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A phenomenological model for throughfall rendering in real-time

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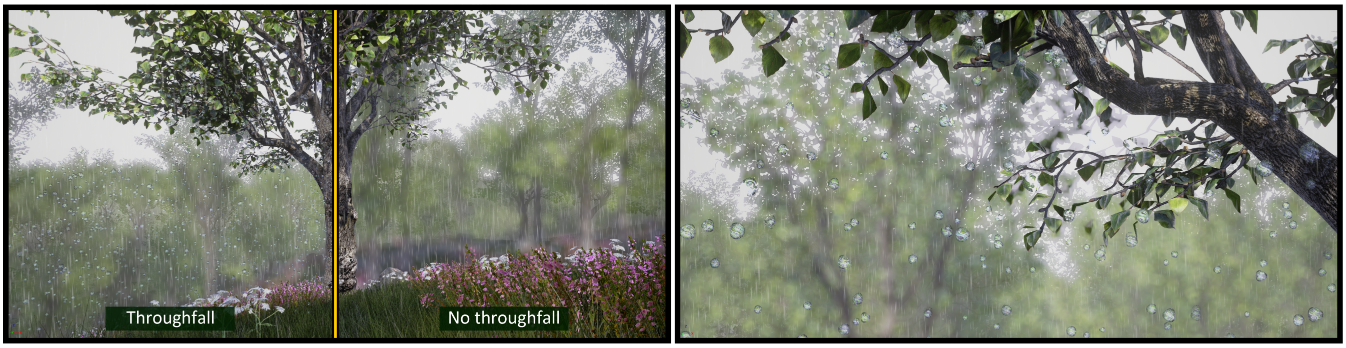

Figure 1: Rendering of drops dripping from foliage based on an hydrological model and a functional form evaluated per-pixel.

Abstract

This paper aims at rendering interactive visual effects inherent to complex interactions between trees and rain in real-time in order to increase the realism of natural rainy scenes. Such a complex phenomenon involves a great number of physical processes influenced by various interlinked factors and its rendering represents a thorough challenge in Computer Graphics. We approach this problem by introducing an original method to render drops dripping from leaves after interception of raindrops by foliage. Our method introduces a new hydrological model representing interactions between rain and foliage through a phenomenological approach. Our model reduces the complexity of the phenomenon by representing multiple dripping drops with a new fully functional form evaluated per-pixel on-the-fly and providing improved control over density and physical properties. Furthermore, an efficient real-time rendering scheme, taking full advantage of latest GPU hardware capabilities, allows the rendering of a large number of dripping drops even for complex scenes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—

1. Introduction

Rendering a realistic rainy scene in a complex natural environment is a challenging task due to the complexity of the interaction between numerous raindrops and the scene objects such as trees, leaves, roofs, etc. However rain rendering enhances natural scenes and the multiple visual effects inherent to rainfall provides more accurate results in Computer Graphics.

In this paper, attention will be paid on the interaction between raindrops and trees. Most of the previous works focus on drops and streaks rendering, but none tackles the throughfall (TF) phenomenon. This phenomenon consists in drops intercepted and stored on foliage and then released from leaves [NOIM11] [NWHS13] [NHS06] (dripping TF), small droplets resulting from water splashes on foliage (splash TF) and raindrops directly passing through canopy openness (free TF). In this paper, we introduce an original method to model and render the dripping regeneration process within the canopy. Splash TF are actually much smaller than incident raindrops and dripping TF, and thus are not visually significant for our purpose. Moreover, splash TF would require to tackle other complex problems which are out of the scope of this paper, e.g. splash animation and rendering, splash locations within canopy, etc.

A rainy scene is usually composed of a great number of raindrops and considering every collisions can be complex with detailed trees where many physical phenomena occur in. Our throughfall model tackles geometric and physical complexity with an hydrological and phenomenological approach. Indeed, a physical approach of these phenomena would require to handle a very great number of leaves and stems, and would thus imply costly computations for a real-time simulation, e.g. flow equations, especially for complex natural scenes. We propose in this paper to efficiently render dripping TF by introducing a phenomenological and intuitive model. Meanwhile, raindrops and free TF are automatically rendered using an existing rainfall method taking into account collisions with scene assets and canopy openness. The main contributions of this paper are:

- an hydrological dripping TF model expressing the temporal and spatial distributions of dripping TF as well as the Drop Size Distribution (DSD) according to intuitive and artistically-controlled parameters,
- a new fully functional form evaluated on-the-fly per-pixel and providing improved control over density and physical properties,
- an efficient GPU-oriented implementation to render a large number of dripping TF for complex scenes in real-time.

2. Related work

We analyse in this section related work including both rain rendering techniques handling dripping drops and collisions as well as physical drop simulations close to our research field. Over the years, the realism of natural scenes has been enhanced by rain rendering methods [WW04], [WLF*06], [GN06], [Tar07], [RJG08], [PCRC09], [SJTK10], [PCSR*11], [CP13] and [WJGG15]. Most of these papers pay attention on drops and streaks rendering. Some of them take into account collision to calculate interaction between drops and assets in the scene but none deals with the regeneration of drops after collision with complex objects such as trees. Only Tatarchuk and Isodoro [TI06] propose in the Toyshop Demo to render dripping raindrops falling from the edge of roofs. A classic particle system render those dripping water-drops. Position and density of particles are artistically chosen without any physical consistency.

A couple of research papers focused on coupling tree and raindrops. In this case Yang et al [YJL*12] construct a tree model by a hierarchical structure to control the influence of drops on each leaf. Drops hanging and leaf rebounding are handled. This paper has been subject of new contributions [YHYW10] to enhance tree animation and level-of-detail. Still regarding research in water droplets field, authors [WMT05], [KIY99] and [ZWW*12] propose to render drops on multiple surfaces. This kind of methods simulates the dynamic coupling between tree and drops based on physical deformation and fluid simulation. None of these methods propose a formulation for throughfall (TF) density according to tree parameters and rainfall intensity. Consequently, our approach focuses on a consequence of coupling methods, i.e. drops dripping from leaves. To this end, we propose a new approach aiming at rendering regenerating drops stored on foliage according to various parameters during rain events. The hydrological model introduced in Section 4 considers the multiple and complex phenomena occurring inside canopy in order to estimate density of dripping TF over time and space.

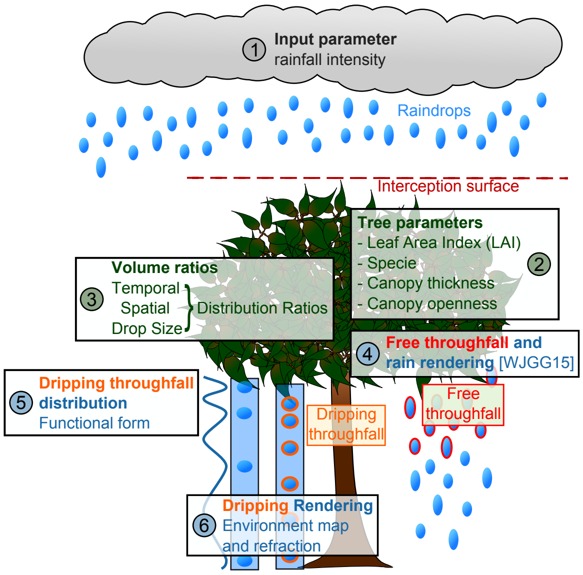

Figure 2: Algorithm overview of our method. User sets rainfall intensity (1) and tree parameters (2). The temporal, spatial and drop size distribution ratios are computed on-the-fly to determine the dripping TF distribution for each tree model (3). Raindrops and free TF are rendered using a rainfall method [WJGG15] taking into account collisions with scene assets and canopy openness (4). A functional form handles the distribution of dripping throughfall (TF) for a specific regeneration location and guarantees user control (5). This representation also allows to have a full control over shape (Figure 5) and density. Dripping TF are rendered using an environment map and refraction calculations (6).

3. Algorithm overview

In this section we describe our algorithm to efficiently render throughfall (TF) and guarantee a user control. Once rainfall intensity and tree parameters are set, our hydrological model compute on-the-fly the temporal, spatial and size distributions of dripping TF for each tree model. We provide a functional form based on this hydrological model for the distribution and rendering processes. This functional representation guarantees a control of TF density and has a constant computation time for any TF density. Our hydrological model gives density of dripping TF over time and space according to rainfall intensity and tree parameters. Dripping TF can be generated by a subset of leaves for each tree model. These locations can be pre-computed for each leaf of a given tree model, using flow equation computations or arbitrarily chosen. In this paper, we pre-computed leaf locations which are visible from ground using a classic ray-tracer. Raindrops and free TF (not interacting with a tree model) are rendered using an existing rainfall method taking into account collisions with scene assets and canopy openness. Figure 2 illustrates the whole algorithm.

4. Hydrological dripping TF Model

TF rendering represents a huge challenge for rendering realistic rain scenes that has not been taken up until now. An approach based on a physical simulation is arduous and would require to solve complex equations, even for a single tree, taking into account stems, small branches and leaves. Such a solution is hardly tractable in practice, especially for real-time rendering of natural scenes. Consequently, the method presented in this paper rely on a phenomenological approach to render small and large scales real-time natural scenes.

Among others, Nanko et al [NOIM11] [NWHS13] [NHS06] have studied this phenomenon and measured the temporal and spatial distribution of dripping TF as well as the Drop Size Distribution (DSD). On this matter, experiments have highlighted key elements influencing the TF phenomenon:

- the spatial and temporal distributions of dripping TF amount,
- the Drop Size Distribution (DSD).

The Temporal Distribution Ratio (TDR) is addressed in Section 4.1 to determine the volume ratio of incident rainfall regenerated under canopy over time. In Section 4.2, we present how the variation of dripping TF within the canopy, e.g. the Spatial Distribution Ratio (SDR), is computed according to the radial distance from trunk and canopy thickness. The Drop Size Distribution Ratio (DSDR), determining the volume ratio for a drop diameter range is presented in Section 4.3. These ratios enable us to determine the dripping TF temporal frequency f and the elapsed time T between two drops for a specific drop diameter over time and space. Finally, we propose a Distribution Function (Equation 6) to model the drops position through time according to gravity and air resistance.

Table 1 summarize the parameters used throughout this paper. In this model, trees are characterised by specie, Leaf Area Index (LAI), canopy thickness and openness. We actually decompose trees into two main species: broadleaved forests and coniferous stands. LAI is the commonly-used dimensionless coefficient to represent canopy density. Canopy thickness is the distance between the top of the tree and the closest branch to ground. Finally, canopy openness corresponds to the fractional canopy element cover.

4.1. The Temporal Distribution Ratio (TDR) of dripping TF amount

When rainwater starts falling down, tree stores water on leaves and branches. TF amount increases linearly as time goes by until tree reaches the saturation point t_{sat} (Figure 3). We refer to this period as the *initial phase*. Once storage capacity is reached, TF amount becomes close to the intercepted incident rainfall. We refer to this period as the *stable phase*. We introduce below the Temporal Distribution Ratio for both initial and stable phases based on Nanko et al's observations [NOIM11]. In the stable phase, experiments [CMG11] show that a part of incident rainfall reaches ground by flowing along branches then trunk and evaporates back into the atmosphere. Indeed, the ratio of incident rainfall dripping from leaves has been estimated at 0.7 - 0.9 in the stable phase.

In the initial phase, measurements show that the temporal distribution depends on tree species, LAI and rainfall intensity. For

Symbol	Definition	Abbreviation	Unit
R	Rainfall intensity	-	$mm.h^{-1}$
A	Tree interception area	-	m^2
S	Storage capacity	-	mm
t	Time variable	-	s
t_{sat}	Saturation point	-	s
D	Drop diameter	-	mm
ℓ_A	Leaf Area Index	LAI	-
q_t	Temporal Distribution Ratio	TDR	-
q_s	Spatial Distribution Radio	SDR	-
q_d	Drop Size Distribution Ratio	DSDR	-
f	Throughfall frequency	-	s^{-1}
T	Throughfall period	-	s
f_h	Distribution function	-	-

Table 1: List of symbols and abbreviations used in our hydrological model.

a given tree, the saturation point is reached more or less quickly depending on incident rainfall intensity. However, storage capacity will remain constant for a specific tree for any rainfall intensity. We compute the tree storage capacity S using Equation 1, introduced by Watanabe and Mizutani [WM96]. They distinguish two types of tree: broadleaved trees and coniferous stands.

$$S = \begin{cases} 0.15\ell_A \quad (mm), & \text{for broadleaved trees,} \\ 0.2\ell_A \quad (mm), & \text{for coniferous stands.} \end{cases} \tag{1}$$

Considering a linear interpolation, t_{sat} is given by :

$$t_{sat} = 7200\,\frac{S}{R} \quad (s). \tag{2}$$

The Temporal Distribution Ratio (TDR) of the initial and stable phases yields the volume ratio of incident rainfall that is regenerated over time for a single tree. As such, the TDR is defined as the quotient q_t of the initial time t over the saturation point t_{sat}:

$$q_t = \begin{cases} \frac{t}{t_{sat}}, & \forall t < 0.7-0.9, \\ 0.7-0.9, & \text{otherwise.} \end{cases} \tag{3}$$

4.2. The Spatial Distribution Ratio (SDR) of dripping TF amount

Studies have been made to understand the variability of dripping TF. Authors [NOIM11] noticed a correlation with canopy shape and branch position. Their experience highlights that TF amount increases as the distance from the trunk does, except for drops released very close to the trunk. This exception is due to the conical shape which causes rain running on saturated branches and flowing toward the canopy edge. We will assume this is usual for trees. Their experiments also show that the canopy structure and thickness determines TF spatial variability. By pruning branches, they

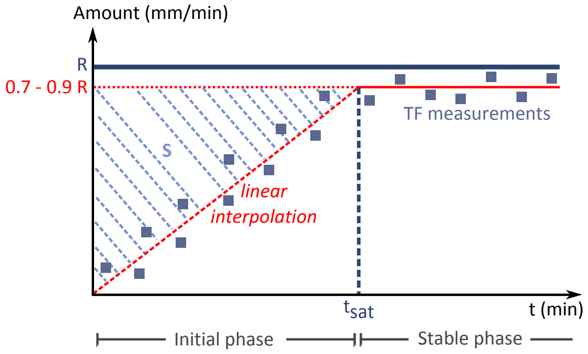

Figure 3: Schematic overview of both initial and stable phases. Once tree storage capacity S is known, the saturation point t_{sat} is computed in terms of incident rainfall R by using a linear interpolation in the initial phase. In the stable phase, dripping TF amount is close to rainfall intensity.

were able to point out canopy thickness as one of the key factors to determine TF variability.

However, Andre et al. [AJJP11] noted that "no general consensus is found in available literature regarding the variation of throughfall volume as a function of distance to tree trunks" neither for coniferous nor for broadleaved species. Some authors reported greater throughfall amounts near the trunk [EDF78] [Her87] [RNRH94], at crown periphery [BHG93] [SM61] [WSBA98], or at intermediate distance [CK90]. Some others [KSW05] [LBGM92]) found distance to the trunk to be a poor predictor for throughfall volume. Meanwhile Andre et al observed greater throughfall volumes at crown periphery than close to the trunks at the early stages of rain events and inversely for larger rainfall volumes, which agrees with observations of Kittredge et al [KLM00].

Moreover, rainfall with no wind is very rare in natural, especially in large rainstorms. Kato et al. [KON*13] showed the positive correlation between stem distance to throughfall in less windy condition, but no relationship in windy condition. Most of previous works were based on outdoor field observations and many kinds of biotic and abiotic factors influenced throughfall generation process and thus spatial distribution [LKCMF11]. However, Nanko et al. experimented using an indoor rain simulator and transplanted trees in order to avoid external outdoor effects. Consequently, we can determine SDR without wind effect according to the radial distance from trunk and canopy thickness. The SDR, defined as q_s, is presented in the form of a table depending on these two parameters (Table 2).

4.3. The Drop Size Distribution Ratio (DSDR) of dripping TF amount

Experiments [NWHS13] have been conducted to observe the Drop Size Distribution (DSD) of dripping TF according to tree species. The DSD pattern appears to be clearly dependant on leaf type (coniferous stands or broadleaved trees). Leaves of same species generate similar drops. We propose to express the DSDR taking into account this observation. Data are summarized in Table 4 in

Canopy thickness \ Radial distance	40	100	150	200
7,8	0,26	0,18	0,22	0,34
6,8	0,24	0,20	0,25	0,31
5,8	0,21	0,19	0,30	0,30
4,8	0,24	0,22	0,28	0,26

Table 2: Spatial Distribution Ratios (SDR) defined as q_s depending on canopy thickness (m) and radial distance (cm) from trunk.

Appendix. Based on the pattern of dripping DSDR, we have fitted these data with a Gaussian function (Equation 4 and Figure 9) and coefficients are presented in Table 3 for each species according to drop diameter. The DSDR, defined as q_d, is expressed as follow:

$$q_d = a \ \exp\left(-\frac{(D-b)^2}{2c^2}\right). \tag{4}$$

Specie	a	b	c
Needle (coated)	0.17	4.45	1.19
Broad-leaf (matte)	0.24	5.40	0.84
Broad-leaf (coated)	0.37	4.37	0.50

Table 3: Coefficients a, b and c for Equation 4 for each specie.

Authors [NOIM11] have also noticed a spatial variation of the dripping DSD according to radial distance from trunk. Experiments have been made using gauges to measure the resulting dripping process. Authors reported that these variations can be explained by splash TF reaching various gauges with a probability depending on canopy thickness variability along radial distance.

4.4. Temporal period of dripping TF

Based on the TDR, SDR and DSDR, we are now capable of calculating the temporal frequency f and thus the temporal period T corresponding to the elapsed time between two released drops over time and space and for a given drop diameter according to tree parameters and rainfall intensity.

$$T = \frac{1}{f} = 6.10^{-4} \frac{\pi D^3}{RA \ q_t \ q_s \ q_d} \quad (s), \tag{5}$$

where q_t, q_s and q_d are respectively the Temporal, Spatial and Drop Size Distribution Ratios of dripping throughfall amount.

4.5. The Distribution Function f_h

We introduce the Distribution Function to formalize the distribution of dripping TF from a given regeneration leaf according to this hydrological model. The Distribution Function f_h is expressed as a composite function of a Periodic Function f (Equation 14) and

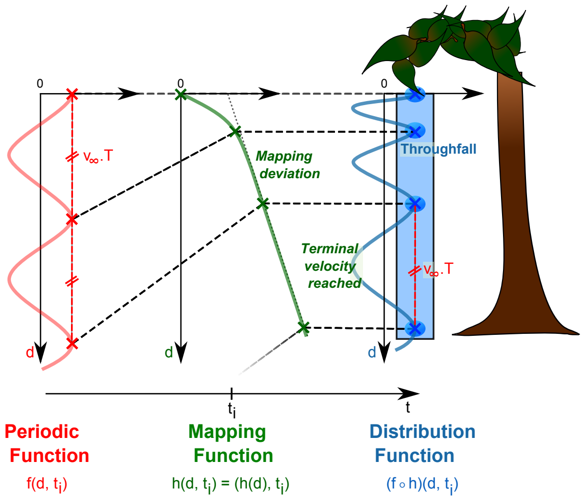

Figure 4: The Distribution Function (Equation 6) is a composite function of a Periodic Function (Equation 14) and a Mapping Function (Equation 20). Space is distorted to distribute drops according to the drop instantaneous velocity.

a Mapping Function h (Equation 20). As shown in Figure 4, we model the distribution of dripping throughfall as a periodical sinusoidal function whose maxima represent the positions of dripping drops. To introduce perturbations by external factors, such as gravity, wind or turbulence, we displace drops position by distorting space using a non-linear mapping function $h(d,t)$. In this paper, we take gravity and air resistance into account. Thus, $h(d,t)$ is used to model variations in drop velocity by non-linearly shifting the evaluation domain of our functional form according to gravity and air resistance. Detailed explanations and mathematical background are presented in Appendix B. This yields the final formulation:

$$f_h(d,t) = \cos\left(\frac{2\pi}{T}\left(\frac{v_\infty}{g}\ \text{arccosh}\ \exp\left(\frac{g}{v_\infty^2}\ d\right) + t\right)\right) \quad (6)$$

where d is the distance between the leaf and the current position in space, t the time variable and v_∞ the terminal velocity of drops.

5. Real-time TF rendering

An outdoor scene can include a very large number of trees, especially forest scenes. Considering every dripping TF for a single tree or whole forest can be computationally costly in real-time simulations. In this section, we describe our method to perform TF rendering in an efficient way based on our hydrological model.

5.1. Rain and free TF rendering

Rain rendering is achieved by the method described in [WJGG15]. Authors propose an hybrid method based on the sparse convolution theory to deal with rain rendering. This procedural rainfall texture consists in convoluting kernels in the entire screen space, and associating a streak pattern at each kernel. In our case, this model is used to render raindrops as well as drops passing through tree canopy (free TF). Although this method is screen-space based , authors explain the possibility to take into account rain occluders and partial rain coverage. This allows us to compute collisions between raindrops and trees when water drops are intercepted by stems or leaves. This is achieved by a camera with an orthographic projection capturing the scene depth from above the user.

5.2. Dripping TF rendering

We take advantage of our hydrological model and drop physical properties to express dripping TF in a functional form.

We propose an efficient approach based on a functional representation considering dripping TF as a stream of drops under each regeneration leaf within canopy. The advantage of our method lies on its simplicity and memory consumption as our method is evaluated per pixel. Each pixel can potentially be affected by every water drops. As computing the contribution of every water drops for a given pixel would increase the computational complexity, we propose to use instanced screen-aligned planes to avoid evaluating every drops. Indeed by using one screen-aligned quad for each regeneration location, we can trigger our rendering process to only compute the throughfall phenomenon for one given regeneration location. Instanced screen-aligned planes guarantee the efficiency of our method. Computation time remains locally constant for a single regeneration location for any TF density. This method only depends on the number of regeneration spots for each tree model. Although a particle system technique [TI06] would yield similar results, this would imply to maintain a constantly updating buffer with numerous memory accesses.

Our technique uses as input data the 3D model of a tree and a set of possible regeneration locations. These locations can be computed in several manners, e.g. physical fluid simulation, manual distribution... In this paper, we choose regeneration locations corresponding to leaves visible from the ground. For simplicity and completeness, we rely in this work on a very simple ray casting method to compute these positions as a data pre-processing step.

During rendering, for a given pixel p, we evaluate our functional form to determine the contribution of the closest dripping throughfall to p. To this end, we define $t(d)$ to express the time needed for a drop to travel through a distance d according to the drop instantaneous velocity. In this case, d corresponds to the distance between the regeneration leaf and the pixel p.

$$t(d) = \frac{v_\infty}{g}\ \text{arccosh}\ \exp\left(\frac{g}{v_\infty^2}\ d\right) \quad (s). \quad (7)$$

The index (drop number) of the closest dripping drop is expressed as follow

$$f_{index}(d) = \lfloor\frac{t(d)}{T}\rfloor + \lfloor\frac{t(d)\ \text{mod}\ T}{0.5T}\rfloor, \quad (8)$$

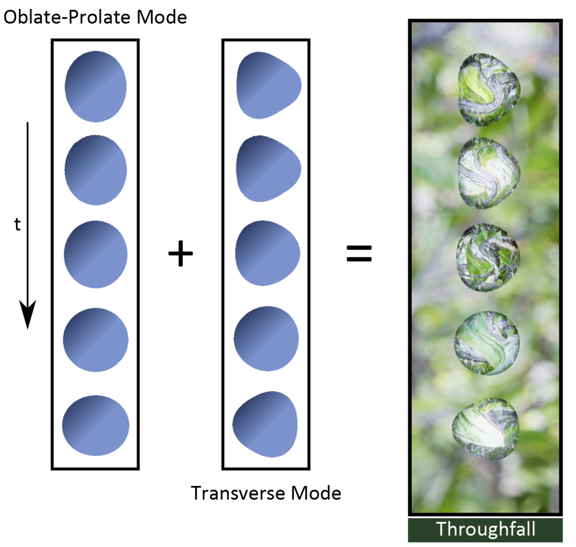

Figure 5: Drop oscillations over time according to [GN06].

Finally, the distance between the closest dripping drop to the pixel p and the regeneration leaf is given by

$$dist(d) = \frac{v_\infty^2}{g} \ln \cosh \left(\frac{g}{v_\infty} f_{index}(d) \times T \right) \quad (m). \qquad (9)$$

This is used to compute the distance between the closest drop and the pixel p. We can now use any method to model and render dripping TF. In this paper, we take into account drop oscillations over time [GN06] as illustrated in Figure 5. Our method enables the straightforward integration of such details at negligible computational cost. In this case, drop radius is determined according to the elevation and azimuthal angles

$$\begin{aligned} r(t,\theta,\phi) =& 0.5D\ (1 + A_{2,0}\ sin(\omega 2t)\ P_{2,0}(cos(\theta)) \\ & + A_{3,1}\ sin(\omega 3t)\ cos(\phi)\ P_{3,1}(cos(\theta)) \quad (mm), \end{aligned} \qquad (10)$$

where D is the undistorted drop diameter, $A_{2,0}$ and $A_{3,1}$ are respectively the amplitudes of the spherical harmonic modes $(2,0)$ and $(3,1)$, $P_{2,0}$ and $P_{3,1}$ are the Legendre functions that describe the dependence of the shape.

Dripping TF are finally rendered using an environment map and refraction calculations. Environment map size can be adapted to the target rendering quality of individual drops. We propose an efficient dripping TF functional representation evaluated per-pixel on-the-fly, encompassing distribution, shape and rendering of drops with an improved control over density.

6. Results

Results are realized using Unreal Engine 4 (Version 4.10) on a Geforce GTX 980 in 720p. All images presented in this paper are screenshots of our real-time simulation. The rendering of the original scene runs at 60 fps, and 50 fps with the rain rendering method of [WJGG15].

Our technique is independent of scene geometry and can be contained in a single shader leading to an easy and efficient implementation in most current graphics engines. Figure 6 shows a complex natural scene in a heavy rainfall event, with and without throughfall (TF), and with TF only. Our method renders numerous drops while maintaining high performance. Figure 7 highlights the variation of TF density in light and heavy rainfall events from close and distant views. In these images, there are about 5000 regeneration locations for each tree. Varying rainfall intensity makes dripping TF amount increase or decrease over time and space according to the hydrological model. Free TF and streaks are rendered using the method presented in [WJGG15].

Our method can handle complex natural scenes as forests and maintain real-time performances. We can handle 15K active visible regeneration locations in real-time (35 fps, drops to 17 fps for 50K regeneration locations). These regeneration locations can be dynamically distributed inside all visible trees. As dripping drops beyond a given range are far too small to visually impact the rendering, only the closest visible trees contains visible throughfall. Our simulations show that 15K active regenerations locations are sufficient in most complex scenarios to obtain realistic throughfall rendering. Finally, Figure 8 shows a typical natural scene with various tree species.

7. Conclusion and future works

In this paper, we introduced a new method for throughfall (TF) rendering taking into account rainfall intensity and tree parameters. We presented an hydrological model to address drops dripping from foliage according to the temporal, spatial and drop size distributions. Raindrops passing through canopy are automatically handled by any rain rendering method as long as the method deals with collisions (in this paper, we use the method presented in [WJGG15]). A fully functional representation was introduced to control efficiently distribution, shape and density of dripping TF over time and space. Thanks to acceleration structures and a GPU-oriented implementation, our method can deal with a large number of dripping TF for complex rainy natural scenes rendering in real time.

However, some limitations remain in our method. Several phenomena, such as splash TF are not handled by our method. Although the proportion of splash TF in a given tree can be computed using our formulation, several issues, such as splash animation and accurate collision handling, still remain.

In this paper, we choose to pre-compute leaf locations which are visible from ground based on a classic ray casting, and use these locations for the regeneration process. Currently our method only handles straight throughfall, i.e. drops falling directly to the ground, and does not deal with cascading effects, e.g. drops falling from leaf to leaf. This would require dealing with complex problems, e.g. fluid simulation for a physical approach, tree discretization into layers to approximate this cascading effect.

Moreover, we suppose the Leaf Area Index (LAI) is known or

Figure 6: An original scene (1) with heavy rain (2) and throughfall (3). We also show the scene with throughfall only (4).

Figure 7: Distant and close views of dripping TF in light and heavy rainfall events.

Figure 8: In this example, we show throughfall rendering for both coniferous (tree in the center) and broadleaved trees (the two others) according to our hydrological model (35 fps).

artistically-fitted for each tree model. It would be interesting to propose a technique to automatically compute this parameter according to canopy structure.

Finally, several complex environmental effects impacting the dripping drops, such as wind, turbulence or interaction between an user and individual branches are not considered in our current method. However, the functional form presented in this paper provides an accurate control over shape, position and density of TF, and could be extended to take into account such effects. Some researchers [KON*13] have shown the difficulty to correlate wind and the TF spatial distribution especially in large rainstorms. New indoor and outdoor hydrological simulations could lead to a better understanding of this complex phenomenon to increase the realism of rainy natural scenes rendering.

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Appendix A: The elapsed time T between two drops

We introduce the volumetric flow rate Q for a single tree and for a drop diameter range over time and space

$$Q = \frac{RA\ q_t\ q_s\ q_d}{36 \times 10^5} \quad (m^3.s^{-1}). \tag{11}$$

Converting Q in drop frequency f (drop per second) based on the sphere volume equation gives

$$f = \frac{RA\ q_t\ q_s\ q_d}{6 \times 10^{-4}\ \pi D^3} \quad (s^{-1}). \tag{12}$$

Then we can express the throughfall period T corresponding to the elapsed time between two drops

$$T = \frac{1}{f} = 6 \times 10^{-4} \frac{\pi D^3}{RA\ q_t\ q_s\ q_d} \quad (s). \tag{13}$$

Appendix B: The Distribution Function $f_h(d,t)$

Let's consider the periodic function f calibrated to consider a drop every $v_\infty\ T$ meter(s). This function assumes drops have already reached terminal velocity.

$$f(d) = \cos\left(\frac{2\pi}{v_\infty\ T}\ d\right) \tag{14}$$

We also need to introduce the instantaneous velocity $v(t)$ of a drop with drag

$$v(t) = v_\infty \tanh(\frac{g}{v_\infty}\ t) \quad (m.s^{-1}). \tag{15}$$

where v_∞ is the terminal velocity for a drop diameter D.

$$v_\infty = 200\sqrt{\frac{D}{2000}} \quad (m.s^{-1}). \tag{16}$$

The tanh function has a limit value of 1. $v(t)$ is equal to v_∞ over a certain point in time, corresponding at the terminal velocity.

We now compute how long it takes for a drop to reach a distance Δy.

$$\Delta y = \int_0^t v(t)\mathrm{dt} \tag{17}$$

This is solved as follow:

$$\Delta y = \frac{v_\infty^2}{g}\ \ln\ \cosh\left(\frac{gt}{v_\infty}\right) \tag{18}$$

Then we express t as a function of distance d where $d = \Delta y$.

$$t(d) = \frac{v_\infty}{g}\ \text{arccosh}\ \exp\left(\frac{g}{v_\infty^2}\ d\right) \quad (s). \tag{19}$$

Distance $h(d)$ if the drop would have already reached terminal velocity after $t(d)$ seconds for a distance d is expressed as follow:

$$\begin{aligned} h(d) &= t(d)\ v_\infty \\ &= \frac{v_\infty^2}{g}\ \text{arccosh}\ exp\left(\frac{g}{v_\infty^2}\ d\right) \quad (m). \end{aligned} \tag{20}$$

The $h(d)$ function can be considered as a Mapping Function which enables to distort space to represent a flow of TF at a given point in time taking into account the drop instantaneous velocity. Consequently, the Distribution Function f_h is expressed as a composite function of the Periodic Function f and the Mapping/Distortion Function h.

$$\begin{aligned} f_h(d) &= (f \circ h)(d) \\ &= f(h(d)) \\ &= \cos\left(\frac{2\pi v_\infty}{g\ T}\ \text{arccosh}\ \exp\left(\frac{g}{v_\infty^2}\ d\right)\right) \end{aligned} \tag{21}$$

Only the phase function $\phi(t)$ remains to animate f_h over time.

$$\phi(t) = \frac{2\pi}{T}\ t \quad (rad). \tag{22}$$

Henceforth the Periodic Function f depends on time.

$$\begin{aligned} f(d,t) &= \cos\left(\frac{2\pi}{v_\infty\ T}\ d + \phi(t)\right) \\ &= \cos\left(\frac{2\pi}{v_\infty\ T}\ d + \frac{2\pi}{T}\ t\right) \\ &= \cos\left(\frac{2\pi}{T}\left(\frac{1}{v_\infty}\ d + t\right)\right) \end{aligned} \tag{23}$$

We also need to define $h(d,t)$ to properly compose f and h functions.

$$h(d,t) = (h(d),t) \tag{24}$$

Finally, the Distribution Function f_h is expressed over time and space as follow:

$$\begin{aligned} f_h(d,t) &= (f \circ h)(d,t) \\ &= f(h(d,t)) \\ &= f(h(d),t) \\ &= \cos\left(\frac{2\pi}{T}\left(\frac{v_\infty}{g}\ \text{arccosh}\ \exp\left(\frac{g}{v_\infty^2}\ d\right) + t\right)\right) \end{aligned} \tag{25}$$

Drop diameter range	Median	Needle (coated)	Broad-leaf (matte)	Broad-leaf (coated)
[1.0, 1.5[	1.25	0.0	0.0	0.0
[1.5, 2.0[	1.75	0.01	0.01	0,01
[2.0, 2.5[	2.25	0.02	0.01	0,02
[2.5, 3.0[	2.75	0.05	0.02	0,04
[3.0, 3.5[	3.25	0.08	0.04	0,07
[3.5, 4.0[	3.75	0.19	0.06	0,17
[4.0, 4.5[	4.25	0.15	0.08	0,37
[4.5, 5.0[	4.75	0.17	0.18	0,28
[5.0, 5.5[	5.25	0.13	0.22	0,04
[5.5, 6.0[	5.75	0.10	0.23	0.0
[6.0, 6.5[	6.25	0.06	0.12	0.0
[6.5, 7.0[	6.75	0.03	0.03	0.0
[7.0, 7.5[	7.25	0.01	0.0	0.0
[7.5, 8.0[	7.75	0.0	0.0	0.0

Table 4: Dripping Drop Size Distribution Ratio (Dripping DSDR) depending on specie.

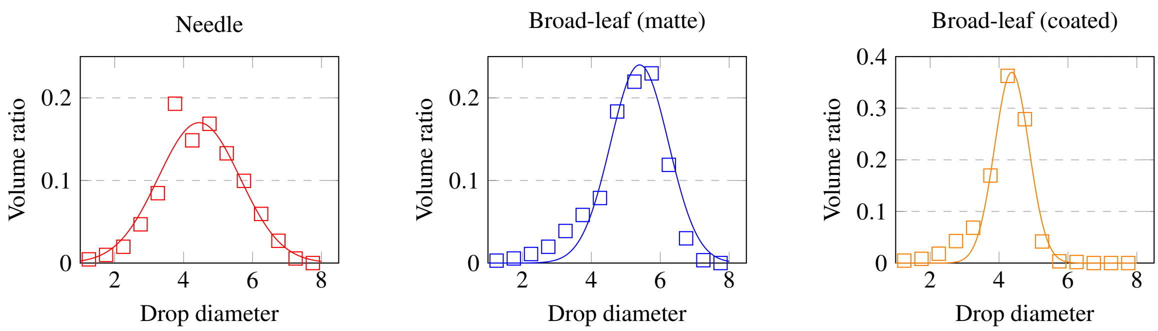

Figure 9: Dripping DSDR in Table 4 are fitted with a Gaussian function (Equation 4). Coefficients are presented in Table 3 for each specie according to drop diameter.