# An Inverted Process for the Streamlined Design of Electromagnetic Coils

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BACKGROUND: We developed a method to design and construct precision surface current coils at the University of Kentucky based on a novel physical interpretation of the magnetic scalar potential. A coil with a specified magnetic field can be designed by solving Laplace's equation in each region of nonzero field using Neumann boundary conditions specifying the magnetic flux density through the boundary. This will give you a value of the magnetic scalar potential within the domain. If you then place wires carrying current on the boundary along the equipotential contours, you will generate the exact magnetic field specified in the boundary conditions, subject to discretization effects. These slight deviations from the target field can also be accounted for by finding the magnetic scalar potential of the residual field with the field from the windings as a background field. This new potential can be added to the original potential to find corrections to the windings. This process was repeated iteratively until the error from the target field converged. This was used to design high precision electromagnetic coils.
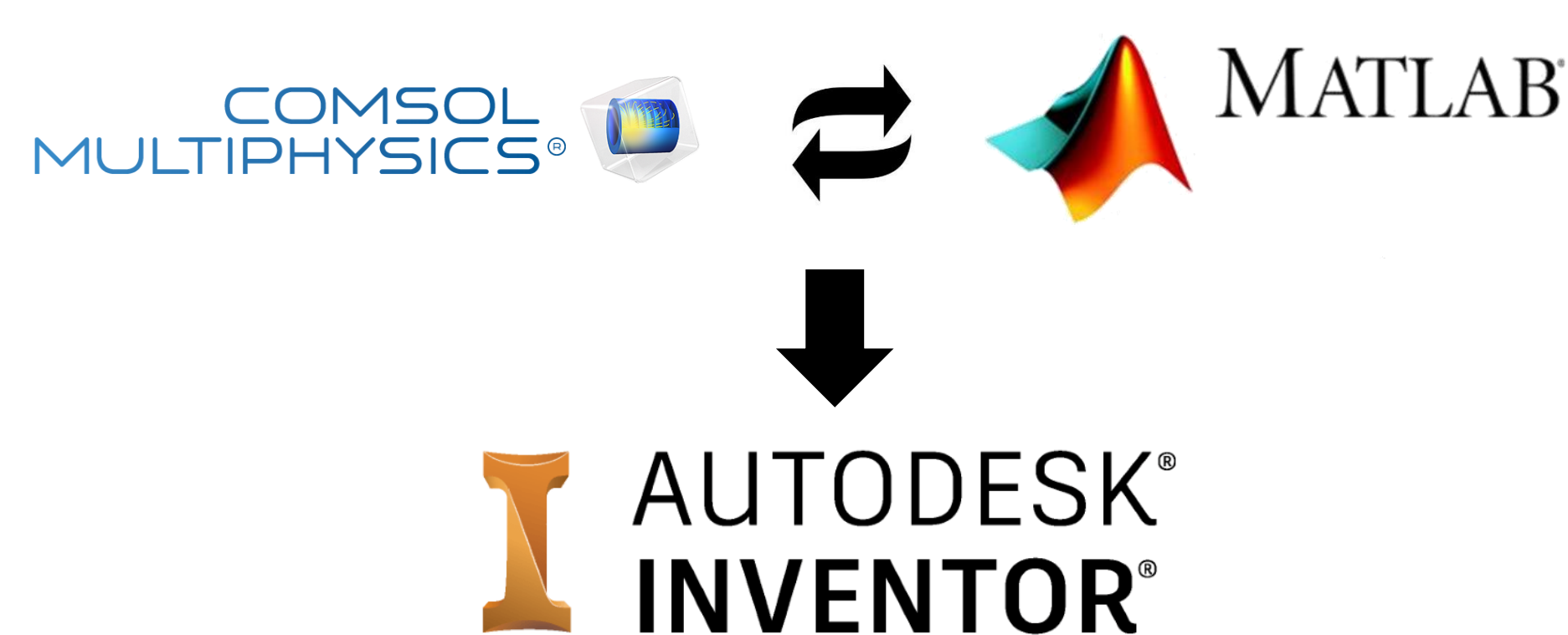
Figure 1. The windings of the coil are found and adjusted iteratively until the ideal windings are found, then these windings are imported into Autodesk Inventor to construct the coil

CREATING THE COMSOL MODEL: The process of solving Laplace's equation for any geometry can be achieved in finite element analysis software COMSOL Multiphysics. The method of finding corrections to the windings is also done in COMSOL Multiphysics using two studies. The first study is used to calculate the field generated by the windings. Initially, with no wires, the field is zero everywhere. Then, the second study has two Magnetic Fields, No Currents physics are created for each domain with nonzero field, they both have the target magnetic flux density as Neumann boundary conditions. The first physics solves for the full field, and the second solves for the residual field with the background field being the field generated by the windings solved for in the first physics. This study finds the magnetic scalar potential for each physics, and the two potentials from each Magnetic Fields, No Currents physics in each domain are added together to find corrections to the windings.

EXTRACTING EQUIPOTENTIAL CONTOURS: The value of the magnetic scalar potential is taken from the plot in COMSOL Multiphysics® along all boundaries of domains with nonzero field. Then, each surface is parametrized to a 2D plane, and the equipotential contours are found along the surface using MATLAB's contour3 function. The direction of the current follows the normal vector cross the gradient vector, so the gradient is measured at each point along the curve, and if the direction of current doesn't match the direction of the points along the curve, the points are flipped to have the correct direction of current. The curves are then transformed back to the original 3D coordinate system.
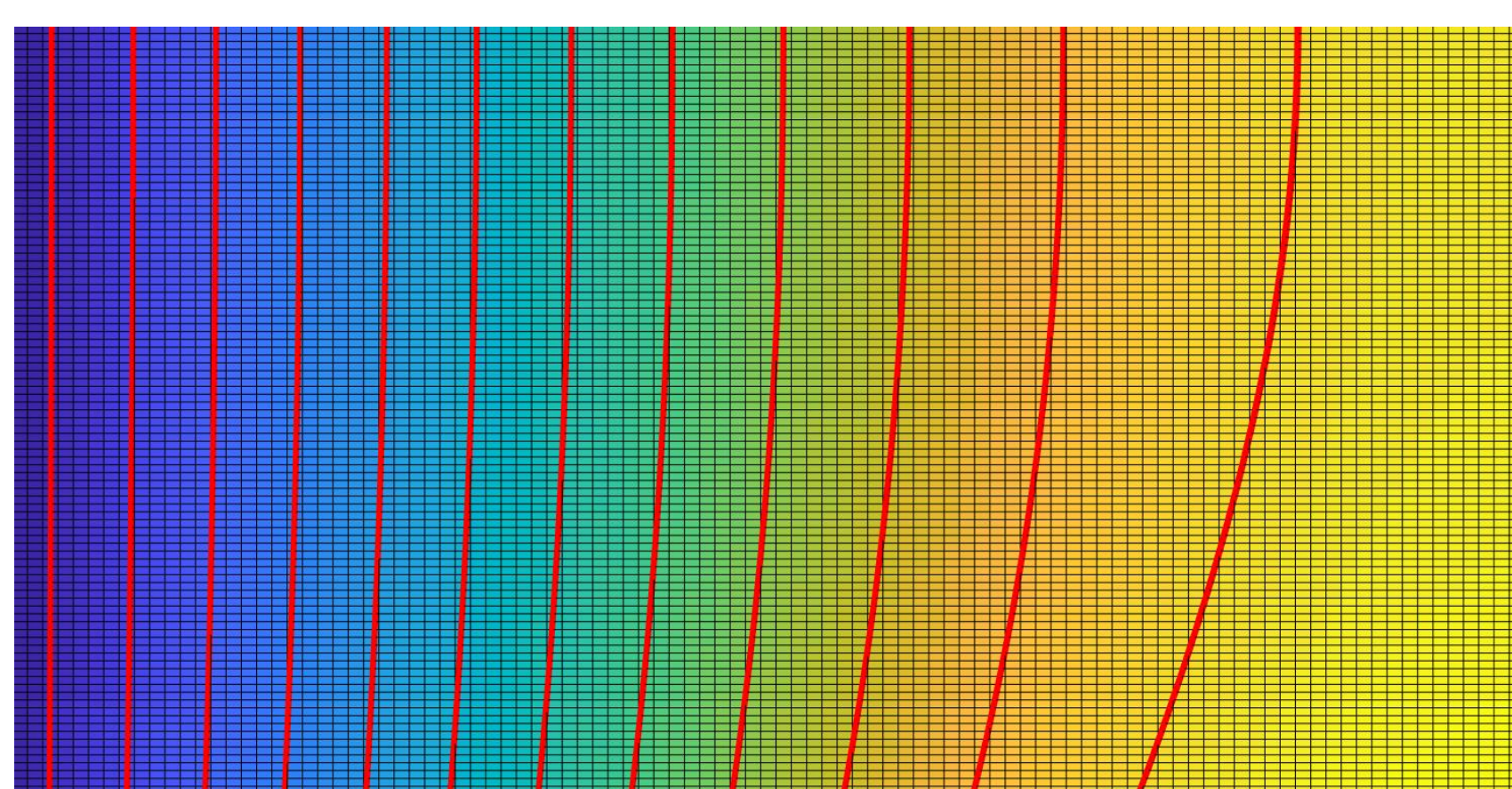

Figure 2. Finding equipotential contours on parametrized surface. This is a parametrization of the outer top surface of the double cosine theta coil with ¼ symmetry

SMOOTHING CURVES: Due to discretization effects, the equipotential curves can have artifacts that cause the curves to become jagged, which if left as-is can cause problems when constructing the coil, long computation times when finding corrections, and even inaccurate results near the windings. Thus, it is necessary to smooth the curves to remove the discretization artifacts. This was done in two ways. The first method is meant to check if each curve is supposed to be a straight line. A linear least-squares regression is fit to each curve, and if the error is within a tolerance value, it is replaced by its two endpoints. This speeds up computations significantly and makes it easier to mesh. The second method to smooth curves, if the curve isn't a straight line, is to fit a smoothing spline to the curve. This is done using MATLAB's csaps function. New points along the curve are then found from the smoothing spline.
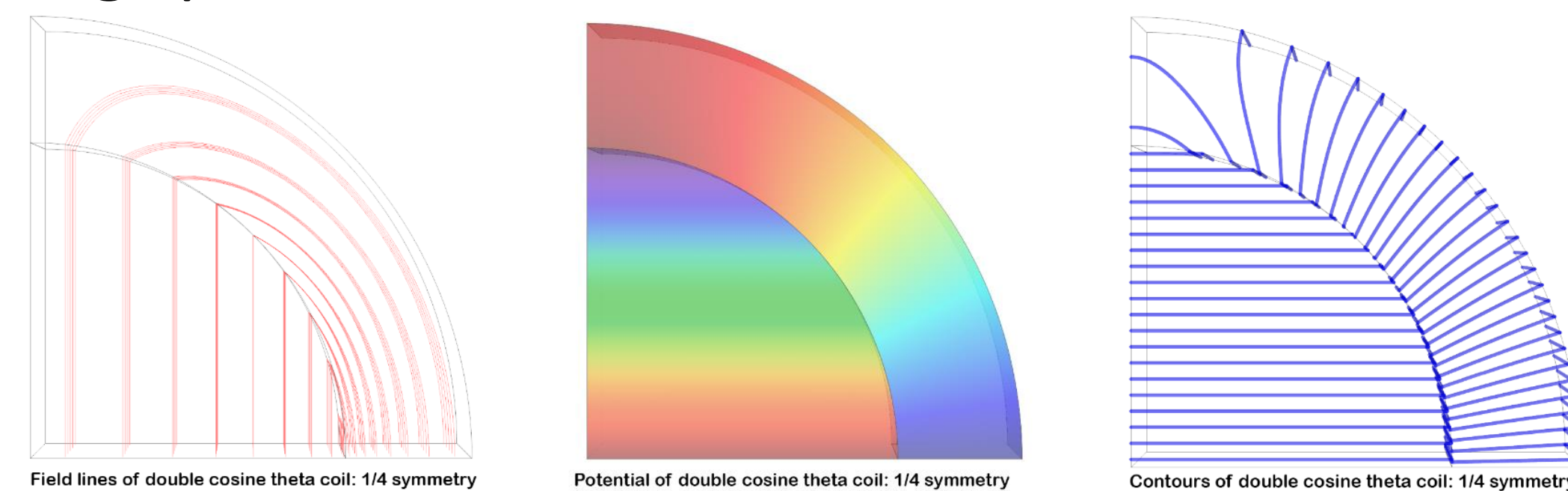
Figure 3. Double Cosine Theta Coil: 1/4 Symmetry

FORMING FULL CURRENT LOOPS: Once the curves have been smoothed to remove the discretization artifacts, the curves must be mirrored, depending on the symmetry of the model, and combined to form closed loops that can carry current. This is achieved by first creating new curves mirrored about each symmetry plane in the model, then the curves are joined. Each curves' endpoints are connected to the nearest endpoint at the same potential level. The direction of current is preserved in this step, so that when imported back into COMSOL, all the wires have the correct direction of current.
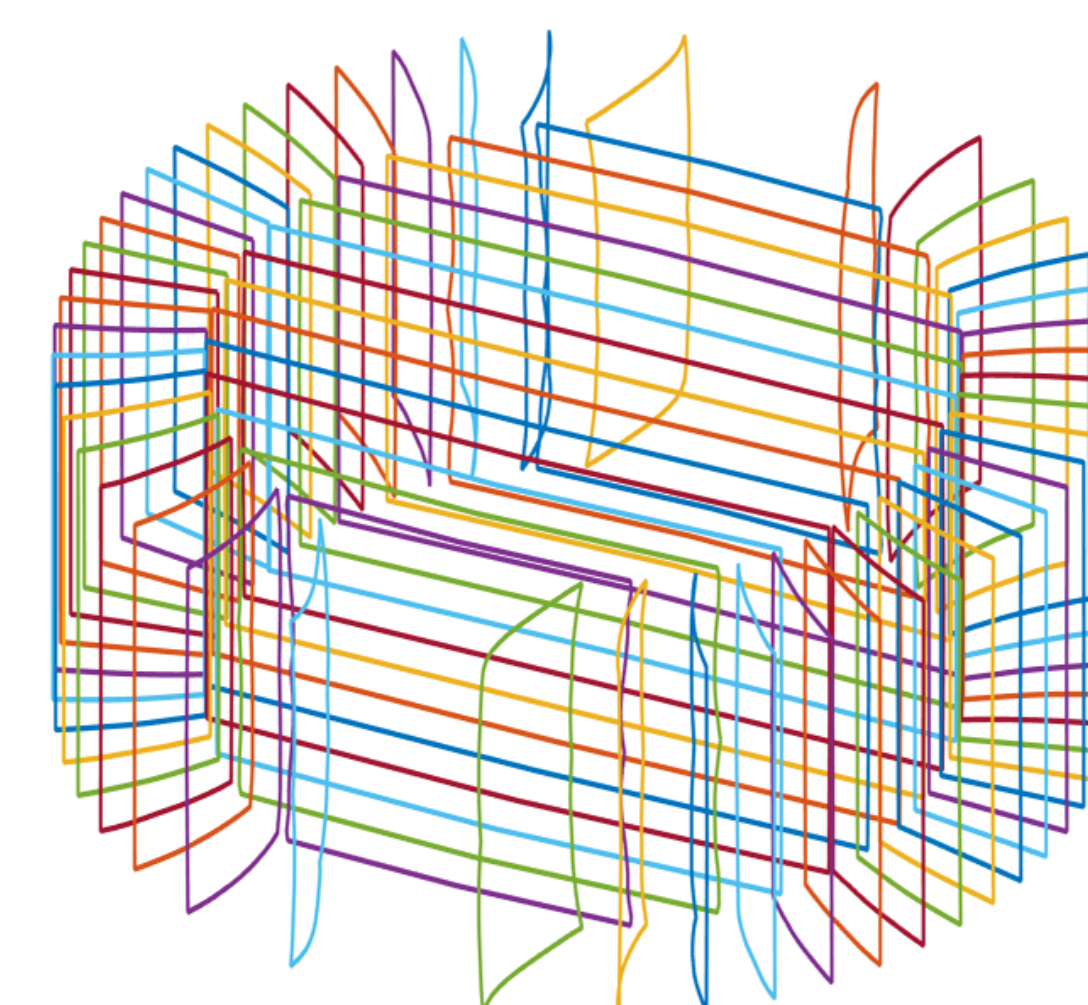
Figure 4. Final windings of coil after iterative corrections

CALCULATING CORRECTIONS TO WINDINGS: The loops are imported into COMSOL and given current. Then, the Magnetic Fields physics is used to find the magnetic field generated from the wires. This is then used as the background field in the Magnetic Fields, No Currents physics to find the difference from the target field. This creates a residual field that is used to find a new magnetic scalar potential in each domain. This new potential for the residual field is added to the original potential to find the corrections to the windings. This process is the same as adding new wires on top of the original wires to generate the residual field and achieve the target field. This new magnetic scalar potential is imported back into MATLAB and the process is iterated until the error between the target field and the actual field converges. The final windings can then be constructed into a coil with the desired magnetic field.

CONSTRUCTING THE COIL: Once the windings of the coil have been found using the process I created, these windings can then be imported into Autodesk Inventor where a 3D model of the coil is constructed. Then, the coil can be printed using a 3D printer.