Reducing the Development Time of Flexible Metal Forming Tools using Hardware-in-the-loop Simulation

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Abstract

The sheet metal forming industry is one of the most important suppliers in the automotive sector. However, the industry sector is struggling with a steadily increasing number of different parts, coupled with decreasing batch numbers. As a result, new flexible tool concepts must be developed. However, because of the high cost and consequently high risk of development of such tools, manufacturers have been careful. This paper presents a new design process based on hardware-in-the-loop simulation. This new process allows development of mechanical and controller design in parallel. In addition, programming of the controller can be tested against the mechanical design of the tool, before the machine is built. The method was applied to a new tool and proved to be effective in reducing development risks and optimizing the process sequence.

Keywords:

Metal forming, Hardware-in-the-loop simulation, Servopress

1 INTRODUCTION

The sheet metal forming industry is an industry defined by its high output of parts with low production costs. The manufactured parts can range from small punching parts, like washers, to complex free-form parts, like the front lid of a car. The capability to manufacture free-form parts at low costs is what makes the sheet metal forming industry one of the main suppliers in the automotive sector.

However, the commonly employed classical mechanical presses with fly wheel limit the flexibility of metal forming systems, due to their fixed sinusoidal motion. In contrast to this, servo presses are no longer limited to this. Due to their direct drive, the servo press is combining the free motion capability of hydraulic presses with the speed of classical mechanical presses. This new freedom of the press motion allows the integration of peripheral processes into the forming tool, thus reducing costs and increasing productivity [1]. However, many tool manufacturers have yet to embrace the new capabilities of the servo press. Until now, the main effort of improving the tool design for servo presses has been to increase the speed during non-contact times. The goal is to increase the overall production speed and thus the productivity of the press.

In recent years the markets have become more volatile. Especially in the automotive sector shorter development cycles and an increased number of different vehicle types have led to decreasing order quantities. This is especially problematic for sheet metal forming companies. The tools and machines for part manufacturing are expensive. In addition to the high cost, sheet metal forming tools are single-purpose tools. Even though tool manufacturers try to modularize the tools as much as possible, the capability to manufacture free-form shapes at relatively low cost comes at the price of inflexible tools. The result being that if the manufacturer cannot sell enough parts, the tool is uneconomic. Therefore, manufacturers have sought new tool design directions, in order to improve the flexibility of their tools. For the development of new flexible tools, a research cooperation with industrial partners named *Formäleon* was funded by the Federal Ministry of Education & Research of Germany. An overview of the project was given in a previous paper [2].

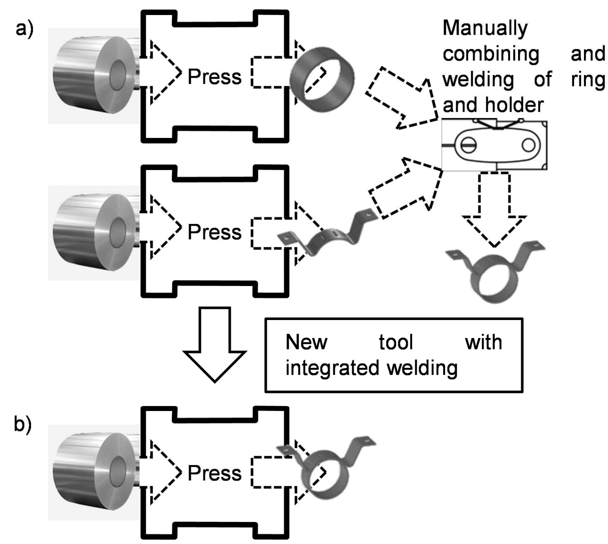

Figure 1: Current (a) and new (b) process layout

In *Formäleon* a new tool was designed. The new tool shortens the current production process significantly. Figure 1 a) shows the currently employed process, manufacturing a clamp for holding pipes. To manufacture the clamp, two presses are used to form holder and ring of the clamp. The two parts, ring and holder, are sorted by hand and inserted into a welding machine. The current manufacturing layout takes a great amount of resources, both in man power and machine time. Therefore, it must be carefully considered if it is economic to manufacture the clamp and for which quantities it is still economic.

In contrast, the new tool, shown in Figure 1 b), can manufacture the clamp in one press, without the need for sorting and inserting the clamp manually into the welding station. This greatly streamlines the production process and allows cheap manufacturing of the clamp. In addition, the tool is designed to scale with respect to production demand, further improving the competitiveness of the parts manufacturer.

This paper will present a new approach to controller programming parallel to tool design, by usage of hardware-in-the-loop (HiL) simulation. In the following sections, the risk involved with the new tool design, the limitation of the currently employed simulation support and the results of the newly employed approach of using HiL simulation for parallel controller programming will be discussed.

2 INCREASED COMPLEXITY - INCREASED RISK

Classic tool designs focus exclusively on the die forming the parts. There is usually no additional need for dedicated actuators in the tool. The formed parts are either interconnected and moved by the feed motion of the sheet metal coil or moved by additional transfer systems with dedicated handling systems. In case of interconnected parts, the part is formed but not clear-cut until the very end of the process. Therefore, the feed motion of the coil can be used to transport the part to each sequential forming step, essentially forming a chain of unfinished parts. Consequently, the motion direction is in line with tool and press. The designer of the tool only needs to make sure that the parts can move freely during non-contact times. This is usually done by lifting the complete chain of partially formed parts with pneumatic actuators.

Where this transfer method cannot be employed, a dedicated transfer system is used. Dedicated transfer systems are usually placed at the sides of the press in line with the tool. During non-contact times the transfer system moves inside the tool area and moves the part to the next forming step. With a dedicated transfer system, parts are moved which are either too big to move in a chain of parts or might be damaged during the movement process.

However, in the new tool design, none of the transfer options employed by classic tool designs are viable. The parts cannot stay interconnected until the forming is completed. Therefore, the feed motion of the sheet metal coil cannot be used as a transfer option for the whole process. The reason for this constraint is twofold. Firstly, the ring cannot be finished while interconnected with the sheet metal. Clear-cutting of a finished interconnected ring would result in deformation of the ring. Secondly, ring and holder need to be combined for welding, this is only possible if both parts are clear-cut and can be handled independently. The standard transfer system cannot be used because the motion direction is not only in line with tool and press, but also across the press. In the usual setup, the transfer system has to move only slightly into the tool for grabbing and moving the part. It is therefore feasible to place the transfer system at the sides of the tool. Because ring and holder must be combined in the welding station, the transfer system must also move across the tool. This makes it necessary to move very far into the tool. Placement of transfer axis at the sides is therefore infeasible because the transfer system would take very long to move in and out of the tool and, in addition, the handling system of the transfer might become instable due to vibrations.

The new tool, therefore, incorporates the transfer system into the tool. Thus, the distance from the actuator to the moved part is shorter and it is possible to add a cross axis to the tool. This cross axis moves the ring to the welding station, in which ring and holder are joined and welded. The cross axis' actuator path is as long as the path of the other handling systems. Therefore, placement precision can be guaranteed. However, this new tool layout with an integrated transfer system poses the problem that now the tool manufacturer has to consider, in addition to the die form, the transfer placement and programming of the transfer axis. The result is a longer design process, as depicted in Figure 2. Moreover, the necessity to program the transfer is a new field for tool manufacturers. Previously, the tool manufacturer had to make sure that iterative forming steps result in the demanded shape of the part and that there are clearances where the transfer actuators can grab the part.

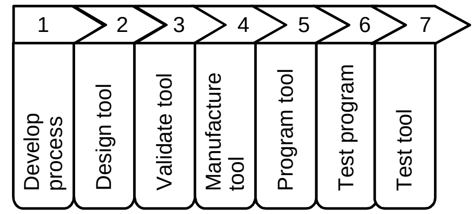

Figure 2: Current design process

In case of tools with the new tool design, manufacturers have to make sure that the parts are moved and combined correctly. With these additional development steps the complexity of tool design and development process is increased. Consequently, the risk of failure during development is increased. The previously employed methods of evaluation in CAD tools for reducing the development risks are not applicable for the new tool design. The functions of the tool are too complex to be modeled in CAD tools. For example, the evaluation of complex interactions, such as the synchronization of the cross axis with the holder and ring axis, are difficult to implement in CAD tools.

3 CURRENTLY EMPLOYED SIMULATION SUPPORT

For more complex die designs and for preemptive testing there are a number of simulation tools to support the tool manufacturer. These systems are mostly supplied by press manufacturers. The simulation allows testing of the die performance on a given press of the corresponding manufacturer. These simulations cover the evaluation of each forming step and the collision detection between die and transfer system. The tools use CAD data of die, press and transfer system. The simulation is performed offline, without need of specialized hardware. In most cases, the simulation allows to change and optimize the stamp motion, which can be exported and used as parameter set for actual manufacturing. Using this simulation support, tool manufacturers are able to evaluate and optimize the process at very early stages. However, the simulation is limited to the manufacturer of the press. Also this type of simulation does not support testing of the programming of the tool. Considering the design of the new tool, automation is going to be a major part in future tool development, therefore testing of the automation is necessary.

Abourida et al. describe a methodology called hardware-in-the-loop (HiL) simulation, in which a simulation is used to test the control program, using actual controller hardware [3]. The merit of the design process associated with HiL simulation is the possibility of testing and detecting errors before deployment or production of the system, therefore reducing impact of said errors. However the overall design process is still mostly linear. The main difference is when the physical system is deployed. In case of the Abourida step four in Figure 2 would be exchanged for the development of a HiL model of the hardware and postponed until the automation program has been validated against the simulation. This reduces risk of malfunction but offers no advantage in development time.

For the new tool design, however, parallel development of both tool form and control is essential in order to reduce time to market and therefore increase competitiveness. Dwivedi et al. describe a method by which parallel development is supported through simulation support [4]. The proposed method uses CAD data as communication basis for parallel development and evaluation in a complex project. The result is a streamlined development process with continuous evaluation of the project status. The development process is parallelized by leveraging a growing simulation environment. This is especially important for the control development, because in standard development processes control development can only start after the machine is completed. In the method proposed by Dwivedi et al., the control development can start after the initial system design process. Missing components or specifications are simulated or emulated, depending on hardware availability. As the model and development becomes more refined and hardware interfaces specified, the previous emulations can be used as stimuli in the more detailed simulation.

4 HARDWARE-IN-THE-LOOP SIMULATION SUPPORTED DEVELOPMENT

The design process based on development methodology by Dwivedi et al. generates a large overhead. Considering the new tool design, development based on this methodology would mean that several simulations must be adjusted with each change in tool design. Therefore, this paper proposes a revised design process. The CAD data are still used as means of communication. Instead of using several simulations for each sub-project, a single HiL simulation is used for the controller development. In the revised version, the design process allows for parallel simulation, although only two development chains are used. In addition, the usage of the HiL simulation reduces the necessity of emulating hardware; instead, real control hardware can be used. The revised development process is depicted in Figure 3.

The previously sequential development steps 5 and 6 in Figure 2 are performed in parallel to the mechanical design of the tool. The development of a HiL simulation starts with the development of the process, as seen in step 1 of Figure 3. The necessary parameters for the simulation, e.g. an estimate of the number of axes, inputs and outputs, can be derived from the specification of the process. Based on this data, an initial model is developed. Step 1 of the design process thus requires more coordination than the previous approach.

However, this higher initial coordination effort makes it possible to perform the development steps 2 and 2’ as well as steps 3 and 3’ in parallel. The initial cost is remedied by the shorter development cycle and an immediate feedback between controller development and hardware design.

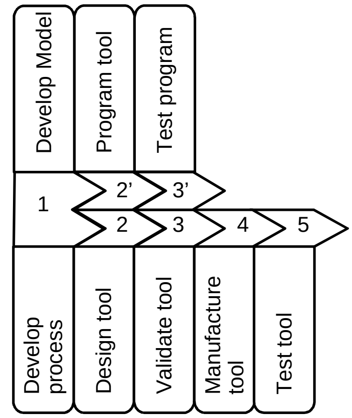

Figure 3: Proposed parallel design using HiL simulation

4.1 Simulation topology

Figure 4 shows the topology and interconnections of the simulation. There are three interconnected systems: press controller, simulation model and tool controller. All systems can either reside each on their own hardware or together on a single hardware. In case of this paper, all three systems were run on a single hardware. Prerequisite for this setup are PC-based control systems. Fortunately, the press controller as well as the tool controller uses a PC-based control system. It is therefore feasible to run all three parts on the same hardware, thus reducing the setup cost. The central element of the topology is the simulation model of the tool. The simulation model is interconnected with the press controller and tool controller. From the press controller the master cam is connected via a field-bus connection. The value of the master cam is used to simulate the stamp motion of the press. Via another field-bus interface, the simulation is connected to the tool controller. Instead of directly interpreting the value, as is the case with the master cam, the simulation emulates the field-bus behavior of the decentralized I/Os and drives. It is later possible to exchange the simulation of the tool with the cabinet of the tool, without the need to make additional changes to the programming of the tool controller.

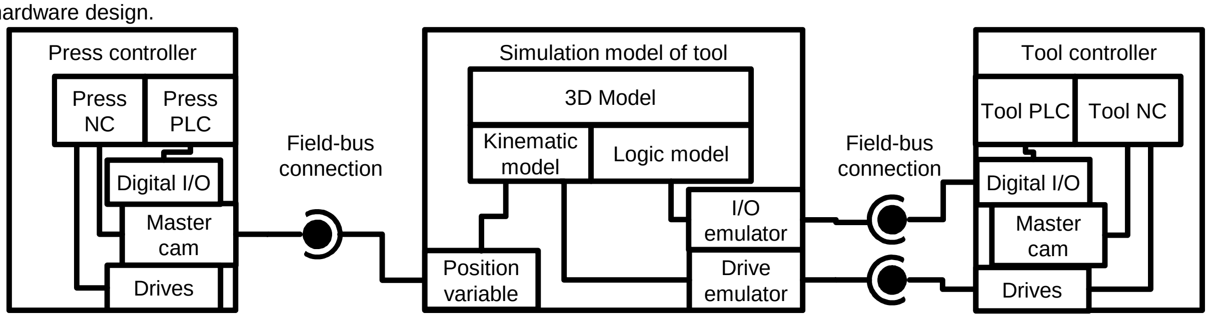

Figure 4: Simulation topology

4.2 Simulation model

The structure of the model is displayed in Figure 5 by the example of a pneumatic cylinder. The pneumatics are controlled via digital I/Os. Therefore, the input to the model is the emulation of the digital I/Os. The control system is configured as if there would be a real field I/O, however, the simulation is just emulating the actual field device behavior. Subsequently, the I/O data from the field-bus connection is interpreted by a logic model. This logic model is the logical reaction of the pneumatic system, e.g. the switching behavior of the valves of a pneumatic cylinder.

The logic model is interconnected with the kinematic model. This model describes the kinematic behavior of the cylinder. The kinematic behavior encompasses the mechanical behavior, e.g. reaction time, movement behavior and stop positions of the cylinder. The kinematic behavior is fed into a 3D model of the system. This 3D model is based on the CAD data of the tool. With the 3D model, the collisions of the system can be detected. The data of the kinematic model is fed back into the logic model.

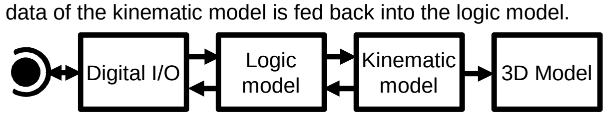

Figure 5: Interconnection in the model

The logic model checks the current position of the kinematics with the stop positions. If a stop position is reached, a logical feedback is given to the digital I/O to be transmitted via the field-bus to the tool controller. As a result, the tool controller can be programmed as if there is a real machine available. The servo axes are simulated in the same way, with the exception that there is no need for a dedicated logic model.

5 RESULTS

As a result of the new methodology the development time of the tool was significantly reduced. An absolute value of the time reduction cannot be given, because the method has been employed for the first time to the development of a sheet metal forming tool of this complexity. However comparing the development time to projects of similar scope showed that about three months of time could be saved, which was about a quarter of the overall programming and testing time, required for a project of this scope. The controller program was developed in parallel to the mechanical design of the tool. In addition, the 3D simulation of the tool based the actual CAD data allowed the evaluation of the effectiveness of the movement sequence and the identification of design and programming errors. The evaluation showed that changing the process sequence resulted in more simultaneous motion of the axes, consequently reducing the length of each transfer step and thus increasing the throughput of the tool.

The evaluation also showed some mechanical design issues, which were subsequently corrected. A picture of the 3D simulation is shown in Figure 6. The area marked with the circle shows an additional cavity inserted after it was found that during pressing the mount of the camera collides with the upper die.

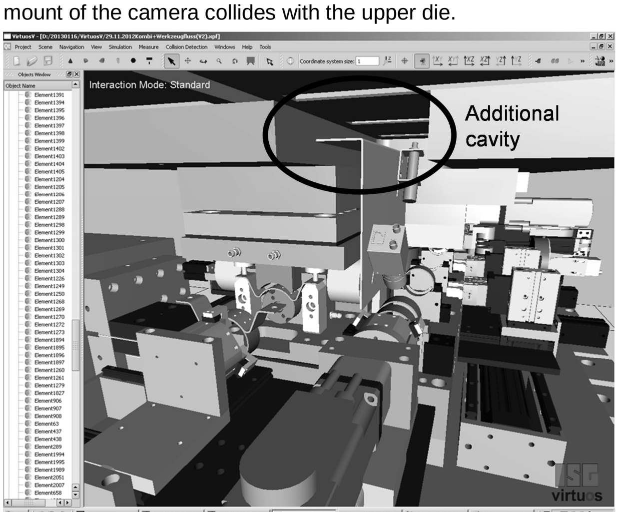

Figure 6: Picture of the 3D simulation

Because the system is interconnected with the real press controller, it was also possible to perform a virtual tryout measuring the tool performance. During the tryout, the speed of the press was slowly increased. The press speed was increased until the tool mechanics could no longer keep up with the stamp motion, resulting in a collision between transfer and die. It was found that the tool easily handles up to 15 strokes per minute, with a sinusoidal motion curve. Adjusting the curve showed that it might be possible to approach up to 30 or more strokes per minute. However, this is a rough estimate. The simulation is currently not considering the material flow of the system. It might be possible that, at high speed, the transfer system introduces vibrations into the moved parts, which in turn reduces the placement accuracy.

6 SUMMARY

The paper showed the current development in the area of flexible sheet metal forming tools. Current tool designs focus on the production output only. However, flexibility becomes more and more important, due to increasingly volatile markets. The development of flexible tools, however, introduces risks, because of an increased complexity of the tool. To reduce these risks, manufacturers use simulations. However, currently available simulation support focuses on tool design only. The presented new tool design, however, incorporates additional motion axes into the tool. Consequently, the design process must also consider the programming of these additional axes. This is impossible with the currently employed design methodology. As a way to parallelize the design process and decrease the risk due to the additional programming of the motion axes, a revised tool design process was proposed, based on hardware-in-the-loop simulation. The new design process was discussed using the example of a new flexible tool design. It was shown how the simulation is structured and by the example of a pneumatic cylinder the setup of the model is explained in detail. The development based on the proposed design process resulted in a shortened development process and in an early detection and correction of mechanical errors. In addition, the capability of the new tool could be tested to the point, where the transfer axes cannot keep up with the stamp motion.

The HiL simulation is currently only considering the kinematics of the tool. Therefore, testing can only provide the validation of tool mechanics, without considering parts mechanics. However, the behavior of the parts is important for the success of the process. Vibrations introduced by the transfer might lead to inaccurate placement of parts. Inaccurate placement in turn might result in malformed parts or damage of the tool. In future research, the material flow and forming of the parts should be considered.

Another open topic, which should be addressed in future works, is the reduction of CAD data. Generally, the CAD data include more information than necessary for the simulation or the CAD data include information, which is not directly accessible in the simulation. In future works automatic reduction, partitioning and kinematic coupling might increase the ease of use of HiL simulation.

7 ACKNOWLEDGMENTS

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