Implementation of Refined Ray Tracing inside a Space Module

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ABSTRACT

Modern space modules are susceptible to EM radiation from both external and internal sources within the space module. Since the EM waves for various operations are frequently in the high-frequency domain, asymptotic ray-theoretic methods are often the most optimal choice for deterministic EM field analysis. In this work, surface modeling of a typical manned space module is done by hybridizing a finite segment of right circular cylinder and a general paraboloid of revolution (GPOR) frustum. A transmitting source is placed inside the space module and test rays are launched from the transmitter. The rays are allowed to propagate inside the cavity. Unlike the available ray-tracing package, that use numerical search methods, a quasi-analytical ray-propagation model is developed to obtain the ray-path details inside the cavity which involves the *ray-launching*, *ray-bunching*, and an adaptive cube for *ray-reception*.

Keywords: Space module, Surface modeling, Ray tracing, Refined ray tracing

1. INTRODUCTION

Although ray tracing has been employed extensively for high-frequency asymptotic EM field computations, particularly for the scattering and diffraction problems, a closer scrutiny reveals that the differential approach to ray tracing have been primarily applied to the convex surfaces [1]. The ray tracing becomes extremely cumbersome in the important applications of crevices and concavities within an enclosure (such as space modules, aircraft engine, cockpit and passenger cabins) due to ray proliferation, arising from multiple reflections, transmission and diffraction. In fact the only route to ray-tracing available in such cases is *ray casting*, which improves the prediction only when the spatial rays are increasingly dense (in angular separation) leading to computational intractability. For the estimation of RF field inside a space module, the ray-path data is required for direct plus cumulative reflected rays up to the N^{th} bounce. In this paper, a refined ray-tracing method is implemented in conjunction with analytical surface modeling for a typical manned space module.

The present work has two parts viz., the surface modeling and ray tracing. Surface modeling of the space module is done by hybridizing a finite segment of right circular cylinder and a general paraboloid of revolution (GPOR) frustum. A transmitting source is placed inside the space module and test rays are launched from the transmitter. The rays are allowed to propagate inside the cavity. As the surface model involves the use of parametric equations, the ray-propagation model takes care of the surface normal at different incident points. The surface normal of the GPOR and right circular cylinder are defined by the analytical equations [2], which significantly reduces the ray-path computation time.

The simulation results for the ray propagation inside the modeled manned space module are presented *w.r.t.* number of bounce. A detailed analysis of convergence studies and computation time is also carried out.

2. SURFACE MODELING OF A SPACE MODULE

A typical manned space module can be modeled as a hybrid of a general paraboloid of revolution (GPOR) frustum and a finite segment of right circular cylinder. In this work all the rays are obtained up to a given time. Hence the rays are provided in a cumulative manner upto a given number of bounces.

Geometry of the space module

The internal dimension of a typical manned space module considered [3] is given as:

Right circular cylinder length: 7.5 m
Right circular cylinder diameter: 4.5 m
GPOR frustum height: 5 m

For the GPOR frustum, shaping parameter is assumed to be 0.75 such that the basis parameter coordinate varies from u_1= 2 to u_2= 3. A matching lower radius of 2.25 m results in the required upper radius of the GPOR frustum of 1.5 m. The transmitter and receiver are located at S(0.5, 0.9, -15.5) and R (0.5,-0.4, -6.0) without loss of generality, inside the space module. The ray tracing is done using ray-casting method. A quasi-analytical refined ray tracing method in conjunction with analytical surface modeling is used here for ray-path data generation.

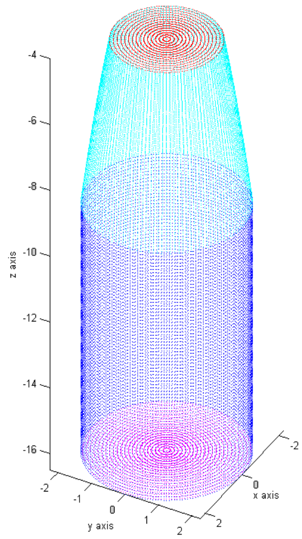

Figure 1 The space module modeled as a hybrid of GPOR frustum and a finite segment of right circular cylinder

3. RAY PROPAGATION INSIDE THE SPACE MODULE

After modeling the space module, the ray-path details between the transmitter and receiver are determined using a refined ray-tracing algorithm described below.

Refined ray-tracing inside the modeled space module

The hybrid structure of GPOR frustum and finite right circular cylinder is assumed to be closed at both the ends.

Ray casting is done from the isotropic source (transmitter) using a *uniform ray launching scheme* [4]. Let the angle that the ray makes with the x-axis and the z-axis be θ and ϕ , respectively. Each ray is defined by their θ and ϕ values. The rays are then allowed to propagate inside the cabin. Considering the intersection formula between a line and the surface of right circular cylinder [5], the first intersection point is determined. As the hybrid structure has four surfaces at different heights, the z-coordinate of the first intersection point is checked and according to the surface, the equation is adopted for calculation of *first incident point*. The corresponding four surfaces of the space module as given below:

a) At $z = -4$, Plane
b) If $-4 > z > -9$, GPOR frustum
c) If $-9 \geq z > -16.5$, Right circular cylinder
d) If $z = -16.5$, Plane

The unit surface normal vector at the first incident point is determined by taking the normal equation of the corresponding surfaces [2].

The intermediate point on the reflected ray is then obtained using the *Snell's law of reflection*. The same process is repeated for the given number of bounces.

A receiver is considered as a small sub-cube placed inside the space module. The centre of the sub-cube is the observation point. The rays that reach the reception sub-cube are considered as the rays required for the field build-up inside the cabin. The ray paths tend to appear as ray bunches (Fig. 2), which traverse nearly parallel manner and reach the receiver. Hence an algorithm is developed for identifying these bunches. The *ray within a bunch*, which is closest to the receiving point, is considered as the *required ray* (Red colour ray: Fig. 3). This ray converges by refining the angular separation iteratively (Green colour ray: Fig. 3), *i.e.*, to yield the ray solutions at the receiver after refinement.

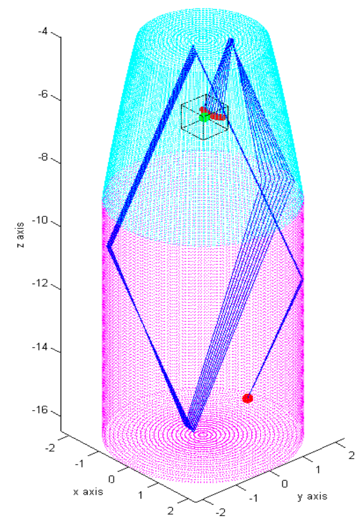

Figure 2 A single bunch of rays reaching the reception cube.

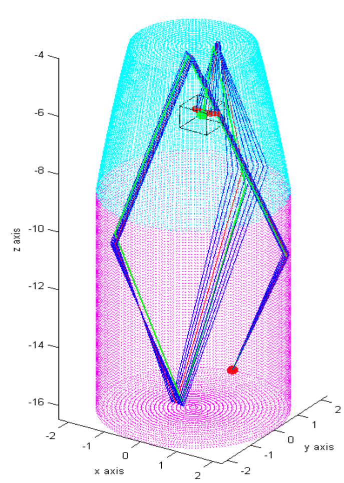

Figure 3 The converged ray (Green colour ray) reaches the receiving point.

Results and visualization of ray-path

The ray-path propagation characteristics are verified for conditions of co-planarity and equality of angles, and the unit surface normal vector for the 2nd degree quadric patches. Hence the ray-path data is imported in *Matlab* and reported in this paper. As ray casting is used, 4126183 rays are launched; out of which only 42 rays reach the receiver cumulatively upto 3 bounces excluding the *direct ray*. There are 4 rays which reach after one bounce, 10 rays after two bounces, and 28 rays after three bounces. Figures 4a through 4c gives the visualization of one-bounce, two-bounce and three-bounce rays reaching receiver and Fig. 4d shows the rays cumulatively till 3rd bounce. Figure 5 gives the 3D perspective of the ray path details inside the space module up to 5 bounces. Similarly the ray path data are generated up to 40 bounces sorted *w.r.t.* their propagation time.

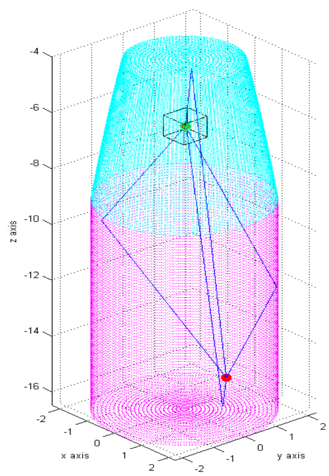

Figure 4a Single-bounce ray paths (Red dot represents the source point and green dot represents the centre of the reception sub-cube)

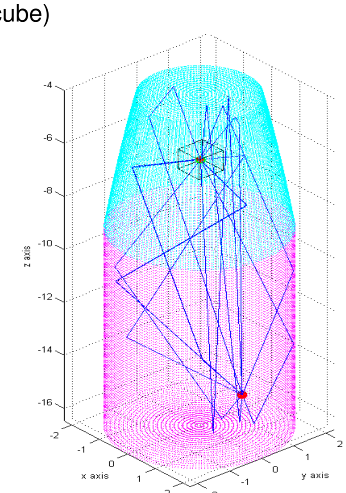

Figure 4b All two-bounce ray paths (Red dot represents the source point and green dot represents the centre of the reception sub-cube)

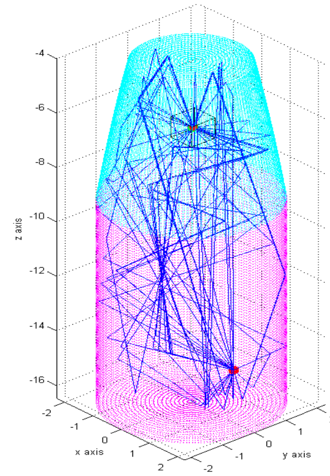

Figure 4c All three bounce ray paths (Red dot represents the source point and green dot represents the centre of the reception sub-cube)

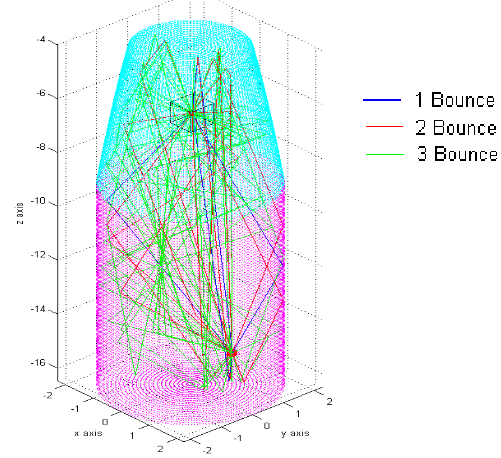

Figure 4d Cumulative rays up to three bounces

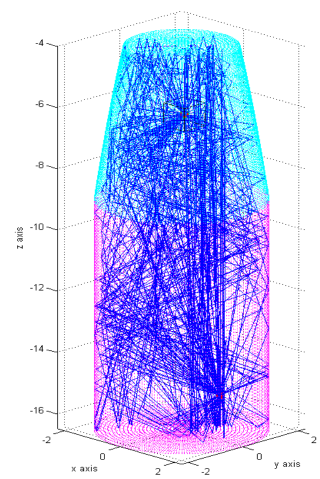

Figure 5 Cumulative rays that reach receiver up to five bounces

Ray Convergence Study

A convergence study of the number of rays that reach the receiving point *w.r.t.* the number of rays launched (a function of angular separation) is carried out. The cumulative rays (till 5 bounce) that reach the receiver after refinement is given in Table I. A close scrutiny on the table indicates that as the number of bounce increases, smaller angular separation (capable of launching more number of rays) is required for the convergence.

Table I
Convergence study of rays reaching at N bounce *w.r.t.* angular separation

Angular separation	No. of rays launched	No. of bounces (b)				
		1b	2b	3b	4b	5b
1	41345	**4**	6	16	11	11
0.5	165197	**4**	6	16	16	18
0.3	458675	**4**	9	16	20	22
0.2	1031769	**4**	**10**	28	23	41
0.1	4126183	**4**	**10**	28	24	54
0.05	16503013	**4**	**10**	**31**	**32**	71
0.03	45839676	**4**	**10**	**31**	**32**	85

Table II
Rays reaching receiver cumulatively upto N bounce and the execution time (4126183 rays are launched)

N--Bounce	No. of rays received	Program Execution time
1 bounce	4	25 Sec
5 bounce	120	1.55 min
10 bounce	538	6.67 min
15 bounce	893	11.00 min
20 bounce	1082	17.56 min
25 bounce	1205	24.35 min
30 bounce	1279	29.45 min
35 bounce	1318	34.12 min
40 bounce	1345	42.35 min

The cumulative ray-path data is generated for EM field computation till 40 bounces. The number of rays that reach the receiver *w.r.t.* N-bounce and the program execution time is given in Table II. From Table I and II it can be seen that at 0.1° the convergence achieved is till 4 bounces only. In the applications where higher bounces are required, denser rays are launched to achieve convergence, which often becomes computationally intractable. This may call for intelligent algorithm towards adaptive ray tracing.

4. CONCLUSION

Ray tracing inside a manned space module is carried out. The ray-path data generation and visualization of the rays that reach a particular sub-cube placed inside the cabin is done by *Matlab*. A *ray-bunching* algorithm is developed to differentiate the bunch of rays that travel nearly parallel and reach the receiving sub-cube. The refinement algorithm is then employed to find out the required ray, which reaches the receiving point from that bunch. A convergence study of the number of rays receiving the reception cube *w.r.t.* the number of rays launched is discussed and finally the cumulative ray path data till a given bounce (till 40 bounce) is generated.

5. REFERENCES

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