Robot-based incremental sheet forming – the tool path planning

A Bârsan*, M O Popp*, G P Rusu† and A I Maroșan†

†Lucian Blaga University of Sibiu, Engineering Faculty, 4 Emil Cioran, 550025 Sibiu, Romania

*E-mail: alexandru.barsan@ulbsibiu.ro, mihai.popp@ulbsibiu.ro

Abstract. To achieve a 3D shape with certain degree of complexity from metal sheets that are flat in the beginning, especially for prototype development or small series production, that also cost efficient by avoiding high-end dies or expensive tooling, the incremental sheet forming process can represent the ideal choice due to its flexibility, reduced forming forces and increased formability. The process is performed with a round tool that follows a predefined path to deform the flat metal sheet into its final shape. The proper selection of the toolpaths affects the productivity and the accuracy of each part. The process has to focus on forming each single point in increments. For cost-effective production, the incremental sheet forming process is performed by an industrial robot. This paper aims to showcase the superior kinematic potential of the robot for complex toolpaths by means of simulation. Singularity issues and robot joints limitation is checked through DELMIA software platform. After the design, simulation, and generation of the tool path, the software code can be generated and also used to steer the robot.

1. Introduction

Recent developments in manufacturing technology as well as the development of machining tools, especially in mechanical machining operations, reflect the flexibility requirements for adapting to changes on the market, in society and global economic environment. To handle global competition, market requirements suggest the use of small series and large variety production, even for a large series production industry.

The results of the latest developments are quantified by the high-precision machine tools [1]. However, an alternative that can meet the needs of today's and tomorrow's industry, at a low cost and ensuring a high degree of flexibility, is given by an industrial robot. In a wide range of technological processes, the industrial robots have been implemented to supplant the human operator involved in repetitive tasks. There are already robotic cells, such as the one shown in the figure 1, introduced in assembly operation, surface coatings, or mechanical machining processes.

In the previous research [2] an overview of current technology was provided based on the technical borders of industrial robots concerning robotic machining. Unfortunately, due to the serial structure, the articulated robots have a lower stiffness compared with a CNC machine. In any case, the industrial robot characteristics must fully correspond to tasks requirements [3, 4, 5, 6].

One of the most important control aspects is given by the tool path planning. The robots mechanical structure and the servo control system are less influenced by a well-planned trajectory. This paper presents the steps taken for a proper selection of the tool paths for the parts manufactured.
with six degrees of freedom anthropomorphic robot during single point incremental forming (SPIF) process. Using DELMIA software platform, in addition to check the singularity issues and robot joints limitation, the program code is generated to control the robot based on a proper toolpath.

Figure 1. Industrial robot used in polishing a vehicle bumper [7].

2. Single point incremental forming
In the forming procedure of metal sheets, conventional processes, such as bending, shearing, or stamping process, are not able to meet the growing demand for shortening product development cycles due to their need to develop process-dependent tools.

Single point incremental forming is a technological manufacturing process of a flat metal sheet into a complex 3D shape, through a series of point to point small deformations, with a high cost efficiency achieved by avoiding the use of expensive dies or other forms specialized tools [8, 9, 10]. In most cases, a simple hemispherical tipped tool, with a diameter between 5 to 20 mm, incrementally formed the sheet metal. The process can be performed on specialized forming machines, NC machines, or industrial robots [11, 12].

The metal sheet (2) and the fixing system, composed by support plate (1) and retaining frame (3), are fixed, while the punch (4), usually, executes a series of combined movements vertically and horizontally. For the unfolding process, a wide range of tool paths may be generated by combining these two movements. The most used processing tool paths, considered by the literature [11, 13, 14], are contour curves and spatial spirals. Figure 2 presents the SPIF process principle.

Figure 2. A simplified SPIF process representation.
3. Robot-forming
Taking advantage of their high flexibility and distribution, but at the same time losing the stiffness of CNC machines, industrial robots can be used in incremental sheet metal, process known as “roboforming”. Considering the SPIF process flexibility, different studies regarding roboforming process can be found.

The manufacturing of parts to use as prototypes or in small numbers can become very expensive. Meier [15] proposed the roboforming concept to keep the cost of production as low as possible. This concept is based on a flexible modeling achieved by easy programming of a synchronous movement of the end effect or of two industrial robots with 6 degrees of freedom that have workpiece-independent forming tools. The resulting end form is made by an incremental ingoing movement of the forming tool in direct depth, and a motion made alongside the geometric contour in the lateral axis, resulting in parallel layers or a helical path.

Schäefer et al. [16] developed a forming method, without using any special die plate, in which an industrial robot is moving a hammering tool on a well-defined bearing over a sheet of metal held in a rigid frame of metal. The first time, using this forming principle, was in producing a sheet metal part of 300 x 300 mm, at a punching frequency of the hammer tool of about 100 hits/s.

The Metal Forming Research Centre from Lucian Blaga University of Sibiu has been carrying out different studies concerning the roboforming process. Chera et al. [17] presents a different way for manufacturing by using a industrial robot to form parts out of sheets of metal through forming of increments via an asymmetric approach. Oleksik et al. [18] had reported a first paper regarding the study of the strains and thinness at the end of a SPIF process. Following the experiments carried out it was observed that the vertical incremental step and the tool diameter are the most important influencing factors. In a second study [19], using a KUKA KR 6-2 industrial robots over CNC milling, showed the possibility of online measurement of the strains and relative thinness, through the Aramis optical measurement system from GOM. Crenganis and Csiszar [20] studied if the 6-axisarticulated robot, model KUKA KR6-2, could be used for SPIF manufacturing with a high degree of dependability. After running the dynamic simulations, the study results showed that the KUKA KR6 robot is well suited for SPIF processes as well as for metallic parts that required greater forming forces, such as Ti6Al4V alloy.

However, the proper selection of tool paths influences the accuracy and productivity of the parts manufactured via SPIF process. In our future research in the Metal Forming Research Centre from Lucian Blaga University of Sibiu, further research will follow with more complex tool paths for unfolding SPIF. A preliminary step for an effective tool path strategy is to design, simulate, and generate the tool path.

4. Tool path planning – simulation of the robotic system
Since the incremental forming process was designed to overlap local deformations along the tool trajectory, the best way to control the final geometry is by directly influencing the main factor, namely the tool path. Designing a successful tool path depends on many variables, such as material parameters, tool diameter, step depth, tool path shape [11, 12, 21].

Since the production time of each part depends on the length of the distortion line, the punch speed and the available power of the equipment used, a preliminary step is to simulate the process.

4.1. Tool path strategies
As conceptually illustrated in figure 3, greatest practiced contouring tool path layouts are Z-level and spiral tool paths. Cutting the part with equidistant planes equally distanced on Z-axis, lead to obtaining of the Z-level tool paths. A proposed tool path for a single feature part represented by dashed lines is presented in figure 3.a, as a section view of a truncated cone with a wall angle \( \alpha \). The vertical increment, \( \Delta Z \), has been exaggerated only for visualization purposes.

Usually, spiral tool paths deliver a better surface finish than Z-level paths due to the continuous vertical transition between following contours. A proposed spiral tool path represented by dashed lines
is presented in figure 3.b, as a section view of a truncated cone. The vertical increment, $\Delta Z$, has been exaggerated only for visualization purposes.

However, complex geometries can prove difficult with the implementation of spiral tool paths. Keeping a 90-degree angle between the surface that is in processing and the tool is a simple solution that not only favors the forming process but also improves the accuracy of the part being made.

![Figure 3. Contouring tool paths layouts: (a) Z-level tool path, (b) spiral tool path.](image)

4.2. Simulation of the robot-forming process

Firstly, to simulate the tool path for incremental forming experiments, a tridimensional model (3D) of the desired part must be designed in a CAD program. The next step is the path planning. The process chain of the robot-forming process is presented in figure 4.

The usage of a CNC machine usually is dependent on 3D CAD models that help the software generate tool path strategies. On the industrial robots side, there are only a few simple yet viable solutions but none with the same potential of a classical CAD/CAM interface.

DELMIA® software from Dassault Systèmes is one of the most powerful, flexible, and easy solution for defining robot movements. CATIA is a CAD software integrated as part of DELMIA which helps not only with the production of parts but also with the modification of them if it is necessary.

![Figure 4. Robot-forming chain process.](image)

As shown in figure 4, the first step is to design and assemble the components for the robotic system in CATIA V5. Then, from the DELMIA program library, the three-dimensional model of KUKA KR 6-2 robot is imported into the Device Task Definition module.

This module is a powerful 3D simulation tool for working cells, providing robot learning capabilities to evolve and practice robot tasks. Through this workbench tool, in an environment where product data and manufacturing resources can be integrated into a single 3D model, is possible to develop and program robot tasks. Each device is individually programmed with tasks that are sequenced and simulated to eliminate any interference. The analysis tools from Device Task Definition provide basic measurements, or collision checking. The simulation reproduces both simple and complex robotic manufacturing processes exactly as they are defined.
After all components were inserted in the Device Task Definition module and the punch is mounted on the robot through “Set Tool” function, the components position must be adjusted to optimize the simulation process.

Studies were carried out on a truncated pyramid and a truncated cone. The proposed tool path for a truncated pyramid represented by white lines is presented in figure 5, with a wall angle 30º, formed using Z-level tool path. The vertical increment, ΔZ, has been exaggerated only for visualization purposes.

![Figure 5. Proposed truncated pyramid tool path.](image1)

The 3D model of the truncated cone tool path, presented in figure 7, which was previous created in CATIA V5 is now imported in Device Task Definition module. The proposed spiral tool path for manufacturing a truncated cone is shown in figure 6. From the “Sequence” toolbar, to the robot is assigned a new task. The waypoints are generated automatically on the defined continuous tool path. Because the orientation of the punch is fixed, in order to manually set the angle of the punch, a secondary path must be created via "Create new robot task" function on the primary path. Now, the waypoints appear in the form of "tags" and the orientation of each tag can be changed as defined by the user. The "Interpolate" function must be used to set the desired orientation on all tags. After setting all the components of the robotic systems, using the "Teach a device" function, the robot must be taught in which configuration to run.

![Figure 6. Proposed spiral tool path.](image2)  ![Figure 7. Detail of the working area.](image3)

The last step before simulating the movement of the robot according to the imposed tool path is to check the singularity problems and limit the joints of the robot. Once you have simulation with no
collisions, applying the “Create Program” function and the programming system will generate robot programs. The two created files are uploaded to the KUKA controllers and based on them the forming begins for the sheet of metal. The tridimensional model of the robotic system is presented in figure 8.

Figure 8. Tridimensional model of robotic system components used for the simulation.

5. Conclusions
To achieve a 3D shape with certain degree of complexity from metal sheets that are flat in the beginning, especially for prototype development or small series production, that is also cost efficient by avoiding high-end dies or expensive tooling, the incremental sheet forming process can represent the ideal choice. Roboforming can be a reasonable alternative to CNC machines that can meet the SPIF process requirements, at a low cost and ensuring a high degree of flexibility, especially for industry-oriented prototypes and small sized production.

The paper shows that simulation of the tool path planning has a huge positive impact in elevating the accuracy in roboforming. The proper selection of the tool paths affects the productivity and the accuracy of the parts manufactured through SPIF process.

The superior kinematic capabilities of the robot were highlighted by means of simulation. Using DELMIA software platform, the collisions, the singularity issues, and the robot joints limitation can be checked. After running the simulation, the program code is generated based on a proper tool path and is used afterwards to control the robot. DELMIA offers a flexible and easy solution for defining robot movements for many robot models.

However, further experimental research must be performed to demonstrate the capabilities of tool path planning, to assess the accuracy of the parts and the use of strategies with higher complexity regarding tool path programs.

Acknowledgments
The experimental test unfolded within this research work were supported by a grant of the Romanian Ministry of Research and Innovation CCCDI-UEFISCDI, project number PN-III - P1-1.2 - PCCDI-2017-0446 /nr. 82PCCDI/2018, within PNCDI III, project title: “Intelligent manufacturing technologies for advanced production of parts”.

References
[1] Cioca L I, Breaz R E and Racz S G 2019 Sustainability Basel 11 315
[2] Bârsan A 2019 ACTA Universitatis Cibiniensis 71 9
[3] Breaz R E, Bologa O and Racz S G 2017 Procedia computer science 122 346
[4] Crenganiș M, Tera M, Biriș C and Gîrjob C 2019 *Procedia computer science* 162 298
[5] Klimchik A, Ambiehl A, Garnier S, Furet B and Pashkevich A 2017 *Robot Comput. Integr. Manuf.* 48 12
[6] Schneider U, Drust M, Ansaloni M et al. 2016 *Int. J. Adv. Manuf. Tech.* 85 3
[7] Pires J N and Bogue R 2009 *Industrial Robot: An International Journal*
[8] Racz G S et al. 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* 564 012023
[9] Tera M, Breaz R, Racz S et al. 2019 *Int. J. Adv. Manuf. Tech.* 102 1761
[10] Bologa O, Breaz R E and Racz S G 2018 *Procedia computer science.* 139 408
[11] Behera A K, de Sousa R A, Ingarao G and Oleksik V 2017 *J. Manuf. Process.* 27 37
[12] Duflou J R, Habraken A and Cao J et al. 2018 *Int. J. Mater. Form.* 11 743
[13] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J and Allwood J 2005 *CIRP Ann. Manuf. Technol.* 54 623
[14] Gatea S, Ou H and McCartney G 2016 *Int. J. Adv. Manuf. Tech.* 87 479
[15] Meier H, Buff B., Laurischkat R and Smukala V 2009 *CIRP annals* 58 233
[16] Schaefer T and Schraft R D 2005 *Rapid Prototyping Journal*
[17] Chera I, Bologa O, Racz S G and Breaz R E 2013 *Trans Tech Publications Ltd.* 371 416
[18] Oleksik V, Pascu A, Deac C et al. 2010 *Int. J. Mater. Form.* 3 935
[19] Oleksik V 2014 *Procedia Eng.* 81 2280
[20] Crenganis M and Csizsor A 2019 *Materials Science Forum* Trans Tech Publications Ltd. 957 P 156
[21] Oleksik V, Bologa O, Breaz R and Racz G 2008 *Int. J. Mater. Form* 1 1187