Mathematical Model for Radar in 3D Virtual Maritime Environment to Aid Dynamic Perception

Dinuni Fernando
dinuni.fernando@gmail.com

N. D. Kodikara
ndk@ucsc.lk

Chamath Keppitiyagama
chamath@ucsc.lk

Department of Computer Science
University of Colombo School of Computing
Colombo 07, Sri Lanka

Abstract **- Laser and radar technology is an area of interest in the field of military research. Currently military services face many challenges in maintaining financial stability and sustainability in training phases. Military trainings exercises focus mainly on strengthening the simulation culture rather than focusing on theoretical aspects. In the sphere of military radars, simulators play very important roll with regard to low cost and lesser risk. In this research we focus on implementing a mathematical model for radar simulation in 3D maritime environment with dynamic perceptions. The proposed approach takes the 3D environment as the input and maps the objects via electromagnetic wave properties. It captures the surrounding environment and gives the 2D visualization of the 3D environment as the end result. This approach uses efficient techniques by embedding the optical phenomena of reflection, refraction, polarization and attenuation in wave propagation.**

Keywords — electromagnetic wave propagation, maritime radar, 3D environment, dynamic, virtual world

I. INTRODUCTION

With the peak improvements in the domain of military training, simulations and modeling has become significant. Virtual reality related simulations and modeling has been vital in military training due to many facts; where it provides cost effective training sessions in maritime environment, where it prepares trainees for critical situations finally it enables the users to get a real-time experience by providing direct feedbacks from system in a safer way. Real time user experience with a simulation system at the initial naval training phase give the trainees prepare for real time system beforehand.

Radar system alone cannot identify targets in the environment. Before the simulation era arise traditional methods such as standalone radars, sonar's and nautical chart plotters which use artificial GPS and AIS data to find the target position, gyroscope to capture the bearing were extensively used. Thus a traditional radar system is not a single device but it requires collection of devices to capture the basic functionality in identifying a presence of an object.

According to Sri Lankan context, in the maritime environment standalone radar is capable of identifying the presence of target. It uses GPS to capture longitude and latitude positions. Gyroscope is used to capture bearing of the targets. Maritime radars do not emit electromagnetic waves to the sea surface or water underneath. Due to the attenuation or extinction caused in medium of water, quantitatively significant portion of electromagnetic wave is attenuated, thus echo sounder is used to capture the depth of the sea. The primary focus of this research is to eliminate vagueness of maritime environment by giving the benefit to naval trainees to prepare for most of the possible incidents in the maritime environment. Proposed mathematical model considers radar origin coordinates as the radar hosted ship coordinates(Fig. 1).

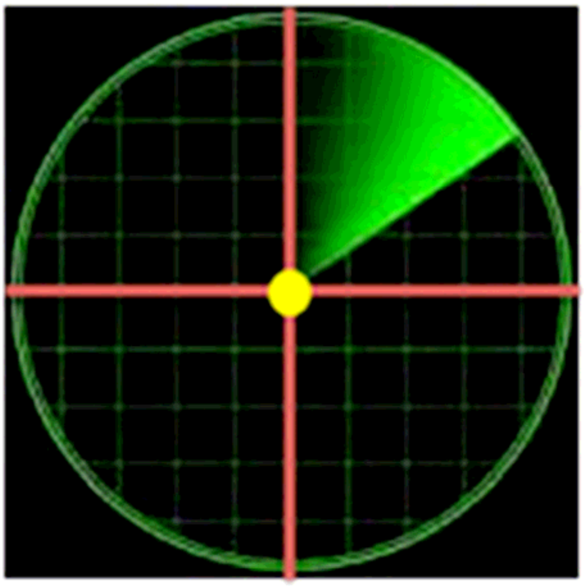

Fig. 1. Using radar hosted ship coordinates as the origin

This paper presents dynamic perception where the radar hosted ship is static while other vessels in the 3D virtual environment are dynamic. Our approach captures 2D coverage by incorporating electromagnetics wave phenomena namely; reflection, refraction and polarization, propagation phenomena namely; attenuation and free space path loss to capture targets in high sea environment. Doppler Effect is used to capture the dynamic behavior.

II. RELATED WORK

For decades, radar simulation in naval training processes was a major topic in maritime environment with greater demand. Several researches have been carried out in this domain to model numerically electromagnetic wave propagation and radar simulations. There were limited models, which were capable of capturing 3D surrounding for scanning the input. Limited number of models was capable of handling dynamic environment where vessels are navigating. Several image processing and robotics [1] approaches have been taken to simulate radar systems in maritime environment, which lead to higher complexity.

Whitted [2] used geometrical optics as an improved illumination model for shaded display. Authors had represented rays to model the propagation of light amidst optical system. Light is a wave subtype of lectromagnetic wave spectrum. According to Whitted technique, it allowed even a complex optical system to be mathematically simulated on a computer. Whitted simulation is valid for high frequency waves where wave length is less than obstacles dimensions. With the Whitted approach, we are able to simulate EM waves in high frequency band as an illumination model, which captures 3D environment. Ikegami [3]et al. presented radio propagation model to capture urban scenario which is 2.5 dimension surrounding. Landstorfer [4] proposed a hybrid model which is a combination of ray tracing and empirical models which captures reflection and diffraction by building a visibility tree. Several databases were used to capture terrain namely indoor, urban and hybrid. Several acceleration methods for ray optical models have been presented in many occasions to capture optical propagation. APLs Trophospheric Electromagnetic Parabolic Routine (TEMPER) [5]was developed with the assumption that radar and targets varies only in range dimensions. They tried to enhance computational efficiency by neglecting scattering and diffraction aspects that is not linearly related to radar theories. Signal processing techniques have been used in identifying moving targets by Sparr [6], where it uses time-frequency methods to identify targets of images.

MODENA a simulation model to capture maritime environment is a research work by Gahaleb at. el [7]. Reproducing the acquisition of a Real Aperture Radar (RAR) moving along its axis is the simulation principle. Sea surface is generated by using a multiscale model by incorporating hydrodynamic interactions in the maritime environment. An important part of the research targeted at modeling and simulating the electromagnetic interactions between the environment and the wave both emitted and received by an antenna of airborne or satellite radars. Sea surface was modeled using meshes and then preprocessed by high-resolution numerical simulations. Statistical models were used to evaluate electromagnetic fluctuations involved by the roughness of the sea surface. Ships in the surrounding meshed in triangular facets to capture accurate estimated contribution. Ships in the environment were limited to simple polygonal objects in order to avoid high complexity. It is a good approach where they capture 3D environment by incorporating sea surface to radar theories.

Ranaweeraat el. [8] had proposed an light weight approach on simulating a virtual radar in 2D environment using height map concept. It uses Bresenham's line algorithm to mark heights of the terrain along each ray angle and plot on the radar map. However, this approach capture the terrain information as height variations but it doesn't take electromagnetic properties, optical properties, and optical phenomena in to account. Our prior research investigates possibilities to capture static perception of the virtual radar system in 3D environment. Where it explores radar hosted vessel and the target vessels in the 3D environment are in static mode [9]. There are commercial available virtual learning and training systems like "Transas" [10], "Oceaniccorp" [11] which are extremely expensive, proprietary and closed systems. Commercial radar simulators have the capability to capture geometry of objects and relative position. Simulation has combined reflection capability of material properties, 3D wave property incorporated earth curvature in the simulation. In contrast to above mentioned related work our approach tries to map the 3D virtual maritime environment to 2D radar coverage by using efficient techniques of optimizations and integrating electromagnetic theories to the virtual world. 3D

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virtual maritime environment is captured as a script of virtual reality modeling language (VRML). Our approach incorporates optical phenomena, optical properties and direct electromagnetic wave accordingly in 3D dynamic environment.

III. SYSTEM DESIGN

As the initiation phase of this research, basic terminology and requirements of real marine radar was collected from Sri Lanka Navy.

TABLE I
RADAR FREQUENCIES AND BAND

Frequency Range	Frequency Band
50-330 MHz	VHF
300-1,000 MHz	UHF
1-2 GHz	L
2-4 GHz	S
4-8 GHz	C
8 – 12 GHz	***X***
12-18 GHz	Ku

As feedbacks captured from Sri Lankan Navy, marine radar used in a battlefield emits electromagnetic waves with the frequency of 8-12 GHz in band X (Table 1 [12]) to search volume where the search space ranges up to 300 km.

A. Concept of real marine radar

Objective of marine radar is to identify presence of sea level targets. Thus marine radar emits electromagnetic waves in frequency band X to search volume. Portions of energy will be reflected back to the receiver as echoes. Marine radar helps the ship to avoid barriers and provides easiness in navigating in the ocean. Identifying targets or barriers display on circular map can be understood by a skilled radar operator.

B. Concept of virtual marine radar

The virtual radar introduces the concept of mapping targets of the virtual environment according to the optical phenomenon and optical properties. Virtual environment is the interpretation of the 3D maritime environment in high sea condition. Virtual radar introduces a mathematical model to overcome several limitations of typical simulation where it uses optimization and statistical techniques to enhance the radar terminology.

Proposed mathematical model is capable of handling calm sea environment incorporating several theories of physics.

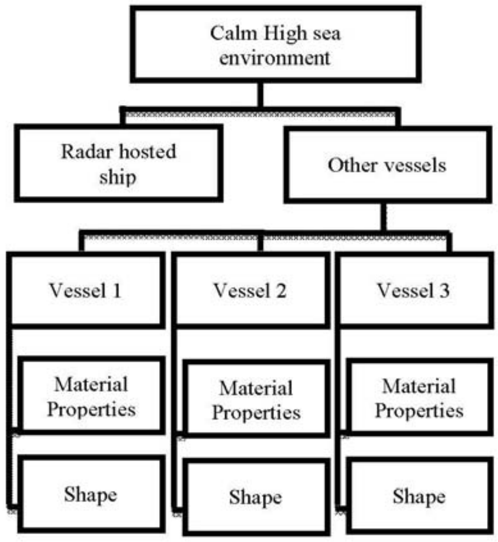


Fig. 2. Scene graph representation of 3D virtual environment

In capturing dynamic behavior of the 3D environment we had to move to a data structure which has the provisions to maintain the elements in the environment (Fig. 2) in a hierarchical manner. Scene graph representation is collection of nodes in a tree structure where a node may have several children but more often a single parent. Effect applied to a parent node will be directly inherited by child nodes.

1. *Representation of ray beam*

To capture the obstacles in the virtual maritime environment electromagnetic waves are emitted to the search volume. Ray beam (Fig. 3) is disseminated to the search volume by varying x, y, z plane coordinates. Ray beam consisted with rays varying x, y coordinates ranges from 0° to 360° and z coordinates ranges from 0° to 10° and 0° to (-10°). Beam strength with strong can be captured by decrementing the angle between two adjacent rays.

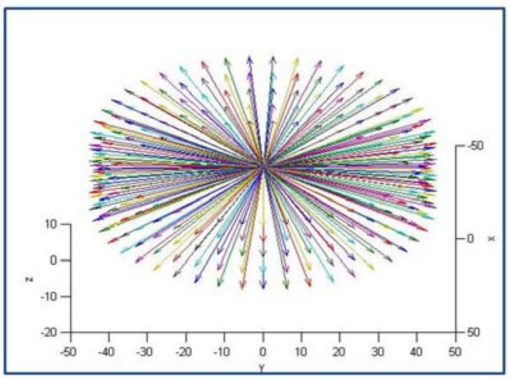


Fig. 3. Ray beam

2. Object representation

In the high sea environment barriers that radar captures are vessels namely fishing boats, tug boats, trawlers, etc. Vessels are made out of different material where each material has different refraction indices. In the proposed prototype model, 5 different opaque materials with unique refractivity are considered.

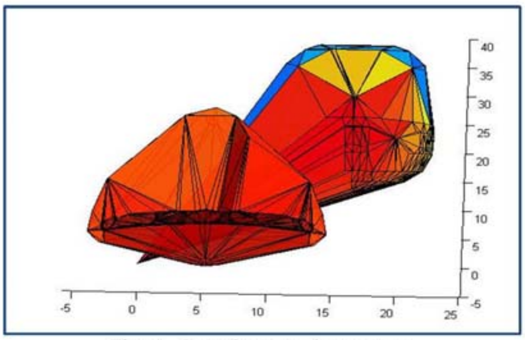


Fig. 4. Complex vessel structures

Vessels in the environment are made out of complex structures where the polygon count of

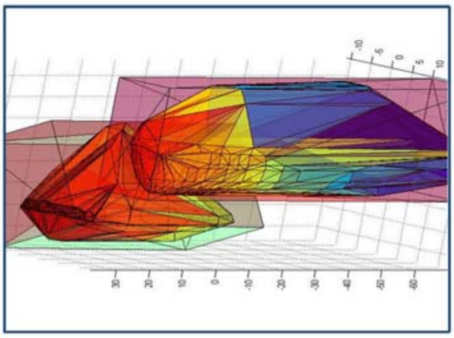


Fig. 5. Complex vessel with bounding box

vessels (Fig. 4) is too high. Each vessel is being triangulated to capture the intersection points with the ray beam to identify the interactions. Triangulation was incorporated thus triangle is the smallest polygon and finding the intersection point of the ray with the triangle is more accurate instead of focusing on complex polygons. Intersections of ray and triangles are being captured using ray triangle intersection algorithm proposed by Thomas [13]. To avoid unnecessary calculations we have used bounding box (Fig. 5) concept to bind the obstacles in the environment. Initially 3D bounding box is being created to identify specific rays that intersect the vessel. After identifying intersecting rays, radar directly emits corresponding rays for further calculations which leads to efficient and effective behavior of the mathematical model.

At the initial emitting point energy of the ray is defined as 1; while propagating electromagnetic wave total energy will extinct due to free space path loss and attenuation incident when propagating through a medium and while at the point of intersection.

As stated in [14], the rate of power attenuation per unit distance is described by the absorption coefficient β_a, (1) which is related to $n_i$by

$$\beta_a = \frac{4\Pi n_i}{\lambda} \tag{1}$$

Where equation (1) is related to the propagation intensity and the overall transmittance t(x) by Beer's Law, depicted in (2).

$$t(x) = \frac{I(x)}{I_o} = e^{-\beta\frac{x}{\alpha}} \tag{2}$$

Free space path loss can be represented in a simple formula as below (3).

$$FSPL = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi d f)^2}{c^2} \tag{3}$$

- λ is the signal wavelength (in m),
- f is the signal frequency (in Hz),
- d is the distance from the transmitter (in m),
- c is the speed of light in a vacuum

Energy of the wave at an intersection is calculated by using Fresnel equations. When considering polarization of the incident beam, there are parallel (p-polarization) and perpendicular(s-

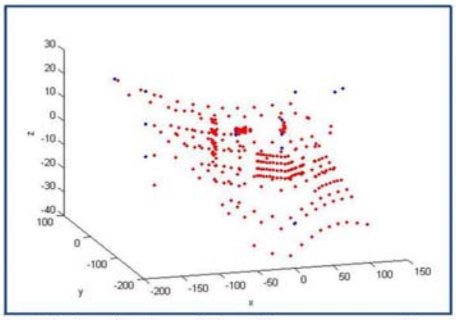
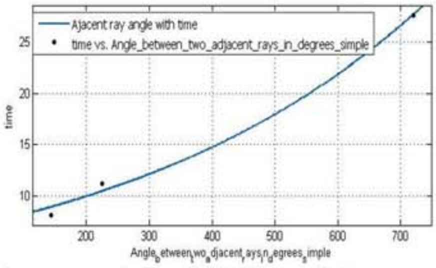


Fig. 6. 2D visualization of the radar coverage as the output

polarization) polarization in electromagnetic wave theories. After critical analysis we identified that in parallel polarization higher conservation energy is identified comparing to perpendicular polarization. Parallel and perpendicular and parallel reflection



coefficients are defined by R_p and R_s.perpendicular and parallel transmittance are defined by T_p,T_s.(R_P,$R_s$refers (4) and (5)) We have identified high conservation energy (T_p,$T_s$refer (6) and (7)) in parallel scenario.

$$R_p = \frac{n_i cos\theta_i - n_t cos\theta_t}{n_i cos\theta_i + n_t cos\theta_t} \quad (4)$$

$$R_s = \frac{2 n_i cos\theta_i}{n_i cos\theta_i + n_t cos\theta_t} \quad (5)$$

$$T_p = 1 - R_p \quad (6)$$

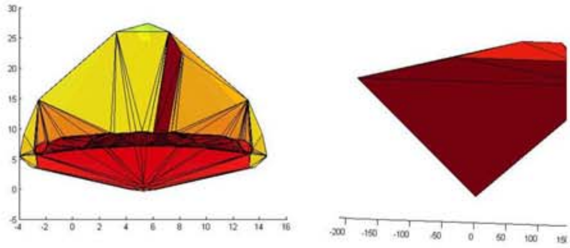
$$T_s = 1 - R_s \quad (7)$$

At the point of intersection of the wave with the change of the medium likelihood of reflection and refraction is being calculated by comparing conservation energy of the wave at the given point. If the conservation energy at a given point is < initial energy*0.1, respective ray will not be considered in further calculations.

Several theories have been incorporated to capture the selected electromagnetic wave properties and optical phenomenon to the mathematical model. In the domain of physics, electromagnetism is a major area of interest. Incorporating electromagnetic and optics theories can make the model more related to the real phenomenon. Thus, it helps maritime decisions to be more accurate on identifying the surrounding.

As defined in "The basics of physics" [15] reflection is one of the obvious properties of light. Reflection is referenced by referring to the incident rays and reflected rays. Incident rays are ones strike on the surface, and reflected rays are ones strike off the surface. The angle of incidence is the angle between an incident ray and a normal drawn perpendicular to the reflecting surface at incident point. According to the Fermat's principle of law of reflection states, that the angle of reflection equals the angle of incidence and that the reflected rays, incident rays and surface normal lie in the same plane. In the prototype, we consider both specular and diffuse reflections.

As defined in [16]and [17] in optics and physics, Snell's law also known as the law of refraction is used to define the relationship between



incidence angle and refraction angle, when electromagnetic wave passing through a boundary between two different mediums.

Snell's law has been defined by the ratio of the sines of the angles of incidence and reflection, which

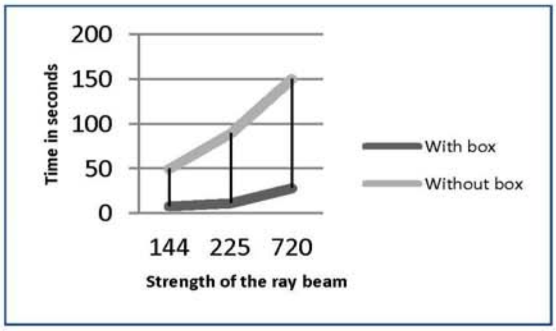


Fig. 10. Bounding box concept varying with time in simple vessels

alternatively defines to be the ratio of phase velocities
in the two mediums or equivalent to the reciprocal of the ratio of the indexes of refraction.
In the virtual dynamic marine environment, targets are given a random velocity. Radar observes the change in frequency of a wave for a source which is moving relative to targets. Change of the frequency is defined as Doppler Effect. In this model, we consider two scenarios where targets move towards (8) and outside (9) to the radar. In both cases frequency differs as follows.

$$fi = \frac{V}{V - Vs} f \quad (8)$$

$$fo = \frac{V}{V+Vs} f \quad (9)$$

Radar screen will be updated with the 2D visualization of the captured 3D environmental data time to time. At each wave propagated cycle, targets will be plotted as the coverage of 3D virtual environment. Identified targets will be delivered as the 2D visualization as shown on (Fig. 6).

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IV. DISCUSSION AND ANALYSIS

Output of our proposed mathematical model is being compared with real time marine radar output (Fig. 6) by Sri Lankan naval radar experts. While evaluating the mathematical model we found that simulation time is directly correlated to the angle between two adjacent rays. An evaluation is being conduct to find the means of improve the possibilities to enhance the performance of the mathematical model to capture the real-time scenario. Incrementing the angle between two adjacent rays will enhance the performance and efficiency while allowing small gaps in ray angle will reduce the performance as clearly stated in figure (Fig. 7).

We identified that low polygon vessel structures are increase the performance of the real-time model comparing to complex vessel structures (Fig. 8 and Fig. 9). Simple vessel structure is being model with lesser number of polygons maintaining simple geometry. We have identified that polygon count of the object directly correlate with the simulation time while after using polygon simplification techniques like introducing low polygon count objects will drastically reduce the simulation time though it lies on exponential curve.

Bounding box (Fig. 10) concept is an optimization methodology where it estimates the rays that intersect with the box and directs the identified rays to real target. Consequently, the number of rays will be limited and it is certain that those rays have the higher probability on intersecting with the target.

V. CONCLUSION AND FUTURE WORK

Marine radar in 3D virtual environment molded using scene graph representation where it captures the dynamic behavior of the 3D environmental in a realtime manner. Finally it gives the 2D visualization of the dynamic behavior of the 3D environmental data time to time. Proposed model captures electromagnetic optical properties namely; shape, refractive index and luster, optical phenomena namely; reflection and refraction, propagation phenomena namely; attenuation and free space path loss into the model. Doppler Effect has been incorporated in to the model to capture the frequency change of the moving vessels. In order to capture the propagation path loss, electromagnetic wave, model considers 10% of origin gain of the wave need to preserve for further interactions and calculations. We have identified time complexity of the simulation arises with the emitting beam strength. Where angle between two adjacent rays decreases simulation time exponentially increases. Processing of complex vessel exponentially increases the simulation time. Identified solution for the complex vessel structures are simple polygonal vessels which represents the vessel using limited polygon count. Our mathematical model is being evaluated by Sri Lankan Navy radar experts. For future work we are hoping to extend this model by enhancing the real-time behavior of the system by using parallel computing techniques.

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