PHILIPS

Radiation oncology

Treatment planning

Improving performance with proprietary optimization

Philips Pinnacle Evolution personalized planning

Proprietary optimizer delivers fast, efficient performance

To meet the growing global demand for radiotherapy services and improve the planning process, Philips is investing in new technologies. Philips' latest planning innovation, Pinnacle Evolution, addresses the need to provide therapy plans tailored to the unique clinical/anatomical requirements of each patient – "personalized," high quality IMRT and VMAT plans created consistently and efficiently.

Pinnacle Evolution achieves "Personalized Planning" by combining latest, Philips-proprietary optimization algorithms[1] with unique personalized goals created by Feasibility technology (Sun Nuclear, Melbourne, FL) and next-generation, intelligent, automated planning algorithms (known previously on Pinnacle as "Auto-Planning").

At the heart of Pinnacle Evolution is a proprietary optimization engine – an advanced replacement of the optimizer used in previous Pinnacle versions. This new optimizer is designed to improve the speed the of IMRT or VMAT optimization, delivering the same high quality results Pinnacle users expect, while allowing for more robust and effective automated planning.

This paper provides a high-level summary of the new optimization architecture, the advanced numerical solvers and algorithms employed to simplify and accelerate the calculations, as well as features that improve optimization, deliverability, and performance.

A new optimization architecture

The optimization engine used in IMRT and VMAT inverse planning accomplishes two critical tasks. First, it accounts for user-determined minimum and maximum doses permitted for contoured targets and organs-at-risk (OARs) and second, it creates a "fluence map," which highlights areas of different radiation intensity (i.e., dose) for all gantry angles delivered in a specific time.

Once this fluence map is made, the optimizer then initiates a process to convert it into a sequence of multileaf collimator (MLC) movements for the linear accelerator to deliver. Fluence map optimization and leaf sequencing present exceptionally difficult mathematical problems, requiring a high-level of computation and powerful algorithms to solve.

Previous versions of Pinnacle employed an optimization engine integrated into the planning system. That optimizer was a "black box" system, in which its input, output and transfer characteristics are viewable, yet details of its internal workings and implementation were unknown. Consequently, users had limited means to guide the optimization process.

Comprised of the latest, proprietary modules for fluence map optimization and IMRT and VMAT plan optimization, the Pinnacle optimizer transitions to an architecture in which optimizer function/logic are transparent and can be manipulated throughout optimization.

This allows Philips complete control of the optimizer and its algorithms, providing an opportunity to improve the therapy planning process of its users with development of features that take advantage of innovations in linear accelerator technology as well as tackling workflow challenges, such as personalized planning and automated planning solutions.

In the development of the optimizer, Philips employed a scientific approach focused on an optimal balance of speed and quality. Philips worked with clinical partners to test the performance and stability of the Pinnacle Evolution optimizer across a wide variety of different treatment sites, including prostate, lung and head-and-neck, in addition to many different beam setups. The principle performance criteria were dosimetric quality, total monitor units and computational speed. The culmination of this years-long, comprehensive validation process provides the confidence that for a diverse selection of cases, the optimizer delivers accelerated optimization speed and plan quality.

Advanced algorithms simplify and accelerate the optimization process

The new optimization engine in Pinnacle Evolution features two powerful, robust algorithms: the Limited memory **Broyden–Fletcher–Goldfarb–Shanno** (L-BFGS) for fluence map optimization and **Layered Graph** for aperture size and shape optimization.

Broyden–Fletcher–Goldfarb–Shanno (L-BFGS): Popular for parameter estimation, L-BFGS is an optimization algorithm that limits the amount of computer memory required for computation1. Philips adapted this algorithm for the radiation therapy domain, accounting for the unique constraints of the modality (i.e., no negatives doses, maximum allowable doses).[2] L-BFGS is used to reduce the dose grid matrix – which contains over a million discrete voxels and 100,000 different parameters – to a more workable size. From a matrix that contains ≥ 100 billion entries used to shape the dose distribution, L-BFGS creates considerably smaller matrices that yield roughly equivalent results as the larger matrix. This reduces the time needed for optimization by reducing the memory needs for computation and storage of entries.

Layered Graph: The Layered Graph algorithm creates a finite number of MLC shapes from the fluence map that will adhere to machine constraints and deliverability by the linac. The new mathematical strategy employed by Layered Graph and the previous optimizer's algorithm to create MLC apertures differs substantially. The previous algorithm used a "local approach," in which it makes an initial educated guess and then proceeds to methodically, iteratively modify parameters for each MLC leaf via a customized gradient formulation to determine an updated configuration, which represents an improvement of the optimization goal.

However, with the Layered Graph algorithm used in Pinnacle Evolution, a "global optimal strategy," concept is leveraged that proposes all possible configurations from a massive graph – with "costs" attached to each aperture possibility – to select the option with the "least cost" (i.e., best fit to the fluence map, while not violating machine constraints). Because of the enormous number of aperture possibilities (i.e., > 1035 different combinations), this brute force method of aperture selection is far too complex to accomplish. To reduce the scope of the problem to a more tractable level, Philips implemented a unique modification to the algorithm that solves the algorithm in only 60 steps with only eight million combinations.[3] The result is, instead of making small iterative steps to arrive at a solution, the algorithm can leap from one aperture to the next, and improve the time it takes the algorithm to converge on an answer.

Radiotherapy treatment plans consist of MLC apertures, where each receives an individual weight (e.g. amount of beam monitor units). The process of simultaneously fitting MLC apertures and weights to a fluence map is among the most difficult of optimization problems called: "non-convex, discrete, non-linear optimization". Philips designed a unique method, deeply embedded in the optimizer, allowing the L-BFGS and Layered Graph algorithms to be "toggled" autonomously during the optimization process after the initial fluence optimization.[4] Starting from a sophisticated initial approximation,[5] the optimization process does that as it alternates between seeking to improve the MLC apertures for the current set of beam monitor units, or vice-versa by optimizing the distribution of beam monitor units for the current state of MLC apertures.[6]

Improving the process – before and during optimization

By designing its own proprietary optimization engine for Pinnacle Evolution, Philips has created features that allow the user to influence the planning process before and during optimization.

Leaf sequencing: The Pinnacle optimizer provides enhanced control of input parameters for leaf sequencing. While this capability was possible for IMRT plans, Pinnacle Evolution extends it for VMAT plans as well.

Temporal smoothing: Previous Pinnacle versions have also given users the ability, during optimization set up, to define certain parameters for IMRT plans, such as minimum leaf separation, minimum segment area and minimum number of leaf pairs. Now, for VMAT plans, Pinnacle Evolution introduces the concept of temporal smoothing (i.e., Temporal Shape Regularization), which enables users to control shape, changes, and modulation, as well as balance between plan quality and stable delivery. To achieve smooth transitions between consecutive MLC apertures, Pinnacle Evolution users can steer this algorithm parameter by adjusting the temporal smoothing setting.

Minimum equivalent square: Another new optimization feature in Pinnacle Evolution provides users with greater control of the size of MLC apertures created by the optimizer. It is well known that dose accuracy suffers as fields become smaller than those measured during commissioning, and that small field sizes are difficult to calculate with precision. The Minimum Equivalent Square parameter prevents the optimizer from creating apertures smaller than commissioning measurements, increasing confidence in dose calculation.

Enhanced segment shape: Similarly, enhanced control of segment shape also helps the optimizer only create apertures of specified monitor units. With the Pinnacle Evolution optimizer, users specify the segment shape requirements in the pre-optimization phase and the optimizer is designed to satisfy these requirements.

Optimization control: The conventional planning process in radiotherapy (as opposed to Pinnacle's Personalized Planning) is repetitive and iterative, and the user encounters challenges for a specific patient during the first steps of the process. Pinnacle Evolution users will have the ability to steer the optimizer from undesired paths by modifying certain parameters, such as dosimetric target levels, their relative importance, or the above described Leaf Sequencing parameters between the steps of the planning process, or even while the optimization is ongoing.

Improving optimization speed performance

The latest Pinnacle optimizer takes advantage of the benefits of a large, multi-core, multithreaded server capability. In general, improving speed in optimization algorithms essentially involves efficient multithreading of matrix operations, such as the evaluation of objectives and dose scaling/summing. Further, the optimizer takes advantage of vectorization to make efficient use of CPU cache with less memory transfer and more SIMD (single instruction multiple data) calculations. Many other operations within Pinnacle were enhanced as well, such as GUI performance, target mask projection and dose calculation.

The original dose engine in Pinnacle was developed to save memory and sequentially compute, i.e. single threaded operation. Since then, newer computer platforms can compute many threads simultaneously with increasingly large memory footprints. In Pinnacle, the dose engine was multithreaded at the pencil beam level with each available thread assigned to each pencil beam. Further, with the increase in available memory, the pencil beams could be computed with greater detail and accuracy more finely and accurately than before.

The capability to multi-thread the convolution stage of the dose computation for each control point had been improved in previous versions of Pinnacle. In each of these versions, the multithreading processors were tasked with specific sub-problems of the dose calculation per control point. Now, the demands for symmetric processing have been moved to a higher level, essentially assigning dose computation at the control point level to each available CPU thread. In this way, performance is increased significantly, because processes that were serial beforehand now become parallel at the control point level. With this approach to multithreading, the CPU is more efficiently used with a higher duty cycle and may further be improved with a number of cores.

What will users notice about the new Pinnacle optimizer?

Although much of what the Pinnacle Evolution solver does occurs "under the hood," at the user/optimizer interface, users will notice a difference in the dose engine, how the optimizer treats iterations and how treatment prescriptions are handled and displayed in the graphical user interface.

Improvements to the Singular Value Decomposition (SVD) dose engine

The SVD Dose Engine found previously in Pinnacle has been replaced with dose modelling and control point weight optimization.

Now, VMAT dose modelling for relaxed ODM (Open Density Matrix) optimization is based on the Delta Pencil Beam technique using Pinnacle's Collapsed Cone (CC) Convolution and Pencil Beam dose engines.

Control point weight optimization uses the high-quality Pinnacle Collapsed Cone (CC) Convolution Dose Engine to ensure accuracy of the correction step throughout the algorithm in VMAT. Parallelization and vectorization methods dramatically decrease computation and optimization times for all VMAT plans. CC, paired with the Successive Dose Update strategy for VMAT, ensures that the most accurate dose information is useable in each optimization step.

Improving plan deliverability with "cyclical" processing

The traditional concept of "iteration" implies a linear process in which the optimizer determines an initial solution, then corrects successively (i.e., iterates) on the error, without regard for plan deliverability until further in the process. This had been reflected in a graph that showed the number of iterations completed and the progression toward a deliverable solution. With Pinnacle Evolution, the process of fluence map optimization and leaf sequencing is a cyclical process, with the optimizer going through more steps, continuously checking plan deliverability. This change in the character of the traditional iteration is displayed as a "Composite Objective Value" that indicates the progress toward the deliverable plan.

Conclusion

For Pinnacle therapy planning to deliver a confident path to treatment, we envision new applications demanding new technologies and new ways of working. A state-of-the-art optimizer is fundamental technology as IMRT and VMAT planning requires faster calculations that do not compromise on plan quality, and fewer iterations to achieve a quality plan, thereby making the overall process more efficient.

Employing a new optimization architecture, advanced numerical solvers and algorithms to simplify and speed up the calculations, as well as other features that improve the optimization, deliverability, and performance, as a leader in therapy planning, Philips is providing a fast, efficient optimizer with greater control for users.

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