Procedural simulation of decaying fruits

Master's Project Thesis

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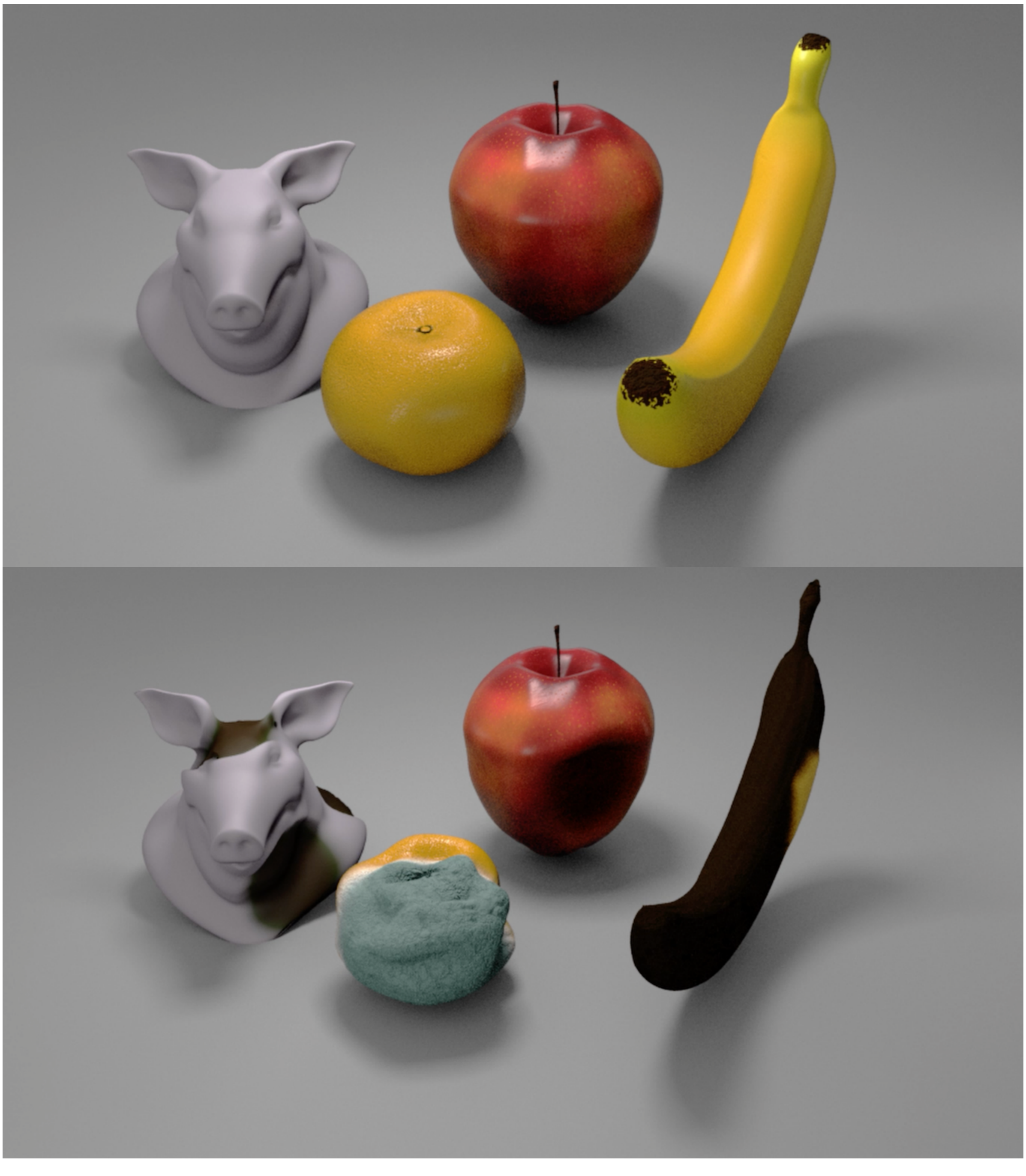

Abstract

This project documents the procedural simulation of rotting and decay, which is a natural phenomime many have seen. It can be simulated to add realism to a scene. Several papers relating to this topic have been discussed, highlighting some of the commonly used techniques. A custom-made solver was developed in Houdini18.5 using the Pyro Sop Solver and predominantly the VEX Wrangles and VOP networks to simulate this process. This report outlines the framework to create a rotting simulation of several fruits; apple, banana and orange. This digital asset will allow the user to input their modelled fruit and set various parameters to create the desired rotting effect they wish. Further development is required to add further realism into the simulation

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1 Introduction

Computer-generated food models are used vastly in movies, games, and other applications to create a more realistic environment. As time passes, various imperfections can be significant visual cues for audiences emphasising the passing of time. All objects, natural or artificial, are affected by either a biological, chemical or physical process in the environment throughout time; these changes must be looked into, as these minor imperfections add realism to a scene.

This project aims to reproduce the natural phenomena of decaying and ageing fruits, creating a tool so users can interactively control specific parameters. The main characteristics I wanted to recreate were the volume changes, fungal growth and colour changes.

The inspiration for this project came about after a previous project where a reference of orange was needed. Day by day, the orange's appearance began to alter - the volume decreased, the colour changed, and the imperfections were enhanced. It was a fascinating process to witness. However, this particular orange had been on the desk for around two months; aside from the subtle changes previously mentioned, no decay was present. It emphasised the natural resistance fruit had to withstand deterioration. Since physically seeing a rotting fruit was not feasible within the given time limit, online research and gathering information and videos was the best path.

Hand designing these intricacies can be very tedious work – on the one hand, artists can model these details using texture mapping or even manually adding the details. However, having a tool to automate these imperfections can drastically reduce this labour-intensive work and allow the artist to have more creative flexibility. Furthermore, the device will be able to change several parameters, subsequently allowing for multiple results quickly. This project aims to create a Houdini Digital Asset (HDA). This tool will enable artists to import models of various fruits and change the parameters according to their desired effect. The model is based on scattering points across the surface of the fruit and uses a Pyro Sop to spread the mould and a point VOP to manipulate the points of the model, causing the illusion of wrinkles and volume shrinkage. Furthermore, the colour of the mould is time dependant; therefore, the artist can alter the colour and growth of the mould throughout the animation.

2 Previous Work

Many people have researched several ageing processes, for example, wrinkling (human) skin, withering leaves/ plants, and even rusting metals. When it comes to food, making food look realistic is paramount, especially in the advertisement industry. It allows the food to look appetising - aiding in sales of the item; however, there has not been much emphasis on the decaying of food – mainly fruits. As previously mentioned, ageing objects are a vital visual cue for audiences, alerting them of time passing. Modelling such complex, intricate details of this evolution (decaying) is a challenging task; therefore, creating a system to solve or simulate this process physically or mathematically would lighten the load for animators.

2.1 Publications

2.1.1 Reaction-diffusion system

Many studies have looked into the reaction-diffusion model to replicate the heterogeneous growth of bacteria/ fungi mathematically. For example, El-Sayed et al., 2009 looked to simulate the development of the bacterium Bacillus subtilis. Wakano et al., 2003 looked into the colony growth of Bacillus circulans. Zozarno et al., 2005, looked into the formation of E. coli.

2.1.2 Quin

Qing, 1997, studied factors influencing the drying mechanism of fruits. Fruits have high water content; therefore, as it loses water and dry, the fruit shrinks, causing a drastic change in volume and appearance. This mathematical model took into consideration several factors such as heat, shrinkage and mass transfer.

2.1.3 Kider et al.

Kider et al. 2011, also created a customisable tool that reflected the decay process on fruits. This model considered the thickness and porosity of the fruit's skin, water content, temperature and even its proximity to other surfaces. The spread of the fungi is dependent on the growth of bacteria and the depletion of nutrients. This model used a reaction-diffusion method to generate mould growth across the geometry. The equation below determines bacterial and fungal growth.

$$\delta u\ \delta t = \nabla \cdot (Dc\nabla u) + \theta\ f(u,n) - a(u.n)u \qquad (1)\ \text{Diffusion}$$
$$\delta v\ \delta t = a(u,n)u \qquad (2)\ \text{Reaction}$$

There is a direct inverse correlation between the proliferation of fungi and the nutrient available. As the active fungi grow, there is a reduction in the nutrients. Equation 1 shows the non-linear growth at a given time t – diffusion term. Equation 2 is dependent on the following nutrient concentration n, fungal density, and environmental parameters (u+n).

The diagram below outlines the framework of the critical steps within the pipeline. As seen in Figure 1, Kider et al. focused on volume and the exocarp shrinking coupled with the mould spread.

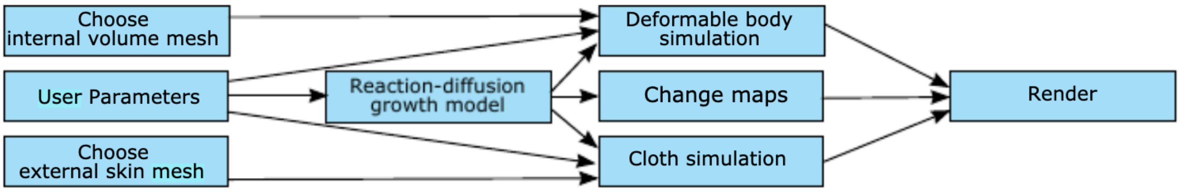

Figure 1. Fruit decay pipeline (Kider et al 2011)

2.1.4 Lui et al.

Liu et al., 2015 simulated the dehydration of fruits (such as raisins or plums) using a finite element method-based (FEM) structure. The moisture content controlled the morphological changes. The diagram below (Figure 2) explains the pipeline of the system.

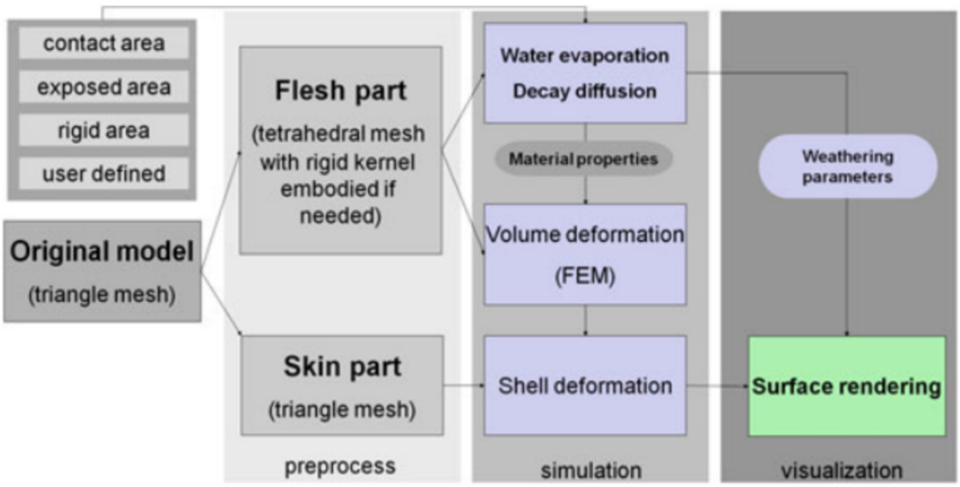

Figure 2. Pipeline of a physically based system for withering fruits simulation (Liu et al. 2015).

2.1.5 Cirdei and Anderson

Cirdei and Anderson, 2018, used techniques from the previous two research and combined the two, aiming to create a more convincing result of fruit decay. Figure 3 displays the pipeline structure.

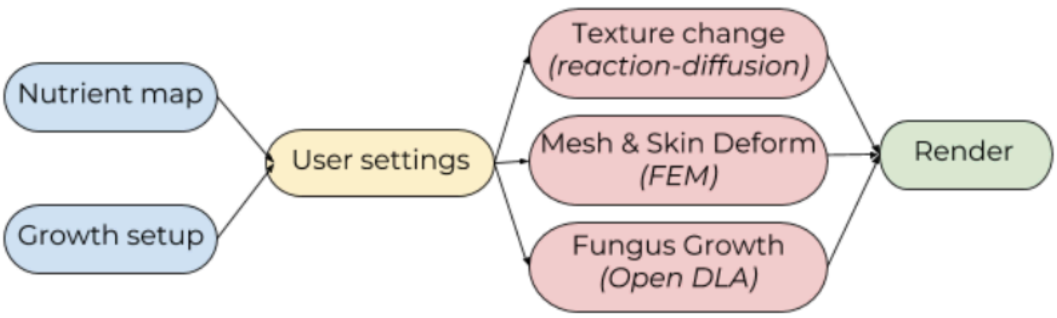

Figure 3. Pipeline structure for the simulation produced by Cirdei and Anderson, 2018

As seen in Figure 3, various techniques in this simulation were inherited. First, this model utilised the reaction-diffusion method for the primary spreading of the mould. Next, the Finite Element Method (FEM) is used for the shrinkage and wrinkling of the model. Finally, Diffusion Limited Aggregation is used to spread the fungal infection across the surface of the geometry.

2.1.6 Other Related work

Various other studies were also researched, which provided good insight into the simulations of other natural ageing processes. Roshmer et al., 2010, looked into animating wrinkling within clothes. Generating wrinkles in a virtual environment is a very time-consuming process if done manually or can be very computationally expensive to simulate. Merillou and Ghazanfarpour, 2008, looked into the importance of ageing and weathering and went into great detail about the art of rendering the ageing phenomena. On research looked into weathered stone; the paper by Dorsey et al. 1999, goes into detail about surface erosion. Kider, 2012, also looked at the physical, biological, chemical and environmental effects of weathering. They were worked by scattering "μ-ton" particles in an environment, causing it to age.

Other biologically inspired methods that was looked into was a study by Li and Kry 2014. They produced a physics-based simulation of wrinkling skin. They looked into the multi-layer skin – various elasticity and thickness of the skin was defined using texture maps. Wrinkle maps are then automatically created. This produced real time speed to create wrinkles in high definition. Another study looked into the particle system approach to cause visible changes in appearance (Verhulst et al. 2017). Their work looked at imperfections in the skin of several fruits.

3 Technical Information

Decay is a natural phenomenon, which is essential to the life cycle of a fruiting plant. This process can happen any time during its life cycle – especially as it ages – however, it is most susceptible after being harvested. Microorganisms feasting on the nutrients and moisture coupled with the cells' chemical breakdown results in the fruit's quick decomposition.

The fruits natural chemicals can eliminate microbes; however, their natural defences weaken as the fruit ripens. Keeping fruits fresh is imperative during post-harvesting and in transportation, as this is where the fruits are more liable to mechanical injury (Jazen 1977). Structural vulnerabilities to the surface make it more susceptible to mould infestation. Fresh fruits have a high-water content making it ideal for pathogenic fungi to invade and multiply rapidly. As fruits have a relatively short shelf life, synthetic chemicals are used to enhance the life span. It is mainly controlled by postharvest fungicide (Tripathi et al., 2004). For this project, post-harvested rot was focused on; there this simulation will take place in a home environment.

3.1 Fungal Diseases

Fungal growth is dependent on various factors such as water content, temperature, pH, time and the atmosphere. It spreads by expanding cell chains; as previously mentioned, fungi thrive in high water content; a required amount to initiate growth is around 70% to 90%. Once it has begun, some can survive in lower moisture levels (60%) (Parrott 2009). The optimal temperature is around 30 degrees Celsius. Fungi and bacteria flourish on nutrient-rich surfaces; as the colonies increase drastically, the nutrient level decreases, impeding the bacterial/ fungi growth. The microbe breaks down the fruit's sugars, converting them to something much less desirable, this breakdown of cells causes the structure to become soft; as the surface weakens, the fruit becomes more vulnerable to infection by other organisms (Kider 2011).

Water transpiration causes drastic changes in the fruit's physical appearance. The majority of the weight of the fruits are made up of water; as the water transpires out, the fruit starts to lose mass and shrinks (Kider 2011).

3.1.1 Orange

There are two common types of fungi in citrus fruits that cause decay, namely *Penicillium italicum* and *Penicillium digitatum*, which produces blue and green mould, respectively. These moulds are the cause of the soft rot in oranges. Oranges are roughly made up of 87% water (Bastin 1997), making them very vulnerable to fungal growth. The orange becomes soft first, and then the white mould starts to grow, followed by the green mould.

Figure 4a and b. Shows images taken in July 2021 and September 2021, respectively.

Figures 4a and 4b are photographs of oranges taken two months apart. The fundamental changes that were noticed were the softness of the orange, the slight decolouration and the very subtle structural differences. However, no mould could visibly be seen, and this highlighted the oranges resistance to mould development. Reference images from online research had to be used for comparison. Figure 5 is an amalgamation of some photos depicting the rot stages in oranges.

Figure 5. Rot stages in oranges (2010).

The images above also highlight how every fruit is unique in the way they decay. Although there is a visible volume decrease in the first images, there is hardly any wrinkle formation on the surface. The mould that has grown on the surface is uniform throughout the geometry. However, in the second image, there are drastic visible changes in appearance. There has been a volume reduction; the exocarp also has wrinkling due to the loss of firmness.

3.1.2 Apple

Apples are made up of 84% water, also meaning they are highly susceptible to mould, therefore limiting their storage life (Bastin 1997). The most common fungi that spoil apple is *Penicillium expansum*, which is blue mould; it is followed by *Botrytis cinera* and *Monilinia fructigena* – grey mould and brown rot (Patriarca 2019). As the apple rots, soft rot appears, causing the exocarp to turn brown; as the water transpires out of the fruit, it starts to shrink, causing visible wrinkles. The fungus then begins to develop on the shell. Figure 6 shows images of the process of rotting during the life of an apple.

Figure 6. The rotting stages of an apple (2010)

In these images, it is clear that the apple's whole appearance changes as it decays. In the first image, the whole apple appears to be affected by the decaying process, whereas only part of the apple is affected in the final image. The other half of the apple has little to no visible damage.

3.1.3 Banana

Bananas are made up of 74% water (Bastin 1997); the fungi which spoil bananas are caused by *Colletotrichum musae* – black rot. This fungus causes anthracnose lesions (dark brown/ black areas) and causes several sunken regions to emerge. The moulding usually starts at the crown or along with the finger (a single banana) (Thangavelu 2004).

Figure 7. The rotting stages of a banana (2016)

In these banana images, it is clear that there is little change in the volume but a significant change in the colouration. First, tiny spots of dark brown appear and then grow over time, eventually covering the entire surface of the banana in a dark brown colour. Furthermore, there are subtle wrinkles that run along the finger's length – it is hard to see due to the brown mould.

4 Implementation

The chosen source of application to create this simulation and a user interface was Houdini. The main pipeline categories are volume deformation, mould growth and surface wrinkles– each having individual parameters in the user interface that the artists can freely customise according to their desired result.

The apple, banana and orange were modelled in Maya 2020 and imported into Houdini using an alembic node. The imported geometry is unloaded and unpacked, and ready to connect to the network.

4.1 Volume Reduction

The first adjustable parameter of the tool allows the user to manipulate the volume of the fruit. The user has two options to affect the volume: create a mask via a ramp or paint. The mask maps areas with values ranging from 0 to 1, which can be visualised in the viewer using grayscale. Moreover, the paint allows users to paint areas where they would like the most deformation to happen. Finally, the shrinking force is applied to each point, some areas being affected more than others.

4.1.1 Mask

Using VEX expressions, a bounding box surrounds the geometry, computing the maximum and minimum areas. Next, a mask attribute is applied using a ramp feature within the tool. Finally, the values are clamped between 0 to 1 along the y - axis, producing a range of values for each point. The points with values closer to 0 (whiter areas) will be the most affected by the shrinking factor; these values can be visualised by setting the mask attribute in the visualiser to grayscale. The ramp can easily be adjusted by the user providing quickly visible results. Below is the VEX expression used to create the bounding box and create the ramp.

```
vector min = getbbox_min(0);
vector max = getbbox_max(0);
f@mask = fit(@P.y,min.y,max.y,0,1);
f@mask = chramp("maskRamp", f@mask);
```

Depending on the user, the mask added can be uniformly applied across the surface of the geometry; therefore, non-periodic or periodic noise can be added to add more variations. For example, Perlin noise is added to the masked areas resulting in more varied volume changes. In addition, the mask can be blurred out to smooth out any harsh edges caused by the shrinkage value. Essentially the mask acts as a nutrient map. As nutrients and cells within the fruit break down, water transpires out, which causes the fruit to lose firmness in these areas. In turn, this causes visible volume reduction in certain areas. Below is the VEX expression used to create a channel controlling the amount the volume decreases.

```
@P -= @N * @mask * chf("strength");
```

This VEX expression controls the normal of the masked points and decreases its position by a given amount (inputted in by the user). The images below are screenshot showing the volume mask.

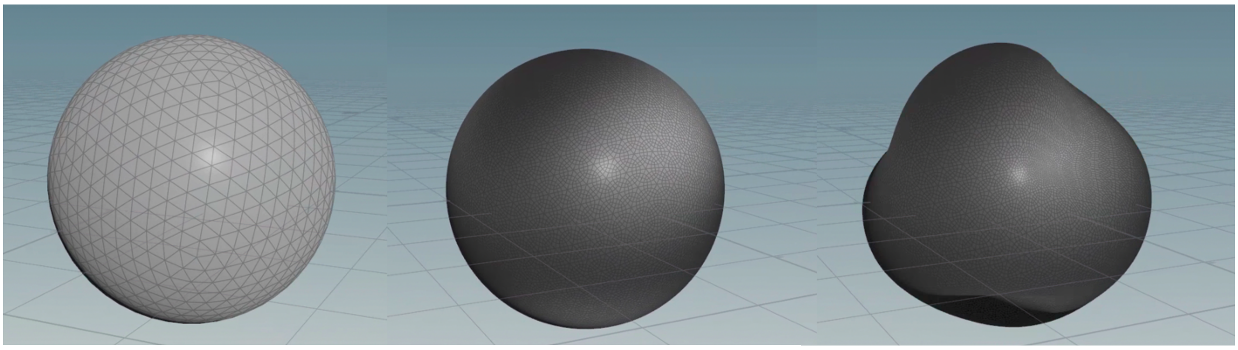

Figure 8. Screenshot of the volume mask function.

4.1.2 Paint

Another interactive method of controlling the volume changes across the surface is using the paint node. Users will be able to paint the areas where they would like more deformation/ shrinkage. For easy visualisation, the paint mask should be viewed as infra-red; the red areas will occur the most significant deformation. Like the volume mask, a channel controls the intensity of the shrinkage, which is adjustable by the user. Figure 9 shows a simplified example of this tool. The red areas seen are where the points get primarily deformed. Noise can be added to the painted areas, and users will adjust parameters such as element size and amplitude to create the desired effect. Furthermore, the paint attribute can be blurred to create a smoother transition between the highly impacted areas to its surrounding.

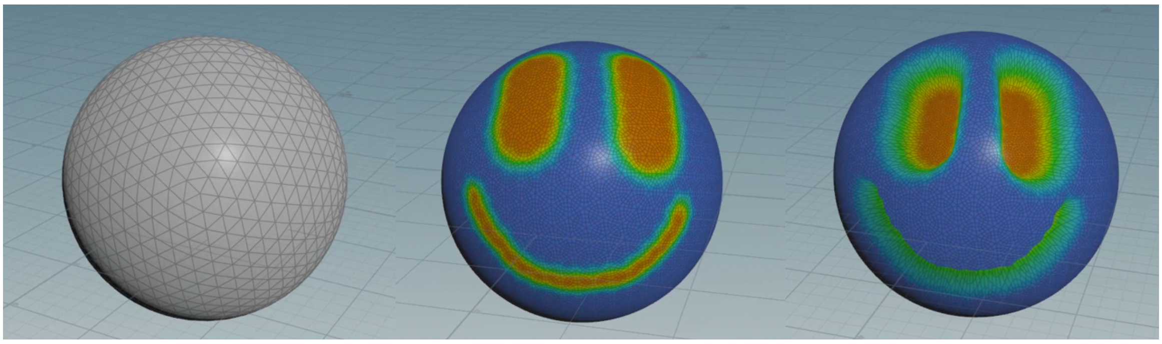

Figure 9. Screenshot of the volume paint function.

4.2 Mould Growth

The Pyro Source SOP in Houdini is used to spread the mould across the surface of the geometry. Points are scattered on a given surface; these points are the seed where the mould growth begins. The user controls the number of mould seeds placed on the geometry. Other parameters such as the spreading and cooling rate are altered to change how the mould spreads across the surface - furthermore, the addition of noise is available to be applied, allowing variation in the growth. VOP Point allows quick manipulation of the geometry using nodes; the bind import node brings the burn attribute (the mould) into the network. There are two

VOP Point ramps available. Firstly, to add noise to the geometry of the mould - adding more dimension and secondly, a ramp controlling the colour of the mould during its lifetime. Figure 10 is a screenshot of the Point VOP network.

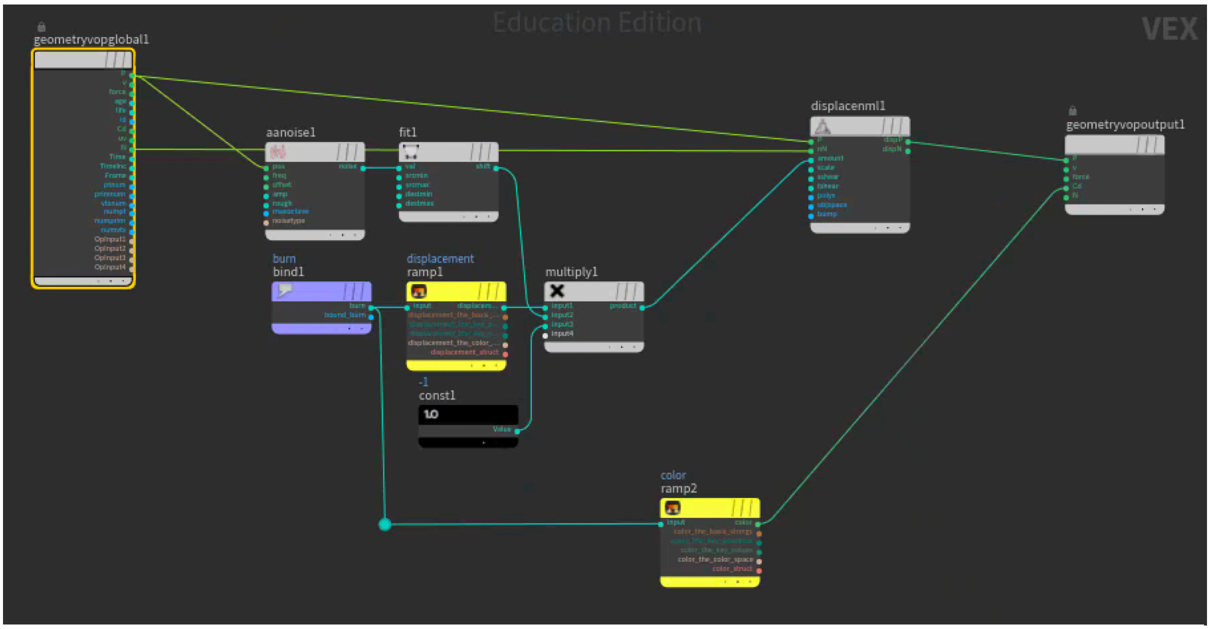

Figure 10. Screenshot of Point VOP

4.3 Wrinkle

Alongside the volume reduction, another attribute of a fruit losing water due to transpiration is wrinkling. As previously mentioned, the fruit starts to lose firmness and begins to collapse; this causes wrinkles to appear. Thus, the next step in the pipeline is wrinkle formation. The chosen path to achieve this effect was using the L-system. First, the user will choose points where they want the wrinkle growth to start, which will extend to an end group (number also adjusted by the user). Next, the ray node projects rays from the wireframe onto the surface of the fruit. Wire capture captures points within a given radius, which can then be used in conjunction with wire deform to deform the surface of the geometry.

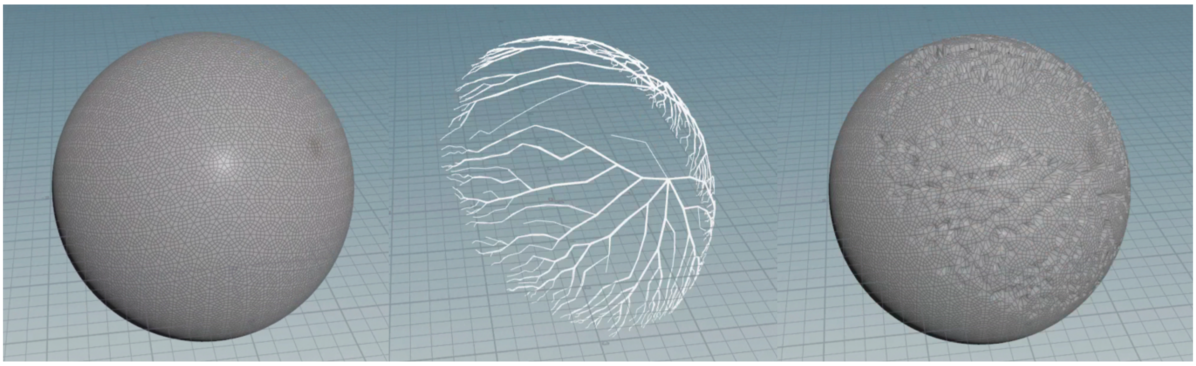

Figure 11. Screenshot of creating wrinkle like structures

This did not produce results that were that great, further work is needed in the development of wrinkles.

4.4 Fungal Growth

The method used to produce the fungal colonies was namely the L-system. Thus, creating fungi is the final stage of the pipeline. As previously mentioned, the L -system is mainly known for creating branch-like structures; however, the structure is resampled and interpolated as a curve, making it look more like a fibre strand. This system creates the individual fibre strand; it can be animated over time. The fungi are scattered amongst the geometry of the mould. The user in the user interface can adjust the growth of the fungi. The images below (Figure 12) show a single fungus fibre structure, which is then copied to points spread across the surface where the mould is present.

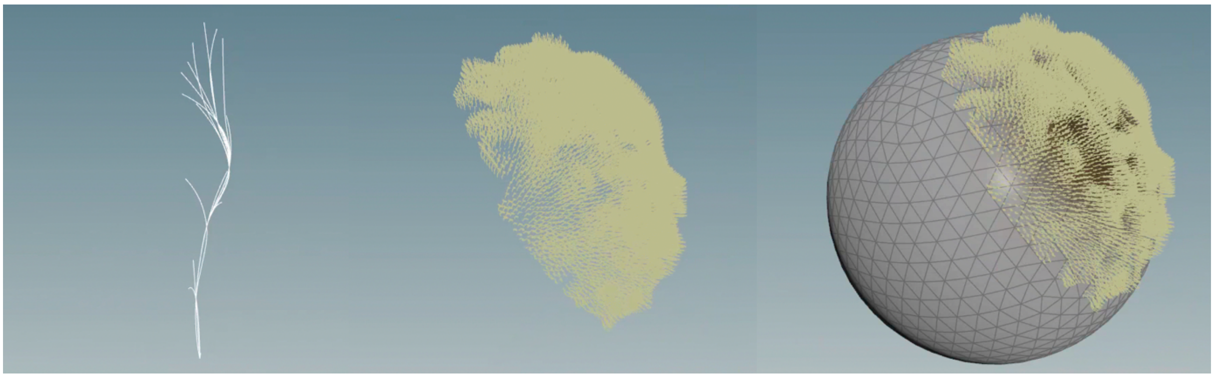

Figure 12. Screenshot of the fungus strand and then copies scattered across a surface

4.5 Rendering

In order to add realism to the fruits, the rendering was done in Houdini using the Mantra. UVs are applied to the models. As the model deforms over time, it was essential to calculate the UVs from the first frame (where there is little to no deformation) and then copy these UV attributes to the rest of the animation. Various texture maps are added to add realism; bump, normal, roughness and displacement. These textures were created in 3D-Coat. To ensure the realism was matched, images were used to get the numerical values for the colour. Finally, the pores and any imperfections on the fruit's skin were hand-painted using a reference.

The orange had the lowest roughness value, therefore, reflected more than the apple and banana. Apple also had a relatively low roughness value as its surface is also quite shiny. On the other hand, the banana had the highest roughness value and seemed to absorb the light more than reflecting it. Thus, there are fewer visible flaws on a banana in comparison to an apple or orange. As mould grows on the surface, the physical properties change, the surface becomes less reflective and rougher. The roughness value increases whilst the index of refraction value decreases. Further details are calculated in the mould through the bump, normal and displacement maps. Another ramp is added in the material section giving the user control over the colours. A bind import is used to bring the "burn" attribute in – which contains information about mould growth. These details are essential to add realism to the surface of the fruit.

5 Results

The focus of this paper has been simulating the decay of three fruits: orange, apple and banana. When trying to recreate reference images, it highlighted the tools advantages and disadvantages. The primary purpose of this tool is to reduce manual labour for the artist, therefore automating the colour changes, structural changes and imperfections. This section will present the results and rendered images as well as the disadvantages of this tool. Below are the results achieved by the tool.

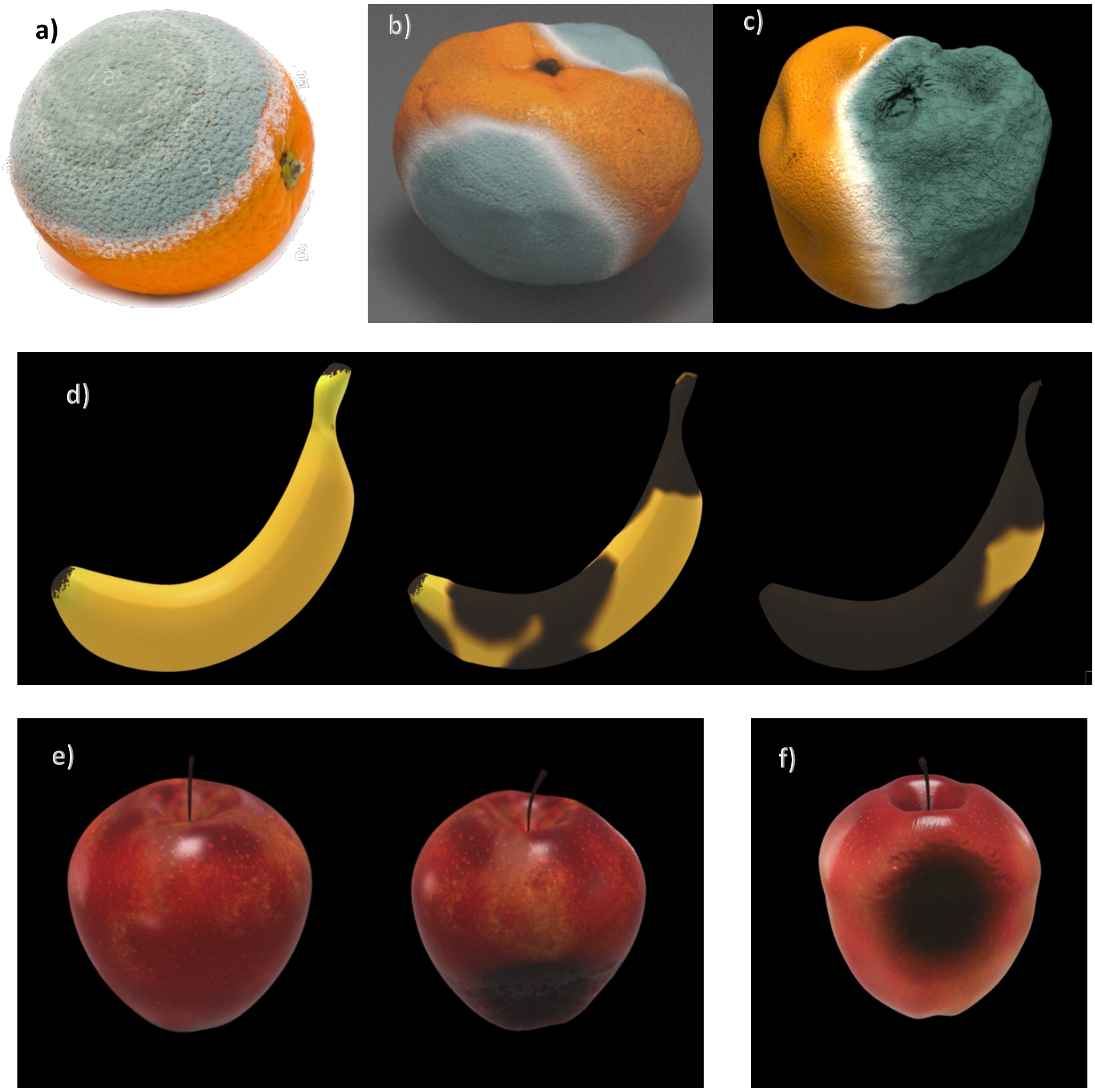

Figure 13a Real image of a mouldy orange (2020), 13b - f, Rendered images of the simulated mouldy fruits

5.1 Strengths and Limitations

The orange was the most successful out of the three. The model, Figure 13b, was modelled against Figure 13a, a photograph of an orange. This side-by-side comparison shows the ability of the tool. The mould's colour and growth are modified to produce similar growth in the reference image. Next, another image of a decayed orange was rendered, Figure 13c. This rendered image can be compared to the images in Figure 5, where it is evident to see structural changes mainly in the volume of the orange. Over time, this orange was simulated to reduce volume and noise to distort the surface. When comparing Figures 13 b and c, it further emphasises the versatility of the tool and its ability to produce remarkable results. On the other hand, there is room for improvements; most of the subtle imperfections in the mould came from texture mapping (bump, normal and displacement), which were hand-drawn and not simulated. Further development is needed to simulate these finer details, as the tools' primary purpose is to reduce manual labour.

The following image, Figure 13d, shows rendered banana during its decay lifetime. This image can be compared to Figure 7. When comparing these images, it is fair to say that the fundamental mould growth and discolouration match well. Spots of darker areas appear on the banana and spread across the surface, where the mould has been it causes slight wrinkles. Once again, more detail is needed to add the finer details in the mouldy areas. During the simulation of the banana, the mould grew at the same rate as each other; this was a significant flaw that was highly noticeable in the banana. As a result of the decaying process, many dark areas develop, growing at different rates. Some spots appear as freckles and do not grow any further. The decay simulator failed to consider this. Further work will be done when there are multiple mould seeds to produce more variation in multiple mould growth.

Moreover, displacing the points using the normal did not provide realistic results within the banana. When comparing images, the wrinkles in the bananas are directional; they run along the length of the finger. Further work on the wrinkle is needed.

Finally, Figures 13e and f are images of the apple. These images can be compared to Figure 6. The mould growth works well with the apple; it spreads across the surface and displaces the surface, creating the illusion of the surface collapsing due to the loss in firmness. When working on the apple, the limitations caused by the wrinkles were very evident. The L-system did not produce the finer details of the wrinkling needed. Instead, the wrinkle effect was computationally time-consuming, as the wire capture took a while to calculate. In addition, it added to the overall time during rendering – slowing it down considerably.

Another noticeable limitation was, where there is thin geometry (for example, the stem on an apple), the tool can cause unrealistic results. Figure 14 shows some examples of these unrealistic results from earlier tests.

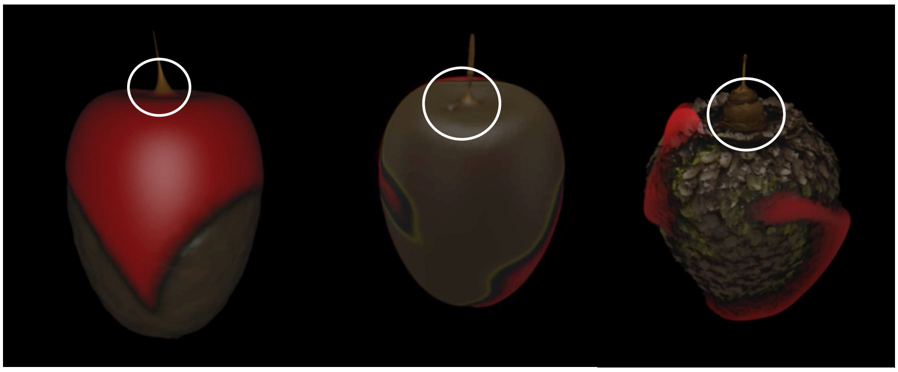

Figure 14. Unrealistic distortion

One of the main strengths of this tool was its ability to easily manipulate the volume of the fruit using the mask ramp or paint attribute. Furthermore, the Pyro Source SOP created a nice effect of the spreading of the mould, and the parameters were easily adapted.

5.2 Alternative Routes

Although this tool provides the basics of a decay simulation, this section explores other routes that may have given better results.

5.2.1 Finite Element Solver

Cirdei and Anderson 2018 and Liu et al. 2015, used a FEM solver to solve the dehydration and add the finer details. The FEM solver replicated the outer mesh as a thin organic tissue. As each point held information such as shrink volume, the FEM solver used the point deformation between them and added the details of wrinkling. This process created realistic wrinkling detail as the volume decreased due to shrinking. This method would provide the wrinkling detail that the L-system overlooked, therefore producing a more realistic result during the decay simulation.

5.2.2 Vellum Cloth Solver

A vellum cloth solver is a new tool added to Houdini18.5. This node allows the user to turn a geometry/ mesh into a cloth-like structure; various parameters such as the stiffness can be altered, allowing users to achieve realistic results. For example, Kider et al. 2011, used a cloth simulation to add the finer details. The model included an internal volume and an external skin mesh. As the internal mesh deformed, the external skin could adapt and create crease like structures reflecting a wrinkling dehydrating fruit. This approach was investigated unsuccessfully; however, it would be adapted into the simulation given more time.

5.2.3 Diffusion Limited Aggregation

The L-system was also used for generating wrinkles as it produces varying results and unique structures. When looking into images of the wrinkling in fruits, it was very randomised and never looked the same. A mathematical method incorporates iteration; the previous result becomes the basis for the next iteration. Various organic structures can be achieved using this method, for example, the final stage – fungal colonies growth.

For the fungal growth, once the structure is complete, it is scattered across the geometry. Another approach involved diffusion-limited aggregation (DLA). It was a work in progress in Cirdei and Anderson's work. They decided to opt for the approach of the DLA to create the long branching filaments, 2018. DLA can produce very organic structures along the surface of the geometry. However, it can be quite computationally expensive.

6 Conclusion

This tool automates the challenging work of hand-fashioning imperfections, resulting in a wide range of appearance controls. Artists can import their models and select areas where they wish the ageing process to happen; quick and easy management and a mixture of results can be seen. As previously discussed, there are vast areas for improvements in making the simulation look realistic; however, it shows promising results as a foundation.

The tool currently allows the change of colour across the surface, volume changes by displacing the points according to their point normal and adding fungi. The simulations produced strike a pleasant similarity to time-lapse videos of other decaying fruits. It has a user interface allowing control over several parameters.

This simulation does not take into consideration several factors. Some of those include the fruits are whole; they have not been cut. If the fruit had been cut, it would speed up the decay process and result in varying end products. The primary decay area will be localised in the cut area. Another consideration is that there are no other organisms, for example, worms or flies. These also increase the speed of decay within a fruit.

Further development will be made in the wrinkling of the fruit as it is one of the principal artefacts displayed by the fruits; this will be done by incorporating a cloth simulation. Furthermore, using a FEM solver could also produce more realistic deformation when the volume is decreased. Finally, having different mesh layers, for example, the skin and internal mesh, would allow the meshes to work together, producing the more delicate details needed. Further work is needed in adding realism during rendering. Furthermore, making the user interface more technically advanced. For example, the ability to have multiple fruits together and them interacting with one another causing the spread of the mould if they are in contact. It may also be appropriate to test the tool amongst a test group and get their opinions on what needs further development.

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