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**Abstract.** Since sheet metal forming has a high percentage contribution in the overall design costs of a new car, this engineering area assisted in the last decades to considerable development efforts. The present challenge is to simulate all the production stages, from the initial blank sheet to the final part ready to assembly. On this particular issue of multi-step deep-drawing simulation, this work presents a new remapping method called Incremental Volumetric Remapping (IVR) developed to minimize the error that occurs, when performing the variable transfer operation between two different meshes. The IVR method is based in a volumetric approach where the calculus of the remapped state variables is obtained by means of a weighted average of the intersection volume between the meshes. The method performance is tested and compared with a standard extrapolation-interpolation, by applying a numerical example of the Numisheet'2005 Conference, "The Channel Draw/Cylindrical Cup Benchmark".

## INTRODUCTION

One of the common problems when referring to the numerical simulation of multi-step processes concerns the mesh modifications over the simulation, which may involve, for instance, several trimming or remeshing operations. Therefore, along each one of these mesh modifications, some kind of remapping procedure is required to transfer the state variables and other quantities from the previous to the next mesh. When reporting the finite element method, the remapping problem can be described as an approximation of a field of quantities at a distribution of discrete points, which represent a donor (initial) domain, given their values to a different distribution of discrete points (target domain) [1]. Several methods can be found in literature that address this subject, in particular, Jiao and Heath [2] group four most relevant strategies: Pointwise interpolation and extrapolation; Area-weighted averaging; Mortar elements methods; or Specialized methods according the application. In

this work, a new method called Incremental Volumetric Remapping (IVR) method is presented and applied to solid finite "brick" element meshes that attempts to minimize, the error that occurs during the state variable transfer operation, for instance, with the classical extrapolation-interpolation methods. The IVR method can be classified as a conservative rezoning one, since the state variables values to put in the new Gauss points (of the target mesh) are determined by a weighted average of the intersecting volumes between the target and donor meshes. Apart of the method description for the state variables transfer problem, a different approach is presented to address the determination of the intersection volumes, by a discrete and incremental manner. To test the performance of the IVR method, a multi-step example of the Numisheet'2005 Conference – "Channel Draw/Cylindrical Cup Benchmark #3" – is used, as well as other remapping method (extrapolation-interpolation by shape functions inversion) to compare the obtained results. All the simulation stages were

carried out with the DD3 family of home codes [3-5] developed at CEMUC (Coimbra University Mechanical Engineering Research Center). In particular the DD3IMP static implicit code for deep drawing simulation, the DD3OSS static implicit code for the springback prediction and the DD3TRIM code to trim hexahedral finite element meshes and also to execute the remapping stages.

## REMAPPING PROCEDURE

One classical way to remap a given mesh domain is to apply extrapolation-interpolation based methods, that, in most cases, make use of the finite element shape functions. In these methods, firstly, the state variables are extrapolated (by inversion of the shape functions) from the Gauss points to the nodes of the donor mesh (see figure 1.a and 1.b) and then two consecutive interpolation operations are performed. The first one, transfers the quantities from the nodes of the donor mesh, to the nodes of the target mesh making use of the shape functions of the donor element that contains the target node (figure 1.c), and the second one, from the nodes to the Gauss points of the target mesh (figure 1.d).
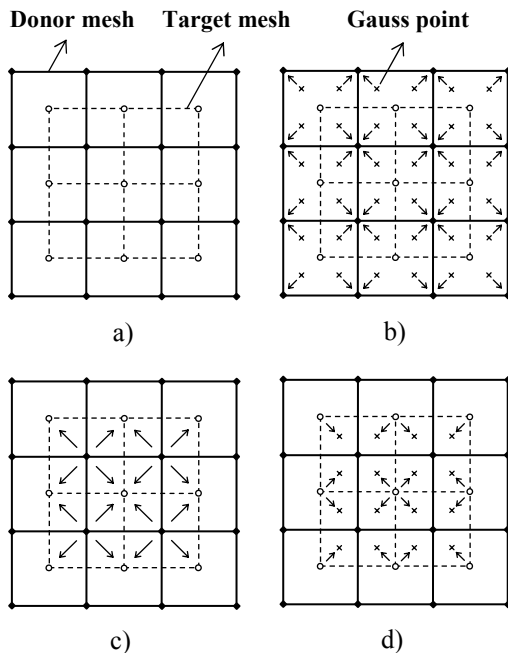
The IVR method is based on the concept, reporting the finite element theory, that the state variables values in all the points of a Gauss volume (an eighth part of the standard brick element) are equal to the state variable quantity placed in the correspondent Gauss point. Therefore, the variables quantities to be placed in a given Gauss point of the target mesh element can be in this way determined by the calculus of a weighted average. The weight function to be used is the Gauss volume percentage of each donor element that is inside of the target Gauss volume (corresponding to the Gauss point in evaluation). However, this kind of volume formulation brings the difficult problem of calculating intersecting volumes of elements belonging distinct meshes (see figures 2.a and 2.b) [1,6]. This issue is here overcome by using an incremental volumetric scheme to determine the intersecting volume between two elements. The methodology begins with the division of the Gauss volume of the target element (figure 3.a, 3.b), in a predefined number of parts (figure 3.c). After the target Gauss volume partition, a loop is performed to determine which donor Gauss volume contains the centroid of each small part (figure 3.d).
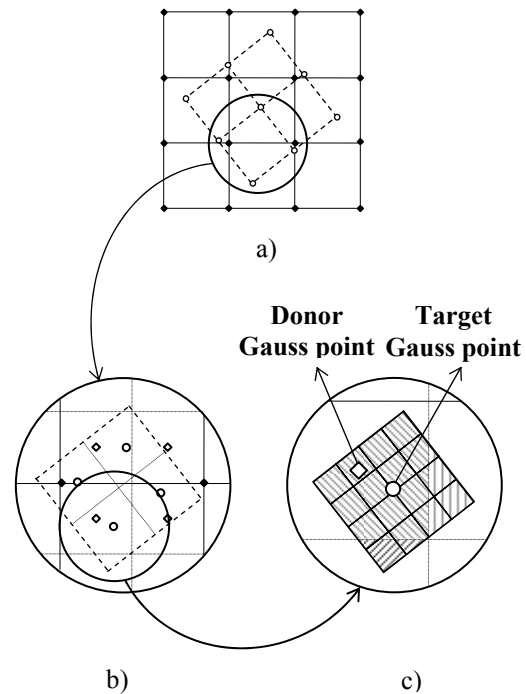


**FIGURE 1.** Schematic 2D representation of the main stages of a typical extrapolation-interpolation remapping method: a) Donor and target meshes; b) Extrapolation stage; c) First interpolation stage; d) Second interpolation stage.



**FIGURE 2.** Schematic 2D explanation of the IVR method: a) Donor and target meshes; b) Gauss volumes intersection; c) Target Gauss volume partition and intersection.

For the point search procedure in the donor Gauss volumes, it was chosen to apply the volume coordinates method that is straightforwardly and avoids predictably higher time consuming iterative algorithms, such as, those based in the parametric inversion of the element shape functions [7]. The state variable quantity that is assigned to each single Gauss volume part is equal to the state variable quantity of the donor Gauss volume, in which the volume part centroid is located (figure 2.c). The total donor Gauss volume contribution for the target Gauss volume (in evaluation) is computed by summing all the small part volumes that belongs to the donor Gauss volume. The calculus of the state variable quantity α to be placed in a Gauss point of the target element is given by the equation:

$$\alpha = \sum_{i=1}^{NG} \frac{\sum_{j=1}^{NL^3} {}^iV_j}{{}^iV_{tot}} \alpha_i \qquad (1)$$

where ${}^iV_j$ is $j$ Gauss volume part of the target mesh contained by the donor Gauss volume $i$, ${}^iV_{tot}$ is $i$ total donor Gauss volume. $NG$ is the number of donor Gauss volumes and $NL$ the number of linear divisions of the target Gauss volume to be partitioned. $\alpha_i$ is the state variable quantity of the $i$ donor Gauss volume.
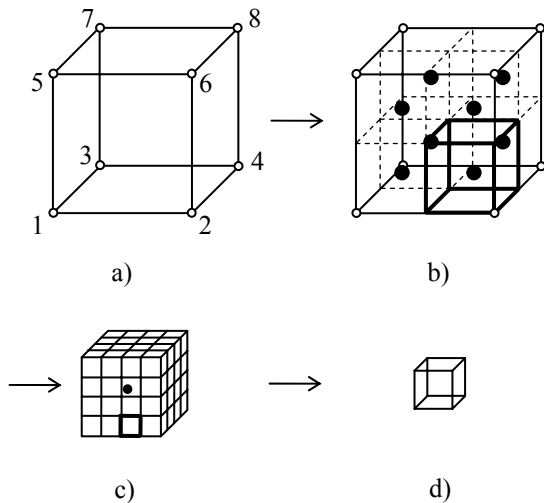


**FIGURE 3.** Brick element decomposition: a) Original element; b) Division in Gauss volumes; c) Individual Gauss volume partition; d) Single Gauss volume part

For the nodal variables treatment, it is used the general methodology, aforementioned for the extrapolation-interpolation methods: The nodal values are interpolated from the nodes of the donor mesh to the nodes of the target mesh (figure 1.c) using the shape functions of the donor elements.

## NUMERICAL EXAMPLE TEST

To test the performance of the developed IVR method, face the briefly explained extrapolation-interpolation one, it was chosen to use one of the Numisheet'2005 Conference Benchmarks (see reference [8] for details). The "Channel Draw/Cylindrical Cup Benchmark #3" is divided in two stages. In this study, the focus will be putted only in the mesh transition between stages, where the trimming, remeshing and remapping operations take place. In the analysis, the used trimmed blank, called Specimen A (figure 4) is obtained by cutting the Stage 1 channel draw panel after springback. It was chosen to use the DP600 material data from the stage 1 simulation results. This trimmed blank is subsequently deep-drawn in stage 2.
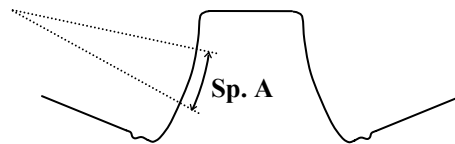


**FIGURE 4.** Location of the trimming positions in the Stage 1 channel draw panel, to create the Specimen A blank that will be deep-drawn in stage 2.

The trimming operations are executed with the home code DD3TRIM [5] to obtain the trimmed meshes, as well as, to perform the rotation and translation of the mesh to setup the blank for the second stage. In stage 1 forming, the original blank (1066.8mm × 254.0mm × 1.0mm) is submitted to a principal load direction that is subject to cyclic bending and unbending loading imposed by the drawbeads. Thus, in the original mesh discretization, it was chosen to use a mesh with three layers in thickness direction and to put more elements in the longitudinal direction to better predict the plastic strain gradients developed in the drawbead influence region. Has a consequence, the number of elements of the Specimen A trimmed mesh in the transversal direction is much lower that in the original longitudinal one (see figure 5.a). Since in the stage 2 the punch tool is axisymmetric, it is imperative to homogenize the number of elements in the longitudinal and transversal directions of the mesh (figure 5.b). For that purpose, a

simple remeshing algorithm is used to reduce or increase the number of elements in a given direction.
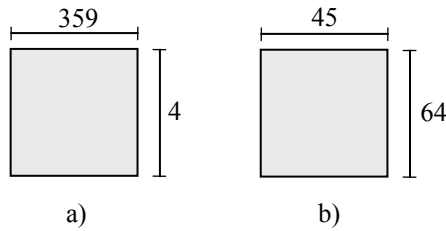


**FIGURE 5.** Number of linear divisions in the longitudinal and transversal directions of the trimmed meshes, before a) and after b) the remeshing operation.

Due to the difficulty of measuring the effective error in a single remapping operation, because of the discrepancy of the nodes and Gauss points location, in the analysis the remapping error is measure after two consecutive remapping operations. Thus, after remapping the mesh that results from the remeshing operation, the original mesh is remapped with the information of the remeshed one and, in this way, the accuracy of the remapping methods can be accessed and compared (figure 6).
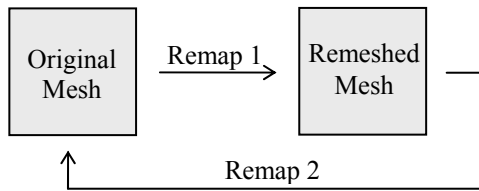


**FIGURE 6.** Evaluation procedure to estimate the remapping error after two consecutive remapping operations.

## Remapping Results

In the conducted remapping tests with the IVR method, three values of NL (equation 1) where tested (5, 10, 15) in order study the influence of this adjustable parameter, in the accuracy of the remapping operation. In all the presented results, the state variable in evaluation is the stress component $\sigma_{xx}$, since in this problem, this variable has strong gradients distribution and, therefore, the remapping error assumes more significance. In figures 7 to 11 the stress distribution can be visualized and the obtained results for each one of the methods and parameters qualitatively compared. Observing the results for the extrapolation-

interpolation method (figure 8) and comparing with the original mesh ones (figure 7) it is easily perceptible that the method conducts to a softening and distortion of the original gradients.
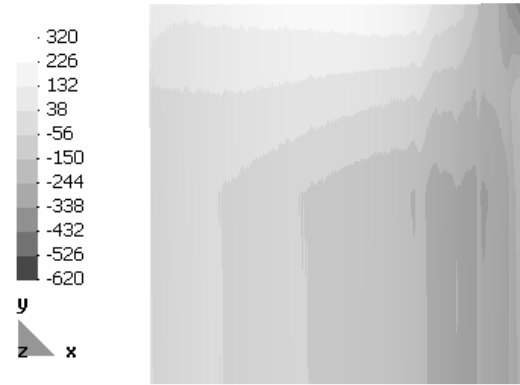


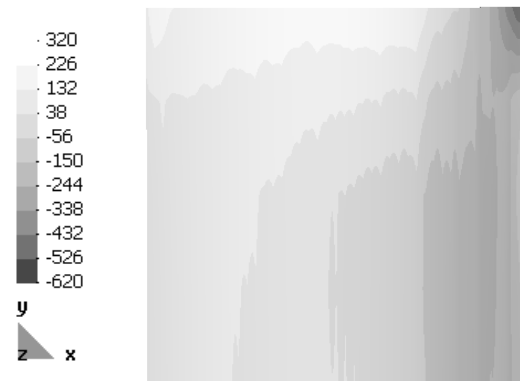**FIGURE 7.** Stress variable $\sigma_{xx}$ [MPa] distribution for the original mesh.



**FIGURE 8.** Stress variable $\sigma_{xx}$ [MPa] distribution for the original mesh remapped with the extrapolation-interpolation method.

In the IVR treated meshes (figures 9, 10, 11) the original global gradients are kept. However, it is noticeable the presence of artificial transversal stripes, that are justified by the discrete base formulation of the method and the high element density in the longitudinal direction in the initial mesh. Nevertheless, this effect is effectively attenuated by the increase of the NL parameter, what indicates that the high mismatch of elements between the two meshes recommends the use of higher NL values. This conclusion is confirmed by the error analysis taken by plotting the number of nodes as function of their absolute error values (see figures 12 to 15) and by the mean measured error for each case (see table 1). By comparing the two remapping methods, it can be stated that the IVR method generates smaller error

values, even in the lowest NL value tested, face the standard extrapolation-interpolation one.
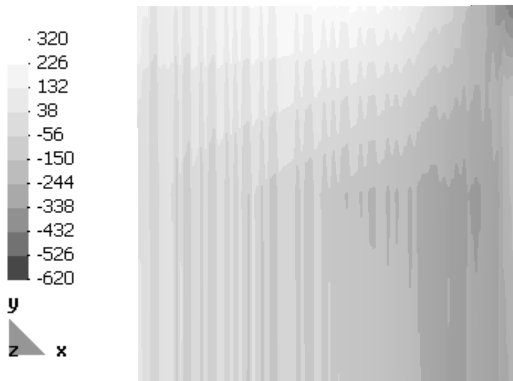


**FIGURE 9.** Stress variable $\sigma_{xx}$ [MPa] distribution for the original mesh remapped with the IVR method, with NL equal 5.
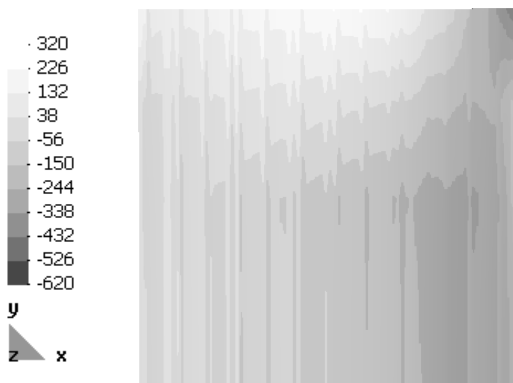


**FIGURE 10.** Stress variable $\sigma_{xx}$ [MPa] distribution for the original mesh remapped with the IVR method, with NL equal 10.
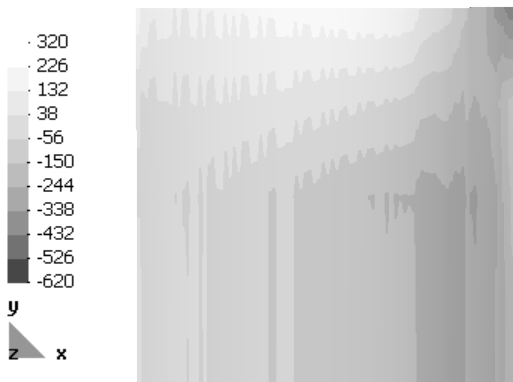


**FIGURE 11.** Stress variable $\sigma_{xx}$ [MPa] distribution for the original mesh remapped with the IVR method, with NL equal 15.

While in the extrapolation-interpolation method (figure 12), the error values spreads above 100 MPa, for the IVR case, the plotted error values are always under 85 MPa. When observing only the NL parameter influence on the error distribution and quantity for the IVR method, it clearly notice that the error distribution moves towards the left side of the graphs (figures 13, 14 and 15), that is, to lower error values as the NL value increases.

**TABLE 1. Remapping error of $\sigma_{xx}$ variable for the different methods and parameters.**

| Method | Mean Error [MPa] |
|---|---|
| Extrapolation- Interpolation | 54.7 |
| IVR (NL = 5) | 29.8 |
| IVR (NL = 10) | 17.5 |
| IVR (NL = 15) | 12.4 |

In the mean error evaluation (table 1) the difference between the two remapping methods can be significant, observing that the mean error associated to the extrapolation-interpolation method is 1.85 times higher than the IVR method, for NL equal 5, and 4.4 times, when NL equal 15.
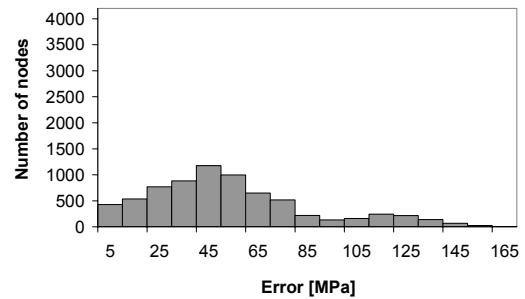


**FIGURE 12.** Frequency error distribution for the original mesh remapped with the extrapolation-interpolation method.
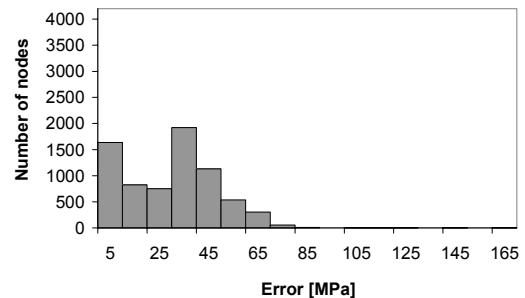


**FIGURE 13.** Frequency error distribution for the original mesh remapped with the IVR method, with NL equal 5.
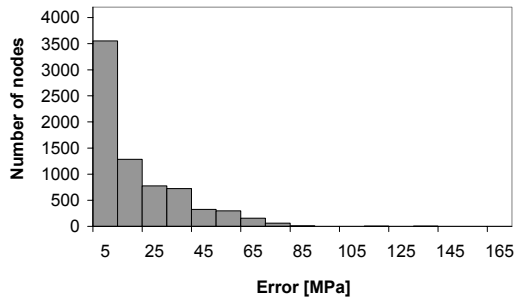
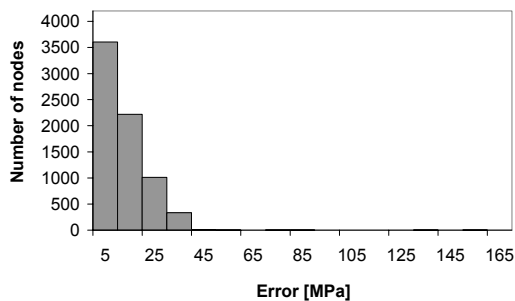**FIGURE 14.** Frequency error distribution for the original mesh remapped with the IVR method, with NL equal 10.



**FIGURE 15.** Frequency error distribution for the original mesh remapped with the IVR method, with NL equal 15.

## CONCLUSIONS

In this work a new algorithm to treat the state variable transfer problem between two distinct finite element meshes has been described. The IVR method is based in a volumetric approach where the state variable value to put in a target Gauss point is determined by a weighted average of the intersection volume between the target and donor meshes. Apart of the transfer problem issue, a discrete methodology is taken to easily determine the intersection volumes without being necessary to calculate any kind of geometrical intersections between elements that can be very delicate to achieve in terms of efficiency and algorithmic reliability. In the performance tests, two consecutive remapping operations based on the Numisheet'2005 Benchmark #3 data, were executed by the IVR method and by a classical extrapolation-interpolation one. The IVR has conducted to very effective results towards the reduction of the remapping error, as well as, to maintain the state variables gradients, avoiding excessive numerical smoothing and distortion. Furthermore, the method has the advantage of being adjustable, to the meshes

asymmetries and dimensions and, therefore, to the remapping accuracy by means of a linear parameter described in the text.

## REFERENCES

1. Rashid, M. M., *International Journal for Numerical Methods in Engineering* **55**, 431-450 (2002).
2. Jiao, X. and Heath, M. T., *International Journal for Numerical Methods in Engineering* **61**, 2402-2427 (2004).
3. Menezes, L. F. and Teodosiu, C., *Journal of Mat. Proc. Technology* **97**, 100-106 (2000).
4. Oliveira, M. C., Alves, J. L. and Menezes, L. F., "One Step Springback strategies in Sheet Metal Forming" in *Proceedings of the 7th International Conference on Computational Plasticity, Complas-2003*, edited by E. Onate and D. R. J. Owen, Barcelona, 2003, paper on CD.
5. Baptista, A. J., Alves, J. L., Oliveira, M. C., Rodrigues, D. M. and Menezes, L. F., "Numerical simulation of multi-step deep-drawing processes: Trimming 3D solid finite element meshes" in *Proceedings of the 4th International Conference on Engineering Computational Technology*, edited by B. H. V. Topping and C. A. Mota Soares, Lisboa, 2004, abstract pp. 78, paper on CD.
6. Grandy, J., *Journal of Computational Physics* **148**, 433-466 (1999).
7. Alves, M. L., Fernandes, J. L. M., Rodrigues, J. M. C., Martins, P. A. F., *Journal Of Materials Processing Technology* **141 (3)**, 395-403 (2003).
8. http://www.numisheet2005.org