Design for Automation: The Rapid Fixture Approach

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Abstract

As product varieties rise and lifecycles shorten, development approaches need to be adapted. Current trends aiming to solve the dissonance of reduced time to market and increased product variety include agile methods. In this context not only product design processes need to be adapted but also development of production processes and manufacturing equipment. At the example of fixture design, this paper presents an approach which allows an agile provision as well as a reconfiguration of equipment. The solution presented consists of a fixture design concept consisting of design rules which allow implementation into a tool for automated fixture design.

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1. Introduction

Agile product development and prototyping requires tools and methods for the agile provision of production equipment such as load carriers, simple handling or assembly fixtures. Also assembly lines with a high number of variants ask for production equipment which either can be used by all product variants or can be reconfigured in regard to the actual assembly task. Automation of design processes and additive manufacturing are two enablers which allow to quickly generate the regarded design documents and to setup a piece of equipment immediately. For an assembly line this allows a constant reconfiguration of production equipment and tools depending on the product...
sequence. Therefore, general production equipment design rules were established, which enable an automation of the underlying design processes in order to quickly redesign the equipment.

These design rules were then implemented into a Solid Works Add-in which is now used to automatically design load carriers and simple assembly fixtures. With this software tool, the Rapid Fixture concept is tested using the example of the StreetScooter variant line inside the RWTH Aachen Ramp-up Factory. In the current application load carriers for the front seat and a letter box are designed using the software tool. The applied design rules allow to quickly reconfigure load carriers as needed in regard to the design output of the software tool when new vehicle type derivates are integrated into the line. This paper presents the underlying design rules, the general concept of the automation algorithms and first results of the application at the variant line.

2. Status quo of rapid fixture design approaches for agile product development

Besides the final customer product, which is the focus of the development activities, the design of the series production environment is an essential development and planning project itself, especially in complex industries such as the automotive industry. Because of the overall system complexity and long lead times, a growing number of production planning processes need to be performed simultaneously to product design. Especially, the demand for a short time to market creates the need to early develop production processes and also design manufacturing equipment. Depending on the manufacturing equipment’s complexity, the required development timeframe for design, setup and validating even for fixtures or simple mounting devices can range from 7 to 20 weeks. Thus, the underlying development process of manufacturing equipment becomes a determining success factor in maintaining the ramp-up timeline. This is especially critical when external resources are involved. [1] Due to shortening development periods, these dependencies lead to a lack of time in case of unexpected disturbances. This is especially challenging during the final process steps before series production, when manufacturing resources such as auxiliary devices or handling equipment, like fixtures and manipulators, have to be adapted during ramp-up due to product modifications. [2]

Typically, the activities performed in parallel by internal or external stakeholders are synchronized through milestones, so called quality gates. [3] As the trend for production planning moves towards less scheduling and more agile scrum-like approaches the success of production planning depends to a major extend on the adherence to the quality gates, such as design freezes during product development [4, 5]. In this context, scrum, known from software-development, is a feedback-driven agile development approach based on the three key figures of transparency, inspection, and adaption. [6] When milestones are met and fewer product design modifications occur as planning and ramp-up processes are carried out, planning efficiency as well as planning quality benefit. Both aspects, planning efficiency and quality, are responsible for reaching planning targets such as short time to market and a steep ramp-up curve. However, long lead times for manufacturing equipment such as fixtures are a major challenge since they restrict the possibility to react to product design changes quickly and thus are a risk for the adherence to schedule and milestones. [7]

This drawback becomes even more relevant as product development trends towards more agile, less stare and less deterministic processes. In this field of ongoing research focus lies on how to transfer the established approach of scrum, to the ecosystems of producing companies with physical products. In this context, agile prototypes are known as a problem-solving approach and are used as a tool to gather hardware experience and to foster communication between stakeholders, and with the final customer. Thus, with those agile prototypes, not only function tests are conducted and development results are secured; rather do those prototypes answer specific customer-relevant issues. Therefore, agile prototypes are developed, utilized, and tested in cooperation with customers within market explorations. To enable this way of product development, not only product prototypes are required but also the ability to provide the required prototyping equipment in an agile manner. Today, this conflicts with the challenging lead times of manufacturing equipment. [8]

For the past decades the scientific community has been researching how to accelerate the fixture development process by making advantage of information technology. The different approaches on how to combine automated
fixture design and algorithms are focus of the research area Computer-Aided Fixture Design (CAFD). Main advances were made by Rong et al., who focused on the automation of special purpose fixtures with individually designed elements without use of construction kits. [9] Shen et al. developed an approach for a specifically design magnet fixture system. [10] Jiang et al. developed a system for tolerance-checking gauges, while Hou & Trapey designed an assisting CAFD system which proposes possible fixture design alternatives. [11, 12] Many authors develop systems for complex milling or welding fixtures with large sets of requirements. This often is presented as optimization problems with various approaches used, e.g. genetic algorithms. Reviewing the available literature on CAFD research, it becomes evident that most of the approaches focus solely on the automation of the design of existing fixtures without fundamentally questioning the underlying design principles. [13]

3. Design for automation for manufacturing equipment

To accelerate the various pre-production phases, a possible solution is the automation of the regarding design processes of equipment such as fixtures, gauges, and load carriers through algorithms that enables automated design-processes. The development of these algorithms is driven by the vision of a one-click solution, that enables to react on product changes without a time delay because of re-design processes. The solution for fixture design envisioned should be able to create a fixture with minimal user input based on the CAD file of a workpiece or product, which e.g. needs to be processed or assembled on the regarding fixture. On the one hand, a one-click solution provides the fixture design quickly and thus reduces the initial efforts for fixture design. On the other hand, the equipment can be re-designed as product design changes occur. These design changes can then be adopted to the fixture by loading the new 3D files into the algorithm and generating a new fixture design. Thus, the solution should be able to change existing and new fixtures with any connected resource, without having to invest time and money to re-design the fixture manually.

To enable the one-click solution, the starting point of the automated design process needs to be the specific operational task of the equipment. As in conventional design processes, the regarded task and the requirements the fixture must meet make up the starting point of an automated fixture design algorithm. These requirements can be separated into two main groups (Table 1). There are standard requirements such as workspace requirements around the workpiece for each process, low-weight fixtures or the ability to use Poka Yoke. Also, there are specific requirements for each use case such as tolerances, costs, short process time and ability for fast (re-)assembly.

Table 1: General fixture requirements [10]

<table>
<thead>
<tr>
<th>Requirement categories</th>
<th>Examples for assembly fixtures cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard requirements</td>
<td>Retaining the workpiece position according to its weight and size</td>
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<tr>
<td></td>
<td>Securing the needed workspace for all process steps</td>
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<tr>
<td></td>
<td>Using Poka Yoke to avoid wrong handling</td>
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<tr>
<td></td>
<td>Avoiding physical damage to the workpiece</td>
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<td></td>
<td>Avoiding pollution of the workpiece</td>
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<td></td>
<td>Staying inside the weight specifications</td>
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<tr>
<td>Specific requirements</td>
<td>Reaching workpiece tolerances by keeping the fixture inside the fixture</td>
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<td></td>
<td>tolerances</td>
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<td></td>
<td>Ensuring workpiece stability during assembly processes</td>
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<td></td>
<td>Avoiding of workpiece- and fixture damages through adequate stiffness</td>
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<tr>
<td>Costs/Time</td>
<td>Enabling of low purchasing costs for the fixture</td>
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<td></td>
<td>Enabling of short assembly and disassembly times</td>
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<tr>
<td>Collision prevention</td>
<td>Using the fixture to reach short process time</td>
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<tr>
<td></td>
<td>Avoiding of incorrect contact between workpiece and fixture</td>
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<tr>
<td></td>
<td>Restricting of contact areas between workpiece and the fixture of certain</td>
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<td>zones</td>
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The Rapid Fixture approach was developed as an automated design approach, which is able to fulfil the mentioned requirements and to integrate them as needed into a fixture concept. Therefore, a construction kit with standard elements is combined with an innovative, automatable fixture design, a plug & use concept and additive manufactured elements. The overall objective of Rapid Fixture is to simplify fixture and equipment design processes by reducing the efforts for fixture design, setup and reconfiguration. This will reduce internal and external links to suppliers for equipment and enable an in-house fixture design and set-up. Consequently, the development process’ complexity and the products’ life-cycle costs are reduced. While the Rapid Fixture concept is developed, first software prototypes show the core functions for the automated fixture design.

4. Rapid Fixture concept for an automated design of manufacturing equipment

The solution presented here focusses on fixtures for assembly operations such as during pre-assembly of product modules. Following the principles of VDI2806, the solution was developed using a combination of automation algorithms, a fixture element construction kit and additive manufacturing. The approach aims to accelerate the design of fixture elements by automation in order to reduce the initial design efforts and necessary timeframes. A fixture construction kit enables a plug & use-concept, a quick setup and reconfigurability. Additive manufacturing allows to reduce interferences between designed geometry and manufacturing feasibility and thus reduces the requirements to the fixture arising from producibility. [14]

The algorithm, implemented as a SolidWorks Visual Basic Add-in, uses the CAD files of the workpiece as an input to follow a standard procedure and to generate fixture-elements. Figure 1 shows the underlying process the algorithm follows. Basic idea of the Rapid Fixture approach is to create a negative form of the workpiece and then place a supporting structure underneath. In detail this is achieved by constructing a bounding box around the workpiece and withdraw the workpiece vertically by a negative extrusion. The remaining form is then cut open horizontally in the X-Y-plane of the center of gravity. Note that an initial evaluation algorithm determines whether the workpiece has to be subdivided into several sub-workpieces for which the preceding steps are performed individually. Result of this process step is the negative form of the workpiece or the negative forms of the sub-workpieces. This is the basis from which the locator elements will be derived later on. This procedure is illustrated in Figure 1.

Figure 1: Rapid Fixture approach

The locator positions are determined during an automated requirements process. Firstly, the number and size of holding zones is determined by the 3-2-1-method or the N-2-1-method in case of heavier or low-rigid workpieces. [15] These holding zones are rough representations of the later positions of locator elements and represent areas
where those elements are necessary to provide a stable support of the workpiece. Therefore, they are determined with an analysis of the center of gravity. Secondly, the holding zones need to be checked for interferences with further requirements such as accessibility with tools. Therefore, required information are derived from CAD features (e.g. joining element features) and are transformed into reference boxes which represent requirements and functions of the fixture. For this transformation, e.g. in case of a CAD feature M12 screw, a tool library can provide information about tool sizes and needed work space from which the sizes of the reference boxes for tool and work space are derived. Around these reference boxes the support structure of the fixture is designed, also at this stage with reference boxes. Thirdly, the holding zones are matched with the reference boxes of the support structure. For the synthesis of the fixture, the support structure and the negative form of the workpiece are superimposed. At the intersection of structure and negative form, the negative form is then transformed into locator elements by cutting the required part of the overall negative form in a way that the required shape remains (Figure 2). Finally, the locator elements are then developed which means that their outer shape is completed and supplemented with the connecting interface to join the element with the support structure.

For the industrial application of the Rapid Fixture concept, a SolidWorks Add-in was developed based on the presented procedures. Once a workpiece is loaded into SolidWorks, the Visual Basic tool can be executed. The tool allows to run the entire procedure at once or during a step-by-step approach for presentation purposes. Main function of the tool is to design the fixture by creating the locator elements and selecting standard support elements. The derived fixture design is then stored in a virtual model of the assembly, while also STL files for the locator elements as well as setup documentations and part lists are developed automatically.

5. Innovative fixture design and additive manufacturing as an enabler for automated design processes

This approach is enabled through a specifically designed architecture, based on a set of standard elements provided by a fixture construction kit and additive manufactured elements (compare Figure 4). Additive manufacturing for example is used to create the locator elements. The regarding additive technologies allow a flexible design of those elements with the potentially complex shapes of the negative form. Thus, there are limited interferences between the workpiece design and the manufacturability of the locator elements. This is why additive manufacturing becomes an enabler of automated design processes with very limited requirements to take manufacturing restrictions into account. Another advantage of additive manufacturing technologies is that neither locator elements nor conjunction elements must necessarily be held in storage and can be printed on demand. As material prices for additive manufacturing remain relatively high, it is possible to replace the conjunction elements by die casted conjunction elements for example for applications with higher quantities e.g.

The design rules presented further below pay respect to this aspect and limit the variety of conjunction elements to a set of fix angles which would not necessarily be required if additive manufacturing technologies were applied. The standard elements provided by the construction kit, e.g. aluminum profiles, need to be held available up to the required amount. These elements are used as vertical pillars, which are placed on a baseplate and hold the locator elements, and for the horizontal struts. The locator elements on top are plugged into the pillar, while these vertical
structures are interconnected by horizontal struts to provide a rigid structure. Conjunction elements, which could also be realized through additive manufacturing, tie the struts to the pillars. Therefore, these elements use the same plug & use joining principle and allow to connect two vertical pillars with two or three horizontal struts.

For the plug & use aspect of the Rapid Fixture approach, horizontal struts and conjunction elements are plugged into each other and then interlocked. To interlock the elements several principle solutions can be applied. In the example setup displayed in Figure 44 the interlock mechanism is realized with a thread bar and a wingnut, but it can also be realized with quick release skewers. The plug & use concept allows to quickly set-up a fixture or to reconfigure the fixture when product design changes. A typical set-up procedure of the fixture can be described by the following steps:

1. The lower level vertical pillars are joined with baseplate connectors and plugged into the baseplate at the regarded positions.
2. Conjunction elements and the horizontal struts are assembled on top of the lower level vertical pillars.
3. The horizontal struts are interlocked to provide stability.
4. The upper level vertical pillars are plugged on top of the conjunction elements and locator elements are plugged on top. To provide a rigid support structure the additive manufactured elements are designed with an offset of 0.1 mm to allow a tight fit when plugging the elements into the profiles.
As a core aspect of the Rapid Fixture approach a set of rules predefines design and setup of the fixture, which is an enabler for automation of the design processes. For example, to this stage, it is required to have one locator element in each holding zone, following the 3-2-1 method, placed on the edge of the workpiece. The locator elements are placed on vertical pillars which again are placed on a baseplate, that is designed to carry a pattern of holes. Additionally, every two vertical pillars, which hold locator elements, have to be placed with a certain distance in the X-Y-plane which is defined by the length of horizontal struts which are parts of the construction kit. In order to reach a stable fixture, pillars have to be interconnected using those horizontal struts, which could be realized like the pillars as aluminum profiles. The horizontal struts are tied to the vertical pillars with connection elements, which are also part of the fixture construction kit. To reduce the number of connection elements in the fixture construction kit, connection angles of horizontal struts are set to 0°, 30°, 45°, 60°, and 90°. Additionally, these predefined angles limit the amount of length varieties of the horizontal strut aluminum profiles which connect the vertical pillars. Thus, the possible shape of the fixture is determined by the available angles and lengths of horizontal struts. To enable even sharp angles in between two pillars via horizontal struts, there are three different layers of horizontal struts. Layers 1 and 2 are to be used on the outer circle-like structure, while the third layer is reserved for an inner support structure. The inner support structure is required, if working on heavy, unusual shaped workpieces or workpieces with a low rigidity. Possible positions of pillars are determined by the available lengths of aluminum profiles. An initial pillar is set over a baseplate hole. Grey circles then illustrate possible position for further pillars while white dots show positions where a next pillar cannot be set. The next pillar is then chosen by checking the distance of baseplate hole and workpiece edge. This is repeated until the ring of pillars is closed. Into an algorithm for automated fixture design allows to simplify the automation since the fixture concept reduces the complexity of required algorithms. The overall algorithm as shown in Figure 1, derives a negative form of the workpiece, while the support structure is setup following the design rules given above. Both parallel paths are combined when the locator elements are developed out of the negative form above the supporting structure.

6. Results

A combination of the regarded algorithms with the enablers fixture construction kit and additive manufacturing offers full advantage of a fast reconfigurable fixture development process at low costs. The advantages especially positively affect ramp-up phases when product design changes occur during prototyping and fixtures need to be adapted quickly. Then, Rapid Fixture allows to redesign and reconfigure the fixture to minimum expenses of time and costs. Also, the reconfigurable fixtures allow to run different types of products through the same production line using the same basic fixture since replacement of fixture elements can be performed quickly. Therefore, during the
research presented here, algorithms and design rules were developed and implemented into a SolidWorks Virtual Basic based Add-in, which is now used at the RWTH Aachen ramp-up factory and tested in various use cases from the field of electric vehicle development and prototyping. Further development of Rapid Fixture is based on a supplementary differentiation of pillar positions to optimize the fixture in regard to number of required elements, size, and cost. Furthermore, the potential of integrating automated fixture-design and laser-scanning technology will be investigated. On the hand this could be used to measure the tolerances of the fixture and to provide measuring protocols when delivering the fixture. On the other hand, this technology could derive the input, the CAD model of the workpiece, from a hardware model before the algorithm described above creates the fixture.

7. Conclusion and summary

As a result of shorter product lifecycles and faster, more agile approaches for product development, production planning is facing the struggle of developing manufacturing resources with higher quality and greater variety in a shorter timeframe in order to reach time, cost and quality goals. The approach presented in this paper aims to provide a fixture concept which is developed with the objective of being an automatable design. By use of design rules which allow to be implemented in algorithms, the design freedom of additive manufacturing and construction kit elements, potentials for providing manufacturing resources arise. Next steps include the development of the underlying algorithms and the implementation of this approach into a software tool. Further research needs to be conducted regarding the transfer of this approach to more complex fixtures like those used for milling or welding processes where stricter requirements make fixture design more complex. With this approach being implemented, manufacturing equipment such as fixtures will be provided in a short amount of time and be able to be reconfigured as needed in case of product design modifications.

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