TTK4550 Specialization Project

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Abstract

Sammendrag

Når man driller etter olje fra en flytende rigg eller et skip, så gynger platformen opp og ned på grunn av bølgene. Normalt blir røret regulert så det står stille selv om platformen/skipet går opp og ned. Men når man skal skru på nye rørsegmenter må røret holdes fast. Dette fører til at røret gynger opp og ned sammen med platformen, og blir som et stempel - som fører til store propagerende trykkendringer.

Dersom trykket blir for høyt eller lavt - kan dette føre til at berggrunnen i den nederste og åpne delen av brønnen slår sprekker eller kollapser inn.

I midten av/ inne i brønnen har man det som kalles en pipe. Inne i pipen pumper man en væske nedover (borevæske) som går opp igjen på sidene og tar med seg stein, olje og gass. I riser/cased section har man metall rundt på utsiden der væsken kommer opp igjen, mens i "open hole" er det bare berggrunn rundt. Dersom trykket blir for høyt eller lavt kan det føre til at bergrunnen slår sprekker eller kollapser inn.

Heavelock har laget en simulator som kan forutsi hvor store trykkendringene langs hele brønnbanen vil bli basert på værforhold og andre paramtere. Hensikten med denne prosjektoppgaven er å visualisere disse simuleringsresultatene på en intuitiv måte - slik at hvem som helst kan forstå den.

Visualiseringen (i 3D) implementeres for nettlesere, kun ved hjelp av verktøy som er open-source/gratis å bruke.

Structure

There will be a lot of details and background material that this report does not cover. Instead, the report attempts to give a higher level and intuition-focused overview of what has been done, how the flow of ideas evolved along the way, which insights were acheived - and the resulting architecture of the final application. Only the code in its final form will be included. The code is where you should look, in case you wonder about actual implementation.

It might be a good idea for the reader to have seen/been exposed to JavaScript/TypeScript, HTML, CSS and Python. Although, the hope is that this is not absolutely neccesary.

Introduction

Background: The Heave Problem

When drilling from a floating rig or drilling ship, the heaving motion of the floater causes major pressure fluctuations in the well when the drill pipe is in slips during connections. Pressure fluctuations in the order of 10-20 bars have been observed in practice, sometimes giving an unacceptable risk of mud loss or kick. The only remedy for the problem is to wait for wind and waves to subside. There is a potential for saving time and cost by obtaining accurate information about downhole conditions on which to base the decision to wait or drill forward. HeaveLock has developed a simulator that predicts downhole pressure fluctuations based on weather information, response amplitude operator of the rig, well geometry, fluid properties etc. The simulator produces a large amount of data and the data needs to be visualized to the user in an easy way. In this project work, the objective is to visualize simulator data for a chosen well by developing a web-based interface.

HeaveLock and HeaveSIM

HeaveLock is a startup in Trondheim that originally set out to create a valve to mitigate the pressure fluctuations caused by the heaving motion. On their way to acheiving this goal - they created a simulator to simulate the actual pressure fluctuations. It turned out that this tool in itself

was very valuable to the oil industry - as it could predict whether it was safe to drill on any given day (given weather conditions, well geometry and fluid properties). This simulator was named HeaveSIM. HeaveSIM produces a range of output files in .txt and .csv formats. Being able to visualize the output data in an understandable and intuitive way is of importance to HeaveLock and their customers - and is the problem that this project work intends to solve. Note that HeaveSIM itself will be considered a black box - where we are only concerned with actually visualizing the input and output data, and not the implementation of HeaveSIM itself.

The HeaveSIM output data

The HeaveSIM simulator produces a range of output files - organized in a folder structure. For the simulation "Connection_4749mMD" of "Well_2", we have the following structure (which is a mix of input and output files):

```
./HeaveSim simulations/Well_2/Connection_4739mMD/
```

- `pipestress.csv`
- `heavevelocity.txt`
- `well_path.csv`
- `geometrydef.txt`
- `pipepressure.csv`
- `chokeopening.txt`
- `trends.csv`
- `fluiddef.txt`
- `annuluspressure.csv`
- `controldef.txt`
- `chokedef.txt`
- `pipeflow.csv`
- `pipevelocity.csv`
- `bitdef.txt`
- `annulusflow.csv`
- `mainpumprate.txt`
- `drillstringcontrol.txt`

NOTE: For this project, only the files `geometrydef.txt`, `fluiddef.txt`, `well_path.csv`, `pipepressure.csv`, `annuluspressure.csv`, `pipestress.csv` will be used. The first three are input files, while the last three are output files.

About the .txt files

The .txt files all have the following format:

```
1.2 # This is a description of what the value 1.2 means
4   # This is another description for what the value 4 means
```

Notice how the value comes first on the line, and the comment/description comes after a `#`-symbol.

`geometrydef.txt`

The `geometrydef.txt`-file looks like the following (where the index represents the line number, starting at 0 for the first line).

Notice that we have four main sections of our well (which we will call our geometry types). These are the riser, cased section, liner, and open section/open hole. The pipe, heavy hight drill pipe and BHA reside somewhere inside of these four sections.

index	comment/description
0	Well diameter in inches (open section)
1	Inner riser diameter in inches

index	comment/description
2	Length of riser in meters
3	Inner casing diameter in inches
4	Length of cased section in m (approximate, casing shoe set on nearest cell interface)
5	Inner liner diameter in inches
6	Length of lined section in m
7	Pipe length in meters (total length is pipe length+bha length+heavy weight drill pipe length)
8	Heavy weight drill pipe length in meters
9	BHA length in meters
10	Inner pipe diameter in inches
11	Outer pipe diameter in inches
12	Inner heavy weight drill pipe diameter in inches
13	Outer heavy weight drill pipe diameter in inches
14	Inner bha diameter in inches
15	Outer bha diameter in inches
16	Density of pipe material in kg/m^3
17	Young's modulus for pipe material in bar (<0.0: Non-elastic drill string)
18	Poisson's ratio of pipe material
19	Static friction factor for drag force on pipe from well wall
20	Dynamic friction factor for drag force on pipe from well wall
21	Weight of BHA and heavy pipe in kg
22	Number of segments in riser section (riser segments must be longer than heavy weight drill pipe segments)
23	Number of segments in heavy weight pipe
24	Number of segments in bha
25	Index at location of HeaveLock within bha (No HeaveLock=0)

`fluiddef.txt`

index	comment/description
0	Mud density in kg/m^3
1	Mud plastic viscosity in cP
2	Mud yield point in lb/100ft^2 (Bingham plastic)
3	Mud low-shear-rate yield point in lb/100ft^2 (Herschel-Bulkley)
4	Mud bulk modulus in bar

`well_path.csv`

The well path is a semicolon-separated data file, where each segment is represented by its measure depth/curve length (md), azimuth angle (azi) and inclination angle (inc). Notice that we also have a column named tvd, which is the precalculated vertical depth at the end of each segment of the well path.

The azimuth and inclination angles are in degrees, and when both are zero, the segment is pointing straight down. The md and tvd columns are in meters.

```
Md;Azi;Inc;Tvd
10;0;0;10
20;0;0;20
30;0;0;30
```

In the example above we have three segments after each other with the same length (10m) all pointing straight down.

`pipepressure.csv`, `annuluspressure.csv` and `pipestress.csv`

These files all have the same format. They also share the same time steps and measure depths. See the example below:

```
0.0,50,150,300
0.0,0,1,2,3
0.1,1,2,3,4
0.2,2,3,4,5
0.3,3,4,5,6
```

From this data you can observe the following:

- The time of the simulation starts at 0.0, stops at 0.3 and has a step size of 0.1. (The first column represents the time)
- The simulation has data for each timestep for the measure depths 50, 150 and 300. (The first row represents the measure depths)
- The simulation values in this example increase as measure depth and time increases.
- At measure depth = 300 meters, and time = 0.3 seconds, the value is 6.

A word of warning: The measure depths in these three output csv files do not match the measure depths used in the well path definition. To work around this, some kind of interpolation would be needed.

How are we going to visualize this?

Using web browser technology that is widely available across browsers, this project work is going to create a 3D visualization of the well path, and use colors to represent the values from the simulations on each of the segments. In terms of using browser technology: this is only made practical and performant in recent years by something known as WebGL (Web Graphics Library).

WebGL is based on something called OpenGL, and allows the browser to utilize the GPU (hardware) for parallell processing. GPUs are typically what allows 3D-games with complex graphics to run smoothly on a computer or a mobile device. To get a better idea of how this can be done, we will look at how WebGL works.

So how does WebGL work?

More specifically, WebGL is a JavaScript API for rendering high-performance and interactive graphics (both 2D and 3D) without the use of plugins in any compatible web browser. The API can be used within the HTML5 `<canvas>` elements. Recently, WebGL 2 was released - but since it is not yet supported by all common browsers, this project will instead be using WebGL 1.

To tell the GPU how to render our scene, we write something known as “shaders” in a language known as GLSL (OpenGL Shading Language). GLSL resembles a restricted version of the C programming language, but with syntactic sugar for vector and matrix operations.

The two shaders that are supported by WebGL is the vertex shader and the fragment shader. The vertex shader is a piece of code that runs on every vertex of the geometry the gpu receives, and outputs this to the fragment shader. The fragment shader then runs on every pixel of the output image - giving each its own color. Usually, 3 and 3 vertices represent a triangle - which the fragment shader is aware of when coloring pixels. If two triangles overlap, the fragment shader might run twice on the same pixel. This is why it is called a fragment shader instead of a pixel shader - since it runs once for every fragment, but can sometimes run multiple times for any given pixel. You can think of a fragment as being a single pixel on a triangle, but not neccesarily the entirety of a single pixel in the final image that is rendered.

It is possible to pass parameters to the shaders from the outside. The first type of parameter is a uniform. This is a parameter that does not change from one shader invocation to the next within any particular rendering call. The second is a vertex attribute - which is a parameter specifically

linked to a vertex, meaning it changes from one vertex shader invocation to the next within a rendering call, but stays the same from one render call to the next for a specific vertex.

The WebGL API is low level - as you can only tell it what triangles to draw, and how to draw them. Imagine that you want to draw a cylinder, and have this cylinder reflect light in a certain way. This would both require a lot of JavaScript code, as well as GLSL code. Since we don't want to concern ourselves with how we can draw a cylinder using only triangles, or writing shaders for reflecting light - we will be using a 3D library that abstracts this away.

The 3D library we will be using is THREE.js. This is by far the most popular 3D library for JavaScript, with 59,000 stars on GitHub, 1192 contributors, and 21,000 forks.

How does THREE.js work?

To understand how THREE.js works, we need to understand the building blocks it uses to abstract away the low level API of WebGL.

Scene

A scene allows you to set up what is going to be rendered by THREE.js. Meshes, lights, and cameras are all "children" of a scene.

Example of creating a scene in JavaScript:

```
import * as THREE from 'three'
const scene = new THREE.Scene()
```

Camera

A camera tells the renderer where the "eye" is, and what will be rendered on the canvas. Typically, a perspective camera will be used when creating a 3D-visualization.

```
import * as THREE from 'three'
import { scene } from './some-file'
const fov = 45  // field of view in degrees
const aspect = 1.5  // aspect ratio (width / height)
const near = 0.1  // The closest distance where something will be visible
const far = 1000  // The furthest distance where something will be visible
const camera = new THREE.PerspectiveCamera(fov, aspect, near, far)

scene.add(camera)  // Adding the camera to a scene
```

Renderer

The renderer tells THREE.js how to render a scene - and WebGL (WebGLRenderer) is actually not the only alternative. (Later, we will be using something called CSS2DRenderer to draw labels on top of our visualization)

```
import * as THREE from 'three'
import { scene, camera } from './some-file'
const renderer = new THREE.WebGLRenderer({
    canvas: document.getElementsByTagName('canvas')[0]
    antialias: true,
    powerPreference: 'high-performance',
})

renderer.render(scene, camera)  // Renders a scene onto the canvas
```

Geometry

A geometry contains all the vertices (corners) of an object. It can also connect attributes to each of the vertices that are passed to the shaders. These could be precomputed normal vectors, colors, or uv-maps for textures. We could also define our own custom attributes if we want.

```
import * as THREE from 'three'
const radius = 1
const height = 2
// Note that we can have different radii on the top and bottom of the cylinder.
const geometry = new THREE.CylinderBufferGeometry(radius, radius, height)
```

Material

The material defines which shaders will be used to render a certain geometry. Some examples of shaders are: MeshBasicMaterial, MeshStandardMaterial, RawShaderMaterial. The RawShaderMaterial allows us to write our own shaders from scratch, using GSLS.

```
import * as THREE from 'three'
// basic material does not interact with light, and is always visible
const basicMaterial = new THREE.MeshBasicMaterial({ color: 'blue' })
// standard material has realistic reflections and is not visible without light.
const standardMaterial = new THREE.MeshStandardMaterial({ color: 'red' })
// shader material allows us to write our own shaders
const shaderMaterial = new THREE.RawShaderMaterial({
    uniforms: { time: { value: 1.0 } },
    vertexShader: '<vertex shader code here>',
    fragmentShader: '<fragment shader code here>'
})
```

Mesh

A mesh consists of a geometry (the vertices), and a material (the vertex and fragment shaders used to render the vertices). Essentially, one could think of a mesh as specifying what to draw (geometry), and how to draw it (material).

```
import * as THREE from 'three'
import { scene, geometry, newGeometry, material } from './some-file'

const mesh = new THREE.Mesh(geometry, material)
scene.add(mesh) // Adding the mesh to a scene
// We can switch the geometry or material of the mesh at a later point
mesh.geometry = newGeometry
// We don't need to re-add it to the scene.
// (Since the scene only has a reference to the mesh)
```

Light

A light is used when rendering to create reflections or shadows based on the type of material.

```
import * as THREE from 'three'
import { scene } from './some-file'
const color = 'white'
const intensity = 0.5
const light = new THREE.DirectionalLight(color, instensity)
scene.add(light)
```

Texture

A texture can be used to map an image to a surface. For example, it could be used to put the image of a tree on one side of a cube. By writing our own shaders (using RawShaderMaterial), we can access individual pixels of a texture if we want. Textures are generally really performant, since no communication between the CPU and GPU is neccessary once the GPU has received the texture.

Note that different devices might have different maximum limits on texture sizes.

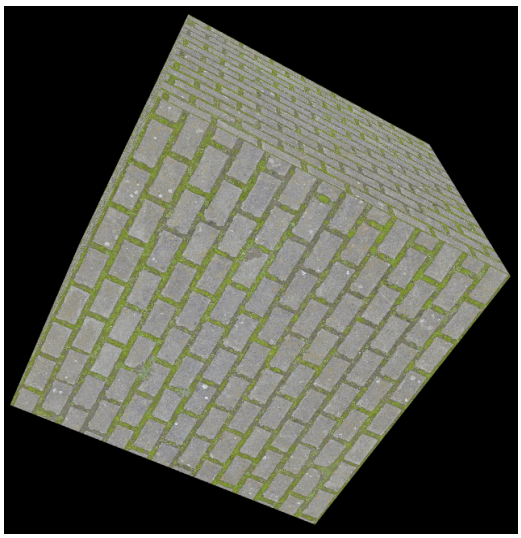


Figure 1: Example of a brick wall image being applied as a texture to the sides of a cube geometry. Source: https://threejs.org/examples/#webgl_loader_texture_basis

Implementation

Algorithm: Turning the well path into cylinders

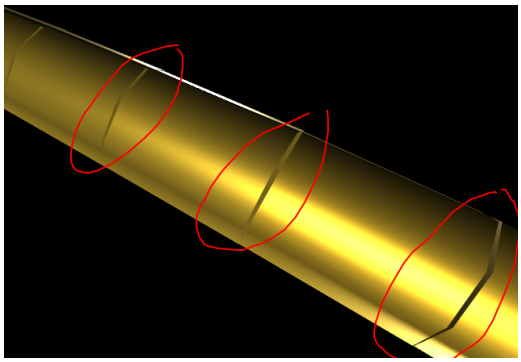


Figure 2: To represent the well path, we are going to draw one cylinder for each segment. A consequence of using cylinders to represent each segment is that we will get visible gaps between when they are rotated relative to each other (as highlighted in the picture)

We define a cylinder to have the following properties:

name	description
posx	Position of cylinder centre (x-coord)
posy	Position of cylinder centre (y-coord)
posz	Position of cylinder centre (z-coord)
rotx	Euler angle (X) in radians

name	description
roty	Euler angle (Y) in radians
rotz	Euler angle (Z) in radians
radius	Radius of the drawn cylinder
length	Length of the drawn cylinder

From our `well_path.csv`, we have the following columns of interest:

name	description
md	Measure depth at the end of segment (cummulative "curve length")
azi	azimuth angle of the segment (relative to world frame) in degrees
inc	inclination angle of the segment (relative to world frame) in degrees

Let $col[n]$ denote the value at the n'th row in the column "col" of the csv file (the first row is $n = 0$)

The length of a segment should simply be the change in measure depth between the current and previous segment (since we define measure depth to be the curve length up to the end of the current segment)

$$length[n] := md[n] - md[n-1]$$

Where we assume that $md[-1] := 0$.

The azimuth angle is our y-rotation, and the inclination angle is our z-rotation. We need to make sure the rotations are in radians and not degrees. Also, note that we assume $-\hat{\mathbf{y}} = (0, -1, 0)^T$ to be the direction when all angles are zero. (A pipe that is not rotated will point straight down)

$$\begin{pmatrix} rotx[n] \\ roty[n] \\ rotz[n] \end{pmatrix} := \begin{pmatrix} 0 \\ \text{radians}(azi[n]) \\ \text{radians}(inc[n]) \end{pmatrix}$$

As an intermediate step in finding the positions, we will create a vector for each segment. This vector will point from the start of the segment to the end of it. The vector without any rotations would then be $(0, -length[n], 0)^T$. After applying rotations (using rotation matrices), we get the following:

$$\mathbf{vec}[n] := \overbrace{\begin{pmatrix} \cos(roty[n]) & 0 & \sin(roty[n]) \\ 0 & 1 & 0 \\ -\sin(roty[n]) & 0 & \cos(roty[n]) \end{pmatrix}}^{\mathbf{R_y}(roty[n])} \cdot \overbrace{\begin{pmatrix} \cos(rotz[n]) & -\sin(rotz[n]) & 0 \\ \sin(rotz[n]) & \cos(rotz[n]) & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\mathbf{R_z}(rotz[n])} \cdot \overbrace{\begin{pmatrix} 0 \\ -length[n] \\ 0 \end{pmatrix}}^{length[n] \cdot (-\hat{\mathbf{y}})}$$

Taking the cummulative sum of the segment vectors up until the current segment will give you a position vector that points from the start of the entire well path to the end of the current segment. To get to the centre of the current segment, we can then backtrack by half of the vector for the current segment.

$$\begin{pmatrix} posx[n] \\ posy[n] \\ posz[n] \end{pmatrix} := \left(\sum_{k=0}^{n} \mathbf{vec}[k] \right) - \frac{1}{2}\mathbf{vec}[n]$$

You may now have noticed that we have every cylinder property wee need, except for one (the radius). The problem we are now faced with is that nothing in `well_path.csv` can tell us what the radius for a specific segment is supposed to be. To figure out this, we have to look at `geometrydef.txt` (which defines the different types of segments).

Algorithm: Finding the cylinder radiuses/geometry types

Let $g[n]$ represent the value at index/line number n according to the geometrydef.txt from the introduction. Let inches(x) be a function that converts x from inches to meters. Note that the riser is considered to be part of the cased section (which means that "length of cased section" includes the length of the riser). We will differentiate the riser from the rest of the cased section since they have different radii.

From this, we define our geometry types:

name	radius	md_start	md_stop
riser	$0.5 \cdot \text{inches}(g[1])$	0	$g[2]$
cased section	$0.5 \cdot \text{inches}(g[3])$	$g[2]$	$g[4]$
liner	$0.5 \cdot \text{inches}(g[5])$	$g[4]$	$g[4] + g[6]$
open hole	$0.5 \cdot \text{inches}(g[0])$	$g[4] + g[6]$	$g[7] + g[8] + g[9]$

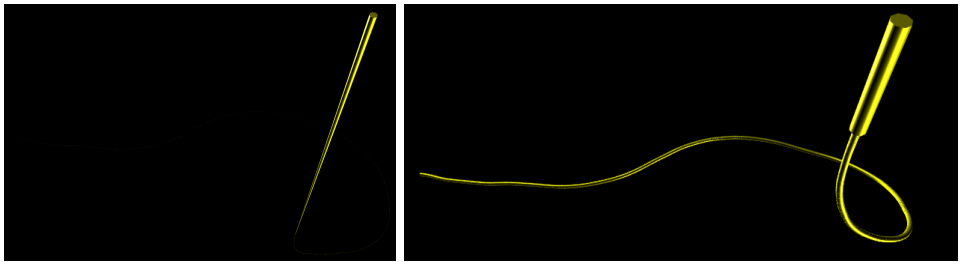
Using this table, it is now possible to set the radius on the cylinders from the previous section. Let the function geometry_radius(md) return the radius from the geometry type table above for which md_start $< md \leq$ md_stop. If no entry matches, return 0.

$$radius[n] := \text{geometry\_radius}(md[n])$$

Now that we have all our path segment properties for creating cylinders, let's create them in THREE.js and render them.

Rendering the well path with THREE.js

Using real-life lengths and radiuses make the pipe appear incredibly thin and long. This is not good for visualization purposes, since the path and the color of the cylinders are hard if not impossible to see from far away.



To solve this problem, we multiply the radius by a factor of 100 for all of the segments, and move a little backwards. The entire well path is now clearly visible at the same time, as you can see in the second picture. In total, around 1700 cylinders is rendered in the pictures above.

Now, this is all well and good - but how can we color each segment independently according the simulation data? Let's start by loading `pipepressure.csv` into the application.

Coloring the individual segments based on data

The `pipepressure.csv` for the well path you see in the image above is around 8MB in size - and this means it takes at least 8 seconds to load over a 8Mbit/s connection. That's a lot of data for a website to load at one time. It has around 2700 timesteps and 160 different measure depths. Notice that this is only around a tenth as many measure depths as our well path has. Before trying to optimize anything related to this, let's at the very least try to get it working.

To start off, we find the min and max values of the simulation data for every cylinder we want to draw. Then we can create a function that takes in time for each of the segments, and outputs a

color relative to the min and max values for that cylinder. This should allow us to see that every cylinder is changing color

For every iteration of the render loop, we then compute the 1700 colors and set them on the material (sending them to the GPU).

This works, but the performance is not great, at less than 20 frames per second. Both on mobile and desktop. It is expensive to compute the colors for every iteration. It is also expensive to send a lot of data to the GPU often in the main render loop. If we want to acheive 60 frames per second (which is what most monitors can display), it means that every iteration of the render loop can only take at most 16.67 ms to run.

So how could we reduce the amount of time spent in each iteration of the main render loop? What about precomputing all of the colors, into a 2 dimensional array of the color values? Each field would then contain the color as a hexadecimal string.

Precomputing colors of the segments

Good, and bad news. Let's start with the good news. After precomputing all of the colors as hexadecimal strings, the performance doubles to almost 40 frames per second on my laptop - even though we still have to send 1700 colors to the gpu every frame.

When it comes to the bad news: Although it improves the framerate once precomputed, it takes around half a minute to do so. In other words, this is not acceptable. On mobile it doesn't work at all - it keeps on precomputing until it crashes, because it runs out of memory.

Let's do some calculations and find a lower limit for how much memory this uses: One character in javascript uses 2 bytes. A color on hexadecimal form (example: `'#ff0000'`) is 7 characters. We have precomputed 2700 color strings for each of the total 1700 cylinders. This means we are now at around

$$2\text{B} \cdot 7 \cdot 2700 \cdot 1700 = 64\text{MB}$$

64MB of data should not be crashing a mobile browser. (although it is still a mouthful for a mobile browser to deal with) This must mean that our first attempt at this was rather inefficient. Maybe there is a way to do this more efficiently.

But wait - we are trying to precompute a 2-dimensional array of colors? Isn't there another name for this? This is also known as **an image**, right?

Precomputing an image

Using python 3 with the libraries pandas, and matplotlib, it is relatively easy to load the csv for the simulation into memory, and save it as a heatmap image. Notice that we transpose the image, just because we want the time axis to be horizontal, and measure depth to be vertical, as this feels more intuitive.

```
import pandas as pd
import matplotlib.pyplot as plt
pipepressure = pd.read_csv('./pipepressure.csv', index_col=0)
plt.imsave('./pipepressure.png', pipepressure.transpose())
```

This looks pretty interesting already - but that gradient from the top conceals the fluctuations we are interested in. To remove the gradient, we will use the Md and Tvd-columns of `well_path.csv` to find the relationship between measure depth and vertical depth, along with the mud density from `fluiddef.txt` to remove the gravity related component of the pressure. This gives us:

And guess what, this operation took less than a second. The resulting image is around 100kB in size. Compared to pipepressure.csv, this is an 80x reduction in size! How is this even possible? Most likely due to lossless image compression along with a much more compact format than storing numbers as text. Image compression is something that has likely been worked on a lot, which we can reap the benefits of here.

This means that first of all, we might no longer need to load 8MB of data, and secondly, we don't need to wait half a minute on a laptop/crash the mobile browser due to running out of memory. It seems that a lot of problems are going to be solved. The next step now is to read the image in to the client.

Loading the image in to the client

We already discussed how iterating over all of the segments and sending 1700 colors to the gpu on every frame affected performance. Now that we have an image, we should in theory be able to transfer this to the GPU as a texture, and perform the pixel lookups on the image from within the GPU! For this we would have to write our own GLSL shaders (using RawShaderMaterial in THREE.js).

Something else that has been affecting performance (which was not mentioned previously) is the fact that we have 1700 meshes in our scene, which the renderer has to iterate over for every frame on the cpu. To fix this, we could in theory merge all the cylinder geometries into a single geometry. To differentiate between the cylinders (from within the GPU), we could give all the vertices in each cylinder a vertex attribute, to tell us which measure depth it represents. Or even better, we just tell it which row of the image/texture it represents.

We would then also give the current time as the image column (using a uniform) to the shader material we will be applying on the entire geometry.

This means that every vertex now has both a texture column and a texture row to look at - yielding a single pixel. One single color for each vertex. Since each cylinder shares the same image row, all its vertices will have the same color.

To sum up, the following will determine the color of each cylinder:

- A texture created from the pregenerated image (accessible from all the vertex shaders)
- An image row (vertex attribute) that was assigned to all the vertices of each cylinder
- An image column (uniform passed to all vertex shaders).

As previously mentioned, however - it would be ideal not to have to write our own shaders from scratch (with light reflections and everything). Turns out we are in luck, since there exists a library called THREE.BAS.

What is THREE.BAS?

THREE.BAS (THREE Buffer Animation System) is a library that allows us to reuse the materials in THREE.js, while injecting our own shader code snippets in a relatively clean way. This means we only need to write the shader code for the exact logic we need - while we are able to reuse the rest of the shader code that THREE.js already wrote for us - except we now control the color from the inside of the gpu instead of the outside. Essentially, we don't need to use RawShaderMaterial directly after all.

What happens to performance now?

First we compute the imageRow for every cylinder geometry, and set this as a buffer attribute every vertex in the cylinder. Next, all the cylinders are merged together into a single geometry (carrying over their attributes).

This geometry is combined with a custom `THREE.BAS`-material to pick color based on imageRow (attribute) and imageColumn (uniform). In the main render loop, we change the imageColumn uniform of the material for every time step. Instead of sending 1700 colors every time step, we now

only send one number: the imageColumn. It is unlikely that it is possible to reduce the amount of data sent between the cpu and gpu each timestep by more than this.

The result is 60 fps on both mobile and desktop. The frame rate is at the maximum the monitor can provide. It was possible - and even quite elegant to acheive. Exactly how the imageRow is computed might be of interest - so this will be discussed in the next section.

Algorithm: Computing imageRow for each cylinder

The first thing to realize is when reading a texture in WebGL, the image dimensions are considered to be 1x1, and you use floating point decimals to specify the row or column. This means that row=0.5, column=0.5 is in the middle of the texture, while row=1.1, column=0.5 is outside of the texture.

To compute the imageRow for each cylinder, we need to look at both `well_path.csv` and `pipepressure.csv`. Why? The image itself is generated from `pipepressure.csv`, so the pixels in the vertical direction corresponds to the measure depths that were used in the simulation. While each cylinder corresponds to the measure depths from `well_path.csv`.

Consider the following example:

measure depths from `pipepressure.csv`	imageRow
50	0.00
150	0.25
300	0.50
400	0.75
500	1.00

We now want to define a function md_to_image_row($md[n]$) which takes a measure depth, and returns an imageRow. When we input md=75, we want the ouput to be 0.125. If we input 350, we want the ouput to be 0.625. This means md_to_image_row will be a linear interpolation between the measure depths, and a linear space of equally distributed values between 0 and 1.

We can apply this function to every measure depth in the `well_path.csv`-file to give each cylinder an imageRow:

$$imageRow[n] := \text{md\_to\_image\_row}(md[n])$$

This could lead to a cylinder receiving either a negative imageRow, or one greater than 1.0. This is not a problem, as we will simply color these cylinders grey in the THREE.BAS material (assuming they exist in the first place)

It seems like we still need to load `pipepressure.csv` into the browser to do what we want - or do we?

Creating a Python API.

To avoid sending unneccesary data to the client, we will create a Python API - which will be responsible for generating images dynamically/on demand (as previously seen), as well as creating and returning a list of the cylinder data structures, which in their final form have the following properties:

name	description
posx	Position of cylinder centre (x-coord)
posy	Position of cylinder centre (y-coord)
posz	Position of cylinder centre (z-coord)

name	description
rotx	Euler angle (X) in radians
roty	Euler angle (Y) in radians
rotz	Euler angle (Z) in radians
radius	Radius of the drawn cylinder
length	Length of the drawn cylinder
imageRow	Row of the generated image to access in the vertex shader

Doing this means that all of the "hard work"/most of the algorithms are offloaded to the server, and only the bare minimum data needed for visualization needs to be loaded by the client. Another advantage is that the API can be protected by a password - to prevent unrestricted access to data.

Along with the API, we also create a reverse proxy, which routes any url paths starting with /api, and /docs to the Python API instead of to the client resources (such as index.html, css files and javascript bundles). This is to avoid thinking about Cross Origin Resource Sharing (CORS), which can be its own adventure.

At last we have finally met our performance goals. Having both a high framerate, and a low load-time for our application. The client is still loading several hundred kB of data. It is likely that it would be possible to reduce this even more - using a more compact packing format for the geometry data.

Additional functionality

An interactive timeline displaying the image

At the bottom of the application, we will create an interactive timeline - which will display both the current time, allow for changing the time - as well display the image being projected onto the cylinders.

Casing Shoes

At the end of each geometry type, we have what is known as a casing shoe. These are visualized as rings in the client - along with labels. The idea is to make it clear where these transitions happen - as the change in radius of the segments might not be big enough to be noticable. The labels are also useful in showing what the actual sections are called.

A GUI Config Panel

Using the JavaScript library `dat.gui`, we are able to create a GUI panel in the application where you can do things like select well and connection for a simulation, set the thresholds used for generating an image, show or hide the casing shoes/labels, an fps counter.

Cross-Browser compatibility

A lot of work has been put in to making the application work in as many browsers as possible. This includes browsers such as Google Chrome, Mozilla Firefox, Mobile Browsers (iOS and Android), Internet Explorer 11 and Microsoft Edge.

Some of the steps taken to ensure this is the following

Transpilation

JavaScript code is "transpiled" to an older version of the JavaScript standard. That is - its syntax is transformed to a less elegant, but older version of the language that is supported by more browsers. The transpilation step is performed using the bundler "FuseBox v4" in this project. FuseBox also "minifies" the code - renaming variables to shorter names and removing all whitespace. This is a common step for minimizing the amount of data the browser has to load.

Polyfills

Although you can transpile the syntax to an older version, this isn't always enough. When a new feature has been added to JavaScript and you are using it - you will need to include a "polyfill" for this feature. This means you include an implementation of the feature in the older standard - which can be used in case the browser has not implemented the more recent feature.

Even though you make sure to transpile and include polyfills for all the features you are using, this is usually not enough - and ultimately, physically or automatically testing in each of the browsers is the best way of figuring out if it works or not.

To give an example - the WebGL implementation on iOS has a maximum texture size of 4096x4096. Breaking this limit simply causes the texture to become entirely black within WebGL. Having a texture of size 73x4320 means it will work in Google Chrome on your laptop - but just be entirely black on your phone.

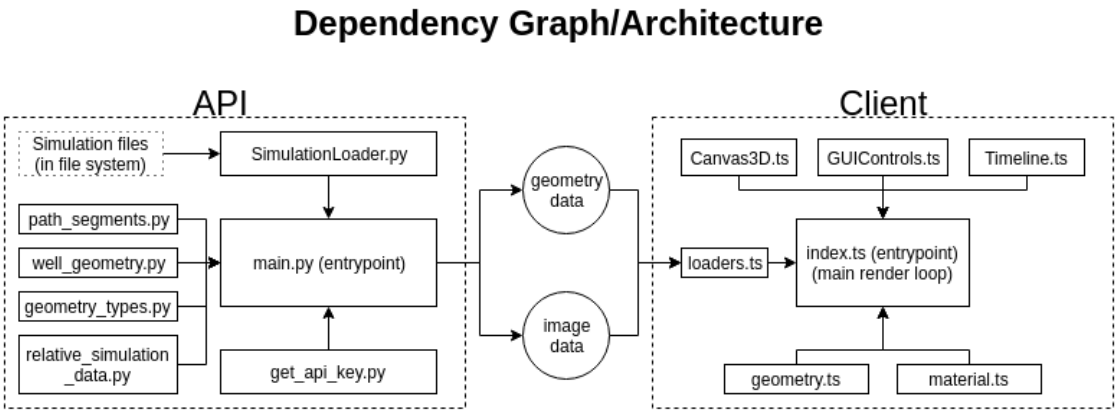
Touch vs Mouse

Touch displays are also different than mouse controls - and should be tested as well. For example: to enhance range inputs on touch displays (used for the timeline), a library called rangetouch was used.

Stylesheets

The different browsers usually all have their own default styles, which might need to be reset - or even set in different ways for different browsers. An example of this is the view-height problem on mobile devices. Or the styling of the range input.

The final architecture



Conclusion

blablabla

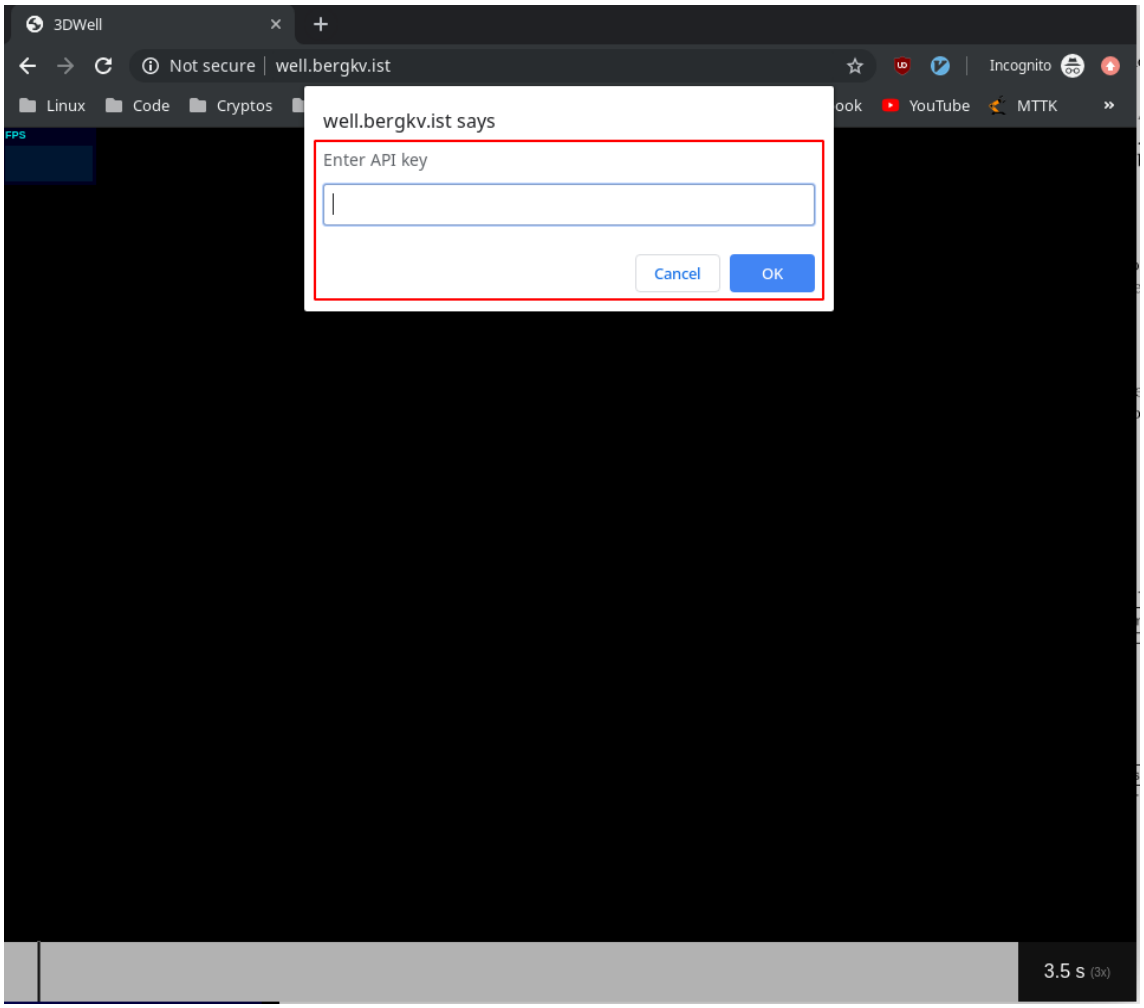


Figure 3: When first opening the web application - the first thing that happens is that you will be asked for an API key/a password. This prompt will keep appearing until you have successfully authenticated with the API. After this, the key will be stored as a cookie in your browser - so that you won't need to enter it again.

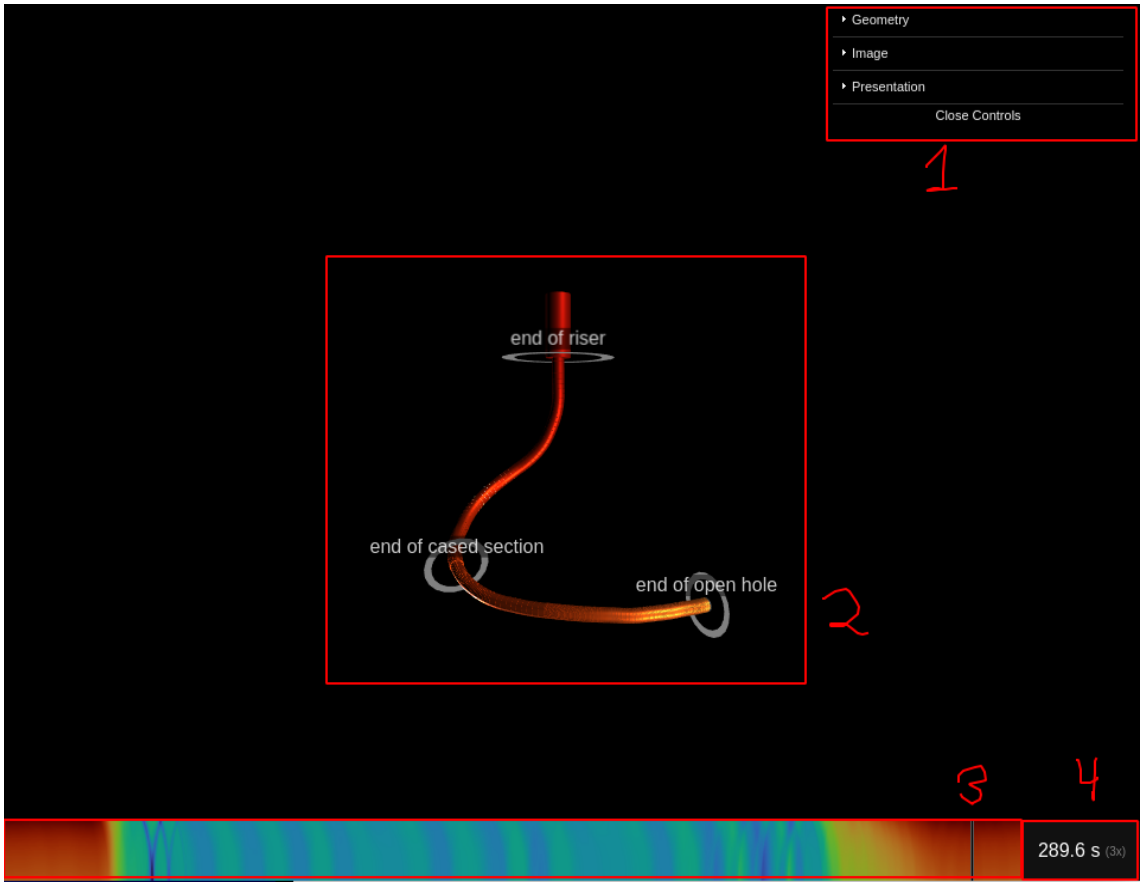
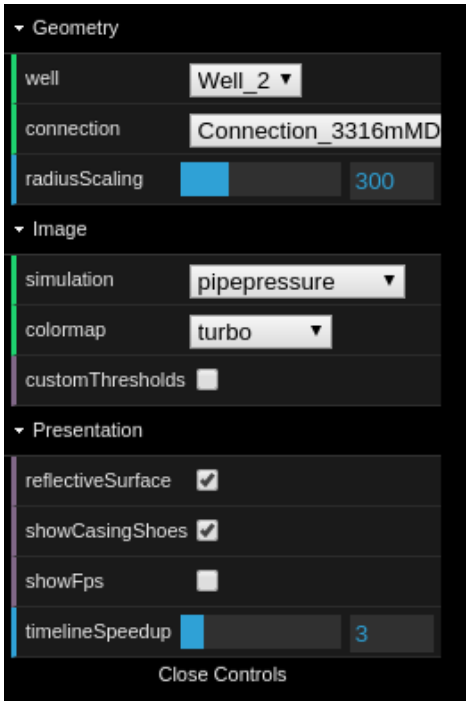


Figure 4: Notice that there are 4 different GUI elements available. #1 is the control panel. Clicking each of the folders will cause them to expand, revealing related configuration. #2 is the actual 3D-visualization. To zoom in an out, use the scroll wheel on your mouse, or pinch with two fingers on your phone. To rotate - left click with the mouse or drag using a single finger. To pan/translate sideways, hold right click on your mouse and drag, or drag using two fingers on a touch display. #3 is the timeline, as well as a 2D visualization of the simulation output (in the form of a heatmap). The cursor shows which column of the image is currently being displayed/drawn onto the 3D-figure. #4 displays the current time as well as the current time speedup in parenthesis, and clicking on it/touching it will pause the application and change its color to red. Click it again to resume.

User Guide



Further Work

Get the min/max thresholds of the image from the api

Allow for defining discrete colormap

Show location of pipe

Fix race condition

Performance problems with range input rapid updates in some browsers

Get the min/max thresholds of the image from the api. Show the thresholds Allow for defining a discrete colormap with custom thresholds.

Abbreviations and terms

Abbreviations

- API - Application Programming Interface
- HTML - HyperText Markup Language
- CSS - Cascading Style Sheets
- URL - Uniform Resource Locator
- CPU - Central Processing Unit
- GPU - Grahpics Processing Unit
- JSON - JavaScript Object Notation
- UI - User Interface
- JS - JavaScript
- WASM - WebAssembly
- C# - A programming language by Microsoft
- WebGL - Web Graphics Library
- IE11 - Internet Explorer 11 (Web browser by Microsoft)

- csv - Comma Separated Values (file format)

Terms

- Transpilation
- Polyfills
- Bundler
- Container (in the context of docker)
- Scene
- Camera
- Renderer
- Mesh
- Geometry
- Material
- Texture
- Light
- Syntatcic Sugar
- Reverse proxy
- Cross Origin Resource Sharing (CORS)

Benchmarks

JavaScript vs WebAssembly

The examples are from https://takahirox.github.io/WebAssembly-benchmark/

Test name	JavaScript (average [ms])	WebAssembly (average [ms])	ratio
collisionDetection	287.4815	426.3495	0.6743
Fibonacci	638.0810	270.7280	2.3569
ImageConvolute	42.0985	58.4185	0.7206
ImageGrayscale	1.4378	10.3431	0.1390
ImageThreshold	9.9412	11.6082	0.8564
MultiplyInt	2584.8935	185.2885	13.9506
MultiplyDouble	2592.6175	477.4770	5.4298
MultiplyIntVec	70.5495	72.8155	0.9689
MultiplyDoubleVec	83.4600	111.8535	0.7462
QuicksortInt	590.5060	413.8590	1.4268
QuicksortDouble	282.6930	223.1245	1.2670
SumInt	161.0785	114.3445	1.4087
SumDouble	69.9845	111.1935	0.6294
VideoConvolute	27.0100	32.2330	0.8380
VideoGrayscale	1.0840	8.7225	0.1243
VideoMarkerDetection	6.4125	11.4205	0.5615
VideoThreshold	5.2104	12.7440	0.4089

Picking a 3D library for JavaScript

Selection criteria:

- **Ability to create custom 3D-visualizations** - The tool must be capable of creating an interactive 3D-visualization.
- **Documentation/Community support** - How well documented is the code, and how "well trodden" is the choice in general?
- **Performance** - Is it possible to acheive a high monitor refresh rate of the scene without consuming a lot of system resources?

- **Accessibility** - How wide is the browser support Is it supported on Internet Explorer 11 as well as mobile browsers?
- **Price** - There must be a free alternative. Entirely open-source is preferrable.

Alternatives for WebGL libraries

Name	Unity3D for Web
Description	Game engine. Compiles C# to produce WASM and WebGL-code.
3D-capabilites	Yes
Community	Possible to receive commercial support.
Performance	Most likely good (I didn't manage to find any open examples/demos).
Accessibility	Mobile browsers are not supported. Neither is IE11.
Price	Commerical: Free personal, $99 professional

Name	d3.js (Data Driven Documents)
Description	JavaScript library for data visualization.
3D-capabilites	Lacking by default. Need to combine it with a third party library.
Community	89k stars on GitHub. 122 contributors. 21k forks.
Performance	Good
Accessibility	Not a problem
Price	Open-source/free

Name	THREE.js:
Description	JavaScript 3D library.
3D-capabilites	Yes
Community	57k stars on Github. 1,192 contributors. 21k forks.
Performance	Good
Accessibility	Not a problem
Price	Open-source/free

Name	Babylon.js
Description	A JavaScript framework for creating 3D-games.
3D-capabilites	Yes
Community	10k stars on Github. 257 contributors. 2k forks.
Performance	Good
Accessibility	Not a problem
Price	Open-source/free

The choice: THREE.js

Based on the selection criteria - it is clear that THREE.js scores highest on all counts, and will therefore be the tool of choice for this project.

—-

Accessibility in this case is superior. (https://threejs.org/docs/#manual/en/introduction/Browser-support) This could work in Internet Explorer 11, Microsoft Edge, Google Chrome, Firefox, Opera, Safari, as well as modern mobile browsers.

This is likely the alternative which has the biggest challenges when it comes to performance - as

JavaScript is an interpreted language. OpenGL Shading Language (GLSL) allows for writing code that is compiled on the gpu. In theory, having most of the work-intensive code written here could help deal with performance issues.

The ability to write code in a highly abstracted scripting language is great for extensibility, as the time investment of extending the system with UI components is low.

References

THREE.js vs BabylonJS performance: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1228221&dswid=-857