DIGITAL PROTOTYPING OF MILK PRODUCTS

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Digital prototyping has revolutionised the automotive industry by providing designers and engineers with digital models of their products that enable virtual product design, visualisation, and simulation [1]. However, digital prototyping does not exist in the food industry as the colloidal nature of most foods make them much more challenging to visualise and simulate realistically. We present models and methods that take steps toward digital prototyping of milk products and other food colloids. To simulate the dynamics of liquid products that only exist digitally, we use deformable simplicial complexes with an optimisation-based, linear finite element method [2,3]. Visualisation of products that only exist digitally requires a model for predicting the optical properties of the product materials. The optical properties (absorption coefficient, scattering coefficients, and phase function or asymmetry parameter) are the input needed for a Monte Carlo based graphical rendering. We have developed a model for predicting the optical properties of milk as a function of its fat and protein contents [4]. However, the model has only been validated to a limited extent. We suggest that diffuse reflectance measurements can be used for more extensive validation and for gathering data that can be used to extend our current model such that it can also predict how the optical properties develop during fermentation or acidification of milk to yogurt.

A well-established way of measuring optical properties is by static light scattering measurements. This, however, is an invasive procedure where a sample must be placed in a relatively small container (like a cuvette) and scanned by a photon detector orbiting the sample. The container must be small enough to ensure that the sample enters the single scattering regime. Diffuse reflectance measurements have the advantage of being noninvasive. However, the analysis becomes more complex as such measurements include multiple scattering effects. To measure optical properties using diffuse reflectance, we capture high dynamic range images of laser at different wavelengths incident on a sample *in situ*. The wavelength of the laser is easily adjustable as we use an NKT Photonics SuperK laser [5]. This enables us to retrieve spatially and spectrally resolved diffuse reflectance images. We also acquire images with the laser at several angles of incidence to enable oblique-incidence reflectometry. This enables us to use existing techniques [6,7] for retrieving the apparent optical properties of a sample. The validation consists in comparison of measured optical properties with predicted optical properties.

One of our goals is to extend our model for digital prototyping of milk products such that it can also predict how the optical properties develop during gelation of milk to yogurt. The influence of the colloidal aggregation on the optical properties is described by the static structure factor. As our method is noninvasive, we can use our setup for monitoring an acidification process over time. The challenge is to investigate whether we can use the resulting diffuse reflectance images to measure the static structure factor or similar optical properties of gels. We can see some correlation between measured diffuse reflectance and the rheology of the gel. This indicates that some quantity similar to the static structure factor is measurable using spatially resolved diffuse reflectance. There are ways of predicting the static structure factor for different types of colloids [8]. Thus if we succeed in measuring a similar quantity, we can extend our model and validate the extension.

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Digital Prototyping of Milk Products

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Motivation

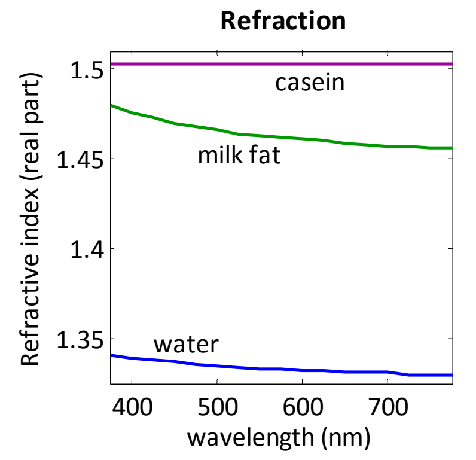
We present models and methods that take steps toward digital prototyping of milk products and other food colloids. The motivation for doing this is the following.

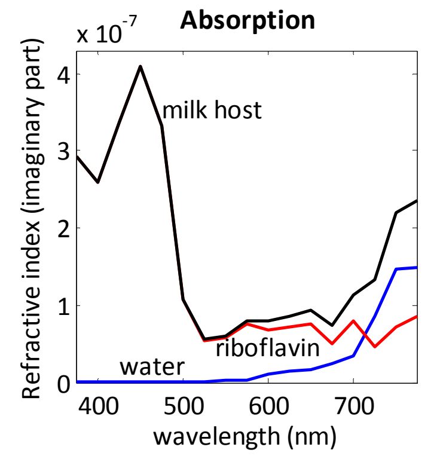
- Digital prototyping has revolutionised the automotive industry by providing designers and engineers with digital models of their products that enable virtual product design, visualisation, and simulation.
- Digital prototyping does not exist in the food industry as the colloidal nature of most foods make them much more challenging to visualise and simulate realistically.

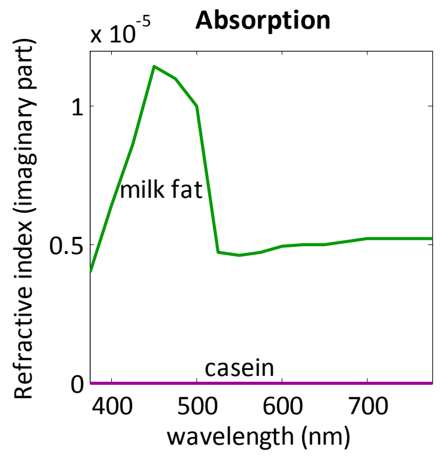
Modelling cow's milk

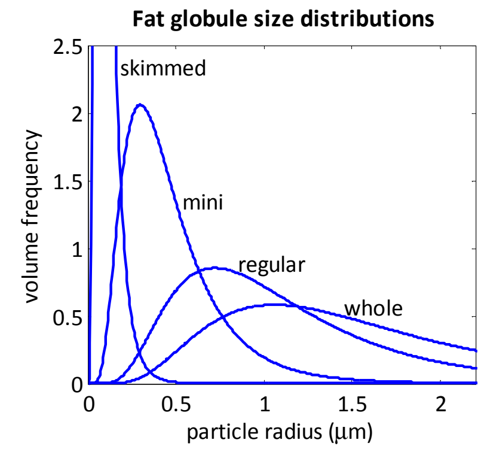
Milk from an optical point of view [1]:

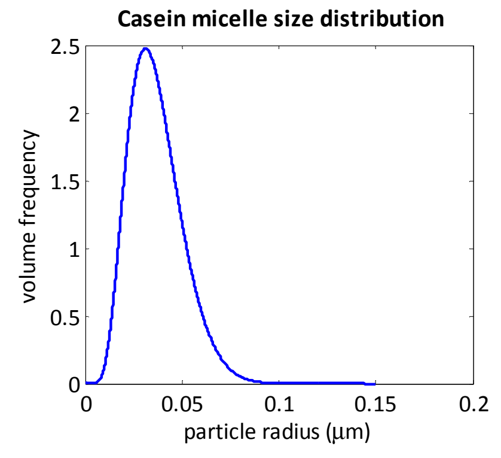
- Two types of nearly spherical particles: fat globules and casein micelles.
- Host medium with almost the same optical properties as pure water.
- Absorption of vitamin B2 (riboflavin) needs to be added to that of the host medium.
- Refractive indices and size distributions of particle inclusions are given by empirical formulae and measured data.



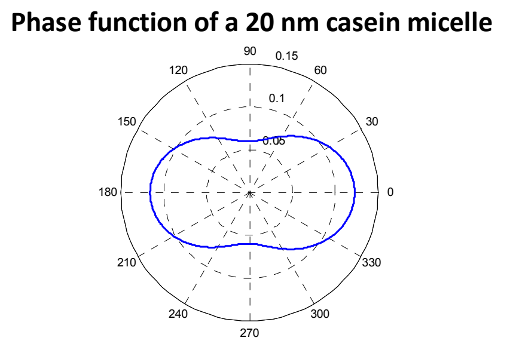


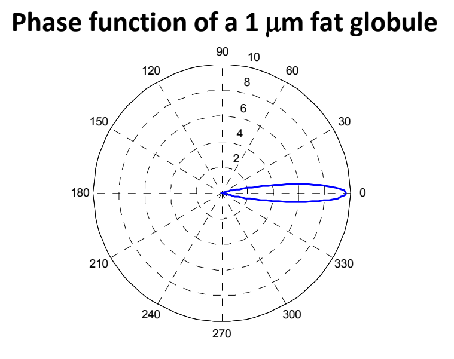


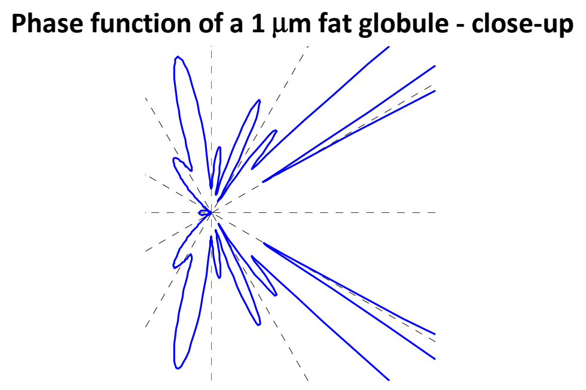


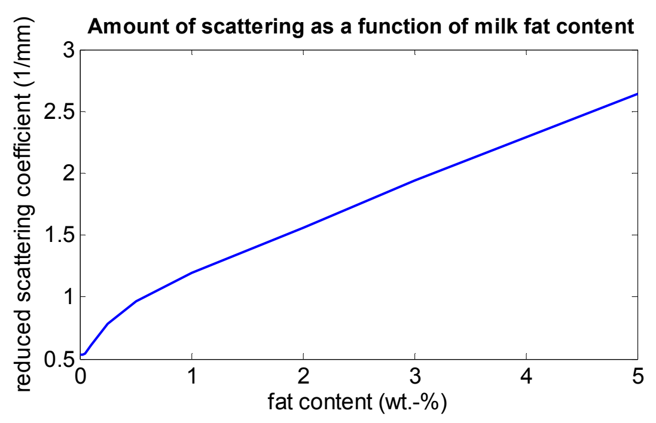


Macroscopic optical properties (absorption coefficient, scattering coefficients, and phase function or asymmetry parameter) are the input needed for a Monte Carlo based graphical rendering. We predict the optical properties of milk as a function of its fat and protein contents using Lorenz-Mie theory with the input specified above [1]. The following plots exemplify our prediction of scattering properties at a wavelength of 650 nm.



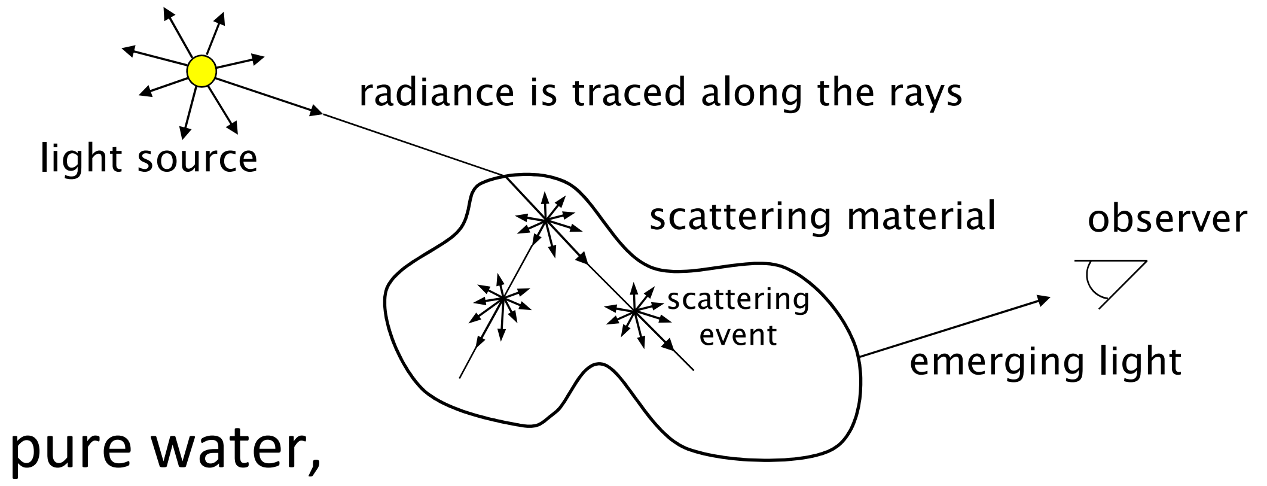






Computing appearance and behaviour

The mathematical model of radiative transfer is used for rendering realistic images. We solve the radiative transfer equation using Monte Carlo path tracing [1], which is a sampling-based rendering algorithm that works in general (see illustration to the right).

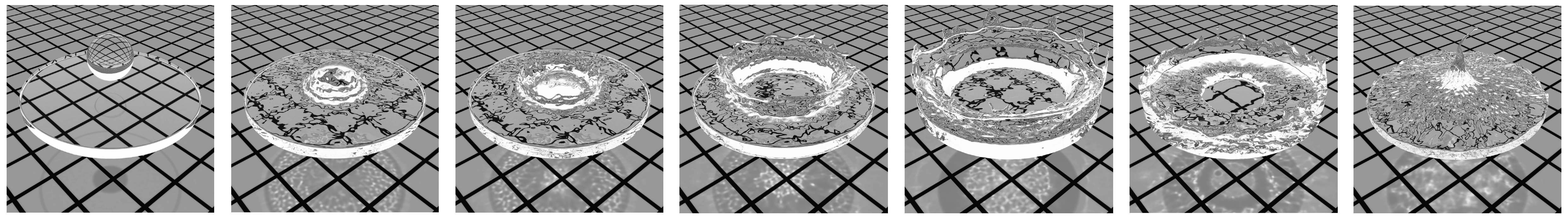


Using our milk model and rendering method, we are able to show the visual significance of each component in the milk.

In the rendered image below, the glasses contain (left to right): pure water, milk host, casein micelles in water, fat globules in water, skimmed milk, regular milk, and whole milk [1].

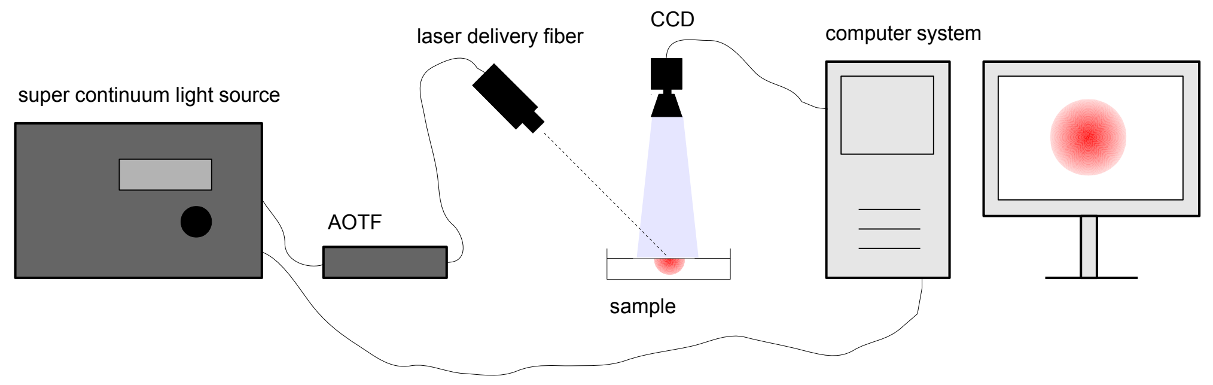
We can also add cocoa particles to render the appearance of chocolate milk.

To simulate the dynamics of liquid products that only exist digitally, we use deformable simplicial complexes with an optimisation-based finite element method [2]. The following sequence of images is an example.



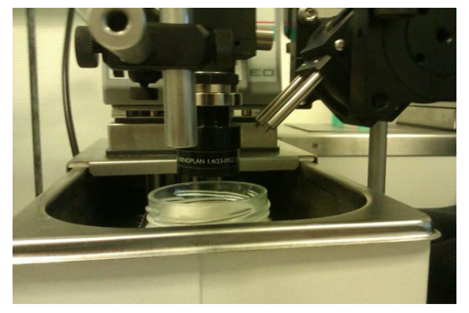
Measuring scattering properties

We capture images of laser at different wavelengths incident on a sample *in situ*. The wavelength of the laser is easily adjustable as we use an NKT Photonics SuperK laser [3]. This enables us to retrieve spatially and spectrally resolved diffuse reflectance images. We also acquire images with the laser at several angles of incidence to enable oblique-incidence reflectometry. With this setup (see below), we can estimate the macroscopic optical properties of a sample using existing techniques [4].

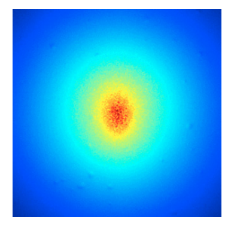


lab setup

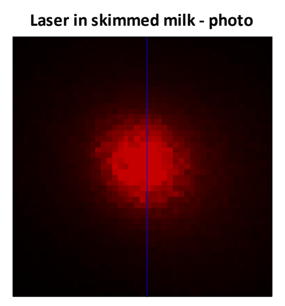
in situ setup

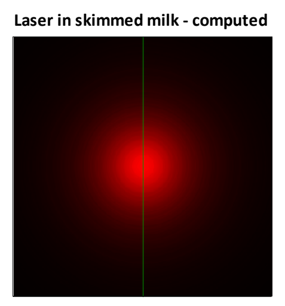


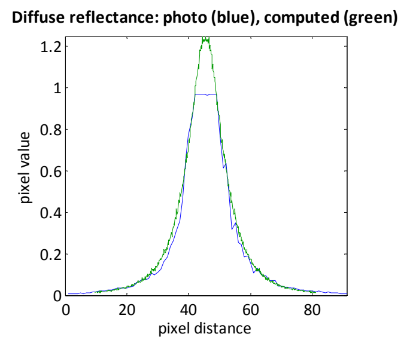
sample image (log transformed, false colours)

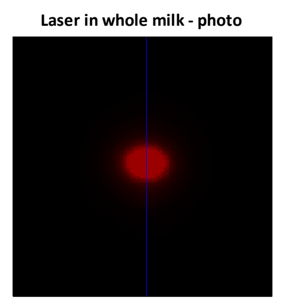


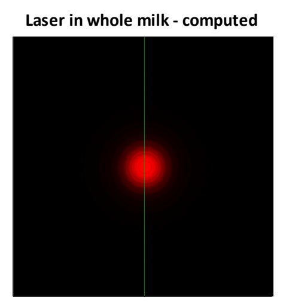
Validation

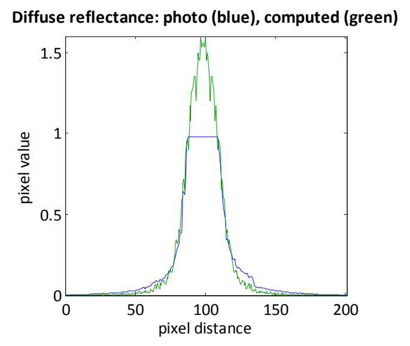






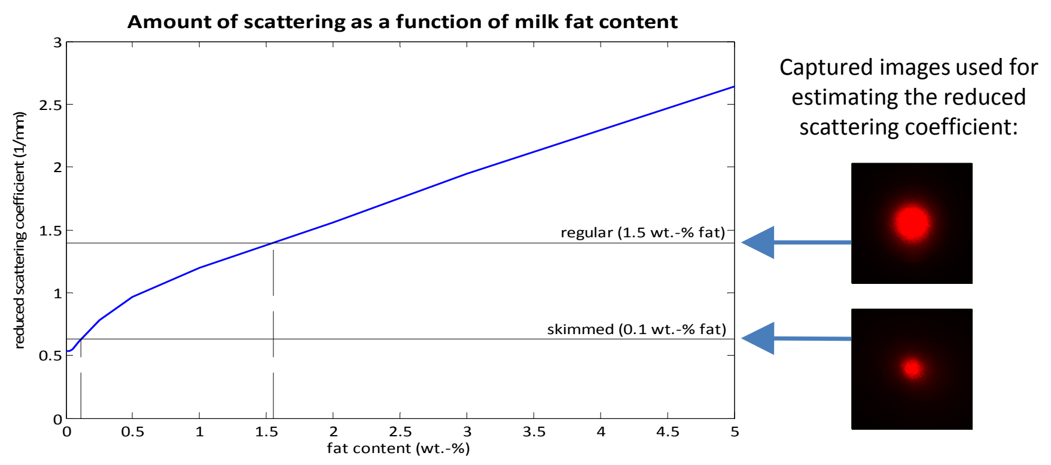






To find out if our model correctly predicts the appearance of real milk, we model our experimental setup digitally. Tests at a wavelength of 650 nm is provided in the figures above. These illustrate that our milk model and Monte Carlo simulation can predict the outcome of our diffuse reflectance image captures.

Finally, we would like to validate our milk model by comparison of measured and predicted scattering properties. This work is, however, not yet finished as our measurement technique is in the process of being calibrated using phantom materials. The figure to the right indicates preliminary results.



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