FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

FACULTY OF ENGINEERING

Ray Tracing Simulation of optically pumped Laser Crystals

Masters Project

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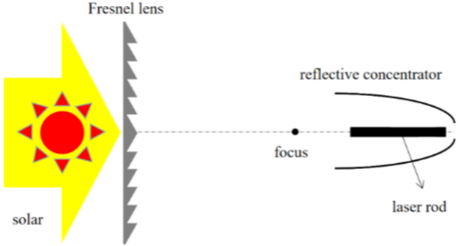
Motivation



Problems to solve:

1. Build a framework for physically accurate raytracing
2. Calculate absorbed power
3. Optimize mirror shape

In the Masters Project a 2D proof of concept was developed.

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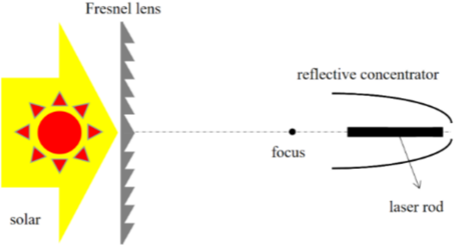

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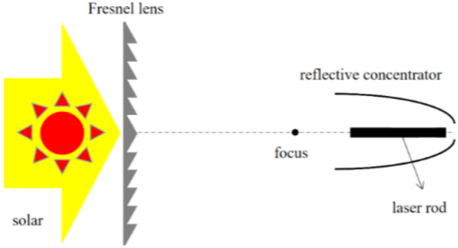

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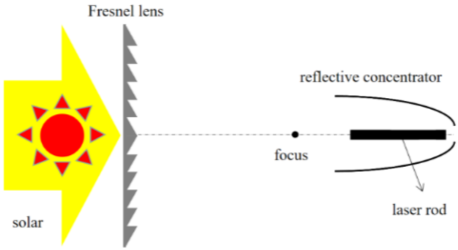

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Outline

Ray Tracing Basics

Scene Tracing

Sampling Techniques

Reflection and Refraction

Calculating Absorbed Power

Outlook for Masters Thesis

Ray Tracing Basics

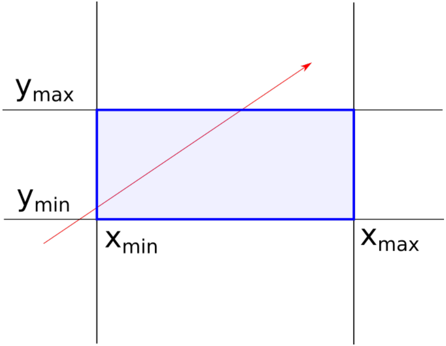
Parametrization

All points along a ray are described as follows:

$$\boldsymbol{r}(t) = \boldsymbol{o} + t \cdot \boldsymbol{d}$$

Testing intersections against primitives involves solving for the parameter t.

Example: Axis aligned box intersection



Parametrization contd.

Solution:

```
    float tx1 = (xmin - ray.origin.x) / ray.direction.x;
    float tx2 = (xmax - ray.origin.x) / ray.direction.x;

    float tmin = min(tx1, tx2);
    float tmax = max(tx1, tx2);

    float ty1 = (ymin - ray.origin.y) / ray.direction.y;
    float ty2 = (ymax - ray.origin.y) / ray.direction.y;

    tmin = max(tmin, glm::min(ty1, ty2));
    tmax = min(tmax, glm::max(ty1, ty2));
```

Other primitives in 2D can be lines, cricles, etc.
Or in 3D triangles, quads, spheres, etc.

All objects in a scene need to be built with a collection of such primitives.

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Scene Tracing

Scene Tracing

If a ray hits an object new rays are genertated according to its type of surface (reflection, refraction).

These new rays are traced again through the scene.

$\Longrightarrow$ Recurse until a desired "depth".

An object is intersected if one of its primitives is hit.

$\Longrightarrow$ Need to check each primitive of every object in the scene.

Runtime of a scene tracing step with N objects with M primitives each:

$$O(N * M)$$

Hierarchical Bounding Volumes

Performance optimization:

1. Preprocessing: Attach a bounding box around each object and recursively subdivide.
2. Tracing: Check if ray hits bounding box. If yes recursively check its subdivisions.

Runtime of a scene tracing step with N objects with M primitives each and 5 recursive subdivisions:

$$O(N * (5 * 4 + M/4^5)) = O(N * M/1024)$$

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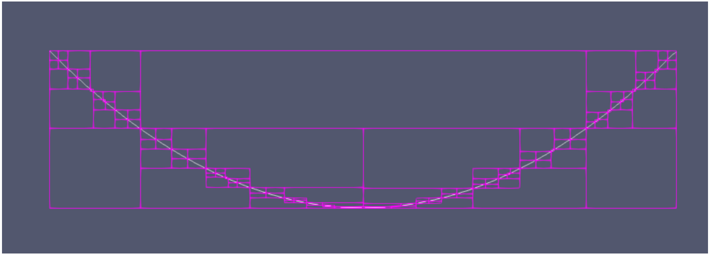
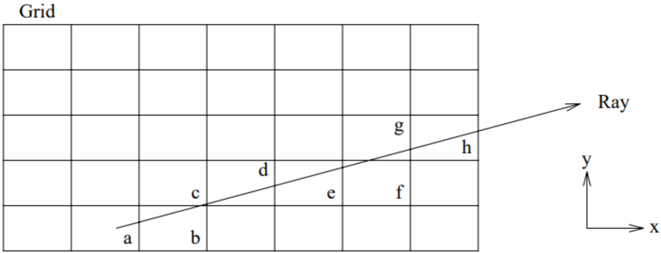
Mirror

Mirror consists of 2D line segments arranged by a 1D shape function (parabolic for testing purposes).



Crystal

The laser crystal is a 2D Box with an internal grid structure and grid tracing algorithm.
Rays need to be traced through cells **in order**[1] because of the absorbed energy calculation.



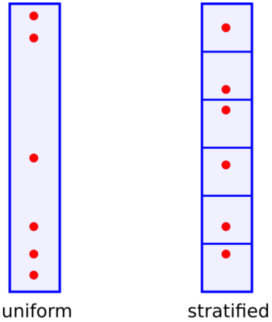
[1] A Fast Voxel Traversal Algorithm for Ray Tracing, John Amanatides, Andrew Woo, University of Toronto

Sampling Techniques

Generating Rays and Random Sampling

The goal is to randomly generate a cone of rays originating in the focus of the fresnel lense.

$\Longrightarrow$ Uniformly sample the opening angle around a direction vector.



$\Longrightarrow$ Not ideal in this case (big gaps between rays)

$\Longrightarrow$ Better: Stratified Uniform Sampling

Inversion Method

In reality sunlight consists of unpolarized light with a specific frequency spectrum. Thus the rays need to carry information about their power, frequency and polarity.

$\implies$ Need mechanism to generate random samples x according to a given distribution density function $p(x)$ (gauss, poisson, sun spectrum, etc.)

Inversion Method:

1. Integrate(sum up) the distribution $p(x)$ in uniform steps x and save the value for each step resulting in $P(x)$.
2. Uniformly sample $\xi \in [0, 1]$ and figure out in which interval it lies.
3. Interpolate linearly within the interval and return resulting x value.

Frequencies and polarisations of rays are not implemented as of yet.

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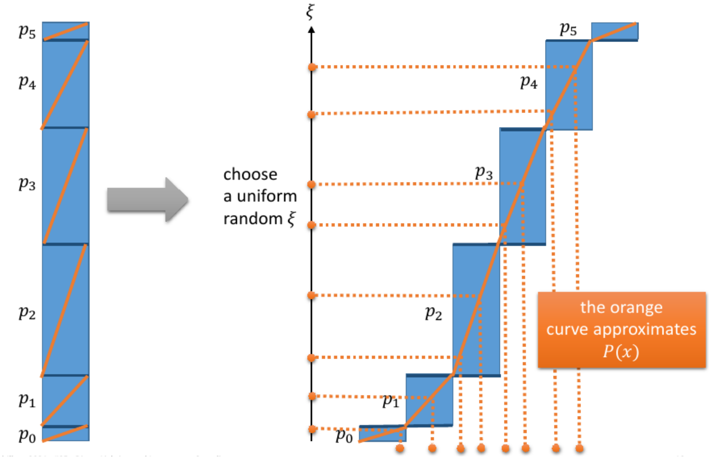
Inversion Method contd.



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Reflection and Refraction

Reflection

A ray is reflected by creating a new ray with the origin at the intersection point and the direction determined by the incident angle.

$$\theta_1 = \theta_2$$

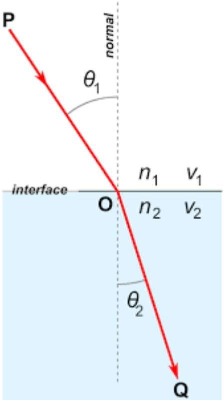
where θ_1 is the incident angle and θ_2 is the reflection angle.

Refraction

Refraction is modelled accurately by Snells' law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

where n_1, n_2 are the indices of refraction.



Fresnel Laws

The transmitted and reflected power can be calculated with the transmission- and reflection rates given by Fresnel's laws.
These are dependent on the orientation of the polarization of the incident ray (perpendicular or parallel) to the surface:

$$R_\perp = \frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)}$$

$$R_\parallel = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)}$$

$$T_\perp = 1 - R_\perp$$

$$T_\parallel = 1 - R_\parallel$$

Fresnel Laws contd.

For now unpolarized light is assumed and only one refraction takes place so the total rates are:

$$R_{total} = \frac{R_{\perp} + R_{\parallel}}{2}$$

$$T_{total} = \frac{T_{\perp} + T_{\parallel}}{2}$$

This will be changed in the future since in reality absorption in the crystal also depends on polarization.

Calculating Absorbed Power

Calculating Absorbed Power

The remaining power of a ray passing through the crystal is calculated by:

$$I_{out} = I_{in} \cdot e^{-\alpha d}$$

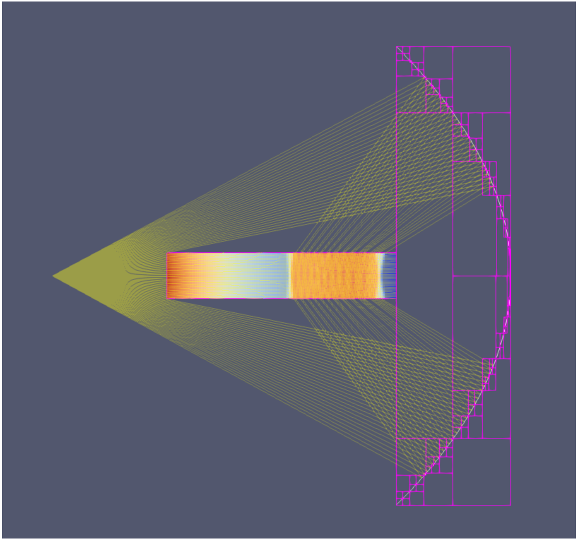
where α is the absorption coefficient d is the distance travelled through a cell. Thus the absorbed power is:

$$I_{abs} = I_{in} - I_{out}$$

In reality the α is frequency dependent but this is not implemented yet.

Outlook for Masters Thesis

Results



Outlook

Todo:

1. Implement custom distribution sampling
2. Use frequency and polarity in raytracing/absorption
3. Make step to 3D or correct 2D values for 3D usage (transversal rays cannot be modelled).
4. Optimize mirror shape using freeform shape functions
5. Model the Fresnel lense and divergent sunlight

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Thanks for listening.

Any questions/suggestions?

References

References I

[1] A. W. John Amanatides, *A Fast Voxel Traversal Algorithm for Ray Tracing*. [Online]. Available: `https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.42.3443&rep=rep1&type=pdf`.

[2] M. Stamminger, *Global Illumination SS21*. 2021. [Online]. Available: `https://www.studon.fau.de/crs3792557.html`.