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FlexLean - Flexible Automation for Automotive Body Assembly

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1. Introduction

The automotive industry has pioneered the large scale use of robots. Long production runs of identical car bodies were the ideal field of application for early industrial robots, and spot welding lines with hundreds of robots have become a familiar sight. However, a lot of the production equipment is still based on hard automation. Today's market is increasingly putting automobile manufacturers under pressure to offer customers more choice of products and variants with decreasing life cycle, while at the same time demanding lower production costs. To fulfill these apparently contradictory requirements, a single line must be able to produce a mix of different models, and must "learn" to make new models without calling for a total re-design of its equipment – and preferably without even stopping production ("rolling launches").

To responded to these demands it is necessary to make the automotive body assembly more adaptable, easier to install and more economic on space. This can be achieved with the presented concept (FlexLean) that introduces modular and highly flexible solutions based on modular, standardized components consequently in all levels of the automation (Negre & Legeleux, 2006).

First of all the line is based on standardized and freely configurable cell modules. The complete line is made up of these highly flexible modules which are connected by a material handling track motion and standard communication interfaces only. The cells again achieve their high flexibility through a rigorous utilization of robot technology, not only for handling and welding with robots but also for clamping and fixturing systems. Key elements are here programmable flexible positioners, called FlexPLPs. These positioners can have depending on requirements different types of kinematics with one up to four axes and replace the tooling equipment used today for locating, handling and fixing car bodies or other parts. A special Deltapod kinematic is described in more detail that combines high accuracy and stiffness with an excellent compactness and light weight. To fulfill the wide range of requirements on the flexible positioners for the totally different tasks in the car body assembly they are built based on standardized components. A concept will be

proposed how different types of positioners again can be designed automatically based on the standard components matching exactly the requirements of the process like workspace, load, stiffness, accuracy. Finally such a flexible automation system needs a control concept that allows the engineering and programming of the cells with minimal effort for the line builder and customer. The proposed control solution profits directly from the concept of the modular and standardized cells. This allows also a very modular control concept based on standardized control modules. Going this way consequently to the end, it will be shown that it is even possible to replace the classical programming by only simply configuring the desired behaviour of the components up to the sequence of a whole cell.
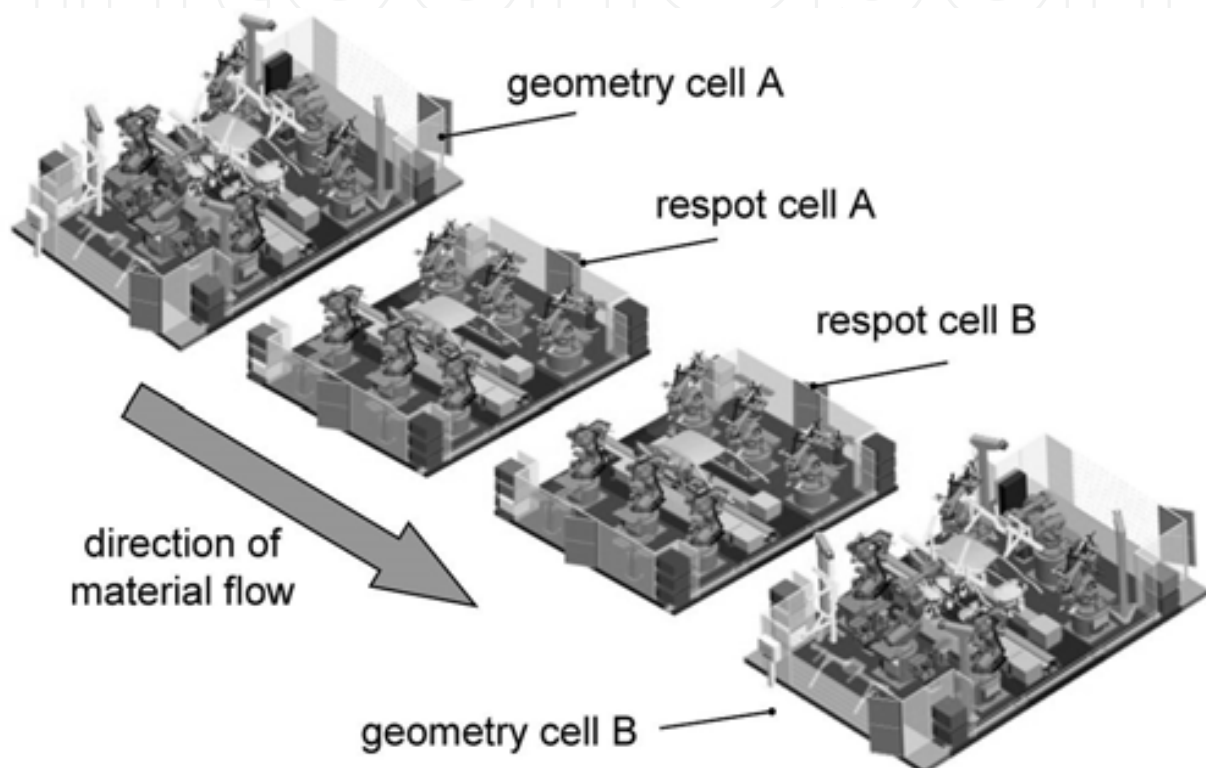

Fig. 1. Assembly line based on standardized modular cells

2. The FlexLean concept

2.1 Flexible and modular assembly line

With FlexLean an automotive body assembly line is composed out of freely configurable and standardized cells (see Fig. 1). Each of these cells is a modular robot cell where all equipment from the robots up to the controllers and cabling are pre-mounted on a platform. Every cell has its own control and operational system responsible for all operations in the cell from robot movements, part handling and transport of the car body up to the whole production cycle. A cell is connected to its neighbouring cells only by a standardized communication interface for handling the handover of parts from on cell to the next and by a handling track motion for the car body. In this way every cell is a standalone system that can, if necessary, be replaced very easily by another cell module at any time or new cells can be introduced in the line to adapt to extended requirements, new processes or a new type of car model.
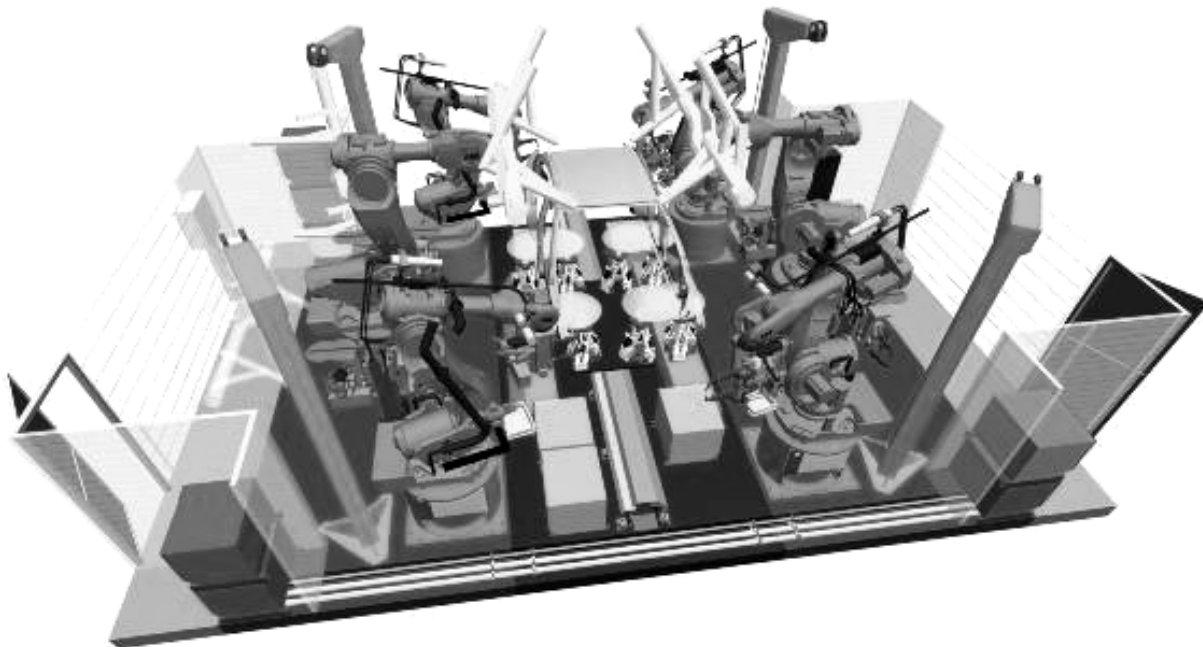
Fig. 2. FlexLean standardized cell with 6 robots, track motion and positioners for multi-model car body assembly

Fig. 2 shows a schematic layout of such a standardized cell. It can have a different number of robots (typically 2 to 6) that can be equipped with a choice of predefined process packages (like spot welding, material handling, sealing ...). Further it can have e.g. a different number of manual loading stations. For the part handling of the car body in the cell and between the cells a robot like servo controlled track is used enabling for precise and high speed part transfer. Further key elements of the standard cells are the programmable flexible positioners that replaces fixed tooling equipment used today holding and fixing car bodies on the track motion as well as for holding and handling of parts in the cell .

2.2 Flexible positioning and gripping
A car body is made out of 300 to 500 parts (Wemhöner, 2005). Robotized spot welding is the most common process to reliably join the parts; to secure the geometry of the car, every part has to be held in place by a fixture prior to welding. The accuracy and stiffness of fixturing of the shaped metal sheets defines the final quality of the car body geometry.

To achieve this, the cars are built often on top of skids which are transported by a conveyor through the factory (see Fig. 3). These skids have some drawbacks: first of all they need to be returned to the beginning of the line after finishing the car. Since they are not flexible and assigned to one car model only, they need to be exchanged when changing to another car model. This requires heavy skid handling equipment in the line and a lot of place for storing the different types of skids. The effort for this explodes with the number of car models produced in one line.

In FlexLean the traditional conveyors have been replaced by the already mentioned track that transports the car body from on cell to the next only. The proposed flexible and lean approach is to avoid car model specific tooling altogether and replace them by fixtures with programmable geometry that can adapt to any car body. This is achieved by the flexible programmable positioners (FlexPLP) replacing every pole carrying a locator by a positioner.
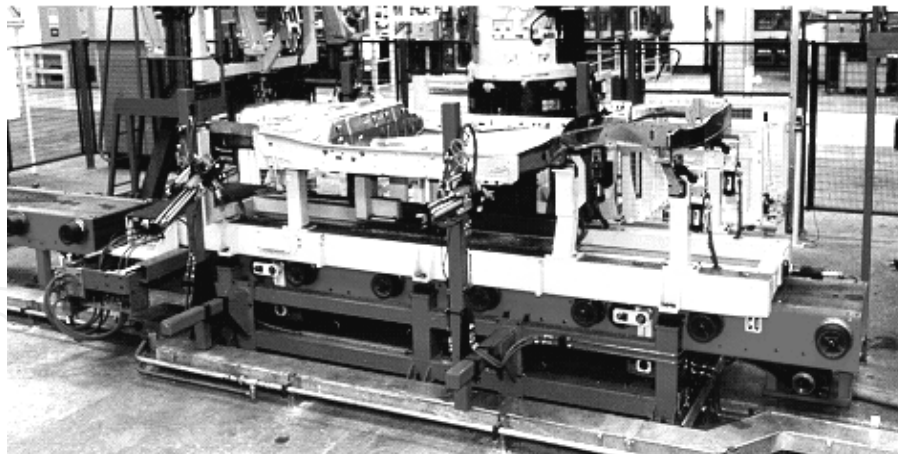
Fig. 3. A model specific skid (pallet) with fixtured car underbody on roller table

Thus instead of the skids a number of FlexPLP is mounted on the track carrying the car body from one cell to the next (see Fig. 4 in the background). In the cell again fixed mounted flexible positioners take over the car body from the track motion allowing the track motion to get the next car body from the previous cell (see Fig. 4 in the foreground).

Fig. 4. Car body on track motion carried by flexible positioners (background) and flexible positioners taking over the car body in the next cell (foreground)

As for the handling of underbodies/car bodies it is also necessary to find a new solution for the part handling in the cell. Today mostly geometric grippers are used, which can already have a modular structure but are restricted to a fixed geometric shape for only one part. To achieve the required flexibility to adapt to different sizes of parts for different car models, it is possible in the same way as for the skids to replace the fixed locators off the geometric grippers with programmable positioners. Fig. 8 shows examples for such a type of highly flexible geometric gripper with different types of flexible positioners that will be mounted on robots. Since all them use robot technology they can be programmed and controlled like the conventional robots integrated in each car body assembly cell.

3. Flexible positioners

3.1 Conventional Cartesian positioners
The obvious approach to build a 3-axis positioner for carrying the pin locators and clamping tools typically used for positioning and fixing car body parts is based on a Cartesian arrangement of single linear axis modules.

Such a design involves low design and engineering complexity on one hand which make them quite easy to use for stationary positioner arrangements. Furthermore they allow for robust and dust protected designs which can be easily scaled for different workspace sizes on each axis separately. But on the other hand this concept involves quite high masses and inertia for a certain level of stiffness which implies directly less suitability for mobile application e.g. the positioners are mounted on the track motion based part transfer system or mounted on a flexible gripper which is attached to the robot. Furthermore the TCP of Cartesian positioner axes can hardly reach out of the footprint without a tremendous design effort which is also required for positioner applications on mobile servo shuttles in order to allow for a short part transfer time.

3.2 Positioners based on parallel kinematic machines
After a screening of machine concepts that would fulfill the requirements, especially the small footprint and the fact that the TCP will have to move outside the footprint, posed a challenge. It became obvious that the combination of requirements called for a parallel kinematic machine (PKM) concept, but none of the known kinematics became an obvious candidate.

3.2.1 The 3 dof challenge of parallel kinematic machines
The 3-UPU machine – based on a characteristic kinematic chain using an universal joint U, and one prismatic joint P afterwards and then another universal joint U – was first introduced by Tsai (Tsai, 1996). It looks strikingly simple and promises to be a very lean and low cost machine for pure translational motions compared to the well known Hexapod, as it uses only 3 instead of 6 variable length struts and blocks the unwanted rotational degrees of freedom by using universal joints. Many researchers have built 3-UPUs and reported interesting results, but the main problem remains that the struts experience very high rotational moments, which results almost unavoidably in a low stiffness, or in a very bulky design. Surprisingly, this fact has not been widely published in terms of real measurements. After prototyping a simple 3-UPU machine, this option was ruled out, and it became clear that 6 legs are needed to avoid torsional moments and get high stiffness. Using Hexapods for translational motions, however, is not an option either in applications that are sensitive to cost. The need for extra motors, cables, power amplifiers and control prohibits the use of Hexapods in purely translational applications in most cases. Other machines for 3-axis translational motions use fixed strut length and linear motions that would either violate the footprint constraint (by moving the foot points horizontally) or the requirement to have a workspace area bigger than the footprint (by moving the foot points vertically up).
A Delta machine (Clavel, 1988) would come closest, but still could not be made compact and stiff enough. So the only feasible machine would be a combination of Delta (for 3-axis motion) and Hexapod (Gough & Whitehall, 1962) (for stiffness and footprint). Such a machine would use parallelograms in a Delta configuration that could be changed in length by a single motor and pivot around 2 axes. Unfortunately, such parallelograms did not exist so far, and it was not obvious how to design them.
A parallelogram that can be extended and retracted by a single motor can be made out of two cylinders with ball screws and a mechanical coupling, like gears or belts. If such a parallelogram is required to pivot around two axes, the distance between the cylinders changes and things become more complicated. Nevertheless, several solutions were developed by the authors, and the most compact one was chosen (see Fig. 5). The coupling

uses a sequence of bevel gears and a synchronization belt to accommodate for the parallelogram's pivoting motion (patent pending). Four universal joints provide the required degrees of freedom.
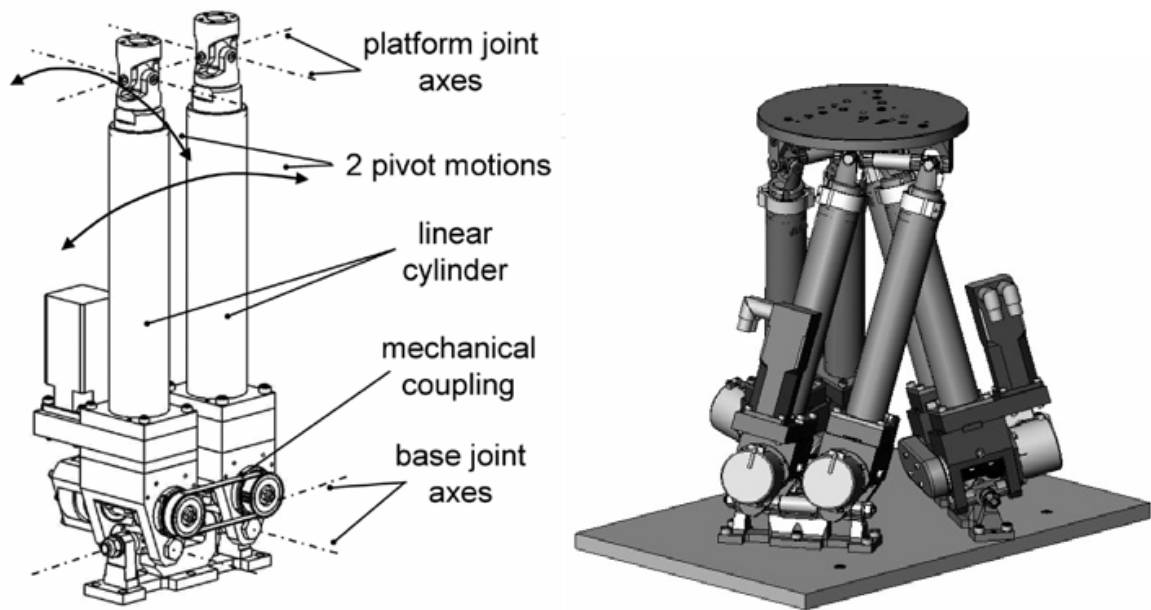

Fig. 5. FlexPLP based on pivotable extensible parallelogram actuator module (left) and its application on a twisted Deltapod mechanism (right)

3.2.2 The Deltapod positioner kinematics

With the parallelogram actuator required machine element in place, a variety of PKMs can be synthesized. According to the above requirements, the Deltapod was constructed, which is based on the Delta geometry with equilateral triangles defining the position of the alignment of the joints on the base and on the moving platform.

However – due to the small footprint and the offset length of the cylinders, a symmetrical Delta configuration exhibits an insufficient stiffness in horizontal direction, and would be badly-conditioned. The solution here was to twist the base joint positions points around the center axis of symmetry, and to twist the upper platform joints in the opposite direction, while at the same time reducing the diameters of the principal circles that define the geometry (see Fig. 6).
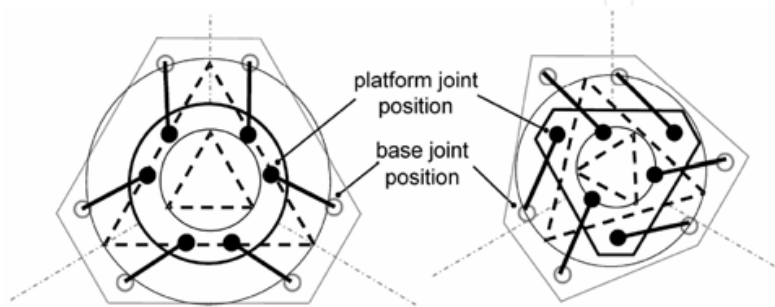

Fig. 6. Compacting footprint by twisting joint axes positions from the classic delta (left) to the twisted delta (right) configuration

The result of this operation is that the machine is compacted, while the condition number remains almost identical – hence stiffness and velocity relations are not affected. The only drawback of this operation is that a twist torque on the plat-form is created due to loss of symmetry. It turns out, though, that this can be easily compensated by anti-rotational measures of the legs – the resulting torsional moments in the legs are much lower than in the 3-UPU design. As a result, a very compact and strong PKM is achieved, and it was possible to meet all of the requirements for the flexile underbody fixturing application.

3.2.3 T-pod4- positioner kinematics

Parallel kinematic machines offer an inherent modularity. It is therefore natural that for any new PKM concept, a variety of derivatives exist.

In the given case, we derive the T-pod based on the developed parallelogram module, by aligning two parallelogram planes such that the upper joints form (nearly) a single line, hereby blocking two rotations, and by placing the third parallelogram plane perpendicular, (see Fig. 7). The name was chosen because the joint locations on the movable platform resemble a T-shape.

The advantage of this machine is the reduced footprint in one direction, so that it can be place in very narrow spaces, but in particular the possibility to remove the synchronization and add an extra motor to the perpendicular parallelogram, so that an optional tilt motion around the symmetry axis can be introduced leading to the T-pod4 configuration. This can be particular useful when fixturing buckled car body parts. The T-pod4 is somewhat related to the Kanuk (Rolland, 1999), even though the drive mechanism is different.
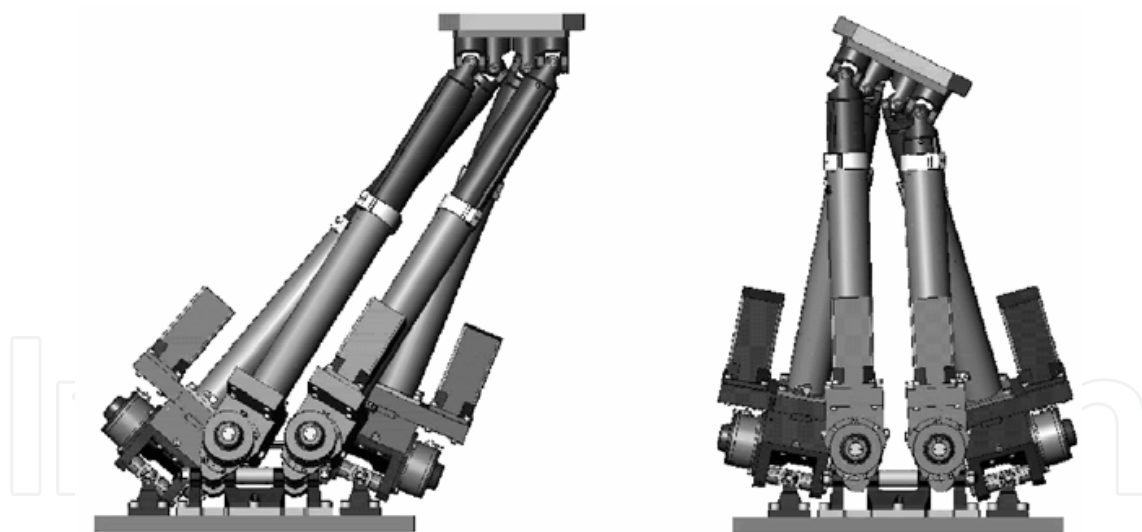

Fig. 7. A T-pod with 3 d.o.f. (left) and a T-pod4 with 4 d.o.f.(right)

3.2.4 Flexible grippers based on positioners

Combining e.g. four of those T-POD positioners to a common backbone attached to a powerful handling robot a flexible programmable gripper can be achieved which provides an excellent payload compared to its own mass (see Fig. 8).

By use of flexible grippers the part logistics within highly flexible car body assembly lines which is another big issue become addressed. With flexible grippers' space and cycle time consuming tool changing of different grippers as well as additional grippers themselves can

be abandoned. Different from typical tool (gripper) changing a flexible gripper will be reconfigured according to the part geometry of the successive car model during the transfer motion of the handling robot without affecting the primary processing time.
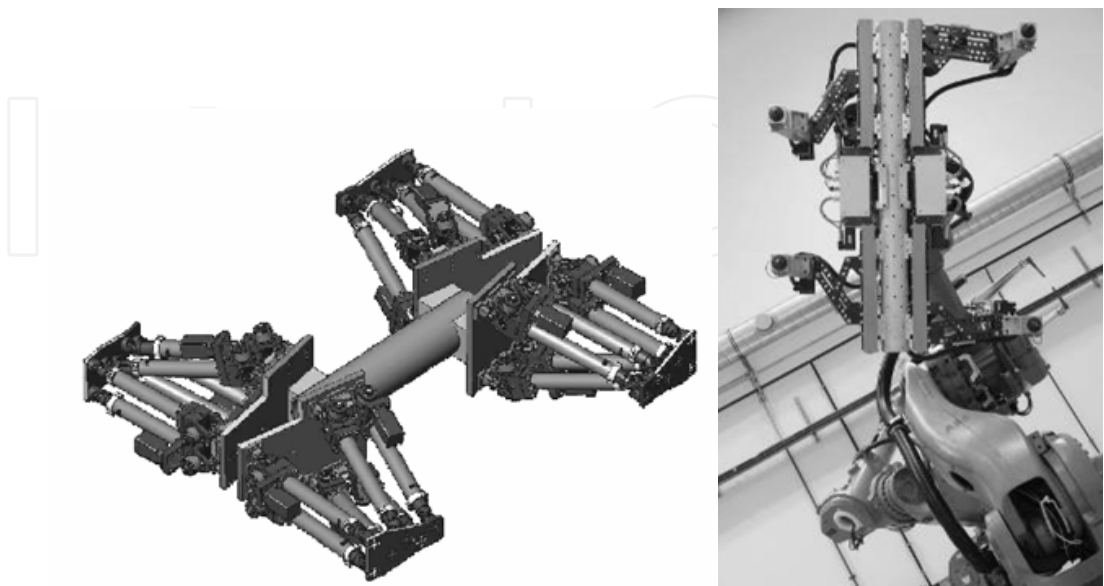

Fig. 8. Flexible Gripper Examples T-pod based (left) and hybrid linear module based attached to a handling robot (right)

4. Engineering of flexible postioners

4.1 Application specific positioner requirements

For the concept for a flexible multi-model car body assembly line presented in this chapter, positioners are used for different applications: These are stationary flexible fixtures, mobile flexible fixtures on the shuttle and mobile flexible grippers. Each application involves different requirements which need to be reflected by an adequate design and configuration of the positioner mechanism. Both the serial Cartesian as well the parallelogram actuator basing parallel mechanisms can be optimized and dimensioned towards these requirements.

	Flexible Fixtures stationary/mobile	Flexible Gripper mobile
Repeatability	± 0.05 mm	± 0.1 mm
Speed	100 – 250 mm	100 mm
Reach per axis	200 – 400 mm	100 – 200 mm
Stiffness	> 1 N/µm	> 1 N/µm
Mass	50 – 130 kg	20 – 40 kg
Payload Dynamic	30-50 kg	5 – 30 kg
Payload Static	150 kg	55 – 100 kg

Table 1. Examples for positioner mechanism related requirements with respect to application

Choosing the optimal mechanism dimensions for the best performance is still a challenging task because variations of the geometric parameters lead to greater variations of the machine

performance than for conventional serial structures. Furthermore there are a lot of performance criteria which have to be taken into account. Another problematic issue is to find global values for criteria which depend on the pose of the working platform of the mechanism. The most important requirements on PKM especially but not only for tooling applications are workspace, accuracy, stiffness, velocity and lifetime. But these keywords must be looked at more precisely and put into mathematical expressions. The characteristic functions allow establishing performance criteria and help to recognize the degree of fulfillment of a PKM structure with regard to the requirements (Tsai, 1999).

Typically all requirements and developed characteristic functions assigned to PKM structures are generally not constant or isotropic, but depend on the location or pose (position and orientation) of the working platform in the plane or space. Isotropic behaviour is strongly desired, but is a subsequent task of selection, often in coherence with optimizing procedures. Almost all performance criteria depend on the position and orientation of the TCP of the PKM. However, in an optimization design process we have to compare and assess different parameterized kinematic structures using global criteria characterizing the structural behaviour inside of the workspace (Krefft et al., 2005) (Gosselin, 1998).

Since these complex calculations are mainly reserved to mechanism experts it is hard to use the inherent modularity of PKM to full potential in view of the requirements give by each single tooling application.
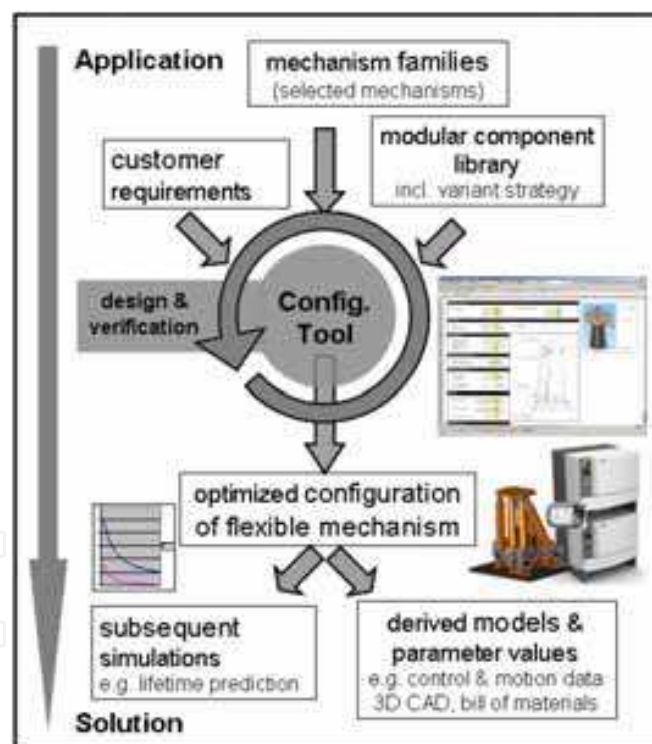

Fig. 9. Schematic architecture of mechanism engineering tool

4.2 Tool concept for efficient positioner engineering

One promising approach is a software tool based methodology that enables an efficient engineering of optimized modular mechanisms for tooling applications based on flexible positioners and grippers. In general it should support the specifics of parallel mechanisms but it is preferably also extendable to serial and hybrid kinematic mechanisms.

According to the concept of the engineering tool the user has to provide all available application related information where the tooling is required for, but the user does not need to provide mechanism design expertise (see Fig. 9). The tool is mapping application specific requirements to an adequate layout of mechanism subsystems and their optimized configuration via defined characteristics functions.

A selection and optimization sub routine ensures to find the best possible mechanism solution in terms of technical requirements but also cost based on the entered information of the specific application.. It considers a variant strategy with a predefined number of standard components and variants provided by libraries for proved positioner mechanism families and their subunits and components.

A set of interfaces provide mechanism related model data for control (motions files and user interface parameters) and for sub-sequent simulations with advanced tools for line concept simulation, offline programming.

These features enable not only an efficient design and planning positioners but also manufacturing, assembly and commissioning of these mechanisms. In order to guarantee for a high uptime of the positioner units during their operation one important element will be to derive some predictions of required maintenance cycles or even lifetime estimates depending on the specific tasks the positioner units are supposed to perform.

5. Flexible engineering of cell control

5.1 Flexible programming and engineering of cells

Full advantage of the FlexLean concept can only be taken if the corresponding manufacturing process control is supporting the concept's flexibility and modularity. Therefore the program of the programmable logic controller (PLC) has to fulfill certain requirements as modular structure, well-defined interfaces, encapsulation and functional flexibility. One PLC program per cell is managing the manufacturing process inside the cell. Each manufacturing device as FlexPLPs, track motion, robots, fixtures, etc. has its own control code module within the PLC program handling all device functionalities. These control modules are interconnected via well-defined standard interfaces allowing high flexibility in module interactions. The working sequence of a device (e.g., handling or welding of car parts) is controlled and executed only by its control module. Working sequences of several devices are synchronized via the module interfaces.

Instead of fixed and pre-programmed working sequences limiting the device functionalities to a few procedures, the working sequences on their part are split into a set of basic standard working steps which can be set in an arbitrary order. For example the taking of a car part by a robot from a fixture and subsequently placing it on the car body for welding is organized in steps as "Approach to fixture", "Pick-part", "Approach to track", "Put-Part on car body on track", "Wait-for Welding", "Back-Approach from track". The single working step is a predefined and independent subsequence without need for synchronization with other device sequences during its execution. Synchronization takes place only between working steps. The working step concept allows high flexibility in coping with a wide range of different working sequences. The control module of each device has a control routine for each possible working step which is executed according to the complete working sequence.

5.2 Configuration instead of programming

One of the most innovative aspects of the engineering concept is that the working sequence is no longer hard coded in the control program but only configured. The customer can

configure the desired working sequences for each devices and product type via a wizard on the human-machine-interface (HMI) just by selecting and configuring working steps from a list (see Fig. 10) without knowledge of PLC-programming.

The time-consuming process of programming, compiling, transferring to the PLC and debugging the generated code is no longer necessary. The control program contains all necessary control functionalities to handle all possible working steps. The corresponding control code for a specific working sequence is not generated and then transferred to the PLC but exists already as pre-programmed and fully tested control module on the PLC. The control module of each device reads the customer-configured working sequence and executes it working step by working step. These sequences of working steps are executed for each device by a sub-control module called sequencer.

The customer can synchronize several sequencer with a working step called "Wait", for which a devices and a working step number are parameterized. Once the sequencer is executing this step, it is waiting until the sequencer of the specified device has reached the corresponding working step number.
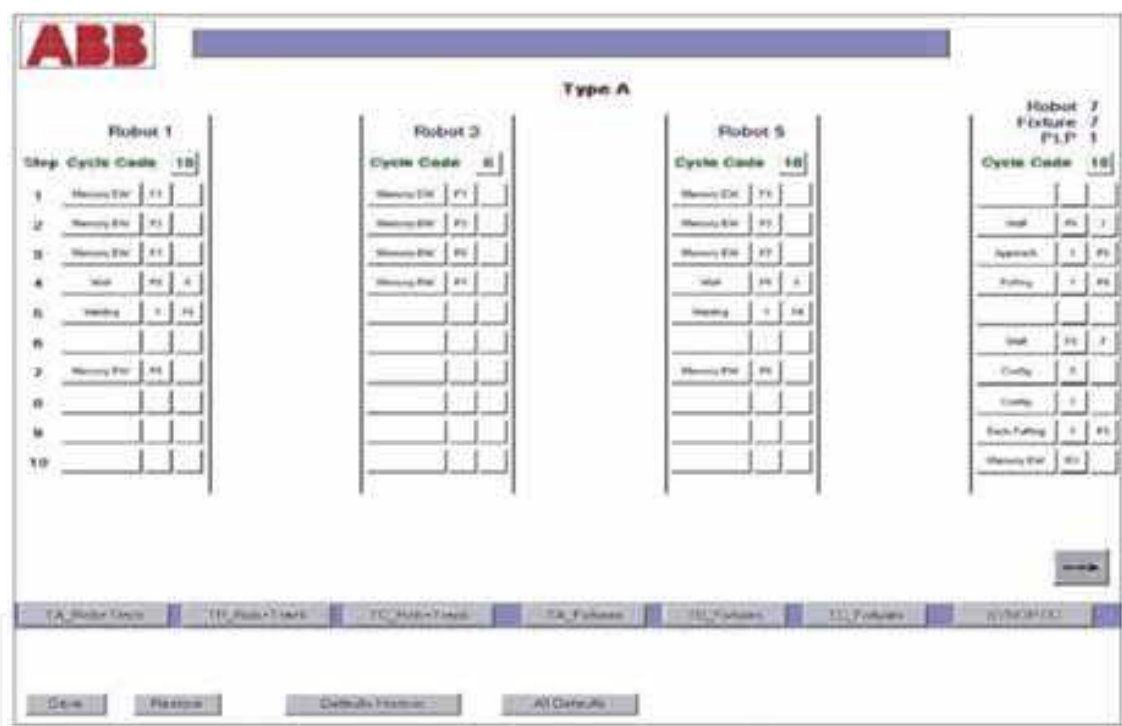

Fig. 10. Configuration wizard for working sequences

Start conditions are checked before executing a working step to ensure that no constraints are violated by starting this step. End conditions have to be fulfilled before declaring a working step as finished and launching the next step in the sequence.

Thus the configuration data contains not only the working sequences but also information about safety constraints for working steps and devices. As for example a robot is only allowed to pick a part from a fixture if certain fixture clamps are open or closed. For each product type different constraints and settings can be configured by the customer. Complete flexibility is available via the configuration of settings for part sensors, fixture clamps, robot moves, safety settings, robot interlocking, working steps and sequences for all devices, etc. Even the cell layout can be configured. If robots, fixtures or operators are present within the

FlexLean cell can be set via parameters on the HMI and thus the corresponding control module is activated for execution on the PLC.

This configuration concept meets the flexibility of the whole FlexLean solution. Starting from basic manufacturing device functionalities, specific working sequences for different product types can be configured by the customer and executed directly after downloading the configuration data to the PLC.

6. Summary

When car model specific and geometrically fixed toolings for fixtures and grippers will be replaced by flexible tooling using programmable and lean positioners, new assembly concepts can be introduced. Thus the FlexLean concept allows designing highly flexible automotive body assembly lines for a changing mix of different models in the same line. The need for redesigning when introducing new models is now replaced by a simple reconfiguration of the cell control. This allows model change on the fly.

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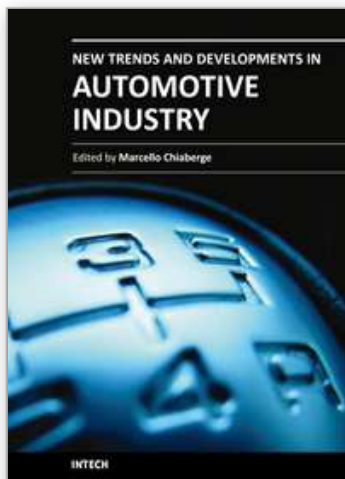
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