# RECONFIGURABLE STRATEGIES FOR MANUFACTURING SETUPS TO CONFRONT MASS CUSTOMIZATION CHALLENGES

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Abstract
The manufacturing industry is distinguished by regionalization and individualization of products accompanied by varying customer demands, faster time to market, short innovation cycles and product life cycles. The introduction of new materials, new processes as well as struggle to achieve economic and efficient use of resources has raised complexities to achieve quick and optimal configuration in manufacturing systems. To resolve the complexities, the reconfiguration at different levels in the manufacturing system is presented by using three distinct examples. The first example refers to reconfigurable joining cell design for versatile joining of automotive subassemblies. Second example refers to strategy for quick reconfiguration of robots for precise machining applications. The third example elaborates fast calibration of monitoring system in joining processes to enable fast reconfiguration of sensors in commissioning as well as in the maintenance.

Keywords:
Reconfigurable manufacturing cell, plug and produce, one-of-a-kind

## 1 INTRODUCTION

The manufacturing industry is encountered with rapid globalization, unpredictable and heterogeneous markets, high product customization [1] [2] [3], variable demands, short innovation cycle, product life cycle, reduced development time and faster time to market. This fact can be observed today in the global markets reflecting in increasing variant diversity and decreasing lot sizes accompanied by early end of life of products [4]. As a result, there is a paradigm shift in the manufacturing systems from high volume production to mass customization. This in turn demands manufacturers to enhance flexibility in their manufacturing systems; to enable them to produce various existing product families as well as the evolving ones. Moreover, they need to demonstrate high responsiveness in product delivery to gain high competitive advantage without lowering the productivity. Consequently, manufacturers can compete in the market by reaping a high market share.

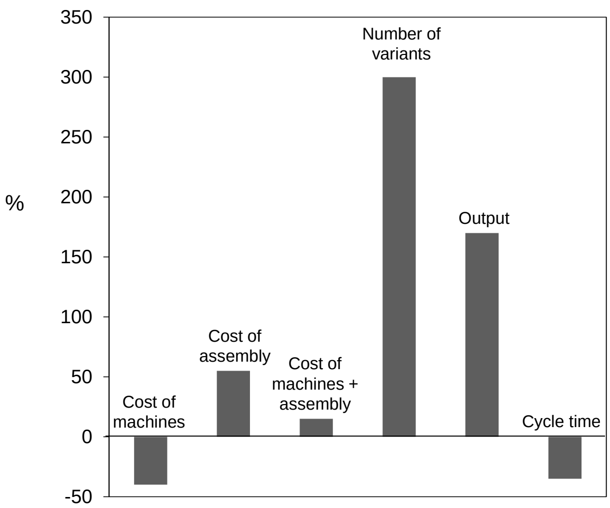


Figure 1: Influence of reconfigurable approach on dedicated manufacturing systems (reproduced from [5])

In order to achieve these objectives, the manufacturers must adapt their production setups very quickly. It will help in reducing lead time as well as any additional delay due to redesigning them. In this respect, numerous cutting edge technologies have been introduced over the past to make the manufacturing setups and software solutions reusable instead of redesigning them. The redesigning procedures and methods are mostly cost-inefficient and time-consuming.

The introduced reconfigurable manufacturing systems [6] can be termed as a viable concept in achieving high competitiveness by allowing reusing the system for developing customized products with varying lot sizes. The most salient feature of reconfigurable manufacturing systems is that they are capable of rapid change in structures as well as in hardware and software modules to allow quick adjustment of production capacity and functionality [7]. The development of reconfigurable machine tools for machining engine cylinder heads, inspection machines as well as assembly machines are few examples of reconfigurable manufacturing systems [6] that are seen today. The main purpose of these systems is to achieve highly customized production. A case study described in [5] highlights this fact (see Figure 1). The main requirement for reconfigurable manufacturing systems is that they must be designed by the changeability enablers i.e. modularity, scalability, convertibility and customization [8], to exploit their advantages highlighted in [9]. Some examples from the industry can be taken in which reconfigurable concepts are applied. Automated guided vehicles are employed in the manufacturing plants for transport of materials inside the manufacturing facilities. Reconfigurable grippers for robots [10] and fixtures for robots as well as CNC machines [11] are developed to accommodate various parts of distinct sizes and geometries for gripping and fixing applications in machining as well as assembly operations. All the highlighted examples reflects the fragmented efforts to allow reuse of manufacturing setups components in handling parts variety as well as reduction in setup time. Moreover, reconfigurable components add more life to the manufacturing systems, saving components as well as manufacturing setup design and development costs. The high product diversity as well as rapid change in process technologies, applications areas and environments may result in enhancement of manufacturing setups. It can be achieved by making them easily upgradable and convertible, into which new technologies and new functions can be readily integrated [12]. Currently, reconfigurable approaches are being implemented, demonstrated as well as evaluated by various research groups from academia and industry. This implies that the implementation of reconfigurable manufacturing systems is still in the early stages. The manufacturers are more than ever trying to make their production structures, layouts, machines, process equipments, material handling units as well as monitoring systems reconfigurable to deal with frequent change of product variety. Moreover, they also strive hard to find sustainable as well as robust solutions for routing, scheduling and planning of tasks as well as resources. Consequently, the following trends in the manufacturing setups are emerging as illustrated in Figure 2.

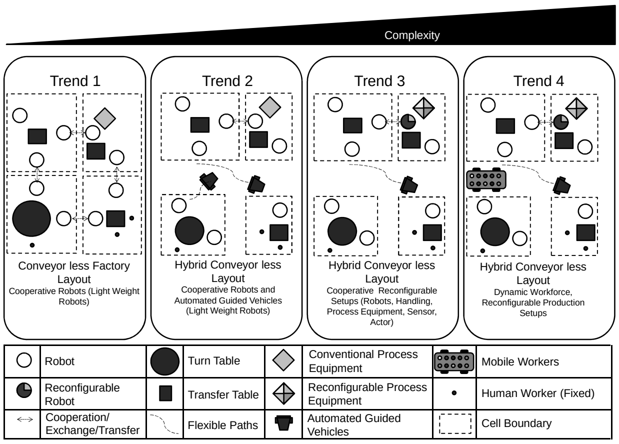


Figure 2: Future trends in the manufacturing industry.

The emerging trends depicts that the layout for future manufacturing setups will be completely cellular based where conveyors or production lines are foreseen to be replaced by robots as well as automated guided vehicles to achieve high flexibility as well as scalability in manufacturing systems. In addition, the machining, joining or assembly of parts with various forms and materials will be made using nearly the same resources. By this way, the planning, designing and commissioning time will be reduced substantially. Additionally, the resource utilization rate as well as throughput time will be enhanced using reconfigurable setups and configuration approaches in all domains of the manufacturing system.

## 2 RECONFIGURABLE MANUFACTURING SETUPS: EXAMPLES

The main focus of this paper is to highlight reconfigurable strategies in the design as well as the planning of manufacturing setups. It allow quick and smooth configuration of manufacturing setups to achieve productivity. In this context, the employed resources must be capable of manufacturing products in small lot sizes down to one-of-a-kind production, to produce highly customized products. This capability mainly depends on the setup time, the flexibility of every single resource part (e.g. tools or grippers), the time required to change tools, calibration of positioning devices, sensors as well as their programming. Furthermore, it also demands less change in resource commissioning as well as in positioning to allow usage of a single resource for multiple purposes.

This particular section addresses these objectives by presenting three distinct examples from the manufacturing systems. The goal is to achieve reconfigurability at different levels in manufacturing systems. It is noteworthy to mention that mass customization complexities cannot be resolved by focusing on any single aspect of the manufacturing system. Instead, it refers to those approaches that address the manufacturing system complexities case wise as well as to those approaches that are consistently applied in the whole manufacturing process. The first example relates to the modular and scalable design and development of automotive joining setups with focus on two innovative joining technologies i.e. adhesive bonding and laser welding. The target is to enable versatile production in a mass customization scenario as well as to reconfigure the production setups for new tasks and applications.

The second example introduces a strategy to implement reconfiguration production at a machining cell level using industrial robots. Industrial robots carry a great potential for using it in various tasks through reprogramming, due to their inherent structure and capability. Employing robots for machining applications has enabled manufacturing of small or medium sized lots. In addition, the development costs can be reduced significantly as robots are economical compared to machine tools. However, these robots are not that precise compared to machines tools for machining applications.

The third example elaborates the strategy to implement reconfigurable approach at the component level. In this example, a special focus is made on quick and smooth calibration procedures for monitoring system with repeatable accuracy. This innovative aspect of adopting this strategy is the enhancement of process reliability and reduction of the setup time.

### 2.1 Reconfigurable manufacturing cell: Joining cell

The state of the art production setups are comprised of several but distinct manufacturing cells connected to single or multiple lines. The innovative production setups are of two prominent types: modular production setups and cellular production setups. The modular production setups are relatively advanced setups that are designed to improve throughput by increasing the efficiency. One such example is the assembly lines feeding into the final assembly lines (fishbone layout). The corresponding automotive production setups involve several shops comprising of various forming, joining, painting and final assembly on their dedicated assembly lines connected with process dedicated joining cells [13] [14]. Another category refers to cellular based layout [13] which is considered as one of the major steps in accessing JIT. They are comprised of machines and robots gathered around to carry out multiple tasks such as material handling as well as assembly operations. These operations are typically carried out by single operator or multiple operator work cell.

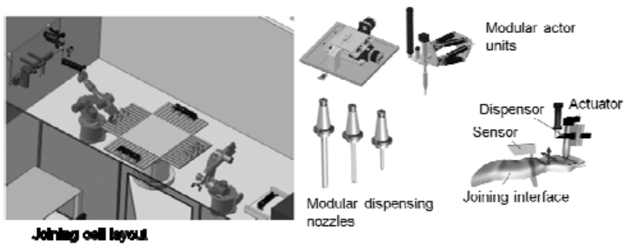


Figure 3: Reconfigurable joining cell (virtual model).

As mentioned before, the main motive behind the development of reconfigurable production cells is the increasing variants diversity in terms of new materials and dimensions. The material diversity has consequently increased the number of joining technologies employed for new product concepts. The multi-material body-in-white is a highlighting example in this regard. Thus, the changing products result in redesigning as well as upgrading of joining setups for handling, joining and monitoring processes. Taking the reference example of joining setups related to adhesive bonding and laser welding, flexibility is mainly seen in handling and fixturing system only. The reconfigurable approach addresses the fact that the flexibility should be raised from the system level up to each component level or vice versa. Comparing adhesive bonding and laser welding processes, the interesting fact about both of them is that they are quite similar. However, the main difference lies in their process equipment as well as in relevant process monitoring devices. They can be modularized to allow switching between the process technologies. It is triggered by smooth exchange of setup modules and sub-modules. In addition, the technology independent equipment controller should be integrated in the setup to enable quick changeover. Moreover, function based modularized embedded control programs can be used to enable quick changeover in the software module. Such a setup enables highly mass customized automotive body-in-white components. The customized products are characterized by material combinations, the material thickness as well as forms with various dimensions. The methodology is being demonstrated as a semi automatic and modular adhesive bonding cell (see Figure 3) to allow joining of variants of body-in-white floor module components using the same setups. The floor module adapter and seat cross member from different vehicle variants are selected as a case for joining these parts in the reconfigurable cell. The virtual model shown in Figure 3 underlines some of the highlighting features of such setups. The dispensing system as well as associated sensors and actuation systems are modularized to be adaptable under different process requirements. For instance, the application of various bead forms is facilitated by using the same dispensing system. Therefore, the glue form can be altered during the process depending upon the joining interface specifications between the mating parts. The online adaptation is made possible by exchanging glue nozzles during the process. Moreover, the cell throughput is increased by introducing multiple as well as distinct floor module sub assemblies. The joining process is mainly carried out by robots in the cell. The robot positioning accuracy and the path repeatability depends upon several geometric as well as kinematic factors. The application of seam must be made at the correct position to achieve high joint quality. There is a prominent advantage behind this objective. It reduces the frequency of post visual checking process of joints as well as the related costs. A robot type and path independent solution in the form of sensor actor head unit as a plug and produce device (see Figure 3) can be attached to any robot type, to correct the seam width and position on the body-in-white parts. This approach enables fast reconfigurability as it reduces the effort involved in processing measurement data through robot controller to correct the robot path in real time. Furthermore, it also eliminates the need for frequent calibration of robot paths.

It is imperative to expose the fact that there are no ISO/EN/DIN standards related to design and safety available that can assist in merging the two joining cells into one at the industrial scale. This stresses the need for development of such standards to support reconfigurable production cells capable of switching between the technologies during the process.

### 2.2 Reconfigurable manufacturing cell: Machining cell

An industrial robot based machining cell is considered as an example to reconfigure manufacturing system at the cell level. The salient advantage of robot is that it is easily reprogrammable as well as can be used for various tasks using easily exchangeable tools. Machining of parts is also very flexible in terms of developing various features on the work piece as the product shape is generated by relative movement between the tool and the work piece. An industrial robot cell that is capable of machining has extended application scope compared to a standard state-of-the-art machining cell. The possibility to integrate machining operations adds flexibility in the manufacturing workflow as it is not always required to perform the necessary operation on a dedicated machine tool. The industrial robot can be employed instead. It also reduces handling operations and the number of required handling resources. Another advantage occurs from the fact that manufacturers often have large quantities of the same robot type available in order to reduce costs for maintenance, provisioning of replacement parts and training. Consequently, smooth changeover between different cells and lines can be enabled. In the manufacturing industry e.g. in the automotive industry, industrial robots are commonly used for applications like spot-welding or pick-and-place tasks where a high repeatability of the programmed positions is necessary. They are optimized to do such repetitive tasks. However, they lack absolute positioning accuracy. It is particularly noticeable when the robot is programmed offline by passing teach in procedure. When an offline robot program generated in such situation is executed on the controller, errors are generated due to deviations between the 3D model and the real cell as well as due to the imperfections of the mechanical robot structure. The offline programming procedure is inevitable for programming robot in machining application. It is because the programs for machining contains huge amount of programmed points. This emphasizes the need to find a solution for enhancing robots absolute accuracy; so that they can be more effectively employed in machining processes. As offline programming is inevitable for machining due to the large amount of programmed points, there is a solution needed to enhance the robots absolute positioning accuracy. Respective methods to improve robot positioning accuracy can be classified either as model based or sensor based [16]. In the *model based method*, the robots position is altered corresponding to the model that predicts the robot behavior and deformation under the anticipated workload. It requires not only a model that covers all aspects relevant to the robots pose accuracy but also precise prediction of the forces generated during the machining process. These process forces are essential to calculate the respective deformation of the robot [18]. The *sensor based method* relies on the measured deviation between the intended and the actual robot position. In case, a deviation is detected, the robots movements are changed accordingly. The processing time for measurement data can be critical for this feedback loop particularly when the robot moves with a high speed [16]. In the presented reconfigurable approach, a combination of both methods is used. At first a model based solution is applied to generate robot programs that enable right machining without any further modification in program. It is a necessary requirement for one-of-a-kind production to avoid high scrap rate. The model based solution handles every single robot as a single entity. It means that even if two robots from the same type are taken, their models are stored independently. It takes into account the tolerances in the manufacturing of the robots and the resulting bandwidth of the respective robot accuracy parameters. The main idea behind this approach is that each robot is measured and behavior is stored in the database. This approach carries a great potential for reducing time and enhance the system availability when exchanging or replacing robots due to easy and seamless programming procedures. The second part of the reconfigurable approach works during the actual machining process. The sensor based compensation method is employed by measuring and determining the deviations between the tool and the work piece. The salient advantage of the combined approach is that main errors are compensated by the model based approach during robot programming. However, minor positioning errors below or equivalent to the physically possible accuracy of the robot can still be generated at this stage. As the robots accuracy is restricted by the smallest possible steps for each axis, it cannot compensate these errors physically. Also the deviations tend to fluctuate as the cutting edges of the tool create a non-static process force. The frequencies of these fluctuations are a multiple of the rotational speed of the milling tool, as one tool tip has several cutting edges. The rotational speed depends on the required cutting speed. Typical rotational speeds are in the scale of 10,000 rpm or above, therefore the robot controller is also not that fast enough to compensate these fluctuating errors. It is mainly due to the fact that the interpolation cycle of typical robot controllers is around several milliseconds. An additional compensation mechanism is therefore proposed as a solution to this problem. It manipulates the relative position between the work piece and the tool. The high speed movements with the desired high speed dynamics and stiffness are generated using piezo actuator platform. The movements are leveraged with the elastic solid state joints. The main difficulties in the development of such actuators are the required low latencies for measurement, the respective actuation and the needed control algorithms.

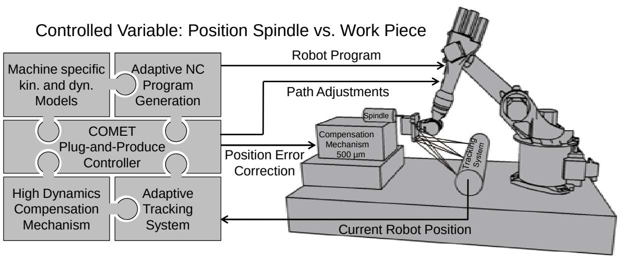


Figure 4: Overall concept for COMET project.

It is an important point to mention that the errors or problems that may result from the initial positioning of the robot would be too large or complex to handle with a sensor based solution only. The overall COMET approach (as illustrated in Figure 4) is promising as these errors will be compensated during the offline programming. Smaller deviations that result from imperfections in the mathematical models or the inaccuracies in the prediction of process forces can be compensated online during the machining process. Challenging aspects are mostly related to the latencies in communication and computation as well as the smooth integration of the every individual component.

### 2.3 Reconfigurable manufacturing cell: Process monitoring system

Laser triangulation sensors can be used in a broad range of applications; particularly they are seen in assembly and joining operations. Their role has increased in process measurements mainly for real time measurements as they deliver high accuracy and measurement frequency. The Integration of such sensors for the accomplishment of assembly tasks has assisted tremendously in reducing the assembly time. Their capability to acquire real time data as well as the availability of flexible analysis algorithms makes them suitable for monitoring paths, edges and other contours in several joining, sealing and assembly applications. The sensors employed in complex assembly operation e.g., in car window joining, require a high effort to orient sensors in an absolute position in six dimensions in the manufacturing setups. It is particularly needed for converting the measured information from 2D to 3D with respect to the absolute coordinate system. Besides, it is mostly needed when the measured points are sought to be compared with the reference CAD data. Another application scenario that requires absolute positioning is referred to the measurement of large parts (automotive sheets or windows). Multiple sensors are used for this purpose that has to be positioned in correct correlation with each other. Otherwise, positioning error from each of the sensor positions would add up to generate error of noticeable value. The third application case relates to the low measurement range of laser sensor (some centimeters). To adjust sensors in all 6 DOF, usually measurement targets with known positions and orientations as well as special geometries to identify rotations and translations of the sensor are taken. The calibration procedures are quite tiresome and time consuming. This is due to low accuracy of manual manipulation and the dependencies between the 6 DOF in the required movements of small values. Available sensor products have no persuasive solution for this problem, therefore a calibration program was developed that assist the operator during the orientation of the sensor and also detects and corrects the remaining orientation error during measurement process. Based on an existing calibration target, an algorithm was developed that analyses data emanating from sensor and calculates the sensor position relatively to the target. As the desired sensor position relative to the target is known from the CAD, the algorithm computes the offset from the ideal position and instructs the operator about the direction as well as the extent to which the sensor must be adjusted to get the desired position. Two aspects are important to elaborate in this regard. Firstly, the origin of the sensor coordinate system is usually not the origin of the spherical joint. Therefore an additional translational matrix has to be used that describes the displacement between the joint origin and the sensor origin. Secondly, the six degree of freedom influences each other, so that it is not possible to change one degree of freedom without altering another. To minimize this problem, the algorithm proposes an optimal workflow to the operator, which DOF has to be changed next, in order to reduce the required iteration cycles. As it is nearly impossible and therefore not practicable to adjust the sensor manually in the range of its possible accuracy, the assistance program gives the operator a signal if the sensor is adjusted within a specific tolerance that can be achieved with a sufficient amount of time and effort. The remaining error is used to calculate a compensation matrix, which is used to correct the measured profiles in all degrees of freedom. The described algorithm uses pre-processing functionalities of the sensor controller. It does not analyze all the points of the measured profile. In fact, it processes only those four distinctive intersection points that represent edges on the target surface.

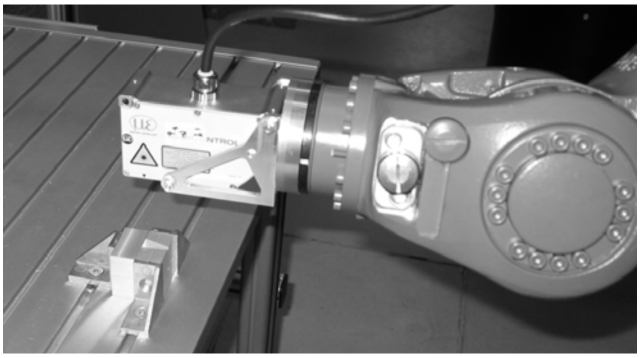

Figure 5: Validation of the calibration algorithm in a laboratory setup.

By using these points, noise is filtered out of the measured signal. It is because multiple points are used to calculate the position of the target surface as well as the position of the intersection points. By analyzing the distances between the points and angles between the target surfaces, a possible plane in space that represents the sensor measurement plane, is calculated. The search algorithm divide and conquer [19] was used to find this plane. Several exit conditions and preferential strategies were implemented to minimize calculation time in order to allow real time indication of the sensor displacement and the proposed correction values. The developed algorithms were validated in the laboratory setup in an environment similar to the industrial used case. The laser sensor was mounted on the tool center point of the robot. But instead of mounting the laser sensor on the combination of spherical joints, it was mounted on the tool center point of an industrial robot to generate designated movements in the different directions. By this way, it was also checked and the required displacement notified e.g. a displacement of 0.5 mm. The positioning accuracy of the robot is comparable to the accuracy that is accomplishable with the manual orientation of the sensor. After ensuring the general functionality of the algorithm, different parameters (e.g. the allowed remaining tolerances) were optimized to ensure a stable and practical calibration workflow.

The evaluation of the experiments has shown, that the developed algorithm works in an environment comparable to an industrial manufacturing situation and is more intuitive to use and requires less time for calibration than other available solutions. But it was observed that the algorithm is sensitive towards changes of orientation especially near the desired position. This can be optimized by adopting the selected strategies in this specific search area. Furthermore, some geometrical changes of the measurement target are proposed in order to generate a more reliable initial measurement profile to help reduce reflections that further disturb the measurement signal. The algorithms can be used to reconfigure any new sensor or group of sensors in industrial application.

## 3 CONCLUSIONS

In this paper, the reconfigurable strategies in the manufacturing setups at various levels of the manufacturing system are presented. Three examples are taken to elaborate the reconfigurable approach. In the first example, the reconfigurable joining cell design is introduced to enable versatile production in mass customized production environment. The joining cell can be reconfigured between two joining technologies to allow joining of mix variants of body in white parts. The setup is modular as well as scalable to achieve efficient reconfiguration. In the second example, the configuration strategy for the industrial robot is presented in the machining cell. The objective of this strategy is to enable quick reconfiguration of robot for various tasks in machining process. A hybrid model and sensor based compensation method was adopted to generate precise robot programs as well as enable compensation of errors that are generated during the process. In the third example, the quick calibration strategy for the laser sensor in the process monitoring application is introduced, implemented and validated as a demonstrator in the laboratory. The overall goal of presenting all these examples is to highlight that highly mass customization is leading the research towards thinking of automation of automatic systems to enable quick changeover during commissioning, maintenance as well as during actual production.

## 4 ACKNOWLEDGEMENTS

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