The Automatic Placement of Cooling Pathways for MRI Gradient Coils Using Path Finding Algorithms

Elliot Smith[1], Fabio Freschi[1,2], Maurizio Repetto[2], and Stuart Crozier[1]

[1]School of ITEE, University of Queensland, Brisbane, Queensland, Australia, [2]Department of Energy, Politecnico di Torino, Torino, Italy

Purpose Magnetic Resonance Imaging (MRI) systems, especially those utilizing superconducting magnets are highly sensitive to heating. A rise in temperature can cause the magnet to increase boil off or even quench. Gradient coils generate a large amount of heat due to the high current used to generate the magnetic gradients[1]. Typically gradient systems are cooled using multiple, water carrying pipes which transport heat away from the system. The placement of these pipes is essential to the effective removal of as much heat as possible. The placement of these pipes may also be constrained by geometric constraints such as access points and mounting points. This research aims to automate this process of pipe layout through common path finding algorithms combined with thermal simulation. Path finding is, in its essence, the traversal of a graph along a path that minimizes a cost function. The field of path finding algorithms is well established and used in many fields. Many simulations represent coils and other volumes as interconnected nodes. This representation forms a graph of nodes on the surface which can be traversed using these algorithms.

Methods In this research the problem has been constrained to a single surface on which the heat to be dissipated is calculated externally using thermal simulation or estimation and passed as a parameter to the routine. The energy is defined at each node on the surface in a common unit. The algorithm is not dependant on any given representation of the heat and changes in these units can be accounted for in later stages through the adjustment of weighting factors. The algorithm allows nodes to be labelled as one of three types. Frontier nodes are the nodes on which a cooling pipe can begin its path. Goal nodes are nodes on which a cooling pipe must end its path. All other nodes are labelled as internal nodes. In many cases one edge of the cylinder will be marked as a frontier, the other a goal and all other nodes marked as internal. The cost function is then defined as a weighted combination between the geometric length of an edge and the heat at the end of the node. The heat and the edge length are combined as seen in Equation 1. **A** and **B** are weighting functions which affect the path shape. Typically as A increases the path becomes straighter and as B increases the path tends to gather more heat through more complex pathways. In this scenario heat is an estimated parameter indicating the relative thermal energy within an area. As the goal is heat transfer through pipe placement this thermal energy is a more suitable measure than temperature.

$$Cost_i = A * length_i - B * heat_i \quad (1)$$

As most scenarios will require multiple pipes the graph is then fully traversed using Dijkstra's algorithm[2]. The node in the goal list with the lowest cost is then used to seed a backtracking step to reveal the path from a node in the frontier set to one in the goal set with the lowest cost function. A pipe is then placed along this path. The newly added pipe removes heat from the system based on either estimation or a repeated thermal analysis of the new system. The process is then repeated with the new heat profile until enough heat has been removed or a set number of pipes have been placed.

To test this method a set of three gradient coils were designed and their heat generation estimated using the resulting current density. The thermal profile was sampled onto a cylinder summing the heat of all coils.

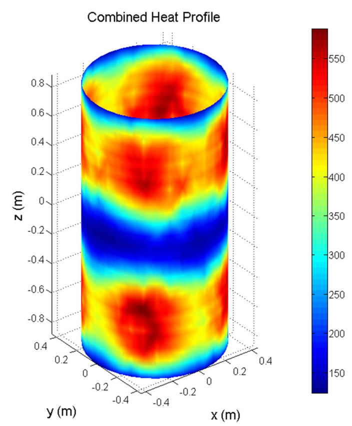

Figure 1 Heat Profile

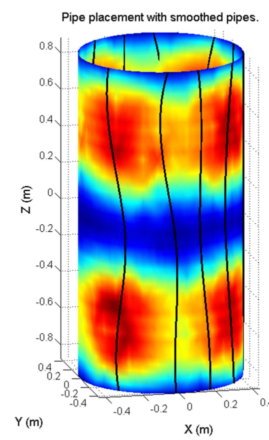

Figure 2 Pipe Placement

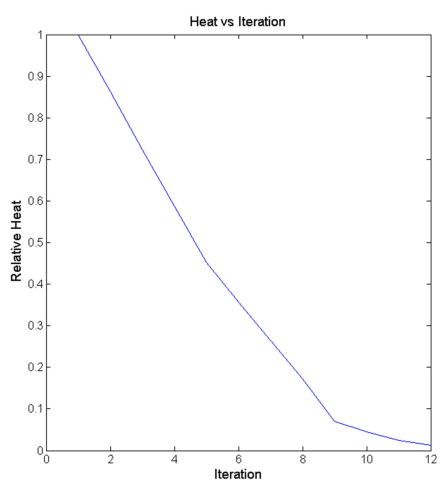

Figure 3 Heat vs Iteration

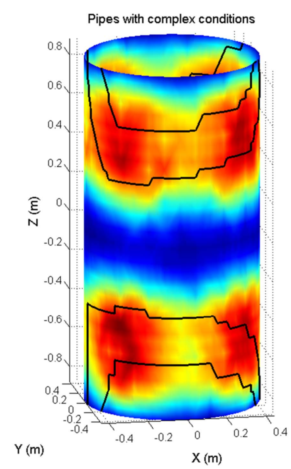

Figure 4 Pipes with complex conditions

Results Figure 1 shows the combined heat profile on the surface in arbitrary units. The algorithm was limited to a maximum of 20 pipes and the removal of 99% of heat using the estimated heat removal. This estimation used a Gaussian drop off around the pipe's centreline with the height and drop off passed as parameters. The top edge of the coil was marked as the frontier and the bottom edge marked as the goal. Figure 2 shows the final placement of the cooling pipes using an equal weighting between the path length and the collected heat. Here the pipes can be seen to be evenly spread around the cylinder, passing through the hottest sections of the surface. Figure 3 shows the relative heat after each iteration.

Discussion The proposed algorithm shows the use of path finding and graph traversal in the determination of ideal cooling pipe placement. As this method places pathways strictly along the surface of the test surface, pipes are able to be placed even on complex geometries such as those seen in split systems. This method could be extended to use a full thermal simulation rather than an estimation which would improve the method. The inclusion of further geometric constraints is achieved by modifying the connections and weights between different nodes in the graph and provides a significant amount of flexibility in the parameters used. Figure 4 shows the same coil with a different set of goal and frontier points. In this scenario the pipes continue to capture the heat while conforming to the constraints. As the pipes are currently constrained to follow the triangulation of the mesh the centrelines appear to change quite sharply, smoothing these lines, as is seen in Figure 1, provides a more viable pathway as rapid changes in the pipes increases the manufacturing complexity significantly.

References

[1] Chu, Kenneth C., and Brian K. Rutt. "MR gradient coil heat dissipation." Magnetic resonance in medicine 34.1 (1995): 125-132. [2] Skiena, S. "Dijkstra's Algorithm." Implementing Discrete Mathematics: Combinatorics and Graph Theory with Mathematica, Reading, MA: Addison-Wesley (1990): 225-227.