Delft University of Technology
Faculty Electrical Engineering, Mathematics,
and Computer Science

Examination for

Course IN4151 - 3D Computer Graphics and Virtual Reality

Monday, 28 August 2006, 14:00 – 17:00 h.

Please use a separate sheet for each question.

Write on **each sheet**: your name + initials, study number, course code (IN4151), date, and the question number. This is important because each question is graded separately.

Criteria for receiving the maximum grade per question are correctness and brevity of the answers. Make sure your writing is legible and drawings are clear! You are free to use English or Dutch.

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1. a. *Describe the different steps in the viewing pipeline. Which coordinate systems are used? (4)*
In the viewing pipeline the vertices of the objects are transformed from the object coordinate system via the world coordinate system to the viewing (or eye) coordinate system. The vertices are then clipped and projected with a perspective projection on the image plane. The projected vertices are then mapped to the screen coordinates with the window to viewport mapping.
The object coordinate system is the coordinate system where each individual object is defined. The objects are placed within the world coordinate system with the object-world transformation. The viewing coordinate system has its origin in the eye position (center of projection) and the z-axis aligned with the viewing direction and the x-axis perpendicular to the viewing direction and the up vector. The screen coordinate system represents the scanlines and pixels of the display device.

b. *Describe the operations for the vertex and the pixel/fragment processing stages in the graphics hardware. (3)*
The vertex processing concerns the vertex related processing such as the shading calculation, the viewing transformation, perspective transformation and clipping, and the window to viewport mapping. As these stages each have a fixed number of calculations, a multi-processor implementation is best done in a pipeline. The fragment and pixel processing takes care of the scan-line processing (edge and span interpolation) and the depth buffer, texture mapping and filtering, and anti-aliasing. As these operations differ by the amount of pixels that are processed for each fragment , and may also involve some re-swapping of textures, these operations can best be performed in a farm.

c. *Which load balancing issues do occur between these stages and between the pixel/fragment processing and the frame buffer?* (3)
If there are many small polygons (or the projection of the polygons are small) then there is heavy vertex processing and only light pixel processing. When there are only a few large polygons in the scene then the vextex processing is neglectable and the pixel processing dominates. The frame buffer is distributed over the pixel processors to avoid having a bottle-neck of all pixel processors writing to the same framebuffer. The frame buffer distribution is interleaved to avoid situations where all processing is done bu one porcessor because all polygons are clustered (eg. near the horizon).

2. a. *The Phong reflection model is given by* $I = I_a k_a + I_i(k_d(\mathbf{L}.\mathbf{N}) + k_s(\mathbf{R}.\mathbf{V})^n)$. *Describe the three components of the model and the physical meaning of the parameters* k_a, k_d, k_s *and n. How is colour represented? (4)*

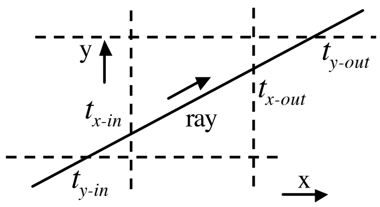
The first component is the ambient reflection due to indirect (background) light. The second component is the diffuse reflection which reflects the light from light sources equally over all directions. The third component is the specular reflection that reflects the light from light sources in the mirroring direction. The parameters k_a, k_d, k_s describe the material specific reflection properties that account for the different reflection and absorption characteristics for the different colour bands. The parameter *n* describes the distribution of the specular reflected light. A small *n* gives a large spread (dull surface) while a high value gives a sharp peak (glossy reflection). The light sources I are specified as a vector for R,G,B or any other muti-dimensional colour system. The k_a, k_d, k_s are in the same way also specified as vectors.

b. *What are the major limitations of the Phong model? Describe some approaches for improving the local reflection model. (4)*
The Phong model is just an empirical model that decomposes the complex reflection behavior into the two main components diffuse and specular reflection. In reality the reflection is a complex function that is not a linear combination of diffuse and specular reflection. The Phong model also assumes a perfect smooth surface and does not take into account surface roughness, i.e. perturbations due to small surface facets, nor does it take self-shadowing into account. Due to Fresnell effects, there are colour changes for different incident angles. The Cook-Torrance reflection model compensates for these effects. Finally the reflection is assumed to be isotropic (independent of the incoming orientation on the surface), while some materials are anisotropic (eg. brushed aluminium).

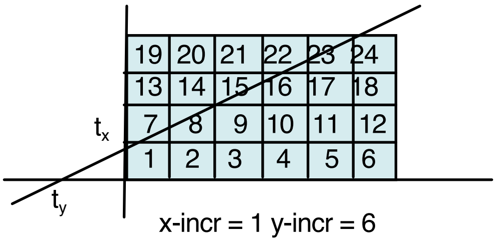
c. *Describe two extensions of the reflection model to take into account 'global' information (as can be sampled with ray tracing). (2)*
Ray tracing can add the sampling of the indirect light at the surface (mirroring, refracted and indirect-diffuse reflection) . A special case of refraction is the subsurface scattering with occurs in substances like milk and the human skin.

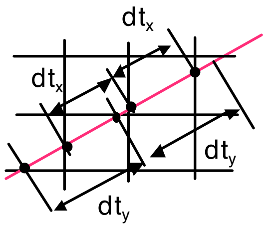
3. a. *Describe the hierarchical bounding box method and the associated ray-box intersection algorithm. (4)*
With the hierarchical bounding box method, objects are enclosed by boxes and these are recursively clustered (bottom-up) and enclosed with bounding boxes. The ‘world’ box at the top of the tree encloses the whole scene. During ray tracing, first the world box is tested and when the ray misses the box, then there is no intersection, otherwise, the boxes at the next level (contained in the box) are tested for intersection. This is recursively done until the enclosing boxes of the objects. If the ray intersects the object bounding box only then a ray object intersection test is done.

The ray-box intersection algorithm calculates the intersection with the three forward facing planes of the box and with the three backward facing planes. If t_{x-in}, t_{y-in}, t_{z-in} and t_{x-out}, t_{y-out}, t_{z-out} are the ray parameter values for the forward facing and the backward facing intersections with the x, y and z planes respectively, then the entry intersection with the box is $t_{box-in} = max\ (t_{x-in}, t_{y-in}, t_{z-in})$ and the exit intersection is $t_{box-out} = min\ (t_{x-out}, t_{y-out}, t_{z-out})$, assuming $t_{box-in} \leq t_{box-out}$, otherwise there is no intersection.



b. *Describe the ray traversal algorithm for a voxel grid. (4)*
First calculate the ray intersections with the *x*, *y* and z forward facing and backward facing bounding planes of the total voxel grid. Further calculate the parameter increment for the *x*, *y* and *z* direction. The first intersection is $t_{in} = max\ (t_x, t_y, t_z)$. The next intersection is the minimum of the incremented values.





Initialize for first intersected cell t_x, dt_x, t_y, dt_y
Do until intersection found or out of worldbox

  $tt_x = t_x+dt_x$
  $tt_y = t_y+dt_y$
  if $tt_x < tt_y$ then
    $nc = nc+xincr$; $t = tt_x$; $t_x = tt_x$
  else
    $nc = nc+yincr$; $t = tt_y$; $t_y = tt_y$

c. *What are the advantages and disadvantages of the hierarchical bounding box method compared to the regular grid method? (2)*
The grid method is optimal for large numbers of small objects that are evenly spread over space. When there are a relative small number of complex objects that are compactly clustered within a large empty space then the hierarchical bounding box method is more advantageous. The grid traversal stops when an intersection point is found, while for the bounding box method the tree lay out is not depth-ordered.

4. a. *Explain the radiosity method. (4)*
The radiosity method calculates the energy exchange within a closed environment by subdividing the surfaces in patches and by calculating the energy exchange between the individual patches on basis of a form factor describing their mutual distance, orientation, surface area, and visibility. This results in a set of *n* equations for *n* patches, where for each patch *i* the unknown radiosity B_i is described as the sum of the (unknown) radiosity values (or known intensities for the light source patches) of all other patches weighted by their form factor for that patch. As no directional information is stored in the radiosoity value the method only works for diffuse reflection.

b. *Which methods can be applied to solve the set of linear equations? (4)*
The set of linear equations can be solved (simultaneously) with standard direct methods such as Gaussian elimination. Iterative relaxation methods such as Jacobi or Gauss-Seidel (solve by row) or Southwell (solve by column) represent “gathering” and “shooting” analogues. These itereative methods do not require to have all data in internal memory. Progressive radiosity is a shooting algorithm where the order of shooting is determined by the highest unshot energy. This method allows previewing.

c. *Standard radiosity is viewpoint independent. If we want to adapt the accuracy to the viewpoint which strategies could be applied? (2)*
The mesh refinement can be made viewpoint dependent. After a change in the mesh structure a re-allocation of the radiosity values has to be done. Also a “final gathering” pass can be done to re-calculate the radiosity values of patches nearby at a higher accuracy and resolution.

5. a. *List the differences between HMD display and projective VR displays (such as the CAVE). Which (different) requirements do these methods pose on the rendering engine? (4)*
In a HMD there is a separate display for the left and for the right eye, while in a projective system the left and right image are projected simultaneaously on the project screen and shutter glasses have to be used to separate the left and right image by using polarization, colour bands

(red-green) or interleaved display. In standard HMD-VR is the user is completely submerged in the virtual world, while for augmented reality the virtual information is presented in overlay with the real world.
For HMD the image update has to be extremely fast (< 20 ms) because with change of viewing direction (i.e. head rotations) the virtual images has to be completely updated, while for projective systems, the perspective projection stays the same and only has to be updated for changes in viewing position, which only occur at a slower pace.

b. *What are the simplifications of reflection mapping, environment mapping and spherical mosaics (eg. Quicktime VR) with respect to the full plenoptic function? (3)*
The plenoptic function describes the incoming light as a function of viewing position, viewing direction and time. Spherical mosaics are only for a specific time and position. To get intermediate values we need interpolation. Environment mapping simplifies the function to a lookup in surrounding texture cube or sphere. It is only correct for the center of the cube/sphere and an approximation for the other points. Reflection mapping is a plain texture map simulating the reflection of the environment.

c. *What kind of "level-of-detail" techniques could be applied in a flight simulator? (3)*
Most used are geometric simplications, a low polygon-count is used for far away objects and full resolution is used for nearby. At a larger distance, shape details can be replaced with texture and finally be replaced with single, textured polygons (imposters). Textures can also be simplified as a function of distance and shading complexity, or be replaced by Gouraud shading.

6. a. *Describe a procedural method to simulate a flock of birds. Which three (types of) rules are used to govern the movement of the individual birds? (4)*
Each bird is represented by a particle. It has several parameters: position, orientation, direction and velocity of movement, wing orientation, etc. For every frame of the animation parameter values are calculated according to a set of movement rules. Then, at the particle position and orientation a bird geometry is rendered.

There are three types of rules:

collision avoidance: avoid collisions with nearby flockmates

velocity matching: attempt to match velocity with nearby flockmates

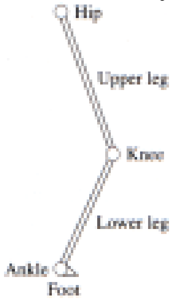
flock centering: attempt to stay close to nearby flockmates

b. *An animation path can be defined with a parametric function $P(t) = (x(t), y(t), z(t))$, for instance with third degree polynomials or interpolating splines. Normally it is not practical to use parameter t to represent time directly. How can we improve the possibility to influence the velocity of movement along the path? (3)*
Normally, equi-distant values in parametric space do not result in equi-distant points in Euclidean space. Therefore, if t is used to represent time, the velocity of movement of the object to be controlled by the parametric function will be arbitrary. To correct this, the following can be done:

- Calculate an arc length parameterization of the parametric function, so convert the parametric function into another parametric function (for instance with parameter t') where equal distances are traveled for equal changes in parameter t'.

- Use for instance slow in/slow out to control the speed of movement along the path.

c. *Make a drawing of an articulated structure representation of a human leg, showing all links and joints. Which transformations must be applied in which order to find the position and* *orientation of the foot in forward kinematics? (3)*



- translate the hip joint in the walking direction (tw)

- translate the hip joint in vertical direction (hip is not always at same height above the ground) (tv)

- rotate the hip-knee link (upper leg) about the hip joint (□1)

- rotate the knee-ankle link (lower leg) about the knee joint (□2)

- rotate the foot about the ankle joint (□3)

end of examination