Surfaces versus networks: bridging their gap with applications in nanotechnology

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Surfaces and networks constitute two complementary mathematical frameworks for representing real world data. Surface representations are particularly suitable when local correlations dominate, as in material interfaces or topographic landscapes. In contrast, network representations are preferred when interactions arise from non local processes and are largely independent of spatial proximity, such as in wireless communication systems, social media, or popularity driven dynamics. Although these two paradigms are often treated as distinct, real systems frequently blur this separation when their functionality depends simultaneously on local structure and non local interactions.

This interplay becomes evident in several physical situations. When a rough surface comes into contact with an external body—whether a solid or a liquid—non local correlations emerge because distant asperities interact indirectly through the contacting medium. Such examples motivate the need for analytical tools capable of bridging surface based and network based descriptions. The aim of this work is to explore this conceptual bridge, driven by challenges encountered in nanotechnology.

Our focus lies on the characterization of rough nanostructured surfaces, whose morphology plays a decisive role in determining interfacial properties such as adhesion, friction, catalysis, wetting, and electrical conductivity. At the nanoscale, where surface to volume ratios are high, these effects become increasingly significant. Beyond their technological relevance, rough surfaces are inherently complex nonequilibrium systems in which order and randomness coexist across multiple spatial scales. Despite extensive study, the characterization of this interplay remains incomplete, motivating the development of analytical approaches that can capture the multiplicity of spatial organization. In this work, we introduce complex network theory as a framework for revealing hidden structural patterns in rough surfaces.

Although network based methods have been widely applied in time series analysis, their objectives differ fundamentally from the surface centric perspective pursued here. Time series approaches exploit temporal evolution to infer future behavior, whereas surface analysis focuses on how height variations govern interactions with external bodies. The network constructions proposed in this study embed this surface centric viewpoint directly into their architecture.

We develop three complementary methods for constructing network representations of rough nanosurfaces. The first employs a height similarity criterion, linking surface points whose heights are sufficiently close. The second uses proximity graph concepts, where nodes correspond to quantized height levels and links encode the closeness of height quanta. The third method binarizes the surface using an appropriate threshold and applies a bulk network approach to capture visibility based communication between asperities.

These methods are applied to a diverse suite of synthesized surfaces—including random, periodic, fractal self affine, and mounded morphologies. By examining key network metrics such as mean degree, degree distribution, clustering coefficient, and average shortest path length, we uncover systematic relationships between surface characteristics and network structure, revealing previously hidden aspects of surface spatial organization.