

Application of Artificial Cognitive System to Incremental Sheet Forming Machine Tools for Part Precision Improvement

A.Fiorentino ^a, C.Giardini ^b, E.Ceretti (2) ^a

^a University of Brescia, Dept. of Mechanical and Industrial Engineering, Italy

^b University of Bergamo, Dept. of Engineering, Italy

ABSTRACT. In Incremental Sheet Forming a hemispherical tool moved by a CNC machine deforms a sheet moving along a predefined path. The process is highly flexible and useful for making prototypes or small series, being characterized by low development times and costs. The part feasibility is strongly influenced by the adopted toolpath and, in particular, toolpath corrections are requested to obtain sound parts in terms of final geometry (part dimension and geometry are affected by springback and punch movement) and sheet rupture. In this paper, an iterative algorithm, based on an artificial cognitive system, is presented and tested on a CNC milling machine when producing actual parts showing how it is possible to obtain sound components by properly varying the original geometry based on of the measurements of the produced part.

Keywords: Toolpath compensation, Incremental sheet forming, Artificial Cognitive System.

1. Introduction

Deep drawing and other traditional sheet forming processes are the most well-known and cost-effective technologies, but the high investment costs and time required to realize the equipments (dies and tools) make them suitable for large batch production. Therefore, the production at low cost of small batches or customized part represents a challenge for the actual market. Typical examples can be found in medical devices, aerospace and automotive prototypes fields [1]. The answers to these requirements are the flexible, time and cost saving manufacturing process as Rapid Prototyping and, in particular, Incremental Sheet Forming (ISF) seems to be the most effective and reliable one when referring to prototypes, small-batch [1] and customized mass production [2,3]. In fact, if the overall production time required by ISF is higher than the ones traditional stamping operations, advantages in flexibility and tooling cost are consistent.

The ISF process uses conventional CNC machine tools or robots to locally deform a blank sheet by means of a hemispherical tool mounted on the machine spindle or end effector and moved according to a suitable toolpath, as shown in Figure 1a. The process is normally realized without die, but some applications are characterized by the presence of a full or a partial die to improve the process performance [1].

With ISF it is possible to achieve higher deformations than with traditional stamping processes, as reported by Allwood et alii in [4] and Martins et alii in [5]. The process also allows to obtain complex shapes since it only depends on the toolpath. As the different passes are closer, the quality of the produced parts tends to increase due to the lower volume of the material to be deformed. The most used toolpath strategies are constant z-level and helical ones so to gradually deform the sheet while increasing the part depth (Fig. 1b). These strategies can be applied either with a constant step depth increment (Δz), or with a variable step depth in order to accomplish the maximum theoretical surface roughness, normally known as “scallop height” h_{sc} , [6].

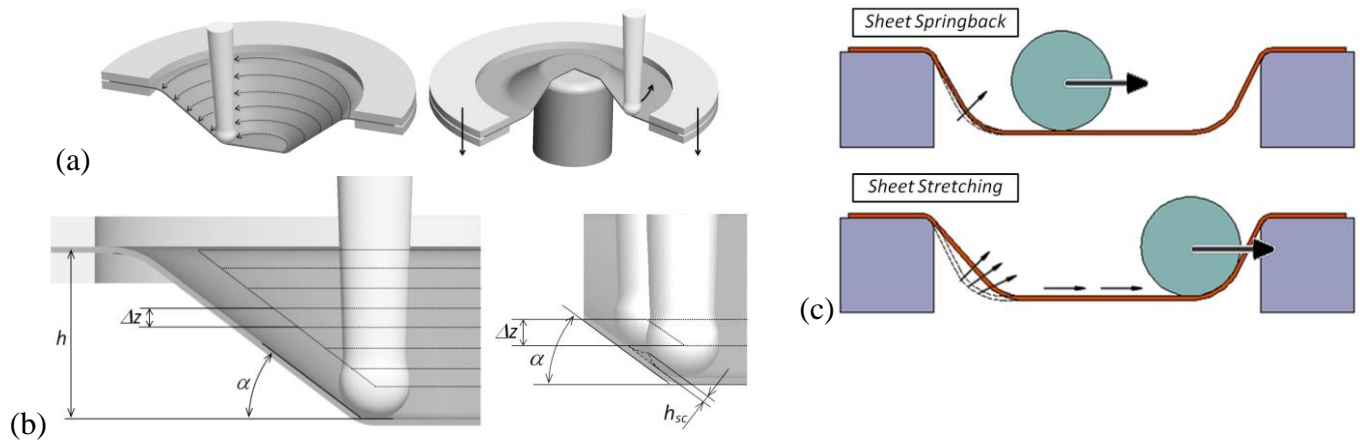


Figure 1. (a) Single Point and Two Points (with partial die) Incremental Forming process, (b) constant step depth increment Δz strategy and step depth increment Δz as function of the scallop height h_{sc} , (c) springback and stretching action in dieless ISF.

Nevertheless the big advantages connected with this technology, there are some critical aspects related to the part feasibility and the part precision. In fact, if ISF allows to overcome the material formability described by the drawing FLC (Formability Limit Curve) [4,5], the part feasibility is limited by reduction of the sheet thickness as the depth and the slope of the wall increase [7] making more difficult the part formality and the prediction of the rupture. Moreover, the part precision is greatly influenced both by the high springback and the deformation that the sheet undergoes because of the punch stretching action as the process goes on (Figure 1c). As a consequence, the main limit of the technology is represented by the geometrical error that can be found on the final shape [8].

To deal with formability problems, some Authors proposed failure criteria using different approaches based on the offline sheet stress and stretching estimations [5,9-11] and on the online forming force measurement [12,13]. Moreover, since the adopted toolpath greatly influences thinning and feasibility, multi-step toolpath strategies were introduced to achieve higher wall angles [14,15].

To improve part precision, it was shown that the part accuracy can be improved by using a die under the sheet [16], but this solution limits the process flexibility and increases the manufacturing cost. Many Authors focused on the tool path correction using strategies based on iterative algorithms [17-19], transfer function [20], part features [21] or neural networks [22,23]. A novel approach is proposed in [20] where the transfer function concept was introduced to correct the toolpath aiming at the precision part improvement. Within a so wide panorama of issues to be considered for obtaining a sound part through ISF, the use of preliminary FE tools is of great help in reducing time and cost for the design of the manufacturing process [24].

The research here reported solves the problem of the toolpath correction from a completely different point of view. In particular, an adaptive approach was used in order to recursively correct the geometry of the part to be produced instead of the toolpath. In particular, the present paper describes a correction algorithm based on the Iterative Learning Control technique that corrects the toolpath improving the precision of the component according to the measurement of the produced parts. The strong advantage of the method is that no predetermined solutions are introduced, so realizing the best correction in relation with the actual part shape and the error distribution. The novelty of the approach lies in the fact that the toolpath correction is realized modifying the geometry of the part from which the toolpath is derived. The proposed algorithm was implemented in a self developed software and experimentally tested showing to be very performing. In particular, it allowed to obtain acceptable parts within a maximum of few iterations. Moreover, the solution here presented is able to improve the machine tool capability in terms of achievable precision on the final part and to increase the machine intelligence learning from the error of the previously produced part.

2. Iterative Learning Control (ILC)

The problem of iteratively learning and controlling a system, can be expressed as the iterative modification of the system input to minimize the output error defined as the difference between what has been obtained with respect to the target.

This type of problem is normally called Tracking Iterative Learning Control (TILC) [25]. The positive aspect of this approach is that the system under control learns and controls in each cycle and, therefore, a priori knowledge is not required and it can be applied to all the cyclic processes. The most interesting aspect of ILC is related to the fact that it is possible to implement a control law acting between one cycle and the subsequent one. To do this, it is necessary to store the errors and to respect the basic hypothesis, i.e. the initial conditions of each cycle of the process are always the same. This can be easily satisfied in ISF since the worked material and the initial shape of the sheet are the same for each repetition.

The scheme of an ILC procedure is illustrated in Figure 2 where the core elements, the system and the ILC, are reported together with the exchanged signals. All the signals are defined in a limited time interval $t \in [0, t_f]$ that can assume either continuous or discrete values. The subscribed k indicates the repetition number ($k = 0$ means the initial test).

In the k -th cycle the $u_k(t)$ input is applied to the system which gives $y_k(t)$ as output. The two signals are recorded in order to be utilized, at the end of the cycle, for the calculus of the next system input $u_{k+1}(t)$, while $y_d(t)$ represents the desired output signal of the system. Hence, the tracking error for the k -th cycle $e_k(t)$ can be expressed as:

$$e_k(t) = y_k(t) - y_d(t) \quad (1)$$

Thus, the generic iterative control law can be expressed as:

$$u_{k+1}(t) = f(e_k(t), u_k(t)) \text{ where: } t \in [0, t_f] \quad (2)$$

The final goal of the ILC is to minimize the error $e_k(t)$, i.e.:

$$\lim_{k \rightarrow \infty} u_k(t) = u^*(t) \quad \text{where: } \forall t \in [0, t_f] \quad (3)$$

$u^*(t)$ is therefore the input signal minimizing the norm of the error: $\|y_k(t) - y_d(t)\|$.

The ILC most important aspects are:

- to fix a first trial input signal $u_0(t)$ for the first cycle;
- the initial conditions are always the same for each cycle;
- the cycle length t_f is constant;
- the error should converge to 0;
- the system is stable during the time since the ILC algorithm is able to better the performance and not to stabilize it;
- the convergence is independent on the desired signal $y_d(t)$; in fact, the ILC controller should be able to self-adapt.

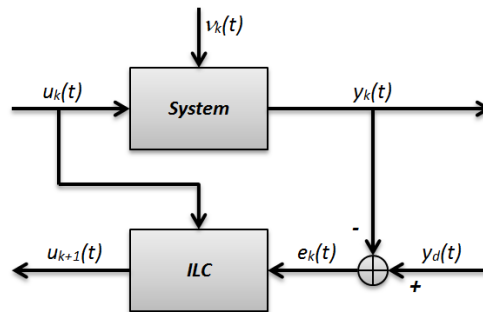


Figure 2. Scheme of an ILC system.

The problem formulation can be seen as to determine the ILC law that can be written according to the following:

$$u_{k+1}(t) = f_{ILC}(y_d, u_{k-m}, y_{k-j}, y_{k+1}) \quad \text{where:} \quad (4)$$

$j, m \geq 0$

By choosing a linear first order algorithm, it is only necessary to store the error of the previous cycle, that is:

$$u_{k+1}(t) = f_{ILC}(y_d, u_k, y_k) \quad (5)$$

Consequently, the ILC function is linear and hence:

$$u_{k+1}(t) = T_u(z) \cdot u_k(t) + T_e(z) \cdot e_k(t) \quad (6)$$

$T_u(z)$ and $T_e(z)$ are linear operators in z , the system variable.

In our case $T_u(z)$ was set equal to 1 while $T_e(z)$ was considered as a weight $(0,1]$ applied to the calculated error.

In such a way the new control signal $u_{k+1}(t)$ is modified with respect to $u_k(t)$ by an amount proportional to the error. Values of $T_e(z)$ greater than 1 should lead the system to diverge.

3. Artificial Cognitive System implementation to ISF technology

3.1 The ILC application

As already said, the accuracy of the produced parts in an ISF process is influenced by sheet springback, stretching action exerted by the punch on the sheet and tool deflection and machine deformation due to the acting forces, especially when a robot is used being less stiff than a CNC machine. To improve the part accuracy, the above described ILC procedure is applied to ISF technology.

In practice, referring to Figure 2 and Figure 3 and to expressions from (1) to (6), the ILC can be implemented considering that, at the k -th step, $u_k(t)$ is the geometry of the part, $v_k(t)$ is the process parameter set, $y_k(t)$ is the actual part geometry formed according to a toolpath calculated on the base of $u_k(t)$, $e_k(t)$ is the error between $y_d(t)$ and $y_k(t)$, where $y_d(t)$ is the target part geometry and the *system* refers to the whole process from the CAD/CAM to the CNC machine and the measuring apparatus. Hence, the ILC is the compensation algorithm that, starting from $u_k(t)$ and $e_k(t)$, calculates the new part geometry $u_{k+1}(t)$ according to (6) from which a new toolpath is derived (tp_{k+1}). At the beginning $u_0(t)$ coincides with $y_d(t)$.

The idea is that, according to this procedure, the precision of the formed part increases at each step until the geometrical tolerance requirements are accomplished. In particular, the “Profile of a surface” tolerance \triangle is considered.

The target geometry $y_d(t)$ is derived from the 3D CAD model, the process parameters $v_k(t)$ (toolpath, step depth, tool diameter, tool velocity, sheet thickness and material) are kept constant during the correction steps, the actual part geometry is sampled by means of a 3D stereoscopic vision system, while the part alignment, the error calculation $e_k(t)$, the compensation algorithm and the toolpath generation $tp_k(t)$ have been developed by the Authors and implemented in a software application.

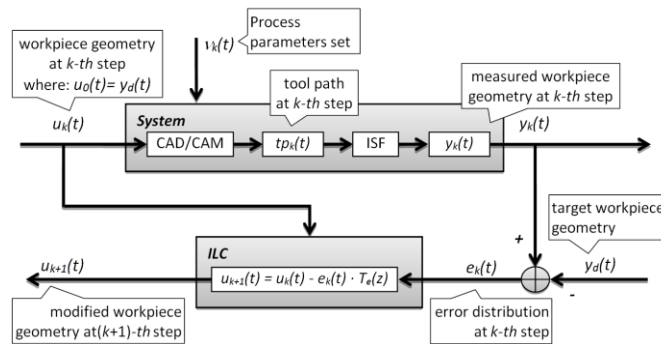


Figure 3. Scheme of the ILC application to the improvement of part accuracy in ISF.

3.2 The developed program

The described ILC has been implemented according to the scheme reported in Figure 3.

All the calculus phases have been implemented in a self-developed software able to manage all the data considering the different iteration steps and the geometries necessary to carry out the compensation

algorithm, to align the actual and the theoretical geometries, to calculate the local error distribution and the geometry correction and to generate the toolpath while recording the iteration history.

The actual/measured part geometry $y_k(t)$ is obtained by digitalizing the produced component by means of the commercial 3D optical scanner REVENG LE 240 HD 1.3 MPx from Open Technologies. The sampled points are saved in a STL file and then passed to the compensation software which performs the following actions:

- The CAD $y_d(t)$ and the measured $y_k(t)$ geometries are firstly aligned; this allows to avoid the problem of defining a common coordinate system origin; the alignment is carried out between the nominal model and the measured point cloud using the Normal Distribution Transform [26] that has been chosen because the spatial distribution of the two sets of points were not homogeneous and their densities were not comparable.
- The aligned geometries are compared and the error distribution $e_k(t)$ (i.e., the distance between the two geometries, see Figure 4) is evaluated according to eq. (1) (Figure 7).
- The error distribution is used for calculating the corrected geometry $u_{k+1}(t)$ starting from the previous $u_k(t)$ according to equation (6) and described in detail in paragraph 3.3. The $T_e(z)$ weight can be chosen by the operator in the range (0,1] (Figure 4).
- From the new part geometry a new toolpath is generated and passed to the CNC machine where a new part geometry $u_{k+1}(t)$ is produced and then newly measured obtaining $y_{k+1}(t)$ and so on.
- The iterative procedure stops when the geometrical error is lower than the one imposed by the part specifications.

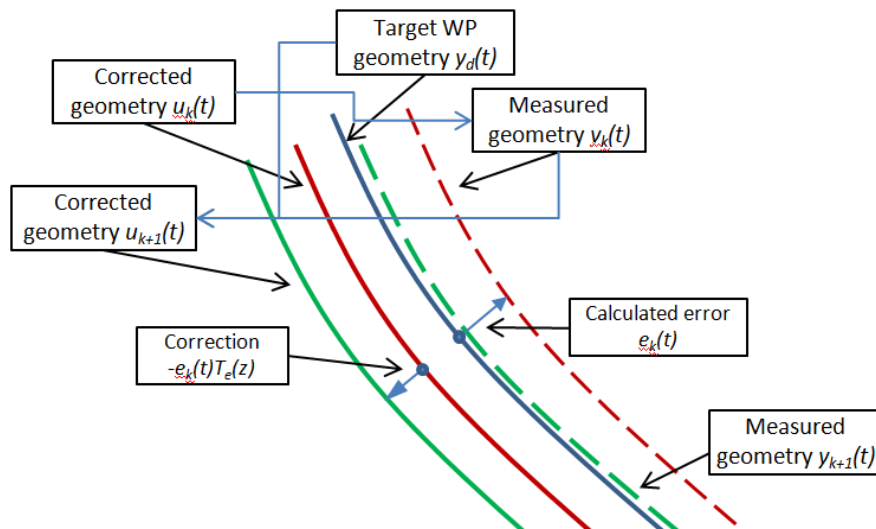


Figure 4. Scheme of the correction phase.

3.3 Error and correction calculation

Considering that all the geometries involved in the error and correction calculation are in STL format, they are initially transformed into a surface mesh representation (nodes plus elements). Moreover, since the nodes of the different geometries are not related each other and are not homogeneous, it was necessary to develop an error calculation and correction algorithm that can work under these hypotheses.

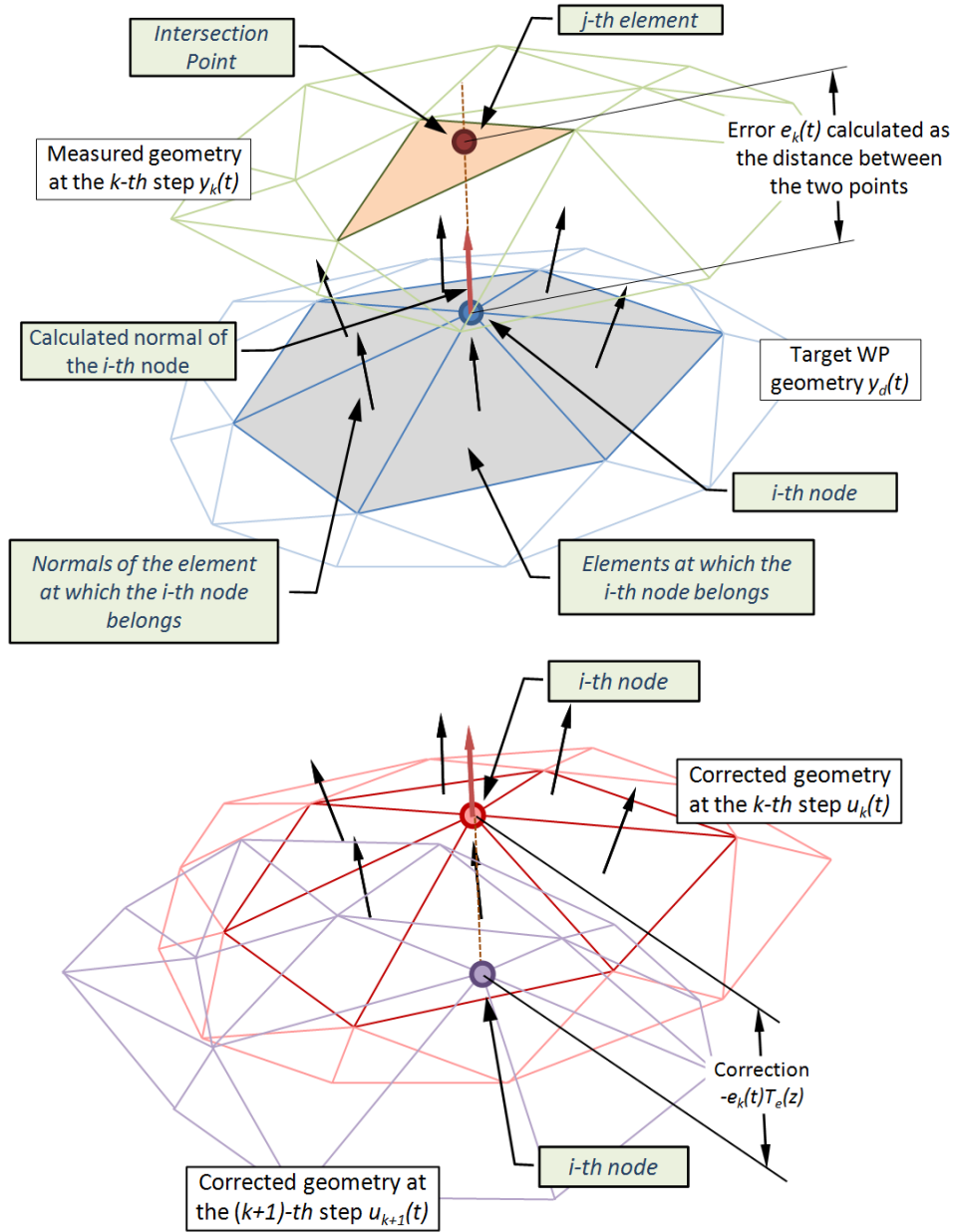


Figure 5. Scheme of the error calculation and the identification of the geometry correction.

In particular, this has been done according to the following procedure shown in Figure 5:

- For each i -th node of the target geometry $y_d(t)$ the elements at which the node belongs are identified;
- The normal of the target geometry at the i -th node is calculated as the vector sum of the normal vectors to the previously identified elements;
- The normal intersects the measured geometry $y_k(t)$ in a j -th element; it is important to verify that the intersection point is inside the element;
- The distance calculated between the i -th node and the intersection point so identified is the error.

By repeating this procedure for all the nodes of the target geometry, it is possible to identify the error distribution function $e_k(t)$ for the measured geometry at the k -th step.

Applying the error function $e_k(t)$ to the worked geometry $u_k(t)$ it is possible to evaluate the new corrected geometry to be worked at the $(k+1)$ -th step $u_{k+1}(t)$ according to Figure 4, Figure 5 and (6).. For this geometry a new toolpath $tp_{k+1}(t)$ is calculated and a new part is produced.

3.4. Case study

The developed ILC system has been tested realizing the multi-slope cone reported in Figure 6. The part is axisymmetric and it is characterized by different inclination angles and different depths so to evaluate, in a single part, several geometric changes. The maximum angle utilized for the part slope is 55° , a value that is considered safe when working by ISF Aluminum sheet, since the objective of the research was the geometry compensation and not the material forming limits identification. The utilized machine is a CNC milling center with an horizontal spindle. The toolpath has been generated using a spherical tool with a diameter equal to 7 mm on an aluminum sheet 1.5 mm thick with constant Z passes with a step depth equal to 0.4 mm. Moreover, different $T_e(z)$ values were considered during preliminary tests so to evaluate its correctness through the experimental results.

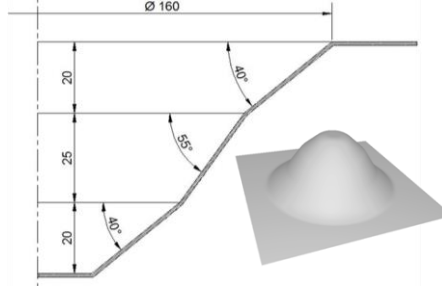


Figure 6. The tested part.

The results of the ILC at each iteration are reported in Figure 7 where it is possible to see how the error $e_k(t)$ decreases together with its distribution scattering. In fact, after three iterations the initial error (ranging from +1.23 to -1.34 mm and centered in 0.3mm) decreases both in range and center value (ranging from 0.3 to -0.16 mm and centered in 0.06mm). Moreover, and the scattering of the errors becomes more uniform and normally distributed.

The improvement of the part accuracy is evident confirming the effectiveness of the application of the proposed method. Moreover, the testing phase showed that, for $k \geq 1$, the $e_k(t)$ values linearly depends on the adopted $T_e(z)$. Therefore, to reduce the number of iterations, the highest working value for $T_e(z)$ was adopted. In particular the value $T_e(z) = 1$ was identified as the best for the analyzed geometry so to rapidly improve the part geometry while maintaining the process stable.

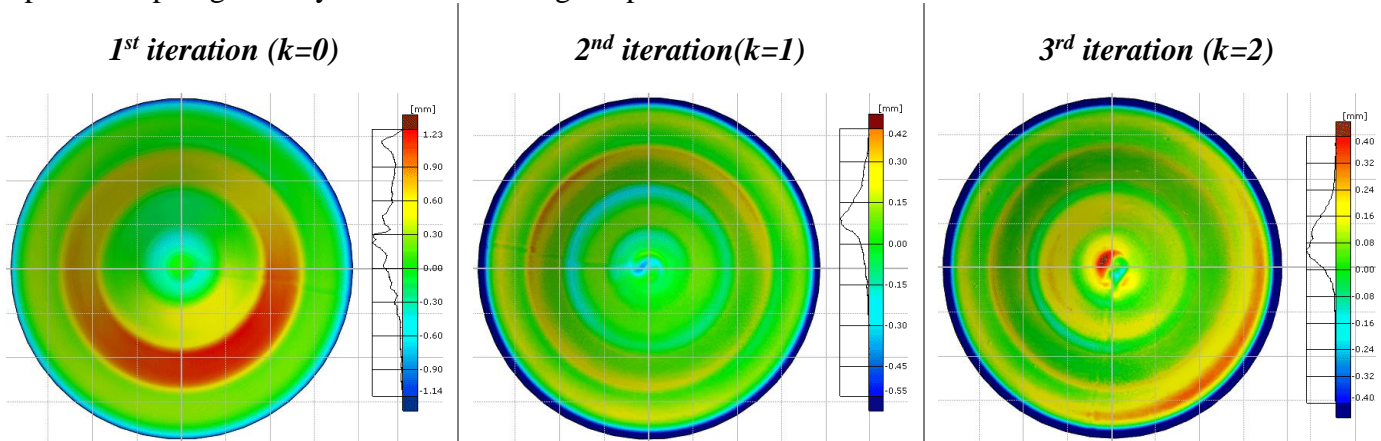


Figure 7. The error distribution $e_k(t)$ after the first, second and the third iteration.

4. Conclusions

The correction algorithm for improving the precision of Incremental Sheet Forming machine tools, developed on the basis of the Iterative Learning Control technique, demonstrated to be successfully applied being able to reduce the geometrical error of the produced parts within a very limited number of iterations. The chosen approach is thus able to consider the errors deriving from the whole forming process, in particular from the sheet springback, the stretching action of the deforming punch and the deformation of the tool and the machine themselves. The proposed method does not need predetermined corrections but

realizes the best correction in relation with the actual part geometry and the corresponding error distribution with respect to the CAD part geometry. Furthermore, the approach is flexible and easy to use and the equipment needed to realize the correction procedure, is only based on a 3D scanning system and on a self developed software.

Finally, the implemented Artificial Cognitive System can be utilized to improve the intelligence of production systems based on traditional and robot CNC machines so becoming able to learn from the geometrical errors of the formed parts and to improve its performance.

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