Computation of Three-Dimensional Electromagnetic Fields for an Augmented Reality Environment

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Abstract: Augmented reality is predestined for visualization of electromagnetic fields in air or inside transparent matter. Real existing objects are studied and invisible electromagnetic fields are added as virtual objects. Hence, experts as well as students are able to connect electromagnetic fields easily with studied objects. They can concentrate on physical effects instead on reading figures. Here, an easy to use augmented reality environment for three-dimensional electromagnetic fields is presented.

Keywords: augmented reality, electromagnetic fields, visualization

1. Introduction

Modern software tools such as COMSOL Multiphysics solve complex real life problems in three dimensions with high accuracy. However, understanding of results is a very important step in numerical simulations and visualization is an established tool for this purpose.

Electromagnetic fields are vector fields. Hence, a lot of information must be displayed in the case of three-dimensional problems. A lack of classical figures is that they are two-dimensional. Three-dimensional data must be reduced to a plane. Then, only a few details are shown or the resulting figures are confusing. Furthermore, a connection between fields and geometrical configuration is often difficult to identify.

A graphical visualization technique is virtual reality (VR). Computed results along with high-quality computer models of geometry are displayed in a special VR environment [1]. Advantages are very vivid figures in three dimensions and pure virtual objects are studied (**Figure 1**). Hence, VR is suitable for analysis of electromagnetic fields inside matter or during product development phase. A real existing object is not necessary.

Augmented reality (AR) is a combination of real objects and virtual objects [2]. A real existing object is examined. Additional data is added by virtual objects. Here, the real object and the belonging electromagnetic fields are displayed together. The presented approach shows possibilities of AR for visualization of electromagnetic fields both in research and in teaching. Altair HyperMesh [3] has been used for modeling and discretization of complex three-dimensional problems. Numerical results have been computed with COMSOL Multiphysics. The software system COVISE has been applied for the AR environment [4].

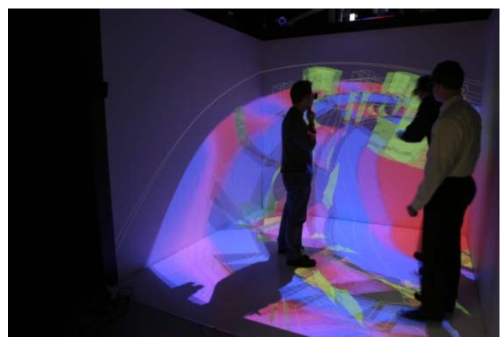

Figure 1. Discussion of computed magnetic fields inside a magnetic gear in a CAVE

2. Augmented Reality Environment

Real and virtual objects are displayed together in an AR environment. Hence, AR is predestined for visualization of electromagnetic fields inside visible domains of the problem such as the air domain.

Preparation of a model for visualization with an AR environment starts at the pre-processing phase. COMSOL Multiphysics is based on the finite element method (FEM) and a discretization of the air domain is necessary. The air domain can be very small in most cases, if boundary conditions are properly chosen (**Figure 2**). However, the air domain is very important in an AR environment. Here, a relatively large air domain is preferred for visualization purposes (**Figure 3**). A problem of a large air domain is that the number of elements grows rapidly in the case of three-dimensional problems along with the size of the linear system of equations. Hence, a powerful meshing tool is recommended. User should have full control about mesh parameters and software must handle a huge number of elements.

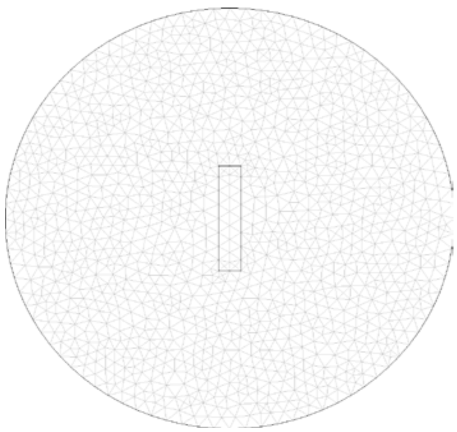

Figure 2. Illustration of a FEM mesh of a magnet

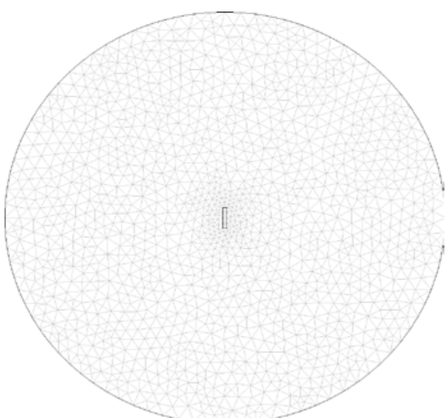

Figure 3. Illustration of a FEM mesh of a magnet for AR post-processing

A FEM model in the context of AR differs often a little bit from the original FEM model. The original FEM model consists of computational domains for each physical domain of the problem. A split of some domains is useful in the context of AR to simplify parameter adjustment for visualization. An experienced user is able to perform the domain split in advance. Nevertheless, necessity of additional domains arises frequently during post-processing phase.

Numerical results are visualized after the solution of the problem. An AR display requires a very powerful post-processing tool. First, fields, which shall be visualized, are computed in given points, e. g. the nodes of the FEM mesh. Then, vector fields are drawn with arrows, field lines or flux tubes, while scalar fields can be mapped to color or displayed as isosurfaces or volume rendering. A geometrical filtering of data is recommended in the case of an arrow plot and fields are plotted in some planes. Otherwise, too much data is displayed and figures are confusing (**Figure 4**). Field lines or flux tubes are very graphically. Here, starting points for lines must be properly chosen to obtain clear figures. Accuracy of field lines depends on accuracy of the solved problem, which is often limited by available amount of memory for three-dimensional problems.

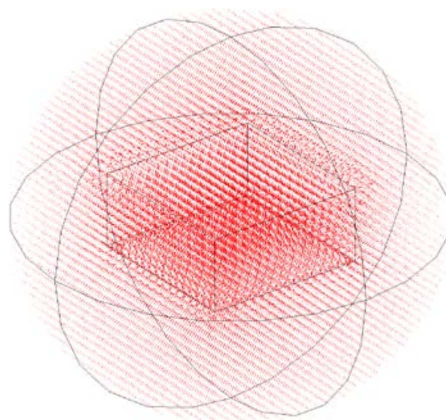

Figure 4. 3D vector plot of the electric field of a plate capacitor

Amount of data, which has to be stored, grows significantly in the case of three-dimensional field problems. Computation of field lines or flux tubes is very time consuming, too. Visualization in an AR environment is accelerated, if field lines and arrows are stored instead of field values in nodes of the mesh.

A geometrical model of the problem is needed for visualization, too. If the problem is visualized in VR, not only geometrical information of this model must be precise, but also color and texture of studied objects (**Figure 5**). Occlusions in AR are calculated based on this geometrical VR model. Hence, a realistic three-dimensional display is obtained.

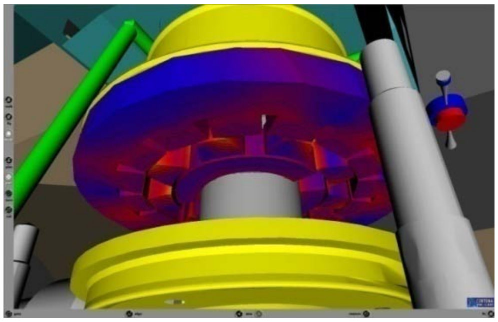

Figure 5. 3D post-processing of magnetic flux density of a magnetic gear in a virtual reality model

Fiducial markers (**Figure 6**) are placed on the real object. These markers are detected in a live video stream using ARToolKit [5]. Camera position is computed from perspective distortion of markers. Field lines and arrows are rendered with the same perspective and added to the video stream. Occlusions are handled by Z-buffer.

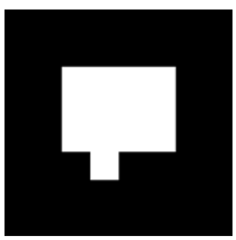

Figure 6. A sample of a fiducial marker

3. Numerical Examples

Three numerical examples are considered. The first example is a permanent magnet. Visualization of the magnet is discussed in detail. The second example is a Helmholtz coil, which is a classical example for static magnetic fields. A horn antenna is examined as third example.

All examples have been modeled with Altair HyperMesh. The model has been discretized with second order tetrahedrons. Computational domains have been defined in Altair HyperMesh as well. NASTRAN file format is available in Altair HyperMesh for data export and can be read in COMSOL Multiphysics without problems.

Problems have been solved on a 64-bit server with two quad-core CPUs. COMSOL Multiphysics with AC/DC module has been used for permanent magnet and Helmholtz coil. Horn antenna has been solved with RF module.

Post-processing is very comfortable in MATLAB. Furthermore, MATLAB can be accessed via Component Object Model (COM). A new plug-in for visualization tool COVISE was implemented, which uses COM. Hence, data is computed and generated on request and only necessary data is stored. This interface is very powerful for future use, too. Data transfer from COVISE to COMSOL Multiphysics is possible.

A laptop computer with a single-core CPU and a midrange graphic card in combination with a USB webcam generates the AR display. A projector enables presentation in a lecture room. Resolution of the camera is 960 × 720 pixels. A frame rate of 15 frames per second suffices for realistic images in real-time.

3.1 Permanent Magnet

The examined permanent magnet is made of AlNiCo3. The geometrical shape of the magnet is a rectangular parallelepiped with dimensions 150 mm × 20 mm × 6.3 mm. The remanent flux density is given with 0.6 T. The surface is colored red and green (**Figure 7**).

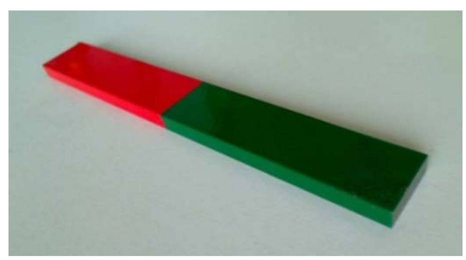

Figure 7. Permanent magnet

Two computational domains are sufficient for a numerical solution of the problem. One domain includes magnetic matter. The second domain is given by surrounding air. Here, the magnet is split into three domains. Each half of the magnet is a separate magnetic domain and the interface between them is defined as a small domain, too. These additional domains are used for visualization of magnetic field lines. The exact solution of magnetic field lines results in exactly closed lines. However, closed lines are difficult to compute for a numerical solution due to numerical inaccuracies. If the small interface domain is excluded from post-processing, the magnetic field lines are cut and clear images are obtained. Of course, the influence of these inaccuracies can be reduced to insignificance. Then, the mesh must be very fine and the computational costs are extremely large for this 3D problem. Since magnetic field lines outside the magnet are visualized with AR, the air domain must be large. Here, the air domain is modeled by a sphere with a radius of 1 m. In total, the problem has been meshed with 105832 tetrahedrons (**Figure 8**, **Figure 9**).

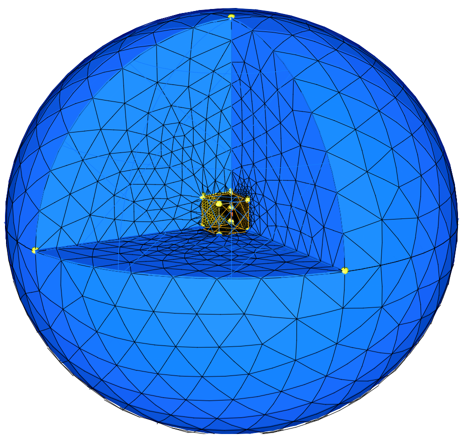

Figure 8. Finite element mesh of the magnet

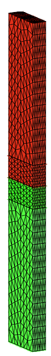

Figure 9. Detail of **Figure 8**

Possible physical values for visualization in a VR environment are magnetic field strength, magnetic flux density, magnetization, and magnetic energy. These fields can be displayed inside and outside the magnet (**Figure 10**).

A marker with dimensions 50 mm × 50 mm is placed on the real magnet for visualization with AR. The size of the marker is relatively large in comparison to the dimensions of the magnet. However, visualization of the field near the magnet and for large distances to the magnet is reliable and accurate.

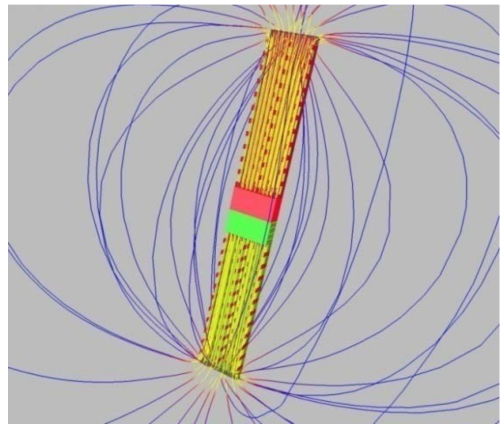

Figure 10. Magnetic flux density and magnetization of a permanent magnet in a VR environment

A virtual object is needed to calculate occlusions. Since the marker is relatively large, the marker must be included to the virtual model, too (**Figure 11**).

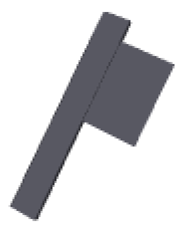

Figure 11. Virtual model of the magnet including the marker

Magnetic field lines and the virtual model are mixed with the live video stream of the camera. Two snapshots are shown in **Figure 12** and in **Figure 13**.

3.2 Helmholtz Coil

The examined Helmholtz coil consists of two coils with a diameter of 38.1 cm. The distance between the coils is 17.9 cm. Each coil has 11 × 14 windings. The electric current is 1 A. The air domain is modeled by a sphere with a diameter of 2 m. An adaptive mesh results in

182592 tetrahedrons. A system of linear equations with 1170004 unknowns is solved with flexible generalized minimum residual method (FGMRES) and a geometric multigrid preconditioner.

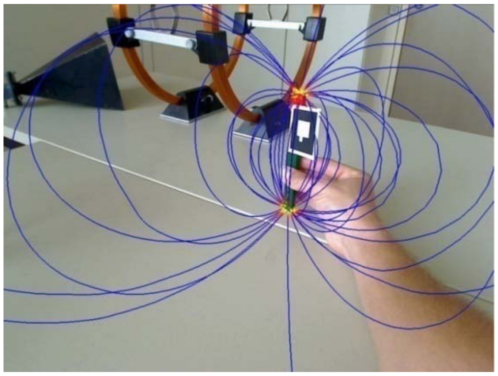

Figure 12. Visualization of magnetic flux density of a permanent magnet in an AR environment

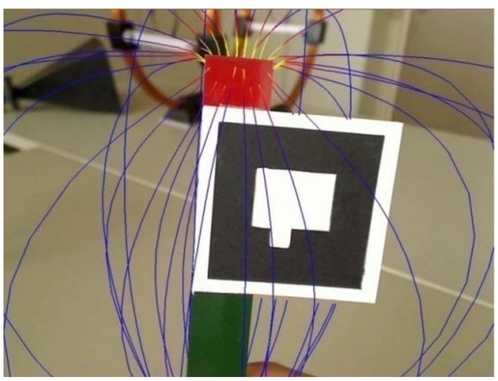

Figure 13. Visualization of magnetic flux density of a permanent magnet in an AR environment

A snapshot of a visualization of the magnetic field strength is shown in **Figure 14**. This example demonstrates that the characteristics of the magnetic field can be very easily connected with the existing object.

3.3 Horn Antenna

A J-band horn antenna is examined as third example. Aperture size of the antenna is 200 mm × 153 mm. The length of the horn is 213 mm.

The antenna has been modeled and discretized for a frequency of 6.2 GHz. An air domain with the shape of half of a sphere and radius 200 mm is in front of the antenna. The air domain is bordered by a perfectly matched layer. In total, a mesh with 241171 tetrahedrons has been generated. This results in a linear system of equations with 1593104 unknowns. It is solved iteratively with GMRES and geometric multigrid preconditioner. The size of the air domain and the size of the elements with respect to the wavelength are strongly limited by available memory of the server (here: 8 GB).

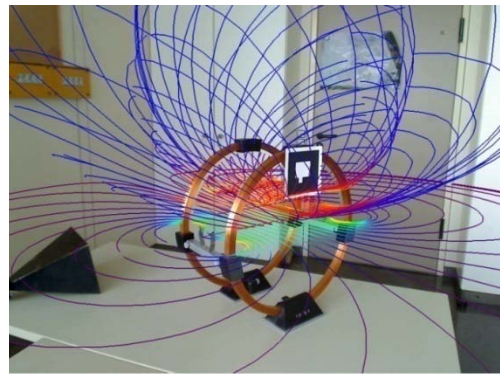

Figure 14. Visualization of magnetic field strength of a Helmholtz coil in an AR environment

A complex linear system of equations is solved for this time harmonic problem. Hence, a visualization of a time-dependent field is possible by evaluation of the solution for several phases, e. g. 33 values.

Visualization of the radiated electromagnetic field is more difficult than visualization of the fields in the previous examples. A calculation of field lines or flux tubes requires a very accurate solution of the problem. Unfortunately, accuracy of the solution is not accurate enough for field lines. Furthermore, plenty of information must be displayed. Fields are time varying and two vector fields, electric and magnetic field, are required. Absolute value of both fields decreases with distance to the antenna. Moreover, fields have harmonic changing amplitude with respect to direction of propagation. Hence, it is difficult to assign a color to the absolute value of field vectors. A scaling of the length of arrows proportional to the absolute value results in large arrows inside the horn and very small values outside the antenna. A better display is achieved by scaling the size of the arrows with a non-linear function. The function

$$f(x) = 1 - e^{-\alpha x} \quad (1)$$

is easy to apply and results in a satisfactory display.

The radiated electromagnetic field of the antenna is displayed in **Figure 15** and **Figure 16**.

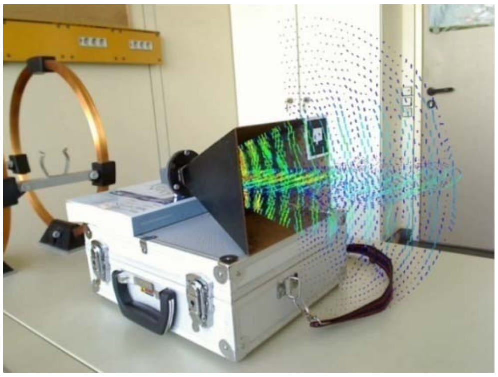

Figure 15. Radiated electromagnetic field of a horn antenna in an AR environment

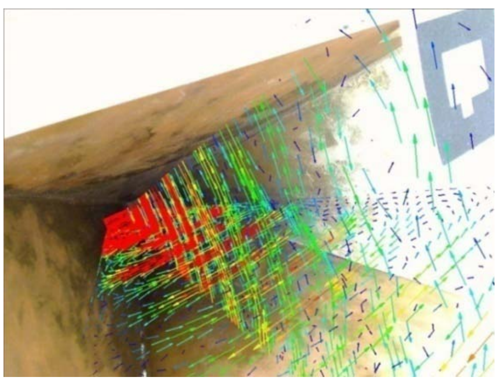

Figure 16. Detail of **Figure 15**

The main direction of power flow can be easily read from displayed electric and magnetic field. Boundary conditions at the conducting walls of the antenna are vivid. Propagation of the wave can be observed in the video stream (unfortunately not in the snapshots in **Figure 15** and**Figure 16**). Change of electric and magnetic field can be studied in a fixed point, too.

4. Conclusion

An augmented reality environment is predestined for visualization of electromagnetic fields in air, which are normally invisible. Since the real object is examined in combination with simulated fields, results are very graphically. Students can concentrate on physical effects and not on reading a plot. Presentation of results in a lecture room is as simple as a laptop computer, a webcam, and a projector.

5. References

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