Computers & Graphics 50 (2015) 13–24

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Technical Section

Procedural bread making ☆

Rodrigo Baravalle [a,*], Gustavo Ariel Patow [b,1], Claudio Delrieux [c,2]

[a] CIFASIS-CONICET, Laboratory for System Dynamics and Signal Processing, Ocampo y Esmeralda, S2000EZP Rosario, Santa Fe, Argentina
[b] Grup de Grafics de Girona, Departament d'Informàtica i Matemàtica Aplicada, Universitat de Girona, Edifici P-IV, Campus Montilivi, E-17071 - Girona (Girona), Spain
[c] Department of Electrical Engineering and Computers, Universidad Nacional del Sur - IIIE-CONICET, Avenida Colón 80, Bahía Blanca 8000FTN, Argentina

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form
9 May 2015
Accepted 10 May 2015
Available online 20 May 2015

Keywords:
Bread
Photorealism
Fractal
Procedural models

ABSTRACT

Accurate modeling and rendering of food, and in particular of bread and other baked edible stuff, have not received as much attention as other materials in the photorealistic rendering literature. In particular, bread turns out to be a structurally complex material, and the eye is very precise in spotting improper models, making adequate bread modeling a difficult task. In this paper we present an accurate computational bread making model that allows us to faithfully represent the geometrical structure and the appearance of bread through its making process. This is achieved by a careful simulation of the conditions during proving and baking to get realistically looking bread. Our results are successfully compared to real bread by both visual inspection and by a multifractal-based error metric.

1. Introduction

Since its very beginning, computer graphics was concerned with the achievement of photorealistic modeling and rendering of real-world scenes [1]. There have been large ongoing efforts to produce realistic results for a large variety of scenes, from natural to synthetic, and from natural landscapes to urban scenarios. This has resulted in spectacular models to represent almost every possible material, natural or man-made, from water to fire, and from clouds to concrete.

However, not much attention has been paid to the modeling and rendering of food and edible materials, and only a few efforts can be mentioned in the literature [2–5]. On the other hand, accurate modeling of bread and its baking process has attracted a lot of attention in food engineering (e.g., [6]). However, this research is not taken advantage of in the computer graphics community.

In this paper we aim to produce a flexible and realistic model of bread, performing an accurate simulation of the different stages that bread undergoes during its cooking process, in particular proving and baking. For that, we use state-of-the-art models from food engineering, simulating first the gas bubbles formation in the dough during proving, and then the heat and mass transfer processes during baking.

The computational modeling of these processes, together with the initial shaping, is encapsulated in a procedural pipeline that is inspired in real bread formation. The pipeline is flexible enough to model arbitrary instances of the material, both in (macroscopic) shape and in (mesoscopic) texture.

The computation can be interrupted to show the material at intermediate stages, for instance to slice the raw dough, or to see the appearance of the bread after partial cooking. Since the crust making process is extremely complex, and not yet fully understood, we added an ad hoc mechanism, inspired in real crust measurements, to simulate and render crusts after the baking process. The complete modeling process requires little or no supervision.

The final images of the crumb and crust of baked breads appear to be quite realistic. To phenomenologically validate the results, we compared slices of the volume texture induced by the bubble distributions with different real bread types using multifractal measures. As far as we could find in the literature, this is the first attempt to develop an automatic process that can be configured to produce realistic simulations of bread.

2. Previous work

Procedural modeling of geometry substantially reduces the need for artistic intervention in domains or situations where repetitive supervised action would turn out impractical, for instance in shaping cities [7], planets [8], buildings [9], and plants [10]. Some methods employ grammars to define mathematical descriptions that represent spatial relationships between primitives, for instance cubes,

☆This article was recommended for publication by Bedrich Benes.

* Corresponding author. Tel.: +54 341 215 6499; fax: +54 341 482 1771.
E-mail addresses: baravalle@cifasis-conicet.gov.ar (R. Baravalle), dagush@ima.udg.es (G.A. Patow), cad@uns.edu.ar (C. Delrieux).
[1] Tel.: +34 972 41 88 32; fax: +34 972 41 87 92.
[2] Tel.: +54 291 4595101lxt3381.

http://dx.doi.org/10.1016/j.cag.2015.05.003
0097-8493/

cylinders, or lines. The final structures usually arise using recursion over tokens in the grammar.

Although there was some initial research in computer graphics on bread crumb modeling and rendering [2,3], the overall process of bread making involves several stages that were not always well accounted for in the field. Earlier works applied physical baking models to certain bread types for rendering animations (e.g. [11]), but the bread crumb bubbles' geometric modeling issue was not considered.

Procedural bread modeling, on the other hand, is a multidisciplinary research subject. Literature in food engineering has various decades of ongoing research aimed at understanding the bread production process. Studies in this area show that the proving stage of bread making strongly determines the features present in bread crumbs, in particular the bubbles [12]. The interaction between the yeast and some nutrients present in the dough produces CO_2. Bubbles' radii and their spatial distributions show fractal-like structures, exhibiting a distinguishable statistical self-similarity at different measurement scales. Studies computed different fractal dimensions for these structures in certain bread types [13], suggesting uniform fractal bubble distributions. The bread baking modeling has also been a subject of significant research [14].

Procedural fractal representations for other materials gave rise to a wide variety of research interests, including disparate topics such as mountains [15], moon craters, and bubble size distributions in cheeses [16]. In addition, complex mathematical models represent the behavior and growing of several natural phenomena. In computer graphics, these models are one of the foundations used to model water and fluids [17,18]. Authors borrow complex differential models from other science fields and compute them using numerical techniques. In recent years, GPGPU technology [19] enabled the possibility of real-time or interactive frame rate computation and rendering of these numerical models.

Notwithstanding these breakthroughs, our final goal still presents several challenges. In addition to an accurate mesoscopic model (3D texture), bread crumb rendering requires an adequate representation of the light transport phenomena, including self-occlusion, self-shadowing, transmittance, and reflection, among others. Only a few publications propose to manage both the geometric and illumination models, and mostly stressing only artistic considerations [3]. Also, these authors did not disclose enough details of the modeling and rendering algorithms (probably due to intellectual property issues) and thus the results are hardly reproducible.

On the other hand, the artistic community usually produces realistic bread rendering results using photographs and defining geometries from them, using translucent materials and subsurface scattering effects[3] and other ad hoc considerations.[4] These solutions generate realistic outcomes, but the required processes are tedious and time demanding. Moreover, defining different bread models requires repeating the whole modeling afresh, making the process far from practical. This way of coping with bread modeling is rigid in nature, and therefore has several other drawbacks. For instance, it is not possible to get arbitrary slices of the resulting object.

3. A pipeline for bread modeling

In relation to the previous work mentioned above, we propose to unify and differentiate the key steps of bread making (proving and baking) to produce a physically inspired pipeline for procedural generation of bread crumb and crust materials. These processes have to be well understood before development of accurate modeling.

In this section we describe all the stages that lead to the final generation and rendering of a realistic bread material. First, we review the state-of-the-art in understanding the bread baking process and we briefly introduce some ancillary mathematical models that will be required for understanding the main computational developments that we will present in our work. Then, we present the modeling procedures that, together with the illumination model, give rise to the main results presented in this paper.

The whole process is comprised in a modeling pipeline (see Fig. 1), where all the stages that emulate bread making are processes operating on a (binary) voxelized space. The user can feed the pipeline with a 3D mesh model of their preference, or allow the system to provide standard shapes, usually found in bakeries. Then, this 3D model is voxelized into a volumetric texture in order to proceed. During the bread proving simulation, the user can change the voxelization of the dough (parameterizing the bubble distribution – amounts and radii of bubbles–), or, again, leave the default parameters that lead to a generic voxelized space and, latter on, to a generic appearance. The dough shape will be intersected with the voxelized geometry in the previous step (the external shape provided by the user) to obtain a final volumetric texture, with its interior filled with the bread material (see Section 3.2). Then a specific baking model is computed [20] to rise the dough while slightly twisting the volumetric texture (and the bubbles therein) according to the effects that baking produces in the bread making process. Finally we apply direct volume rendering (DVR) [21] to the final voxelization, obtaining realistic images of the resulting bread.

3.1. Model voxelization

Users can generate arbitrary 3D bread shapes using our pipeline. The first step voxelizes a user-provided mesh with the open source `binvox` utility[5] [22]. The voxelization generates a binary volumetric texture, where 1 represents that the given voxel is inside the geometry, and 0 means that the voxel is outside. In the proving simulation step (next subsection), we generate the material that lies inside this voxelized model. This allows us to generate arbitrary bread types such as *baguettes*, *sliced* breads, or fancy shapes.

Once the user-provided geometry is converted into a volumetric texture M, we generate a second volumetric texture of the same size that contains, in each voxel, the result of computing the distance to the closest boundary voxel in the original volumetric texture [23] as follows. Given a binary volumetric texture M, the algorithm evaluates the new volumetric texture DF_M as

$$DF_M[i,j,k] = \min\{\delta([i,j,k],[i',j',k']) : M[i',j',k'] = 0\},$$

where $[i,j,k]$ and $[i',j',k']$ are cells in the respective textures representing the (i,j,k) and (i',j',k') spatial positions, and δ is the function that computes the distance between two cells, computed as either the Manhattan or the Euclidean distances. Entries far from the object boundaries get higher values than closer ones. This new volumetric texture acts as a discrete distance field, which will be required later at different stages of the pipeline.

3.2. Proving simulation

As stated above, the actual volume texture of the bread dough is due to bubble patterns, which in turn are the result of complex processes, including chemical reactions and physical deformations. The proving step accounts for the free bubble growth produced by living yeast in the dough. Then, human intervention deforms

[3] http://www.blenderguru.com/tutorials/how-to-create-realistic-bread

[4] http://design.tutsplus.com/tutorials/create-a-realistic-loaf-of-bread-in-photoshop–psd-10555

[5] http://www.cs.princeton.edu/min/binvox/