Modeling flexible/curved PCBs using RBF mesh morphing

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Abstract. In the recent past, flexible printed circuit board (PCB) electronics have seen a significant surge in many electronics products ranging from smartphone/watches that wrap around our wrists, displays that fold out as large television sets, reconfigurable electronics that conform to the roofs/trunks of cars or as flexible implants that can monitor and treat diseases. Whatever the need is, it is quite evident that the near future is bound to see a significant uptick in day-to-day usage of such electronic products and hence as a direct result there is a need for numerical modeling, simulation and analysis of PCB’s that conform to different shapes. However, given the complexity of PCB’s, numerical modeling of such structures remains a challenge and there is a need for a clear and simple methodology to accomplish this. In addition, the developed methodology should also be applicable to both the trace mapping and trace modeling techniques typically used while working with Electronic-CAD files. In this work, the RBF (Radial Basis Function) method has been presented as a capable technology that can morph the flat mesh electronic data to a curved space which can be further used for analysis purposes. Since the morphing is being directly implemented at the mesh level, a lot of obstacles and complexity typically encountered while generating curved PCB CAD files can be avoided. The RBF Morph ACT Extension has been the tool of choice in the current context. This extension was built on the modular architecture of the ANSYS Workbench and is hence deeply integrated into Mechanical which makes it easy to work with. While RBF Morph offers a wide range of morphing capabilities, a 2-step morph process which relies on an auxiliary body and 2D coordinate filtering technique has been identified as most reliable technique of choice for most curved geometries. The morph technique developed has been successfully applied to a wide range of curved structures which include solid PCBs as well.

1. Introduction

Flexible printed circuits, also known as flex circuits in their purest form include a vast array of metallic layers or traces (conductors - typically made of copper), bonded to a dielectric layer (usually polyimide). Recently, they have seen an increased usage in a wide variety of electronics products (smart-watches, laptops, etc.) and their exponential growth can be attributed to the following unique characteristics:

- **Space Savings**: Flexible printed circuit boards (FPCBs) are thin and lightweight. They require only about 10% of the space and weight of an ordinary circuit board assembly, offering great installation and packaging freedom.

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• **Durability and Costs:** FPCBs require fewer interconnects, which lead to lesser number of contact crimps, connectors and solder joints thereby making them more reliable in regular use. They are also typically cheaper to manufacture compared to printed circuit boards.

• **Compatibility:** FPCBs are compatible with virtually any type of connector or component and work well with options such as ZIP connectors. They also perform very well in extreme temperatures and offer superior resistance to radiation and chemicals.

If fact, one market research group ([Grand View Research, Inc.](https://www.grandviewresearch.com)) estimates that the Flexible PCB Market Size will be $26.8 Billion by 2025 [1]. Hence, in order to achieve optimum design and performance, numerical modeling and analysis of FPCBs becomes essential.

However, numerical analysis of PCBs is challenging ([2], [3]) as it is required to model a large number of geometric features (traces, vias) to accurately predict the structural behavior, this approach of physically modelling all geometric features is known as Trace Modelling [4]. Flex PCBs add to this complexity due to their various forming requirements i.e., bent and twisted installation shapes. In order to reduce the complexity involved in analyzing PCB’s a new modeling approach also known as Trace Mapping was introduced by Refai-Ahmed et al [5], where the effective material properties for the structural finite element is calculated based on the metal and di-electric distribution. It has been established by Refai-Ahmed [5] and a few others [6] that the trace mapping approach is as effective as trace modelling for a wide range of cases when performing thermo-mechanical analysis.

Irrespective of the trace modelling or trace mapping approach used for the analysis, the challenge of forming a flat flex cable into its installed state still remains. Numerical modeling of such structures requires a full non-linear analysis to deform them into the installed shape. However, this approach could result in hours of simulation time (even on High-Performance Clusters). While a full non-linear analysis cannot be completely avoided as long as the initial pre-stresses in the PCB is critical, in many cases, the flex/curved PCB’s remains in a deformed state for a long duration (smart-watches, fitness tracers etc.) and in such scenarios, the effects of initial pre-stress can be assumed to be minimal.

In this context, there is a need for a clear and simple methodology to adapt the FEA mesh onto the curved shape while preserving the trace mapping and trace modeling feature typically used while working with Electronic-CAD files. In this study, the potential of advanced mesh morphing based on Radial Basis Functions [7] has been explored. ANSYS Mechanical [8] has been used to generate trace maps on the uninstalled PCBs and the mesh morphing has been carried out using the RBF Morph ACT extension [9].

The paper is arranged as follows: an overview about the growing need of curved/flexible PCB and the challenges posed by numerical modelling is provided in section 1; the proposed mesh morphing approach based on RBF is presented and described in section 2 and then demonstrated in section 3, two specific industrial cases are then detailed in section 4 where the results are discussed; conclusions about what was achieved and goals of the next steps of the ongoing research are given in section 5.

### 2. RBF mesh morphing

#### 2.1. RBF background

Radial Basis Functions (RBFs) are a mathematical tool introduced in the early 60s and mainly used to interpolate multidimensional scattered data ([10]). RBFs can interpolate a scalar field in a generic point of the definition space, also called target point, knowing field values at discrete points. These points are called source points.

Given that data to be interpolated is in the form of scattered scalar values at source points $x_{k_i}$ in the space $\mathbb{R}^n$, the interpolating function can be written as in (1).

$$s(x) = \sum_{i=1}^{N} \gamma_i \varphi (\|x - x_{k_i}\|) + h(x)$$

The points $x$ at which the function is to be evaluated are the target points. $\varphi$ is the radial function, which is a scalar function of the Euclidean distance between each source point and the target point considered;
mainly used radial functions are shown in table 1, considering \( r = (\|x - x_i\|) \), \( \gamma_i \) are the weights of the radial basis which are to be evaluated solving a linear system of equations, whose order is equal to the number of source points introduced. The polynomial part \( h(x) \) is added to guarantee the existence and the uniqueness of the solution: in mesh morphing applications, a linear polynomial can be used:

\[
h(x) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z
\]

in which \( \beta_n \) coefficients are to be evaluated together with \( \gamma_i \) weights in the solving RBF system that can be assembled introducing orthogonality and uniqueness conditions (see for reference \[11\]). Once solved, the RBF system is used to interpolate each imposed displacement component as an independent scalar field:

### Table 1. Most common radial functions.

| RBF type              | Equation                                      |
|-----------------------|-----------------------------------------------|
| Spline type (Rn)      | \( r^n \), \( n \) odd                       |
| Thin plate spline     | \( r^n \log(r) \), \( n \) even              |
| Multiquadric (MQ)     | \( \sqrt{1 + r^2} \)                          |
| Inverse multiquadric (IMQ) | \( \frac{1}{\sqrt{1+r^2}} \)            |
| Inverse quadric (IQ)  | \( \frac{1}{1+r^2} \)                        |
| Gaussian (GS)         | \( e^{-r^2} \)                               |

\[
s_x(x) = \sum_{i=0}^{N} \gamma_i^x \varphi(\|x - x_i\|) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z
\]

\[
s_y(x) = \sum_{i=0}^{N} \gamma_i^y \varphi(\|x - x_i\|) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z
\]

\[
s_z(x) = \sum_{i=0}^{N} \gamma_i^z \varphi(\|x - x_i\|) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z
\]

In mesh morphing, source points are the mesh nodes on which the displacement is imposed, whilst the target points are the whole set of nodes that have to be morphed in order to obtain the new numerical model configuration.

2.2. CAD2CAD approach

RBF mesh morphing is an effective approach suitable for a variety of actions: local reshaping according to fields available on surfaces, global resize according to simple actions (translations, rotations, scaling, offset) prescribed on surfaces or curves. In this paper we use the term CAD2CAD to define a morphing action defined to warp a mesh connected to and underlying geometrical model onto a new shape defined as a variation of the geometrical model itself. We assume that the variation preserves the topology of the brep (i.e. same number and connectivity of points, curves and surfaces). An example of such approach is provided in the paper \[12\] and an in depth explanation is given in \[13\]. The CAD2CAD functionality adopted in this study is implemented in two sequential steps. In the first step the new positions of RBF sources lying on curves are computed walking on the nodes of the mesh and retrieving the parametric coordinate along the curve itself. Updated positions of nodes are computed at the same parametric
coordinate along the same curve in its new varied position. An RBF field is defined from such source points arrangement and then used to update the positions of all the nodes onto the surface; after this RBF action the nodes lying on the curves will have the correct position, the ones in the inner portion of the surface will be on surface for 2D problems (flat surfaces) and very close to the surface itself for complex shaped surfaces; a projection onto the surface allows to complete the update. Once that all the nodes on surfaces are controlled the morphing action is propagated in the inner nodes of the volume mesh.

2.3. 2D control using manufacturing constraint

For situations in which only a single curvature of complex shaped part is needed (that is common to the PCB studied in this paper) the mesh morphing problem can be simplified by studying a 2D case that is representative of a cross section of the geometry. An auxiliary mesh is generated onto the curves and the control is achieved by defining an RBF field that maps such sources from the original onto the updated shape. The field is received then by the full 3D volume mesh by applying an action that is usually adopted to prescribe manufacturing constraints: the coordinate in the transverse direction of each node is replaced with the one of the cross section, the transformation computed and then the original value of such coordinate restored. In this way all the nodes, regardless the transverse position, will receive the same action of the controlled cross section.

3. Workflow for flexible/curved PCB explained using the Galileo board

In this section, different strategies used to morph a PCB have been discussed for the Galileo board [14] (figure 1). It has to be noted that the end deformed shapes (Target Geometries) shown here are hypothetical and are used just for illustrative purposes. The goal is to morph a 11 layer Galileo Board (with 25 vias) to the wavy and wrap structures as shown in figure 2.
Figure 1. Trace mapped Galileo board in an uninstalled state (bottom-layer). Red indicates the greatest fraction of copper.
Figure 2. 11-layered Galileo board and the target shapes

3.1. Strategy 1: 2D control with manufacturing constraint adopted to control 3D shapes

This morph strategy reduces the dimensionality of the problem and works for most bend scenarios as long as the cross-sections of the source (initial flat shape) and target (installed shape) bodies lie in the same plane. In other words, the cross-section of the structures should remain constant as they are translated along the normal direction. This strategy includes a 2-step process:

- The creation of an auxiliary surface/body for the PCBs: The auxiliary body acts as a bounding box and occupies the same physical space as the multi-layered PCB. It mainly helps in reducing the number of edges that can be tailored to match the target body. This helps produce much cleaner morphed shapes as each source edge has its equivalence on the target body.
- Planar Definition: The definition of a co-ordinate system and filtering of nodes on the cross-sectional plane aims to first match the nodes on the selected edges between the source and the target bodies. Since the cross-section of the structure is constant along the normal direction, the remaining nodes follow along.

A quick preview of the morph strategy and results can be seen in figures 3, 4, and 5.
Figure 3. 2-step morph strategy with co-ordinate filtering for the Wavy structure.

Figure 4. 2-step morph strategy with co-ordinate filtering for the Wrap structure.
Figure 5. Solid Trace mapped Galileo board in an installed state. Red indicates the greatest fraction of copper.

3.2. Strategy 2: Full morphing achieved by direct control of 3D shapes

While strategy 1 discussed above works well in most scenarios and is typically recommended, there are other morph strategies that can be employed in situations when dealing with more than one body becomes important (such as rigid-flex PCBs). A full 3D morph strategy discussed in this section can also be employed in cases where the cross-section of the surfaces is not necessarily constant. For the sake of simplicity, a 3D morph strategy has been discussed here for the shell trace mapped Galileo board where the cross section of the source and target bodies remain constant. However, the same logic can be extended to cases where this assumption is not necessarily valid.

In this approach, boundary curves typically forming a closed loop (but not necessary) are matched to perform the first morphing step. The projection onto the target surface subsequently takes place in the second and final morphing step (figure 6). It has to be noted that this strategy doesn’t require the creation of an auxiliary body.
Figure 6. 3D morph strategy for the Wavy and Wrap structures.

Figure 7. Shell Trace mapped Galileo board in an installed state. Red indicates the greatest fraction of copper.
4. Applications

4.1. Flexible PCBs

Flex PCBs are widely used in consumer electronics products such as laptops and are primarily used to carry the signals from the motherboard (in the base) to the display. They are typically installed using hand and are subjected to cyclic loading over their lifetime. Flex PCBs usually experience fatigue damage from the repeated loading and hence there is a strong need to understand and improve their performance numerically.

In this scenario, both solid and shell trace mapped models are mapped to a rather complicated target geometry as shown in figure 8. The 2D morph strategy discussed in Section 3.1 has been used here and the results for both shell and solid trace models have been shown in figure 9. It has to be noted that for the Solid case, an averaging scheme was used for material representation which showcases the capability of the trace mapping technology and explain the differences in colors with the shell results.

Figure 8. Flex PCB and the target geometry.
4.2. Rigid-Flexible PCBs

Rigid-Flex PCBs are hybrid circuitry that integrate elements of both the hardboard and flexible circuits. They are rigid in certain locations and flexible elsewhere. Due to this reason, rigid-flex PCBs can be folded or continuously flexed while maintaining the shape of areas that need extra support. Additionally, the circuits can be multi-layered and are comprised of flexible circuit substrates joined with rigid boards. The flexible layers are buried internally and completely penetrate the rigid sections of the PCB. Once such PCB and its end installed state are shown in figure 10.

Due to the presence of additional rigid bodies a more complicated morph strategy is required and has been implemented in the current application. First, morphing of the rigid part primarily undergoing translation and rotation has been shown in the top part of figure 11 following which the 3D morph strategy discussed in Section 3.2 has been employed for the flex cable as seen in the bottom part of figure 11. The end results of this approach result in the desired installed shape for the shell trace models as seen in figure 12.
5. Conclusions

An advanced mesh morphing workflow based on radial basis function mesh morphing has been proposed for curved/flexible PCB modelling. Two strategies were presented, the first strategy discussed the 2D control with manufacturing constraint adopted to control 3D shapes and the second strategy discussed the full 3D morphing by controlling all the curves (adopted only for shell bodies in the current
study). For all the curved/flexible PCBs investigated in this study, the proposed approaches give good results for the deformed shapes and represent the traces accurately. The promising results observed in this initial study open up to further investigations in this field which include but are not limited to:

- Generic double curvature deformation.
- Simplified computation of strain and stress by differentiating the RBF field [15] [16].
- Use of deformed configurations to guide/restart full FEA structural assessment.

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