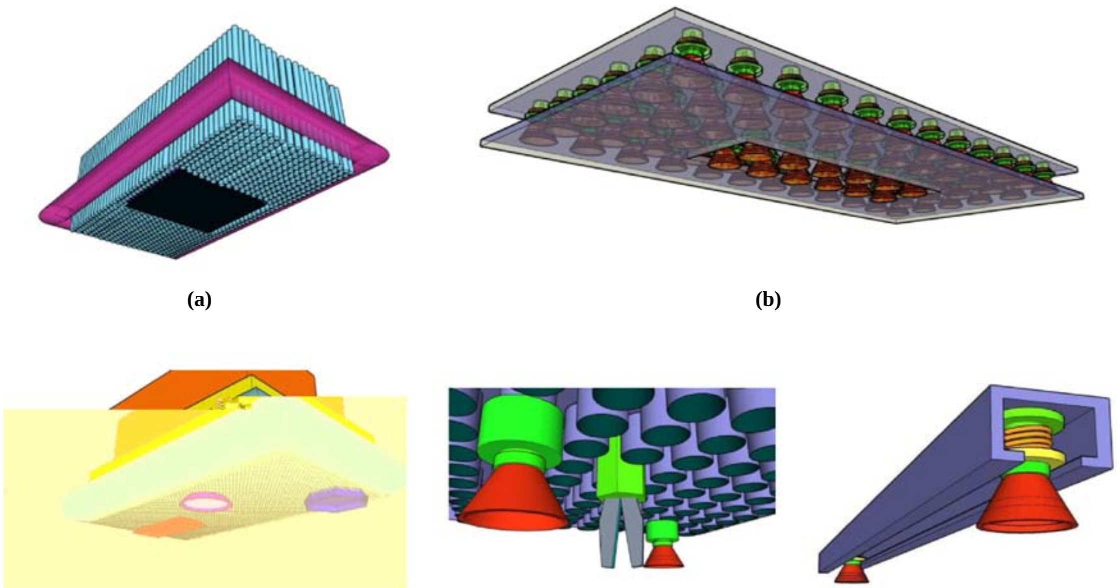
Symbol	Relationship	Weight
▲	Strong	9
■	Medium	6
●	Weak	1



Customer requirements		Maintainability	Cost	Material	Size per unit	No. of units	Weight	Shape	Accuracy	Durability	Compatibility	Reconfigurability	SMED level	Importance	*Existing method*	*Expected solution*
Actual costs	Cheap to Commission		▲	■									●	3	9	5
	Cheap/easy to maintain	▲			●	●	●	●		■				7	9	8
	Low use of storage space				▲	▲		■						4	4	10
	Utilizes current installation				●						▲			10	10	8
	Able to be recycled			▲										2	5	5
	Long lifespan	●		▲						▲				6	8	9
Performance	Able to handle hot parts			▲										8	7	7
	Can handle different tools				■			■				▲		10	2	9
	Quick set-up				●		●	●					▲	9	2	8
	Able to place parts accurately								▲					8	8	9
	Does not damage parts			▲										10	9	9
Safety	Safe in use and maintenance			■			■	●						8	9	8
Aesthetics	Looks aesthetically pleasing		●	■										1	2	4
	Weighted score	69	28	306	122	43	64	108	72	96	90	90	84			

Technical parameters

Figure 4 Generated concepts for the main working principle



(a) (b) (c) (d) (e)

Notes: (a) Pin-box; (b) suction gripper matrix and blanking plate; (c) perforated polymer pad; (d) plug board; (e) reconfigurable rails

The first step in constructing a decision matrix was the establishment of the evaluation criteria. These were based mainly on the requirements specified in the PDS list and also on the constraints around the developed product. The criteria included several technical, economic and also safety factors, thus giving a broad spectrum of criteria on which the concepts could be evaluated. The factors chosen were ones which are decision-relevant, as well as general constraints. The factors are also relatively independent of one another.

Each of the evaluation criteria was given a weighting of between one and ten, according to how much the specific criterion contributed to the overall satisfaction of the customer requirements in relation to the other criteria. The weighting values were determined from the detailed discussions with the customer. Criteria which were given a weighting value of ten were considered to be indispensable, and thus if a concept failed to satisfy these criteria, the concept in question was not considered an adequate solution to the overall project problem. The computed decision matrix is given in Table I. The highest score in this exercise was obtained by Concept 5, the reconfigurable rails concept.

The FMEA exercise for the reconfigurable rails concept showed that the most likely potential failure modes of this concept could be countered with simple maintenance routines and good overall design. This concept was therefore selected for further development.

5. Embodiment design, fabrication and testing

After the solution concept had been selected, a new morphological chart was drawn up to evaluate and select the best methods to achieve the required functions of the prototype. Two key parameters that were analyzed were the locking mechanism between the grippers and the mounting rails, and the sliding mechanism between the mounting rails and the cross rails.

For the locking rail mechanism, the generated concepts included magnetic locks, screw friction locks, bolt locks and spring loaded pin-in-hole locks. These candidate solutions were evaluated in terms of flexibility, set-up time, positional stability, cost and availability. The selected concept for this function was the spring loaded pin-in-hole lock, due to its high-position stability, and low-cost and set-up time. A CAD drawing of the gripper fixture design is shown in Figure 5(a). A similar mechanism was selected for the movement and locking of the mounting rails relative to the cross rails, and a CAD drawing of the fully assembled system is shown in Figure 5(b).

After the detailed designs of the reconfigurable gripper were completed, a prototype was fabricated in order to test the reconfiguration and locking abilities of the system. For the prototype, the rails were fabricated out of mild steel box section, and the gripper fixtures were fabricated out of aluminium. Details of the prototype can be seen in Figure 6.

All of the sliding and locking functions of the prototype have been tested, and have been found to function well under the expected loads. During testing to failure, failure of the locking mechanisms occurred at between 6 and 8 kg loading. This load is well above the maximum weight of the parts to be handled, and exceeds also the payload capacity of the robots (see Sections 2.2 and 2.4).

6. Discussion

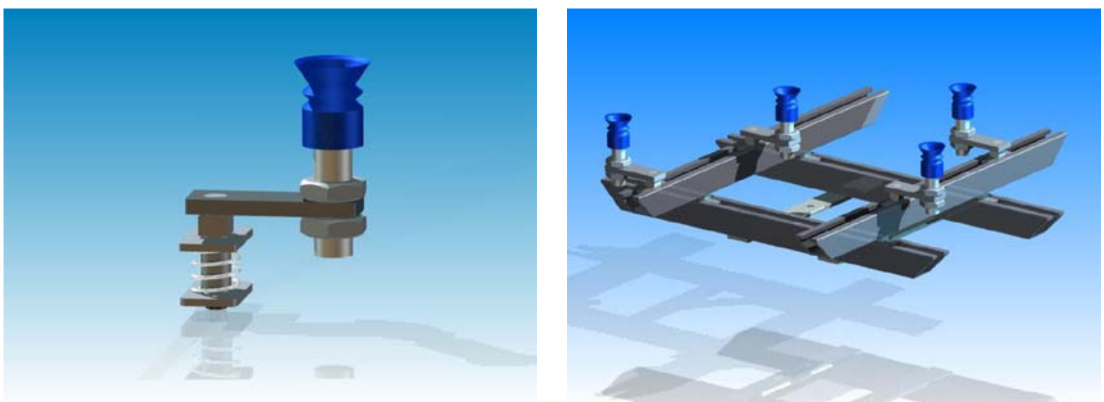
This paper has addressed two important issues in industrial automation, as discussed briefly in this section.

The first issue relates to the critical decision that often needs to be made between flexibility and reconfigurability in manufacturing automation. In the current application,

Table I The results of the decision matrix

Evaluation criteria	Weight	1. Pin-box	2. S. matrix	3. Poly. pad	4. Plugboard	5. Rails
No part damage	*10*	20	70	80	90	90
High shape flexibility	*10*	80	100	100	90	100
High mould layout flexibility	*10*	70	60	70	80	90
Low set-up time	*9*	81	72	90	72	81
Low-running cost	*7*	21	49	56	56	63
Low-initial cost	*3*	12	21	9	18	27
High accuracy	*8*	40	64	64	64	72
Ease of development	*9*	36	81	18	54	90
Low-storage usage	*4*	40	28	40	32	32
Low modification of robot/tool	*7*	49	49	49	70	70
Long lifespan	*6*	48	54	42	54	54
High maintainability	*4*	8	24	20	28	32
Easy to re-use/recycle components	*2*	4	16	6	14	16
Total weighted score		509	688	644	722	*817*
Percentage score		15.0	20.4	19.1	21.3	*24.2*

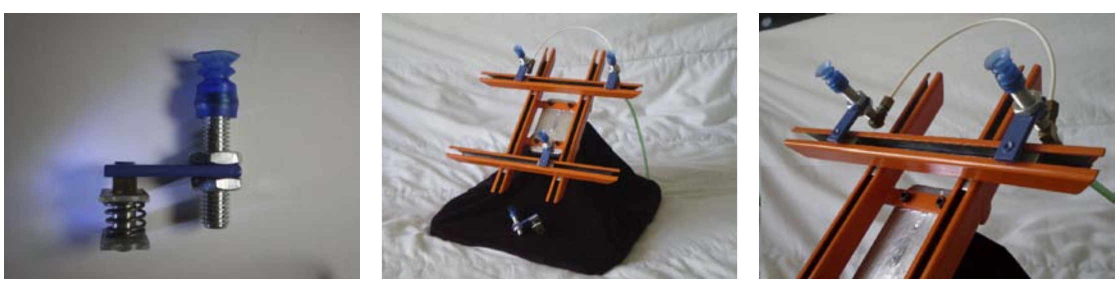
Figure 5



(a) (b)

Notes: (a) Gripper fixture design; (b) reconfigurable rail design

Figure 6



(a) (b) (c)

Notes: (a) Gripper fixture; (b) prototype end effector; (c) reconfigurable rail

if a flexible solution had been selected, the gripper may have been able to handle the different sets of parts from all 400 moulds without human intervention between batches. The key question here however, is whether the greatly increased complexity and cost of such a gripping device would be justified in an application where large batches of approximately 50,000 identical units are being processed. The answer to this question, in our opinion, is in the negative. By selecting instead a reconfigurable solution, it is seen that, due to the large batch size, the added penalty incurred in reconfiguration time is in fact negligible when compared to the production time for each batch, and is well offset by gains in simplicity, reliability and lower cost.

The second issue relates to the fairly common problem, particularly in the plastics industry, of needing to grasp different sets of different objects in batch-wise fashion from the same working area. In this application, each set of objects corresponds to a particular mould, and in each set there are two types of objects to be grasped – the products and the runners – requiring two very different types of grippers. We have addressed this problem using two of the basic concepts of reconfigurability – modularity and adjustability. Through modularity, we are able to attach different types of grippers (in this case, suction-type and jaw-type) as required, and through adjustability we are able to place these grippers at the required locations. It is further noted that a key issue in modularity is the design of an appropriate interface between modules, and in our work this was achieved through the development of an appropriate setting and locking mechanism for the gripper fixtures to the rails. The required adjustability was achieved through the use of the sliding rails concept.

In the case study addressed in this paper, the company is expected to achieve significant savings in costs related to the introduction of new products, since it will no longer need to develop new robot plates. The company is also expected to achieve significant reduction in the storage space needed to store the handling equipment when not in use.

7. Conclusion

In this paper, the design and prototyping of a reconfigurable end effector for the plastics industry has been presented. The developed concept has applications where different batches of products need to be unloaded from plastic injection-moulding machines during production, and where the number and location of products may differ between moulds. The end effector also caters for the disposal of the runners and sprues associated with the moulding process. A formal design approach has been adopted in the development of the solution, and this has led to a solution, from among several alternatives, that best satisfies the various requirements of the customer. The developed solution may have further applications in automation outside of the plastics industry, in situations where a number of objects need to be grasped simultaneously using different types of grippers, in an environment of high variety between batches.

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About the authors

Michael A. Saliba graduated in Mechanical Engineering from the University of Malta in 1986. He received the MASc degree in Mechanical Engineering and the PhD degree in Physics from the University of British Columbia in 1991 and 1998, respectively. He has been a Canadian Commonwealth Scholar and a Westcott Memorial Fellow. He is a licensed Engineer in Malta, and between 1986 and 1989, he was a Planning and Development Engineer with Air Malta plc. He is currently a Senior Lecturer in the Department of Industrial and Manufacturing Engineering at the University of Malta, where he is responsible for research and teaching in the areas of Robotics and Automation, and where he directs the Industrial Automation Laboratory within the department. His main research interests are in robot hands, sensors, teleoperation and reconfigurable automation. Michael A. Saliba is the corresponding author and can be contacted at: michael.saliba@um.edu.mt

Andrew Vella Zarb graduated in Mechanical Engineering from the University of Malta in 2007, and is a licensed Engineer in Malta. He was awarded a diploma by the Malta Branch of the Institute of Engineering Designers for the Undergraduate Mechanical Engineering Project with the most innovative design in 2007. He was also awarded a certificate of recognition for the same project by the Chamber of Engineers. Shortly after his graduation, he joined Baxter, a medical device manufacturing facility, as a Quality Assurance Engineer. In January 2008, he moved to the production department of the company taking the role of Production Engineer. Here, he is responsible for the department's team of technicians. This involves all machine improvement projects, cost-saving exercises, preventive maintenance scheduling, breakdown repairs, design/commissioning/installation of new machinery and also lean initiatives. He is currently also involved with the

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implementation of visual data analysis systems on both moulding machines and automated assembly machines. His professional interests include design, industrial automation, plastics manufacturing, robotics, lean physics as well as environmental engineering. He has also attended several courses related to process improvement Multivariate Data Analysis, 3D CAD design, 6s Strategies, Lean Manufacturing implementation and is also a certified Energy Performance Assessor for local dwellings as well as a qualified internal auditor.

Jonathan C. Borg graduated in Mechanical Engineering from the University of Malta in 1989. He received the MSc and PhD degrees from the University of Strathclyde in Glasgow (UK) in 1993 and 1999, respectively. He is currently an Associate Professor and Head of the Department of Industrial and Manufacturing Engineering at the University of Malta (Malta). His current research interests include DFX, collaborative design, product life design, virtual prototyping and digital manufacturing.