Session: MR Systems Engineering

Systems Engineering of the MR Front End

Michael A. Morich, Ph.D. michael.morich@philips.com
Philips Healthcare, Highland Heights, Ohio, United States of America

Highlights

This contribution will cover some of the technical and process aspects of Systems Engineering of the MR Front End. The talk focuses on circular cylindrical geometry MR systems. A particular aim is to relate the science and engineering of MR bore space utilization to end-user relevant MR system characteristics and features. We will also touch on systems engineering of other key MR front end components that are relevant to the end-user. Topics that will be covered include:

- The role of systems engineering in fundamentals of decision making and optimization in MR front end design.
- Review some of the key developments that have occurred under the MR system covers in magnet, gradient, RF transmit, RF screen, shimming and other bore space components technology.
- Explore the tradeoffs encountered in the MR front end to provide insights into technical evolution of the main components that integrate within and near the MR system bore space.
- Review the MR front end's richly complex multidisciplinary interactions that have, at times, yielded to elegant design solutions.
- Relate the technical aspects and limitations of state-of-the-art bore components to certain MR system characteristics that are relevant to the end-user.
- Discuss systems engineering aspects of other key MR front end components: system covers, bore lighting, ventilation, table/couch, RF coils and accessories.
- Discuss the never-ending quest to more efficiently utilize the radial space between magnet clear bore and finished system aperture.

Target Audience

The target audience is both end-users and researchers/developers of MR systems, subsystems, components and related technology. The talk is aimed at basic to intermediate level and early to mid-career level.

Outcome/Objectives

Upon completion, participants should be able to:

- Explain the relevance and role of Systems Engineering in MR front end design
- Describe the unique environment of the MR front end
- Describe the main MR bore space components and their general spatial relationships
- Describe the primary functions and key characteristics of MR front end components
- Describe some of the key challenges and tradeoffs involved in modern MR system front end design

Introduction and Purpose

Systems engineering by definition involves an interdisciplinary approach to definition and realization of a product design. It requires an intense focus on all aspects of the product development lifecycle, from the early phase of defining customer needs and required functionality, to engaging in requirements definition, design, integration and testing. A systems engineering approach also considers the impact of design choices on other (non-engineering) aspects and functions of product realization and support, e.g., schedule, operations, manufacturing, reliability, service and training, etc. The purpose of this talk is to illustrate and emphasize the role of systems engineering in fundamentals of decision making and optimization in MR front end design. In particular, we review the systems design motivation behind some of the many developments that have occurred under the system covers in magnet, gradient, RF transmit, RF screen, shimming and other bore space components technology. We also discuss systems engineering aspects and key needs or characteristics that drive design of other MR front end components including system covers, bore lighting, ventilation, table/couch, RF coils and accessories.

The MR Front End

The MR front end is one area of significant technology development and innovation and is rich with interesting and complex multidisciplinary interactions. Due to the complexity, a systems engineering approach to MR front end design can be very helpful. Different schemes may be used in practice to define or compartmentalize the elements of the front end. For purposes of this talk, we split the MR front end between all components under the main magnet system covers and all other components located within the magnet room. We focus mainly on the MR front end components under the system covers but will also touch on the other key MR front end components.

In combination with the essential back end components required to realize a whole system, the front end drives a number of the MR system characteristics that are relevant to the end-user of the product and also significantly influences other product characteristics. This includes useful imaging volume, certain aspects of image quality, imaging speed/performance and consistency, certain aspects of workflow and ease of use, and the accessible bore space (system clear bore). Thus, in recent generations of MR product development there has been intense focus on yet more efficient and refined utilization of bore space and on a sharpened understanding of end-user needs and requirements. A structured, systems engineering, approach has evolved accordingly. Importantly, continued forward progress requires a close multidisciplinary collaboration, as much of what can or should be realized in the front end requires not only good insight into what is believed feasible but also knowledge of the history and learning from past designs. Foremost, tradeoffs and design choices should be driven by a keen awareness and understanding of end-user needs and requirements as well as good design principles. The extension of the end-user as a member of the multidisciplinary team is highlighted.

On the highest level the basic requirements or purposes of components under the system covers appear at first simple: 1) to establish a high strength, spatially homogeneous and temporally stable polarizing B_o magnetic field, 2) to provide three spatially linear and orthogonal, high fidelity, highly repeatable and stable, pulsed gradient magnetic fields and 3) to provide a relatively uniform RF transmit B_1^+ magnetic field, with high sensitivity and stability and with (non-simultaneous) capability to perform a body scale RF receive coil function.

Again, on the highest level, the basic requirements or purposes of selected other MR front end components appear at first simple: 1) the system covers isolate/protect the end-user and patient from electrically live high power components under the system covers and provide for a unique and appealing product finish or look, 2) bore lighting is intended to eliminate any dark regions in the system's clear bore space that the patient enters, 3) ventilation is to provide for air flow to help maintain patient comfort, 4) the table/couch is to provide for ease of patient setup, patient positioning/movement into the system's clear bore space, and patient physical stability throughout the MR examination process, 5) RF coils are to provide for anatomy or application specific optimized signal reception with preferably easy and quick setup and consistent imaging performance, 6) accessories such as pads, headphones, mirrors, call button and physiological gating accessories, etc. are to provide for comfort, communications, or to support application specific needs for cardiac or respiratory signal gating, etc. We will review how workflow-driven design, focusing on improved reliability, consistency, and ease and speed of patient setup, has influenced the selected implementations of many of these components over recent generations of products.

While high level requirements are an important starting point, to realize subsystem designs further decomposition of requirements is typically needed, if not essential; a systems engineering approach enables this process. For example, in the case of B_o field, what strength?, what homogeneity level over what volume of space and according to what definition of homogeneity and measurement method?, what shimming methods and processes?, how temporally stable and under what conditions?, what spatial fringe field (5 gauss contour) is acceptable?, what technology is feasible to achieve the basic requirements and what are the collateral requirements imposed by that technology (e.g., cryogenic maintenance in the case of superconducting magnet technology, serviceability aspects, safety aspects…)?, and so on. Requirements may not be static and may be refined or added to as design concepts are refined and selected. In each case of decomposition and refinement one attempts to maintain a link to an end-user (or other 'customer') relevant aspect or need.

We will follow this and similar lines of decomposition for each of the major front end components and provide insight into their complex interactions, design tradeoffs, evolution and development.

The MR Bore Space

A schematic/notional representation of the MR bore space for a circular cylindrical geometry MR system is shown in Figure 1. The System Clear Bore Space is the finished aperture or accessible/open bore space. For a human scale imaging system, the physical scale of the human body constrains or places requirements on the System Clear Bore. For cylindrical systems, there was a time when <60 cm aperture was not unacceptable or uncommon, when 60 cm aperture became a norm, and now, of course, we have also realized 70 cm aperture in practice. During the talk we will review some of the important considerations in bore space allocation. We will also review the evolution toward a system type with larger (70 cm) aperture as this was, arguably, driven and sustained primarily by user needs/requirements, not by bore components scientific or engineering preference.

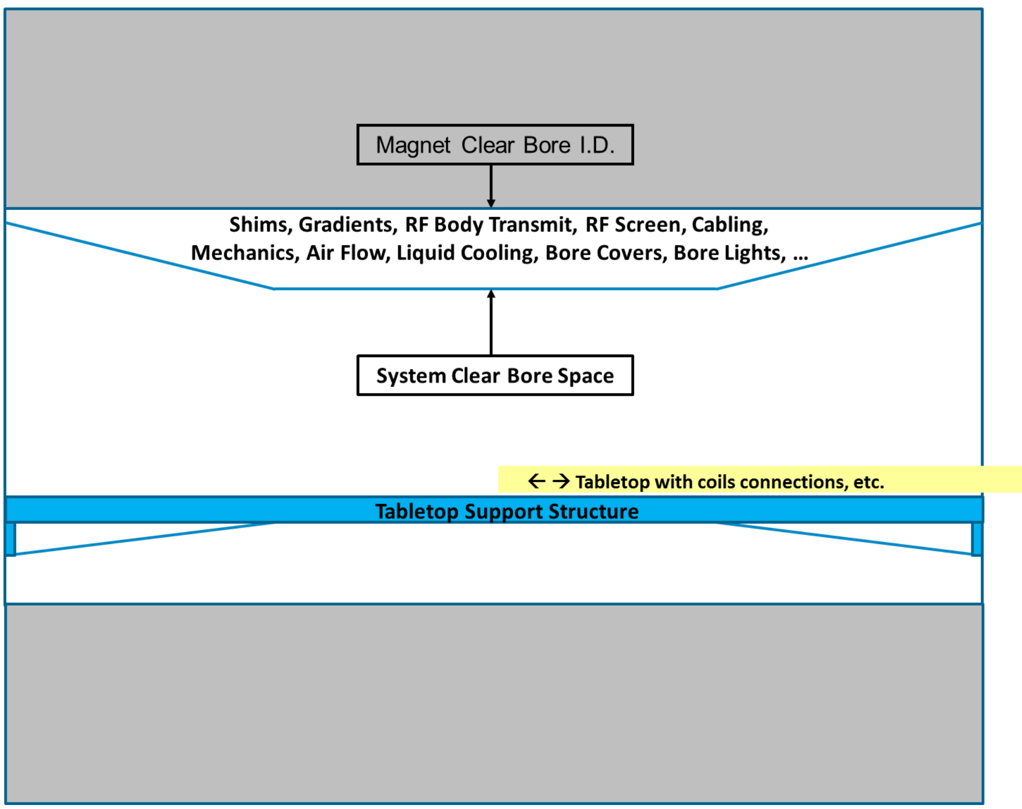

Figure 1: Notional representation of bore space for a cylindrical MR system.

Each of the elements/components under the system covers is important to a well-functioning MR system. The environment they must operate in and partly self-create presents multiple challenges. It is restrictive and in some ways a very harsh environment. We provide a partial summary below and will review and expand on these further during the talk:

- High heat generation from gradients → cooling challenges
- High forces and vibrations → reliability and acoustic noise challenges
- Strong background/static magnetic field → limitations on materials choices
- High transient fields from rapidly switched gradients → interactions with nearby metals
- High Q RF transmit coil → sensitivity to properties of nearby materials
- High RF power transmission and E-fields → RF interactions with nearby components
- Physical space restriction → certain components squeezed in the middle

The net result is that some bore space components are squeezed in the middle and engineers must develop design solutions that meet basic requirements, realize high fidelity, reliability, stability, repeatability and simultaneously solves a highly constrained packing-factor problem.

This is where systems engineering comes into benefit as 1) the magnet designers are highly focused on achieving the B_o field and shimmed homogeneous volume requirements at minimum magnet cost, 2) the gradient coil designers on optimizing for gradient G_x, G_y, G_z performance, the RF transmit body coil designers on B_1^+ transmit performance, 3) the mechanical engineers on mounting, cabling, provisions for air flow and liquid cooling, as well as overall structural integrity of the various components and interfaces, and 4) the industrial designers on achieving a unique and aesthetically pleasing system covers design. One key role of systems engineering is to bring a balance to these otherwise separate design processes, manage the interfaces and certain design choices, and assure the right tradeoffs are made, while keeping in sharp view the overall product design requirements, as driven by end-user needs.

We will review in this talk both past and current technical characteristics of the bore space components and some of the author's experience in how a balanced system design is maintained.

Discussion/Conclusion

Due to the inherent complexity, multitude of technologies, strong interplay, interactions and tradeoffs between bore space components, and for other front end components in modern MR system design, a systems engineering approach is beneficial. There may be multiple ways to achieve a given subset of features and performance levels but not all solutions will necessarily satisfy a complete set of user requirements. An architect and/or systems engineer brings the various and required disciplines together, to decompose and refine requirements, review tradeoffs, analyze and decide upon the implementation choices…while keeping a view on the total set of requirements. This approach will continue to be increasingly important in both the MR front end and overall MR system designs of the future.