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14. ABSTRACT
The Objectives are as follows:
High-frequency integral equations: Multiple-scattering/shadowing interactions
Periodic and random surfaces and structures
Canonical Integration: Edge scattering
Canonical Integration: High Frequency
Geometry representation and solution of challenging real-world problems

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Computational Electromagnetics

Grant #FA9550-05-1-0006

Final Report

Oscar P. Bruno

OBJECTIVES

* High-frequency integral equations: Multiple-scattering/shadowing interactions

* Periodic and random surfaces and structures

* Canonical Integration: Edge scattering

* Canonical Integration: High Frequency

* Geometry representation and solution of challenging real-world problems

REPORT

Progress in the proposed areas is as detailed in what follows. In addition to these efforts, work on a number of related but different areas was conducted, including efforts leading to integral equations for scattering by open surfaces requiring small number of iterations, integral equations for electromagnetic problems requiring small number of iterations, problems related to cloaking of objects from electromagnetic radiation, development of unconditionally-stable high-order time-domain solvers, development of convergent, highly accurate computational boundary conditions, evaluation of high-frequency scattering with applications to discovery of new planets (in connection with Northrop Grummann), development of a Graphical User Interface (GUI) for use in conjunction with our surface representation algorithms and scattering solvers, and problems of scattering by wire antennas.

HIGH-FREQUENCY INTEGRAL EQUATIONS: MULTIPLE-SCATTERING/SHADOWING
INTERACTIONS

Our efforts in this area during the period of performance of this grant include the results of two main thrusts: 1) Extension of the geometrical optics multiple-bounce ray-tracing algorithm, needed by for ansatz generation, to three dimensional geometries (In collaboration with F. Reitich and Y. Boubendir); and 2) Development of a technique for the solution of the multiple-scattering problem that bypasses the need to account for successive reflections iteratively, by allowing for their determination in a single-pass solution procedure (In collaboration with F. Reitich). Of major significance in our results relating to point 1) above is the ability of the three-dimensional code to handle surfaces that are only locally parameterized through an atlas of charts (or "surface patches"). In this approach the multiple bounce iterations are precomputed in a finite set of regular meshes via "inverse ray tracing" and subsequently parametrized, prior multiplication by appropriate "Partitions of Unity", by means of Fourier series - thus allowing for accurate (high-order) and fast evaluation of the three-dimensional ray tracing required by our ansatz generator. With regards to point 2), in turn, our new method seeks to determine, in a single sweep (and without recurse to an actual iterative multiple-scattering implementation) a multi-ansatz, resulting from several multiple reflections (and thus, containing a combination of exponential with various phases, determined as discussed in point 1) above). This approach is advantageous over the previously considered explicit multi-scattering method in regions where singular ray-tracing maps occur.

PERIODIC AND RANDOM SURFACES AND STRUCTURES

A significant achievement in this context was obtained in collaboration with graduate student Andy Monro. Here we studied the possibility of windowing the equations of scattering by a periodic surface. To explain this consider that, as is well known, summation of the periodic Green's functions of a very high order is required by rough-surface solvers based on integral equations to achieve even the lowest degree of accuracy, which gives rise to a very significant computational expense. For this purpose efficient algorithms have been introduced for the evaluation of the periodic Green's function, including Veysoglu's and Ewald's summation methods. In collaboration with A. Monro we found that, interestingly, although the accurate summation of the Green function does require accurate summation of extremely large portions of the Green function series, the solution of the scattering problem itself *does not* --- even for very challenging diffraction gratings, with high height-to-period ratios and high frequencies. To achieve this desirable effect it is necessary to truncate the integrals smoothly, using suitable smooth windowing functions (Partitions of Unity). The (recent) results of our numerical experiments in these regards are very clear; the development of a full theoretical explanation of this phenomena is now close at hand and will be part, it is hoped, of Mr. Monro's PhD thesis dissertation.

CANONICAL INTEGRATION: EDGE SCATTERING

The concept of Canonical integrals we introduced recently, in collaboration with R. Paffenroth, has given rise to significant improvements in the treatment of integral equations in geometries containing edges, including both closed- and and open surfaces such as plates. (The open-surface problem, which gives rise to additional difficulties concerning conditioning of the needed first-kind integral equations, is being treated in collaboration with graduate student Stephane Lintner.) These canonical integration methods proceed by using a parametrization of the scattering surface near edges such that the full singular behavior in the integrals to be calculated is given by expressions that are *closed form functions of the integration variables*. This allows for efficient integration of nearly-singular functions without recourse to fine discretizations. An alternative approach developed over the last few months involves use of real-space polar integration. Such real-space integrations leads to highly peaked angular integrands. Using a localized integration technique based on Chebyshev integration, these peaked integrals can be evaluated efficiently. We are currently evaluating which of the two procedures should be most advantageous in practice.

The canonical-integration mechanism for edges works only in situations in which the integrands do not become nearly-non-integrable - as they do when currents become infinite. To tackle this problem we introduced, further, new "edge-integral-asymptotics": basically, all infinities arising in an integral equation as a result of non-integrable quantities have to cancel out in order to match the given (finite) right hand sides. The edge-integral-asymptotics approach mentioned above produces such cancellations in an explicit *analytic* manner, thus reducing the infinite-current integration problem to one that can be treated by means of the Canonical integration approach mentioned above. A corresponding corner-asymtptotics approach is being developed in collaboration with graduate student Zhiyi Li.

CANONICAL INTEGRATION: HIGH-FREQUENCY SCATTERING

Significant progress has been attained in this area (in collaboration with C. Geuzaine): using a concept of canonical integration related but different to that mentioned in the previous paragraphs, we developed a solver for high-frequency scattering problems in three-dimensions which can evaluate in a couple of hours, and in single processors, scattering by objects much larger than the largest that could be tackled by other methods, even by means of large supercomputers. In detail, using our high-frequency method we have produced preliminary three-dimensional results for a spherical scatterer of radius a. In these preliminary examples we have demonstrated computational times that do not change significantly, with essentially fixed accuracies, when the frequency increases. For example, we have obtained results for $ka=800$ up to $ka=3200$ with less than 5% error in a 200 minute computational time in a single 1.5 GHz PC processor. This computing time is several orders of magnitude smaller than the computational time required by other state of the art algorithms. For reference, results produced by means of the Fast Multipole Method (FISC), the solution for a 120λ sphere required 9.6 million unknowns and 14.5 hours of CPU time on a 32 processor SGI Origin 2000, leading to an RMS Error of 4.6%. Although this is only a rough comparison (since the FISC results were obtained for the vector Maxwell system and our preliminary results were obtained for the scalar Helmholtz equation), our solutions were obtained using 4096 unknowns in about three hours on a single processor 1.5 GHz PC, and for much higher frequencies.

GEOMETRY REPRESENTATION AND SOLUTION OF CHALLENGING REAL-WORLD PROBLEMS

The problem of producing smooth representations from a triangulation has been considered often in recent years. Previous methods have sought to utilize piece-wise polynomial approximations, and, under certain asumptions concerning regularity of a given triangulation, have provided representations with continuous derivatives of first order. Higher order differentiability has not been produced by any other means as yet, and the prospects for the feasibility of such extensions do not seem favorable: it appears that piecewise polynomial approximations may not be helpful in our context. Our approach to high order geometry representation (developed initially in collaboration with Matt Pohlman, and continued presently in collaboration with YoungAe Han) is based on use of Fourier series for certain periodic functions associated with the given surface. As a result of our efforts during the last year in this area, our methods of surface representation have been extended, giving rise to improved rendering of complex features. For example, we have changed some of our projection strategies, and we use now projections onto non-planar parameter surfaces, which has resulted in much improved renderings of curved objects. Significant progress, further, was brought about from an interaction with Stanford Prof. A. Jameson, who provided a number of high-quality airplane meshes. We have agreed to reciprocate: we will provide the Stanford group smooth parametrizations (produced through application of our algorithms) of the meshes they forwarded to us. These meshes could then be used for the purposes of the Stanford group, which include design and optimization of airplane geometries.

In addition to the geomtry representation problem we are pursuing, in collaboration with a group at the Jet Propulsion Laboratory (JPL), a number of comparisons of our theoretical/computational results to results of experiment. The JPL group is interested in establishing the validity and accuracy of our solvers for geometries that include bodies with edges as well as *wire geometries* (antennas); they are nearly completing the corresponding experimental setup. To extend our capabilities to the treatment of wire geometries we produced, in collaboration with postdoctoral associate Mike Haslam, a wire scattering solver. (This is an accurate and efficient solver, in the spirit of others we have developed in recent times. A number of difficulties, of a spirit similar to those arising in the development of canonical-integration methods, needed to be addressed to develop this solver. These contributions will be described in detail in a forthcoming manuscript.) This solver was combined with our full Maxwell solvers; the combined solvers can currently evaluate scattering from geometries containing bodies with edges and wires attached to them within a fully three-dimensional framework. We expect results of comparisons between computations and experiments will be available in the next few months.

INVENTION DISCLOSURE

The following invention was reported and not pursued

Accurate, high-order representation of complex three-dimensional surfaces via Fourier-Continuation analysis

Serial Number: 60/894,179 Filed: 3/9/2007

CIT File Number: 4857-P

Inventors: Oscar Bruno; Youngae Han; Matthew M. Pohlman

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RELEVANT PUBLICATIONS

"Exact non-reflecting boundary conditions based on equivalent sources for time-dependent scattering problems", O. Bruno and D. Hoch, in preparation. Also D. Hoch's forthcoming thesis of the same title.

"High-order unconditionally-stable ADI algorithms for general domains", M. Lyon and O. Bruno, in preparation. Also M. Lyon's forthcoming thesis of the same title.

"High-Order Solution of the Scattering Problem for One-Dimensional Perfectly-Conducting Periodic Surfaces", O. P. Bruno and M. Haslam; In preparation.

"Evaluation of Propagation of GPS Signals through the Atmosphere via High-Frequency Localization and Rytov's Approximation", J. Chaubell, C. O. Ao and O. P. Bruno, In preparation.

"Spectrally accurate windowing for rough-surface scattering problems"; O. Bruno and Andy Monro J., In preparation; see also A.Monro's thesis: Caltech, September 2007.

"A highly accurate integral method for open-surface scattering requiring small numbers of GMRES iterations", O. Bruno and Stephane Lintner, In preparation.

"Well-posed Integral Equations for Acoustic Problems on Open Surfaces", O. Bruno and Stephane Lintner, In preparation.

"Superlens-cloaking of small dielectric bodies in the quasistatic regime", O. Bruno, T. Elling, R. Paffenroth and C. Turc, In preparation.

"Superlens-cloaking of small dielectric bodies in the quasistatic regime", O. Bruno and Stephane Lintner, Submitted.

"Accurate, high-order representation of complex three-dimensional surfaces via Fourier-Continuation analysis", O. Bruno, Y. Han and M. Pohlman; To appear in J. Comput. Phys.

"Regularity theory and super-algebraic solvers for wire antenna problems", O. Bruno and M. C. Haslam, SIAM Jour. Sci. Comp. 29, 1375--1402, 2007.

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"One-dimensional inverse scattering problem for optical coherence tomography" , O. Bruno and J. Chaubell; Inverse Problems 21, 499-524, 2005.

"Higher-order Fourier approximation in scattering by two-dimensional, inhomogeneous media", O. Bruno and M. Hyde; SIAM J. Numer. Anal. 42, 2298-2819, 2005.

"A Fast, High-Order Method for Scattering by Penetrable Bodies in Three Dimensions", M. Hyde and O. Bruno; J. Comput. Phys. 202 236--261 (2005).

HONORS/AWARDS

"Fast High-Order High-Frequency Solvers in Computational Acoustics and Electromagnetics", O. Bruno (Plenary Speaker), Workshop on wave scattering problems, INRIA and University of Pau, France, December 12-14, 2007.

"Fast High-Order High-Frequency Solvers in Computational Acoustics and Electromagnetics", O. Bruno (Plenary Speaker), 2007 biannual conference on Differential Equations & Computational Simulations, Birmingham, Nov 1-3, 2007.

Wokshop on "High-order methods for computational wave propagation and scattering", O. Bruno and R. Kress, Organizers. American Institute of Mathematics, Palo Alto, CA, Sept. 10 - 14, 2007.

"High-order scattering solvers and surface representation algorithms", O. Bruno, Industry Days, ICIAM 2007, Zurich, Jul 16, 2007.

"Fast high-order high-frequency solvers in computational acoustics and electromagnetics", O. Bruno (Plenary Speaker), in "Effective Computational Methods for Highly Oscillatory Problems: The Interplay Between Mathematical Theory and Applications", Newton Institute, Cambridge University, Jul 16, 2007.

"Efficient evaluation of high-frequency propagation and scattering, with application to propagation in non-spherically-symmetric atmospheres", O. Bruno (Plenary Speaker), in "Oscillatory Integrals and Integral Equations in High Frequency Scattering and Wave Propagation", Newton Institute, Cambridge University, June 19, 2007.

"7th International Conference on Mathematical and Numerical Aspects of Wave Propagation", O. Bruno (Plenary Speaker), (WAVES'05, Brown University, Rhode Island.) June 20-24, 2005.

"High Frequency Wave Propagation", O. Bruno (Plenary Speaker), (University of Maryland's Center for Scientific Computation and Mathematical Modeling). September 19-24, 2005.

Accurate, high-order representation of complex three-dimensional surfaces via Fourier-Continuation analysis

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