Driving as an Innovative Manufacturing Method for Mass Customization of Individualized Sheet Metal Products.

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POMS 19th Annual Conference La Jolla, California, U.S.A.

May 9 to May 12, 2008
Abstract

Driving of sheet metal is one of the oldest manufacturing methods and does not require highly expensive single-purpose forming tools. The current working process is carried out manually using inexpensive kraftformer machines and universal tool sets. Driving allows the creation of almost any 2D or 3D geometry and is therefore very powerful, but a highly interactive process that is difficult to be automated just by traditional approaches. For this purpose, the incremental forming method driving is chosen as a perfect test bed to demonstrate challenging, novel cognitive forming methods in the future. To handle the complexity of this incremental and work piece dependent process, powerful sensors, flexible actors and sophisticated cognitive capabilities must be involved. This paper provides general information about the application of cognitive methods for forming and with it the qualification of driving as a manufacturing concept for the production of individualized sheet metal products.

1. Introduction

A tendency towards higher individualization of products is strongly gaining in significance. This results in decreasing production output of identical products, while the output of similar products will increase in number. Manufactures of these individualized sheet metal parts will need new flexible manufacturing methods, which can be adapted fast and cost-saving to the production of similar but unique products to cope with the different customers’ demands. Driving as an incremental forming process can be carried out by the means of relatively small, inexpensive C-frame presses, so called kraftformer machines, using universal tool sets. [1] [2] [3]

Driving allows the creation of almost any 2D or 3D geometry and is therefore very powerful, but a highly interactive process that cannot be automated just by traditional approaches. The potential for automation is limited due to the inevitable variations of the incremental forming process (mechanical properties, tribology, wear etc.) and the high number of forming steps necessary. The reason for the high degree of interaction is the incremental production process, where the worker decides about the next manual action based on the outcome of the last driving steps. For this purpose, the incremental forming method driving is chosen as a perfect test bed to
demonstrate challenging, novel cognitive forming methods. To handle the complexity of this incremental and work piece dependent process, powerful sensors, flexible actors and sophisticated cognitive capabilities must be involved. [4]

At the Institute of Metal Forming and Casting of the Technische Universität München, Germany a kraftformer has been equipped with measuring and controlling instrumentation. As a first step, the system will guide an inexperienced worker by the means of an interactive navigation system. An optical tracking system is installed to detect the geometry deformation of the current work piece and to visualize the deviation between the actual and reference geometry during the whole production process. [5] [6]

2. Kraftformer Technology

Driving is a free forming process by hammering of sheet metal. Kraftformer machines as they are in use today are C-base frame presses with universal tool sets for a variety of purposes (Fig. 1). Forming is generally done by a kraftformer machine by the means of shrinking and stretching tool inserts. A tool set consists of an upper and a lower tool part.

During every forming stroke the tools clamp the sheet and transform the vertical stroke into a horizontal movement. By that compressive (shrinking) or tensile (stretching) stresses are induced into the sheet causing the forming of the sheet (Fig. 2).

![Fig. 1: Eckold Kraftformer KF 30 Piccolo and a variety of tool sets](image)
In addition, the use of special sophisticated tool sets (Fig. 1) expand the possibilities of driving enormously.

Driving, especially when using the flattening or straightening tool sets, can also be used to remove unwanted deformation in the sheet (buckles, wrinkles, wrong bending radius etc.). Presently, personal expert knowledge of a skilled worker is necessary to fashion customized sheet steel parts. An overview of the different tool groups available for kraftformer machines is shown in Fig 3.

One of the basic applications for kraftformer machines is the production of individual L-shaped sheet metal plates. Fig. 2 shows how stretching and shrinking of one leg of the sheet metal creates a concave or convex curved angle, which can be extended to arbitrary Z-shape or even spline-shape sheet metal when both tools are applied to the same piece of sheet metal (Fig. 4).
3. Automation of the Production Process

As the handling of the work piece itself is the most time-consuming manual activity in the production process, research has been carried out on how to automate it using a standard KUKA industry robot.

For elementary 2D geometries such as sheet metal angles of given radii, it is possible to pre-determine a fixed production strategy, i.e. that based on the assumption that the result of a stroke series is the sum of results of every single isolated stroke, each stroke-position can be calculated previously to the start of the production process.

However, this cannot hold for more complex 2D- or even 3D-geometries, as material properties of the sheet metal change due to strain hardening, thinning and thickening occurring along with deformation. These complex geometries like pots or even body parts of cars can be produced by skilled workers using a great variety of tools shown in Fig. 3, demand long production times (Fig. 5).

<table>
<thead>
<tr>
<th>Product</th>
<th>Manual production time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spare wheel vat</td>
<td>10-15 hours</td>
</tr>
<tr>
<td>Car ceiling</td>
<td>40-60 hours</td>
</tr>
<tr>
<td>Car door</td>
<td>40-60 hours</td>
</tr>
</tbody>
</table>

**Fig. 5:** Production time for kraftformer produced parts

3.1. Conventional Approach

An application has been implemented to produce elementary 2D-geometries (i.e. geometries where the interdependencies between two strokes can be neglected and which are either convex or concave → no change of kraftformer-toolset necessary during the production process) (Fig. 8).
Fig. 7 which shows the deviation between two L-shape sheet metal parts produced with the same control data-set by the means of the robot. It proves that the repeating accuracy of the process is very high for those elementary geometries but also indicates that the deviation (e.g. along the edge of the angle) does not only arise from intrinsic automation inaccuracies, but from earlier steps of the production process like rolling and bending operations. These may include inhomogenous material properties for different batches, the rolling direction, parameters of the bending process, etc.

Fig. 8: Kraftformer machine with KUKA KR-30 industry robot

Hence, this complex and challenging manual forming method is a perfect benchmark for novel cognitive production approaches. To handle the complexity of this incremental and work piece dependent process, powerful sensors, flexible actors and sophisticated cognitive capabilities must be involved.

3.2. Cognitive Strategy

Therefore, and due to the fact that a production strategy based on simulation of several thousand strokes (with each changing the material properties of the sheet metal) might not always yield repeatable and reliable results, a different approach is suggested. This task should be handled by a cognitive technical system, which perceives the current geometry of the work piece and plans the next incremental forming actions based on acquired and/or learned knowledge. As a first step, the
cognitive system should guide an inexperienced worker by means of an interactive system and later controls the robot and the driving machine completely.

Their workflow is a constant cycle of positioning the work piece, applying a series of strokes, checking the result and adjusting the production strategy autonomously. Fig. 9 shows a more abstract definition of this iterative process to be implemented in an automated production cycle, making it necessary to be able to adjust each robot command after every single stroke applied by the kraftformer machine.

![Fig. 9: production cycle as "feedback loop"]

4. Real-Time Optical Tracking System

The real-time 3D measurement system Vicra Polaris (NDI, Waterloo, Ontario, Canada) (Fig. 10) is used for optical tracking of the work piece. The Polaris Vicra system offers a calibrated measurement volume that goes back to 1.3 m and an accuracy of 0.25 mm RMS.

![Fig. 10: Optical Tracking System Polaris Vicra](image)

Reflecting markers are necessary. They are made of a thin, diffusely reflecting foil with a diameter of 8 mm. They are sticked on magnetic foil with a constant, known distance. For each experiment the magnet foil can be fixed to the working piece easily. The number of markers is variable and can be fitted to the length of the working piece. The reflectors are arranged in a row with a constant distance. (Fig. 11)
The spatial position of the markers is determined by the optical tracking system. This data is used to calculate the deviation from the reference geometry. Here the desired geometry is radius of 110 mm (Fig. 11).

5. Cognitive Driving

The long term goal is to create a cognitive production system which is able to produce individualized sheet metal. Starting from an automated driving system it is not clear yet what capabilities and components are mandatory to transform the automated into cognitive driving.

A perception-cognition-action closed loop has to be developed (Fig 1). In the early stages the system perceives the actual state of the work piece in process by capable sensors (e.g. stereo-cameras), compares it with the reference geometry (CAD-Data), learns from earlier actions, plans the next actions based on existing knowledge – achieved by learning, analysing the actions of experienced workers and FE simulations – and guides the inexperienced human in joint action by means of a user interface in real-time. Later the cognitive system should also control the action of a robot which handles the work piece in process. Furthermore the cognitive driving cell has to communicate with the control system of the cognitive factory as a part of it.
In the first phase, the cognitive closed loop was still on a primitive cognition level enabling the forming of L-shaped 2D work pieces. Thus, the cognition level of the current system will be increased in the next phase, so that the customized 3D parts can be produced at the end of the requested funding period.

The system cognition capabilities will be enhanced with the following methods in information acquisition, pattern recognition, action and path planning, loop controlling and process optimization:

**Acquisition**
An intelligent sensor network will be established to acquire adequate information for the subsequent steps. So the information fusion from a laser scanner and a stereo camera will be proposed to achieve a wide view and high measurement accuracy.

**Recognition**
The acquired raw data will be interpreted for estimation of geometry parameters and classification of objects. Subsequently, the working environment can be reconstructed virtually for path planning.

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**Fig. 12:** Schematic Cognitive Closed Loop of CoDrive
Planning
Using a virtual environment a barrier-avoiding path for transporting work pieces will be planned autonomously, so that the robot carries out grasping, moving, and laying down the work pieces in the path. While driving, the robot and the driving machine will be synchronised. Furthermore, the path from the original to desired geometries of work pieces will be generated with the help of human experiences or rather modelled using inverse engineering.

Controlling
While driving, the driving machine is controlled to adjust the driving infeed and stroke depth for hammering the work pieces at a given position suitably. The controller for it will be proposed with a hybrid combination of the fuzzy controller and the artificial neural network that concerns the human control strategy and learning procedures respectively. Additionally, the robot will be controlled also in closed loop to deliver highly precise positions of the work pieces.

Optimization
Finally, the total process will be optimized by means of the best possible calibration of the sensor network, suitability of the algorithm for estimation, classification, reconstruction and tracking, the shortest path in distance or time, and the evolutional algorithm for the neuro-fuzzy controller.

A driving system with these abilities closes the cognition loop on a high cognition level to allow producing arbitrary individualized sheet metal parts.

Synergies with ongoing satellite research projects will be utilised. Target groups will not only be CoTeSys researchers and students but also potential users in the industry.
The general economic framework is in a change towards higher grades of individualization in consumer goods. Well established strategies like using the economies of scale through mass production have to be reconsidered. Especially metal forming technologies strongly base on this effect. Since they generally utilize huge presses for high forces and expensive tools needed for one-step geometry generation, the strongly rely on large production numbers. This contradicts the demands of mass customization.

In order to employ the advantages of sheet metal forming, e.g. high strength, damping of vibrations, fast production and high formability etc., in mass customization applications, new technologies will have to be found. Driving being a process of sheet metal forming with significantly lower invest than deep drawing. Since considerably lower forces are needed, small presses can be applied. Forming is done incrementally, so that only comparable simple universal tools are needed. Investment can be reduced by the factor 10 or more. Nevertheless, the forming costs are quite high due to the requirement of expensive manual work. Also the production time is much higher compared to traditional processes. Automation of the driving process is the logical
answer to that problem. If forming strategies can be pre-determined and produced by the means of a robot automatically, the potential of this technology for personalization and customization is tremendous even only for elementary geometries.

As a big advantage the complexity of the desired work piece geometry can be adjusted to the progress of development of the cognitive components and their capabilities. Simple 2D-geometries can almost be produced by an automated system without any cognition. 2D-freeform-geometries already demand a basic cognitive system for their production. The next step could be to manufacture regular 3D-geometries like sectors of spheres and ellipsoids, respectively. Finally the ultimate goal is the manufacturing of any 3D-freeform-geometries and individualized sheet metal products.

7. Conclusion and Summary

The manufacturing technique of driving has a great potential for mass customization and personalization of sheet metal products if the grade of automation is high enough. The intended project is very descriptive but highly visionary and needs interdisciplinary cooperation and contribution. Previous work showed that a complete automation of the process will never be possible without a cognitive technical system. Cognitive Driving combines the need for Perception, Knowledge & Learning, Control, Planning, Joint Action and Interaction. First steps on this long march have been done.

8. Acknowledgement

The investigations presented in this paper have been supported by German Research Foundation (DFG) within the Collaborative Research Center “Production of Individualized Products Close to the Market” (SFB 582) and within the excellence cluster CoTeSys. Details on this project can be found on the websites: www.sfb582.de and www.cotesys.de.

World market leader in kraftformer machines is Eckold AG, Trimmis, Switzerland: www.eckold.ch. The robot was provided by KUKA: www.kuka.com.
9. References


