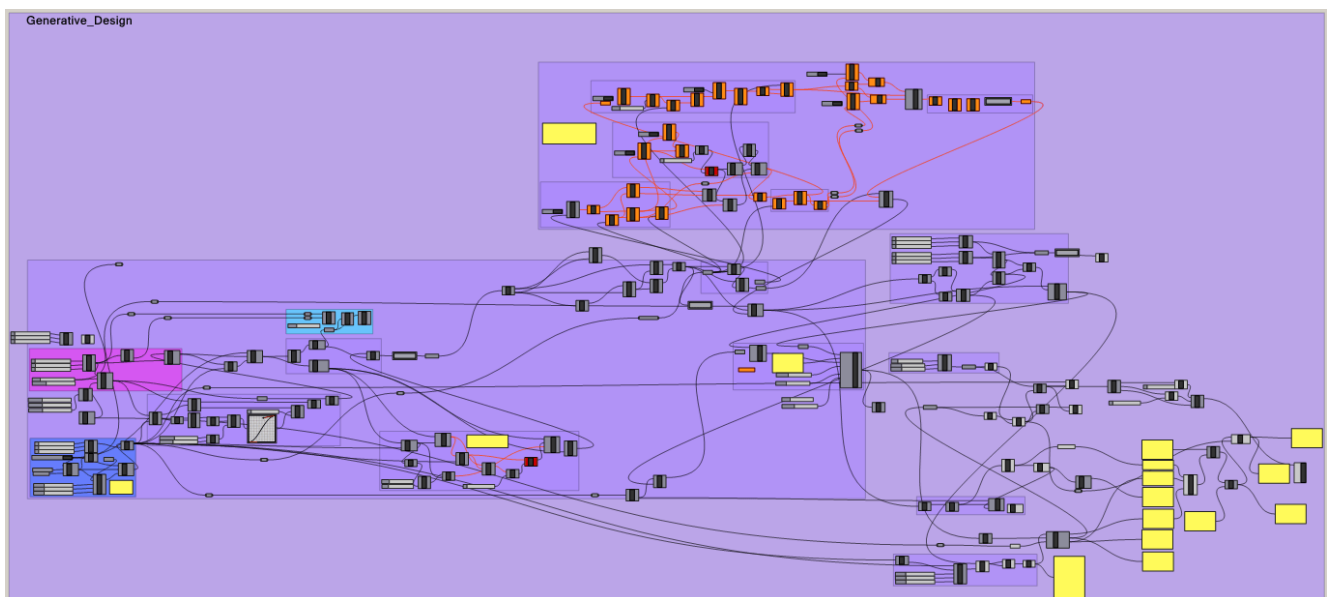


VITRO-P: Generative Design for Customizable Vascular Networks in Optical Tissue Phantoms

Advances in optical sensing and spectroscopy are transforming biomedical research, enabling non-invasive diagnostics and real-time monitoring of physiological processes. However, the development of these technologies is often limited by the lack of reliable, repeatable testing environments that accurately mimic the complexity of human tissue.

Developed by researchers in the [Barman Lab](#) at [Johns Hopkins University](#), the VITRO-P (Vascular Integrated Tissue Replica Optical Phantom) is a project that addresses this gap through a computational design approach, combining parametric modeling, generative algorithms, and digital fabrication. At its core, the project leverages [Rhino 3D](#) and [Grasshopper](#) to design intricate vascular systems that can be embedded within synthetic tissue phantoms, offering a highly customizable platform for biomedical experimentation.



Overview of the generative workflow developed in Grasshopper. The definition integrates geometry input, node population, rule-based logic, and filtering mechanisms to produce fully

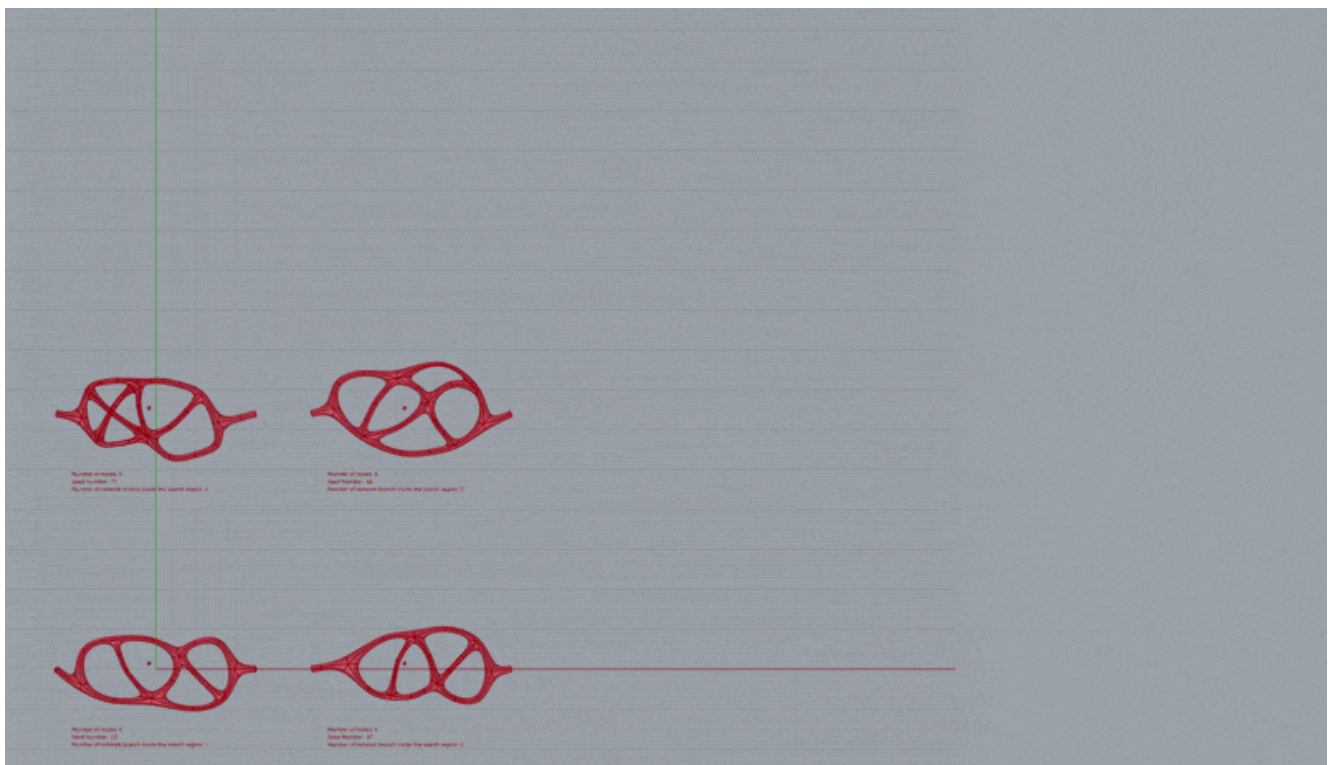
parametric vascular networks ready for fabrication.

COMPUTATIONAL DESIGN & GENERATIVE WORKFLOW

The vascular geometry is generated using a hybrid system combining **parametric control and rule-based logic**. Within Grasshopper, a node-based algorithm defines the structure of the vascular network, allowing users to manipulate key parameters such as node density, vessel diameter, and inlet and outlet positions.

As described in the paper, the process begins with a user-defined geometry that is populated with nodes acting as branching points. These nodes are then influenced by attraction forces to simulate realistic vascular density gradients.

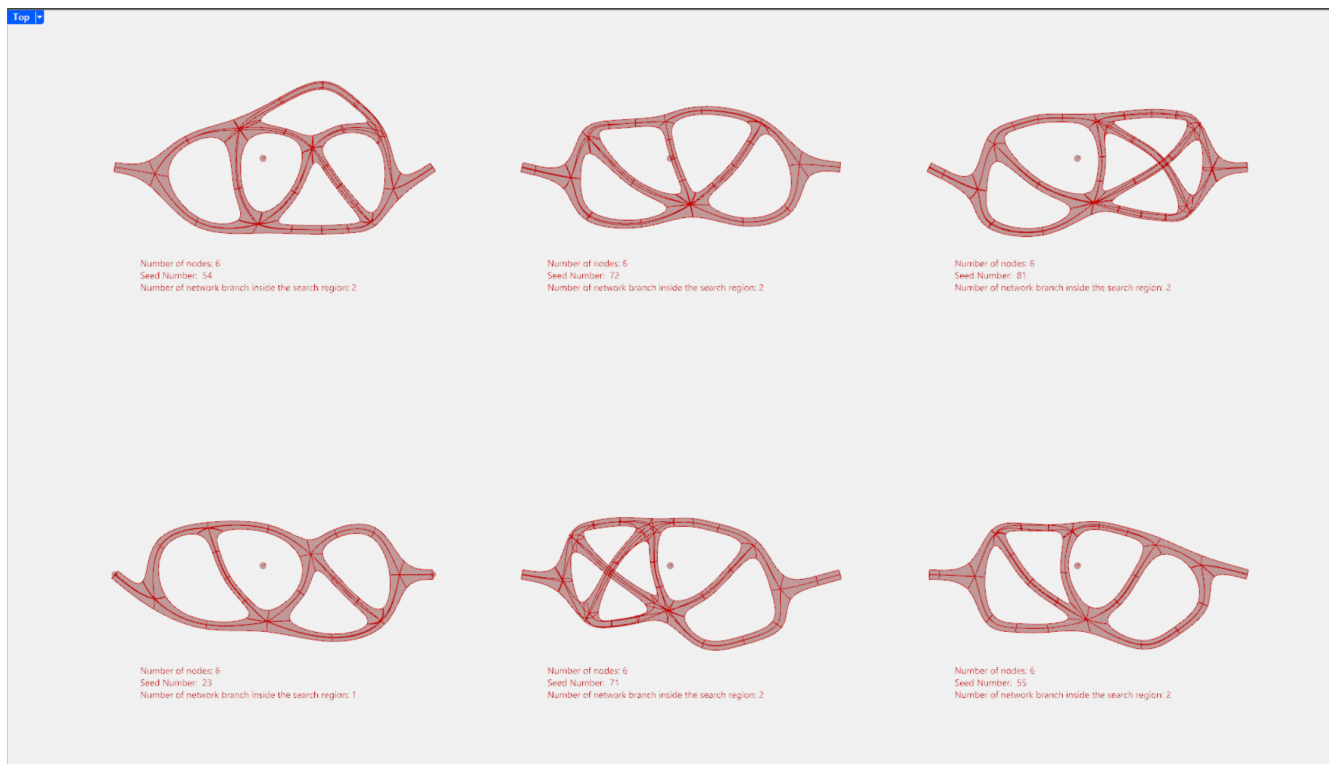
A key step in the workflow is the use of **Voronoi segmentation**, which subdivides the geometry into regions that introduce controlled randomness and spatial variation. This mirrors biological tissue organization and enhances the realism of the resulting network. The centroids of these regions are then connected to form a continuous vascular system, with additional sub-algorithms ensuring the removal of “blind ends” and the introduction of functional flow paths.



Real-time feedback inside the Rhino viewport. The algorithm iterates through multiple configurations instantly, allowing rapid exploration of vascular topologies while maintaining consistent input parameters.

Beyond geometry generation, the team developed a **real-time path replanning system** capable of detecting collisions with embedded objects, such as simulated bones. When intersections occur, the algorithm dynamically reroutes vascular branches around obstacles while maintaining network continuity. This level of adaptability is critical for simulating complex biological environments.

To explore design variability, the system can generate large batches of vascular configurations using randomized seed values. These variations are then filtered through a rule-based selection process to identify optimal solutions based on criteria such as branch density or spatial distribution.

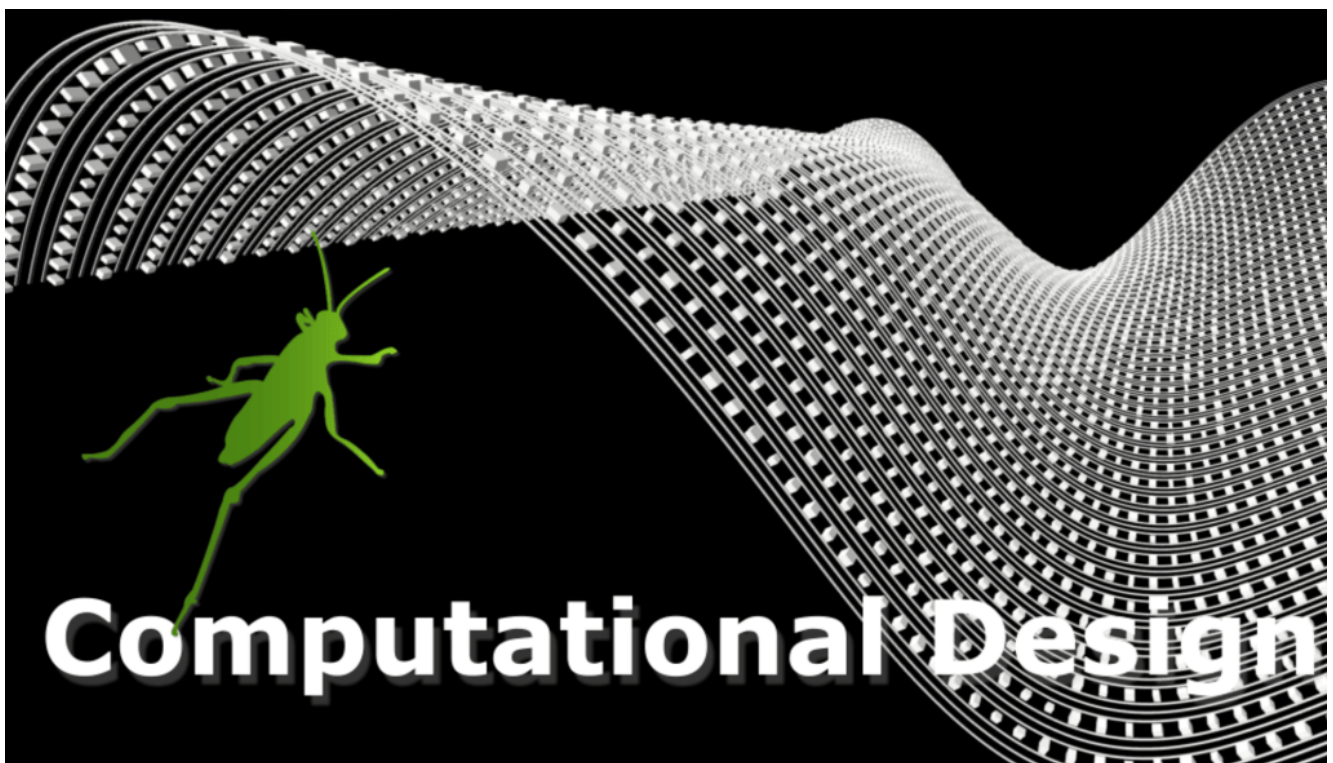


Parametric variation study generated from a single definition. By modifying the seed value, the system produces entirely new vascular layouts while preserving constraints such as node count, connectivity, and inlet/outlet conditions.

FROM DIGITAL MODEL TO FABRICATION

Once generated, the vascular networks are translated into physical models using a hybrid digital fabrication workflow. The process relies on 3D-printed sacrificial structures that define the internal vasculature within the final phantom.

A [UniFormation](#) GKtwo resin printer was used to produce hollow, water-soluble vascular molds. These are embedded into materials such as agarose, PDMS, or silicone, which replicate the optical and mechanical properties of biological tissue. After the surrounding material solidifies, the sacrificial structure is dissolved, leaving behind a network of hollow channels.



[See Also](#)

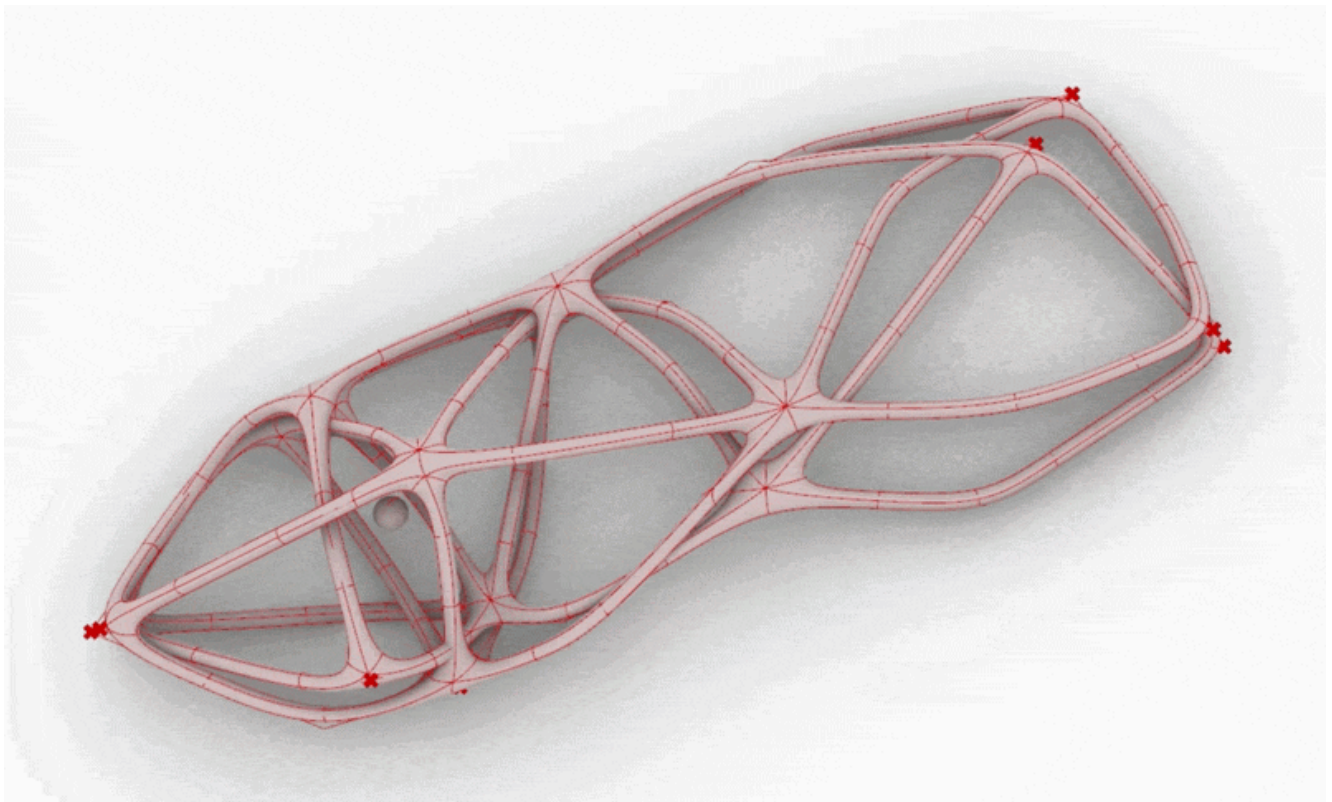
[COMPUTATIONAL DESIGN WITH GRASSHOPPER](#)

One of the main challenges in this process was balancing printer resolution with material behavior. While the computational model could generate extremely fine vascular geometries, reproducing these at

small scales proved difficult. Additionally, standard resins could not be used, as they would interfere with optical measurements such as Raman spectroscopy.

To address this, the team selected a water-soluble resin ([3Dresyn IM-UHT-WS](#)) that could be removed without introducing unwanted chemical signals. However, this material introduced its own challenges, including difficult post-processing and residue formation. A workaround was developed by air-drying the resin instead of post-curing it, combined with rapid cooling techniques to stabilize the surrounding agarose structure.

Despite these fabrication constraints, the workflow remains intentionally **fabrication-agnostic**, meaning the same computational models can be adapted for other production methods such as bioprinting or microfabrication.

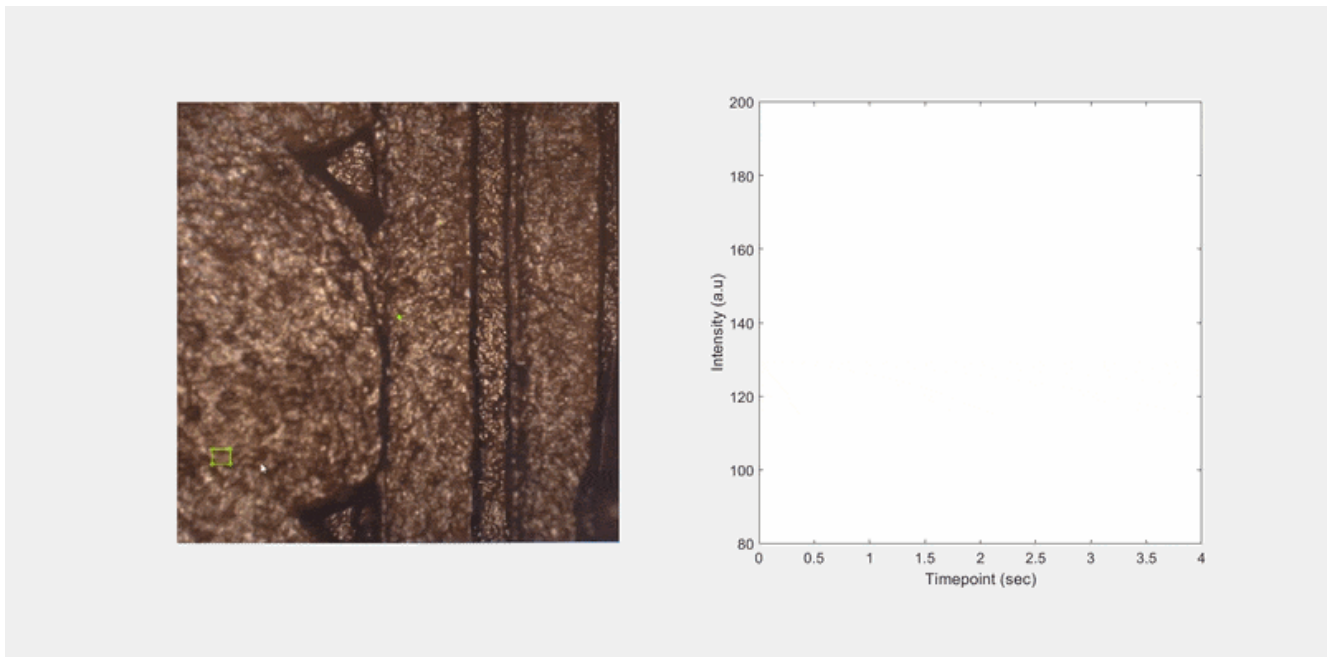


Rule-based node attraction system. A user-defined reference point controls local branch density, simulating physiological conditions where vascular networks concentrate around specific regions.

PERFORMANCE & APPLICATIONS

The resulting phantoms demonstrate a high level of functional realism. The embedded vascular networks support **continuous fluid flow for extended periods**, enabling controlled experimental conditions.

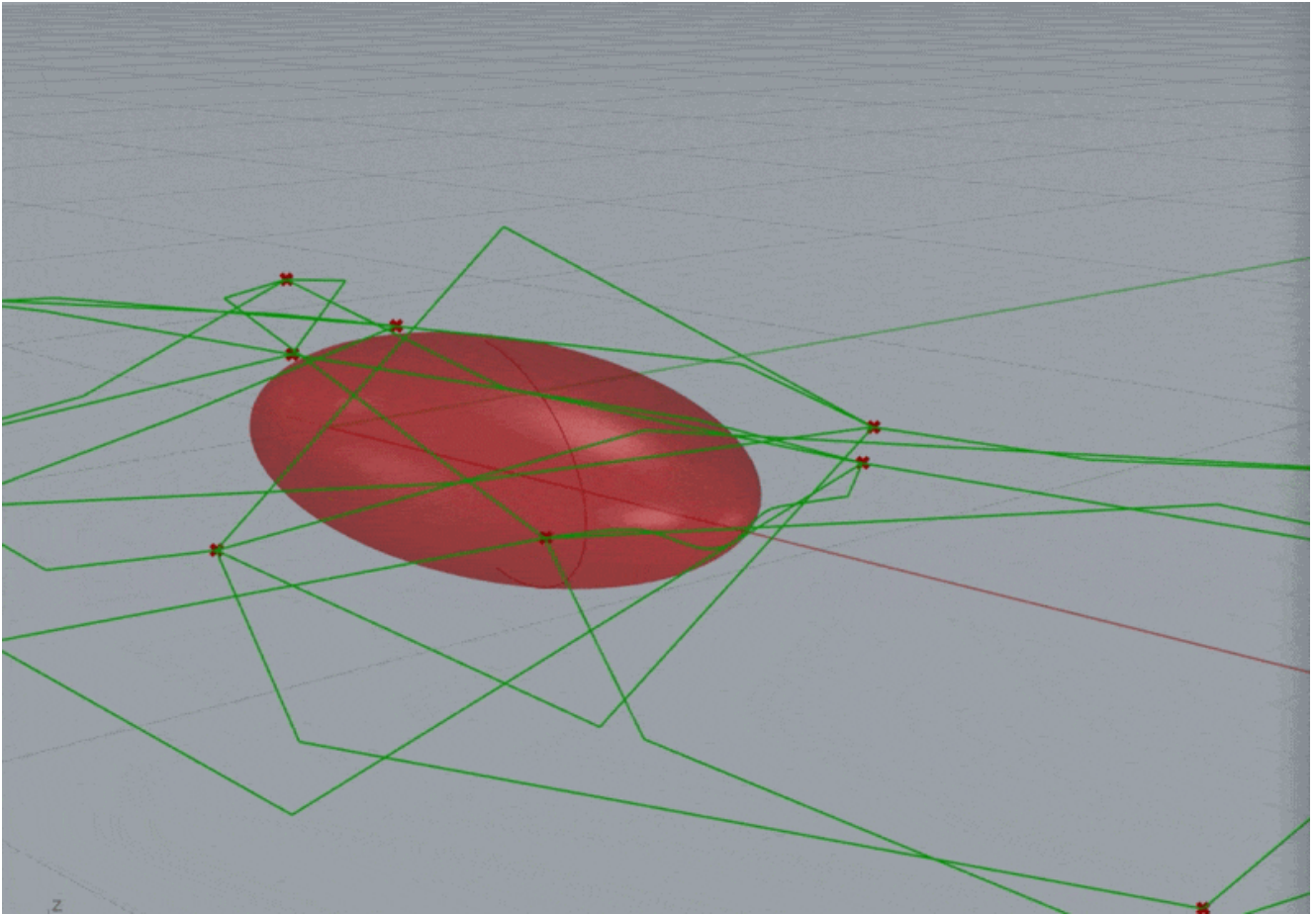
Flow velocity tests showed values comparable to physiological ranges found in human arteries. Pulsatile flow experiments successfully replicated heartbeat dynamics, including the detection of waveform patterns analogous to P-waves and T-waves.



This animation shows the tissue phantom simulating active pulsatile flow to mimic a human heartbeat. Real-time imaging captures waveform patterns analogous to P-waves and T-waves.

These capabilities position VITRO-P as a versatile platform for applications such as:

- Developing and validating medical devices
- Testing optical imaging and sensing technologies
- Studying fluid dynamics and particle transport
- Simulating surgical conditions and training environments



Adaptive path-replanning in action. The algorithm detects collisions with embedded objects and automatically reroutes branches, maintaining network continuity and functional flow paths.

A COMPUTATIONAL APPROACH TO BIOMIMICRY

Rather than focusing solely on fabrication, VITRO-P emphasizes **computational design as the primary driver of innovation**. By decoupling design complexity from manufacturing constraints, the system enables rapid iteration and customization of vascular structures that would be difficult to achieve through traditional methods.

The integration of Rhino and Grasshopper into this workflow highlights how tools commonly used in architecture and design can be extended into highly specialized scientific applications. The project demonstrates a clear shift toward **algorithm-driven biomimicry**, where variability, adaptability, and control are embedded directly into the

design process.



Fabricated VITRO-P system with active fluid flow. The hollow vascular network, generated in Grasshopper and produced 3D-printed sacrificial molds, enables controlled flow experiments within a soft tissue phantom.

CREDITS

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