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Simulating fibre assemblies: from Hollywood illusions to physical predictions

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What is the common feature between *Final Fantasy: the Spirits Within* (2001), *Moana* (2016), and *Avatar, the Way of Water* (2022)? These three computer-animated movies, though made at different periods of time over the three last decades, have all requested huge efforts and energy to capture, as realistically as possible, the motion of one of the most familiar fibrous object: human hair. Should it be long, braided, wavy, or fuzzy, hair is one of the most visible and fascinating features of a human character; as such it greatly contributes to the visual asset of a movie, and enriches its storytelling. More broadly, since the advent of modern computers in the 1960's, Computer Graphics has always striven to develop powerful simulation tools for capturing fascinating phenomena of our everyday life, such as cloth folding, granular flowing, or plant fluttering in the wind. Animating hair virtually and giving the illusion that it is real has become an endless quest since the 2000's.



Figure 1: Simulating the combing of a curly hair wisp with frictional contact ©ELAN team at Inria, 2023.

From very distinct fields... Computer scientists were not the first to draw their attention to fibre systems. Many physicists and mathematicians aimed for centuries at understanding the principles governing those complex mechanical phenomena, providing a number of continuous models for thin elastic rods [1] and frictional contact [2]. In the XXth century, industrial applications such as process automatisation and new ways of transportation boosted the field of Mechanical Engineering, and in particular the finite-element modelling of elastic fibres – called 'beams' in that community. There however, not much room for fantasy nor entertainment: material strength, reliability of mechanisms, and safety, stood for the main priorities. Assimilated to failure cases, large displacements of structures, buckling, tearing, entanglement, and even dynamics, were at that time considered as undesirable behaviours, thus restraining the search for corresponding numerical models. In contrast, Computer Graphics, from its very beginning, was eager to capture such peculiar phenomena, with the sole aim to produce spectacular images and create astonishing stories.

... to recent convergences Nowadays however, although the image production still remains the core activity of the Computer Graphics community, more and more research studies are directed in this community towards the virtual and real prototyping of mechanical systems, notably driven by a myriad of new applications in the virtual try-on and fashion industries, e.g., hairstyling or personalised textile manufacturing. Furthermore, the advent of additive fabrication is currently boosting research in the free design of new mechanisms for various applications, from architecture design [3] to the fabrication of metamaterials [4]. Computer scientists are hence faced with new challenges including methodology and skills for quantitative validation and predictive simulation.

In parallel, the Mechanical Engineering industry has recently shown some growing interest into the modelling of dynamic phenomena prone to large displacements, buckling, contact and friction. For instance, vehicle and aircraft manufacturers encounter large-scale problems involving buckling or entanglement of thin structures such as nylon or carbon fibers [5]; they clearly need predictive, but also robust and efficient numerical tools for simulating and optimising their new fabrication processes, which shares many common features with the large-scale simulation scenarii traditionally studied in Computer Graphics applications.

Furthermore, since a few decades, a new generation of physicists became interested again in the understanding of visually fascinating phenomena, and started investigating the tight links between geometry and elasticity [6].

Common fibrous objects such as twined plants, knitted cloth, bird nests or human hair, have thus regained some popularity among the community in Nonlinear Physics [7, 8, 9]. The term 'extreme mechanics' [10] has been coined precisely to designate all kinds of phenomena involving large displacements, nonlinear deformations, buckling instabilities, or dynamics with dry frictional contact – thus falling outside the standard, well-studied regimes. A major breakthrough was to show that instabilities emerging from such nonlinear (and even nonsmooth) regimes, previously considered as the first route toward failure in engineering structures, could in turn be harnessed to activate matter and program new materials with specific functions: the field of functional materials was born [11], together with a myriad of applications ranging from deployable structures and new metamaterials to soft locomotion [12, 13, 14]. Beyond offering a formidable tool for complementing experimental investigations when laboratory experiments are too cumbersome or costly to perform, numerical exploration rapidly started being perceived by physicists as a valuable tool for getting insights into the early search for analytic solutions, thus fully participating in the modelling stage and physical understanding. Here again, the simulation of fibrous materials turns out to become crucially requested for improving the understanding of physical phenomena unexplored so far, and for designing new materials with controlled properties.

Overall, it turns out that over the last decades, Computer Graphics, Mechanical Engineering, and Nonlinear Physics have finally ended up sharing a strong common interest for simulating extreme mechanical phenomena – and in particular fibrous systems – in a predictive way, while possessing very complementary skills. Unfortunately, in spite of all these observed convergences, Computer Graphics and Computational Mechanics/Physics remain today desperately compartmentalised.

Predictive simulation of fibre assemblies In this talk I will show that although building a simulator that is both predictive and scalable remains an open challenge when dealing with extreme mechanics, advances towards this goal can be made possible thanks to a pluridisciplinary modelling approach combining skills across Physics, Mechanics, and Computer Graphics. In particular, I will present the numerical models that we have been building in the ELAN group at Inria for the last ten years in order to achieve reliable dynamic simulations of fibre packings subject to large displacements, should it be for special effects, virtual prototyping, or physical exploration [15, 16, 17, 18, 19]. Our methodology draws inspiration from Nonlinear Physics for the simplicity and elegance of the reduced rod models, the scaling laws, and the controlled experiments developed there; Mechanical Engineering for the convergence properties of discrete element formulations and the robustness of frictional contact methods, especially within the context of nonsmooth mechanics; and Computer Graphics, for the efficiency and agility of the algorithms and free softwares deployed for optimisation solvers, contact detection, and code benchmarking.

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