Automated Design Tools for Biophotonic Systems

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ABSTRACT

Traditional design methods for flow cytometers and other complex biophotonic systems are increasingly recognized as a major bottleneck in instrumentation development. The many manual steps involved in the analysis and translation of the design, from optical layout to a detailed mechanical model and ultimately to a fully functional instrument, are labor-intensive and prone to wasteful trial-and-error iterations. We have developed two complementary, linked technologies that address this problem: one design tool (LiveIdeas™) provides an intuitive environment for interactive, real-time simulations of system-level performance; the other tool (BeamWise™) automates the generation of mechanical 3D CAD models based on those simulations. The strength of our approach lies in a parametric modeling strategy that breaks boundaries between engineering subsystems (e.g., optics and fluidics) to predict critical behavior of the instrument as a whole. The results: 70 percent reduction in early-stage project effort, significantly enhancing the probability of success by virtue of a more efficient exploration of the design space.

Keywords: system simulation, parametric modeling, optical system design, design automation, biophotonic instrumentation, flow cytometer design, virtual prototyping, 3D CAD modeling

1. INTRODUCTION

The evolution of a technology is typically marked by improvements in its capabilities and by a parallel increase in the sophistication of the tools used to create it. While a back-of-the-envelope estimate is often a sufficient basis for a proof-of-concept experiment, the design and production of complex systems require a solid understanding of the performance of components, the interaction of subsystems, and the behavior of the system as a whole. In the semiconductor industry, for example, this evolution made it possible to go from the demonstration of a single bulk germanium transistor[1] based on fundamental physical principles[2] to the large-scale modeling and simulation of massively parallel integrated circuits containing billions of transistors, modeling tools that are now essential to semiconductor design and manufacturing[3].

In the field of free-space photonic systems, over the last 20 years a number of design tools of increasing sophistication have taken root. Platforms like Zemax, CODE V, TracePro, OSLO, and others have provided the ability to model the behavior of optical radiation to a very fine detail. Capabilities like nonsequential ray tracing, aberration analysis, physical beam optics, stray light analysis, and advanced packages to handle spectral and scattering behavior can deliver, if wielded expertly, highly accurate predictions on the optical performance of complex optical systems.

The ability to simulate the optical behavior of a system, while clearly central to the realization of complex photonic assemblies, is only part of the solution. As but one example, in the rapidly expanding field of biophotonics, light is used to interact with biological material, whether *in vitro* or *in vivo*, and whether for analytical/diagnostic purposes or for therapeutic ones. Prediction and control of this interaction requires an understanding, and ultimately modeling, not only of the optics, but also of the system under study or treatment. In tissue, it is important to represent highly heterogeneous bulk turbid media; when measuring proteins or single cells in suspension, it is often helpful to model at some level the behavior of the fluids the interrogating light passes through on its way to the analyte. Many component-focused tools developed to accurately model beam propagation even in complex, but fundamentally “traditional,” optical systems do not easily lend themselves to this kind of multi-domain simulations. A detailed, bottom-up approach makes for powerful simulation tools, like Comsol’s Multi-Physics, that are essentially agnostic as to what the beams are propagating through, but that are also poorly suited to the kind of parameter optimization needed in design and engineering of commercial products.

In addition, regardless of the application, lenses and mirrors do not “float” in space pegged to an imaginary reference frame, but need various mounts, brackets, supports, posts, post holders, bases and mounting plates in order to be physically implemented in the context of a real system. Tools that focus on modeling optical functions generally treat these optomechanical elements as secondary, if they account for them at all; in reality, the engineering design process often involves a compromise between the desired optical behavior and what optomechanical solutions exist or can be practically created to support it. Lacking the ability to represent the optomechanical aspect of a system can mask the needed trade-offs and result in costly redesign efforts and unnecessary prototyping iterations.

2. CONCEPT

A few new and improved tools have emerged recently that address these unmet needs in the simulation and design of photonic systems. IDEX's Semrock offers a web-based spectral design tool, SearchLight™, that significantly simplifies filter selection and fluorescence system design[4]. SearchLight also dovetails with Semrock's MyLight, a filter modeling tool that incorporates a database of spectral models and product specifications[5]. In the area of sources and optical fibers for telecommunications, Synopsys's RSoft packages LaserMOD and OptSim provide a dual-level modeling framework to represent the detailed device-level performance and the higher system-level behavior[6]. And Radiant Zemax's optical propagation modeling package now offers PartLink™, a more streamlined integration with computer-aided design (CAD) software platforms like SolidWorks[7].

2.1 LiveIdeas: parametric system design

We have developed two software frameworks to make the design and development process of complex photonic systems simpler, faster, more intuitive, and less prone to errors. The first one, LiveIdeas™, is a high-level interactive system simulation tool designed by Kinetic River Corp. to account for the disparate domains commonly found in biophotonic systems. Built upon National Instruments' LabVIEW platform, LiveIdeas is a standalone tool that provides the ability to model a complex photonic system, inspect the predicted behavior, and explore in real time the effects of design choices on system outputs. By focusing on a high-level description of the system, it refreshes instantly, avoiding the lengthy delays typical of detailed-level numerical simulations and allowing an intuitive exploration of system response. Being built at a high level, LiveIdeas can easily accommodate domain boundaries like those encountered in optofluidics and biophotonics. Beyond system exploration, it can be used as a platform for automated tolerance analysis and global parameter optimization. LiveIdeas is not meant to replace detailed-level optical modeling tools; rather, it complements them, providing additional insights and capabilities.

2.2 BeamWise: automated 3D CAD modeling

The second framework, BeamWise™, is used to automate the generation of CAD models and drawings of complex photonic systems. Built on top of Design Parametrics' Design++ knowledge-based engineering platform, BeamWise takes as input an intuitive node-and-vector-based description of an optical assembly and creates a system model; from this model, it automatically generates 3D CAD renderings, 2D CAD drawings, and parts lists. 3D CAD models can be exported for use by third-party CAD software like SolidWorks and AutoCAD. BeamWise is *beam-anchored*: the model it creates is referenced to the main optical beam that propagates through the system, and any changes to the beam description cause automatic updates to the model and the drawings. By incorporating not only a way to represent optical components, but also the optomechanical components used to mount and support them, BeamWise gives designers the ability to envision a photonic system in its physical entirety before any metal is ever cut, and it does so automatically, making it possible to quickly, and virtually, explore what-if scenarios. For instance, it can be used to evaluate and resolve spatial conflicts in component mounting, to identify manufacturability and serviceability access issues, and to minimize physical footprint and component cost for commercial deployment.

3. RESULTS AND DISCUSSION

We used LiveIdeas and BeamWise to design the optofluidic bench of a flow cytometer, a laboratory biophotonic instrument used in cell biology research and in clinical diagnostics. A flow cytometer optofluidic bench consists of one or more light sources, a sample interrogation flowcell, and several detectors of scattered light and fluorescent emission from cells in the sample stream. Flow cytometer design has traditionally relied on piecemeal modeling of subsystems and on trial-and-error prototyping, resulting in lengthy and expensive design and development cycles lasting months if not years. Our goal for this demonstration project was to show that such process can be jumpstarted and significantly shortened.

3.1 System layout sketch

We start by sketching out the desired optical layout on paper or a whiteboard (Figure 1). Here only the essential functional elements of the design are called out: a laser light source, turning mirrors, beam shaping optics, the flowcell, three detectors, and filters for spectral selection.

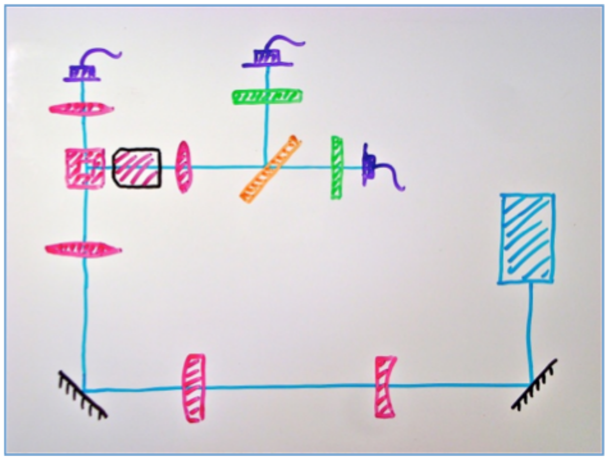


Figure 1. Whiteboard sketch of the optical layout of a flow cytometer. Laser light source in light blue, mirrors in black, lenses and flowcell in pink, beamsplitter in orange, filters in green, detectors in purple.

3.2 LiveIdeas system simulation

Next, a LiveIdeas model is built, reflecting this basic layout. The model (Figure 2) incorporates optical design parameters such as lens powers and component distances, but it also captures fluidic subsystem parameters, such as the size of the sample core stream within the flowcell; and it provides important system-level metrics, such as the Coefficient of Variation (CV, a measure of the intrinsic system response function). By running the model and exploring the design space, we choose design parameters that predict an in-spec system performance with component values chosen for manufacturability.

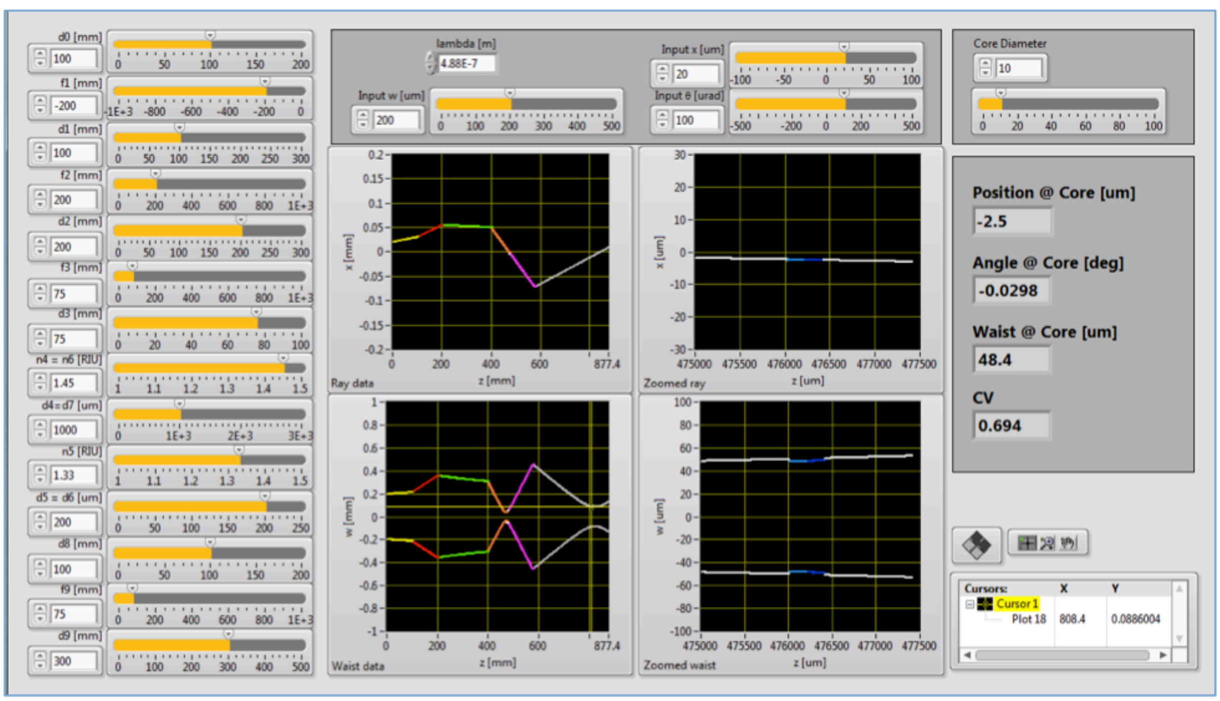


Figure 2. LiveIdeas model created to represent the flow cytometer optofluidic bench from the conceptual sketch of Figure 1.

3.3 Parameter extraction

The key design parameters from LiveIdeas are captured in a spreadsheet that includes the specifications for each of the nodes (functional components and supports, not shown) and each of the vectors (component relationships, Table 1). This spreadsheet is used as input to BeamWise to create the internal model of the system.

Table 1. Vector-based description of the flow cytometer optofluidic bench. The vector magnitudes are generated by LiveIdeas. Components are identified by codes: MIxx = mirror, LExx = lens, etc.

Network Path ID	NetList Vector	From	To	Magnitude	Mag. Units	Direction	Dir. Units
B1	v01	SO01	MI01	50.00	mm	270	degrees
B1	v02	MI01	LE01	100.00	mm	180	degrees
B1	v03	LE01	LE02	150.00	mm	180	degrees
B1	v04	LE02	MI02	50.00	mm	180	degrees
B1	v05	MI02	LE03	100.00	mm	90	degrees
B1	v06	LE03	FC01	100.00	mm	90	degrees
B1	v07	FC01	LE04	50.00	mm	90	degrees
B1	v08	LE04	PD01	30.40	mm	90	degrees
(B2, B3)	v09	FC01	MO01	38.00	mm	0	degrees
(B2, B3)	v10	MO01	LE05	65.00	mm	0	degrees
(B2, B3)	v11	LE05	BS01	70.00	mm	0	degrees
B2	v12	BS01	FI01	60.00	mm	0	degrees
B2	v13	FI01	PD02	25.00	mm	0	degrees
B3	v14	BS01	FI02	60.00	mm	270	degrees
B3	v15	FI02	PD03	25.00	mm	270	degrees

3.4 BeamWise 3D model generation

BeamWise then automatically generates a 3D CAD model of the system, using the specified component relationships, and the built-in beam-anchoring rule sets, to place components and their supports (Figure 3).

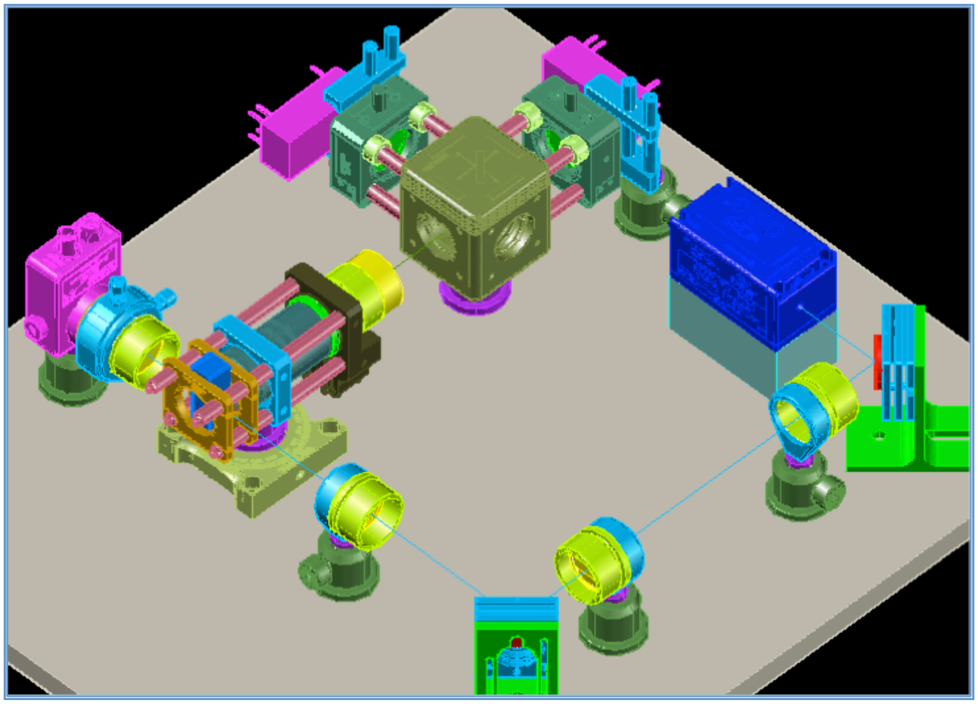
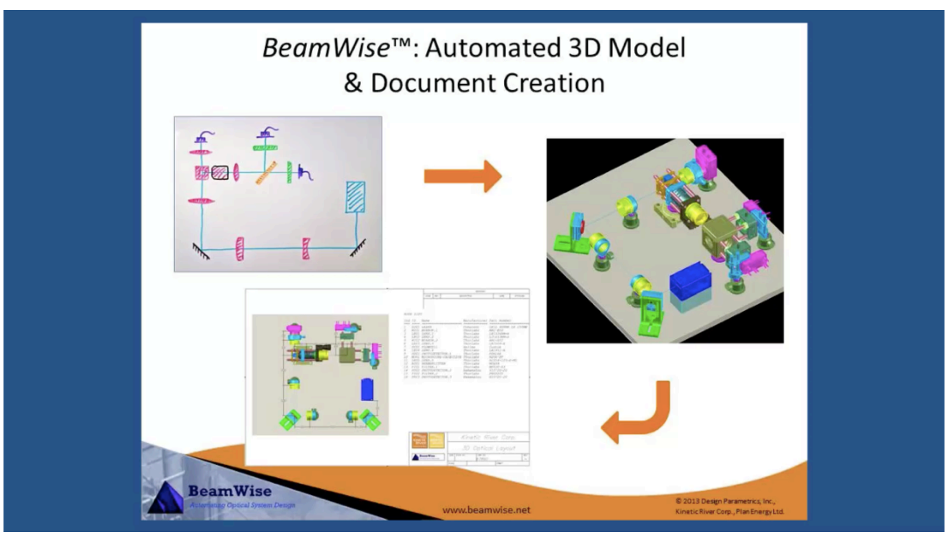


Figure 3. Automatically generated BeamWise 3D CAD rendered drawing of the flow cytometer optofluidic bench.

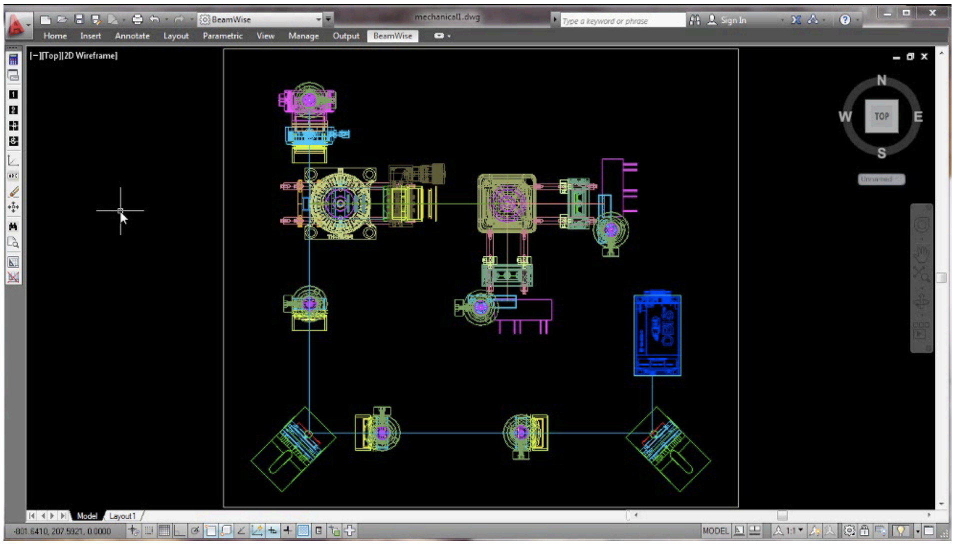
Like any other 3D model, the BeamWise-generated system model, which can be rotated, zoomed, and manipulated as customary, allows the designer to inspect the underlying model for any potential issues, such as spatial conflicts between components or their supports, lack of access to optomechanical elements like adjustment knobs or fasteners, and tight spaces preventing the use of diagnostic tools during the manufacturing process or service visits. Video 1 shows how the optofluidic bench model is created in BeamWise.



Video 1. A short walkthrough of BeamWise, from model creation to automatic design documentation.
http://dx.doi.org/10.1117/12.2045500

3.5 BeamWise real-time change updates

Unlike static CAD models, the BeamWise model is *dynamic*: any change in the underlying model is instantly propagated through the entire system, keeping all the remaining relationships unaffected. For example, a beam segment between two lenses can be shortened or lengthened with a few clicks, and the downstream lens and everything following it are repositioned accordingly—without having to manually update anything. Video 2 shows how in BeamWise a system model can be changed on the fly, while all the spatial relationships among components are automatically updated to give instant feedback on the impact of planned modifications, such as, e.g., footprint reduction.



Video 2. Changes can be made on the fly in BeamWise, with the software automatically updating the system 2D and 3D models. http://dx.doi.org/10.1117/12.2045500

3.6 BeamWise design documentation

From the BeamWise internal model, one can generate design documentation in several forms. The 3D CAD model can be exported in common formats, like SolidWorks and AutoCAD, for use on third-party software. A 2D CAD drawing can be generated as a PDF file based on a standard template, with dimensional callouts and switchable layers (Figure 4). Also on a standard template is the full parts list, which can include costing information as part of the Bill of Materials for the entire system. PDF diagrams of the internal (node-and-vector network) model representation can likewise be created.

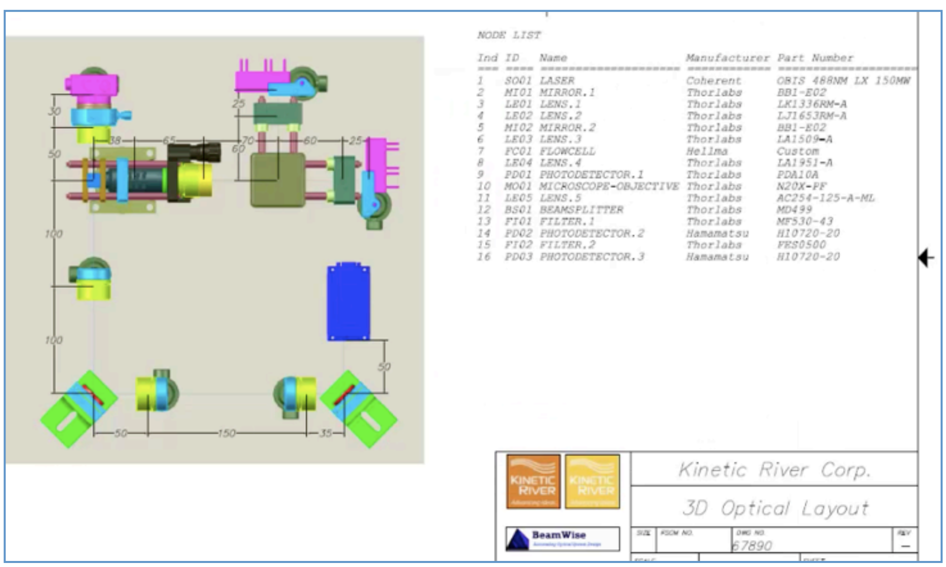


Figure 4. Detail of automatically generated BeamWise 2D dimensioned drawing and parts list.

4. CONCLUSIONS

Parametric modeling has entered popular culture, through strikingly innovative architectures like Frank Gehry's Jay Pritzker Pavilion in Millennium Park, Chicago, and Herzog & de Meuron's National Stadium in Beijing[8]. LiveIdeas[9] and BeamWise[10] apply the concept of parametric modeling to optical systems, offering new ways to explore a design space, visualize preliminary outcomes, and iterate designs virtually. By making it fast and straightforward for a developer to generate and then evolve system designs, they allow a thorough and efficient design process that results in fewer prototyping steps and less rework—and a shorter time to market.

REFERENCES

[1] Bardeen, J., and Brattain, W. H., "The Transistor, A Semi-Conductor Triode," *Phys. Rev.* **74**, 230–231 (1948).

[2] Shockley, W., "The Theory of *p-n* Junctions in Semiconductors and *p-n* Junction Transistors," *Bell Syst. Tech. J.* **28**, 435-489 (1949).

[3] http://en.wikipedia.org/wiki/Electronic_design_automation

[4] http://www.semrock.com/searchlight-welcome.aspx

[5] http://www.semrock.com/mylight.aspx

[6] Patel, J. K., Mena, P., and Ghillino, E., "Laser Modeling Software Requires Minimal Parameter Knowledge," *Laser Focus World* **Sept. 2013**, 31-35 (2013).

[7] http://www.radiantzemax.com/zemax/features/partlink

[8] Arieff, A., "New Forms That Function Better," *MIT Tech. Rev.* **116**, 95-98 (2013).

[9] http://www.kineticriver.com

[10] http://www.beamwise.net