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The virtual FIB: Simulating 3D in situ lift-out for visualization and technique development

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Focused ion beam (FIB) specimen preparation is regularly used in a wide array of material systems due to its precision and site specificity [1]. Using an *in situ* lift-out needle in combination with a 5-axis stage, such as schematically depicted in Figure 1(a), both cross-section [2] and plan-view [3] specimens can be extracted.

In recent years, lift-out needles with motorized rotation and accurate encoders have become more common. For the widespread case of lift-out needles mounted above the chamber door, as shown in Figure 1(b), the needle rotation axis is complementary to the existing stage movement axes and provides an interesting new degree of freedom for *in situ* lift-out. Lift-out needle rotation thus enables new protocols within a range of different 3D orientations and can be leveraged for advanced lift-out procedures such as backside preparation, FIB specimen preparation for scanning probe microscopy [4], or specimen preparation on MEMS chips for *in situ* experiments. However, the full usefulness of this new degree of freedom is limited by the difficulty of visualizing and predicting how the final lamella will be oriented for various combinations of rotations along the different axes.

At the same time, new triple-beam instruments are emerging. These systems further complicate sample navigation by integrating elements such as femtosecond lasers for bulk milling [5] or low-energy argon ‘polisher’ beams [6]. These extra elements may not always be suitable for image formation but must still be carefully aligned along new axes. Moving between three beams in these systems can quickly become challenging with current 5-axis stage designs, and so the stage is often supplemented with pre-tilted stubs or substages. These add more degrees of freedom, but also increase complexity in navigation. This becomes especially relevant when multiple rotation operations along different axes interact, such as when using stage rotation and tilt if the sample is mounted on a pre-tilted stub.

In all, it is becoming increasingly common for advanced FIB processing to involve rotations along multiple different axes beyond the well-established behavior of the 5-axis stage. Understanding the final 3D orientation of samples or lamellas can quickly become difficult, creating a growing need for ways to facilitate the process of working with complex 3D geometries. To that end, this work presents an open source software tool to simulate common degrees of freedom in FIB systems, mimicking FIB controls to manipulate a 3D model that can be freely observed. This assists operators in visualizing, exploring, and communicating different ways of using the numerous three-dimensional degrees of freedom in FIB. By providing a simple, FIB-centered interface it also aims to be a useful tool for technique development involving multiple rotation steps, such as for advanced *in situ* lift-out.

An example of how such a tool can be useful for plan-view lift-out is shown in Figure 2. A lift-out animator interface (a,b) takes as input three relevant degrees of freedom: stage rotation, stage tilt, and lift-out needle rotation. The system performs the sequence of rotations and automatically creates an animation of the process. Alternatively, with a live preview, changing any value immediately updates the model, thereby providing instant feedback on the impact of that parameter on the final lamella orientation. As shown in (c,d), a 180° rotation of the lift-out needle orients a plan-view lamella such that it can be directly welded to the post of a half-grid, in a single lift-out step and without opening the chamber. Furthermore, it may be desirable to tweak this procedure to avoid exposing features on the top surface (A) to the ion beam more than necessary. By testing the effects of the different rotation options on the final lamella orientation it becomes clear that if lift-out is performed at 15° stage tilt instead of 0°, the top surface (A) now faces away from the ion beam as shown in (e), shielding it from accidental milling without overly complicating the overall lift-out process. Crucially, the ability to instantly observe and understand the final effect of various potential changes to the lift-out process allows for rapid experimentation and makes it possible to iterate on new lift-out protocols before irreversibly milling a sample or attaching it to the lift-out needle.

Finally, as it is based on the open source (GPL) 3D creation suite Blender [7], this FIB simulation sandbox is fully open source, with every aspect available for customization. This makes it system-agnostic as elements can be adjusted to correspond to any specific FIB system. The core goal of this project is to provide a simplified, user-friendly and FIB-relevant interface for operators of any skill level to explore the available degrees of freedom in complex situations like lift-out or alignment of multi-beam systems. For advanced users, the full capabilities of Blender are still present and can be leveraged to create animations clearly communicating their specific FIB protocols [8].

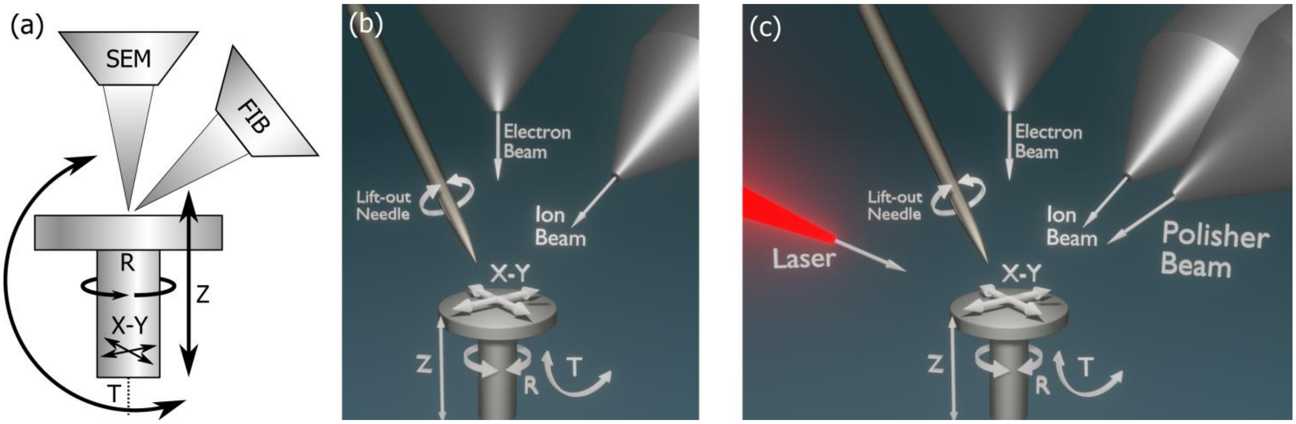
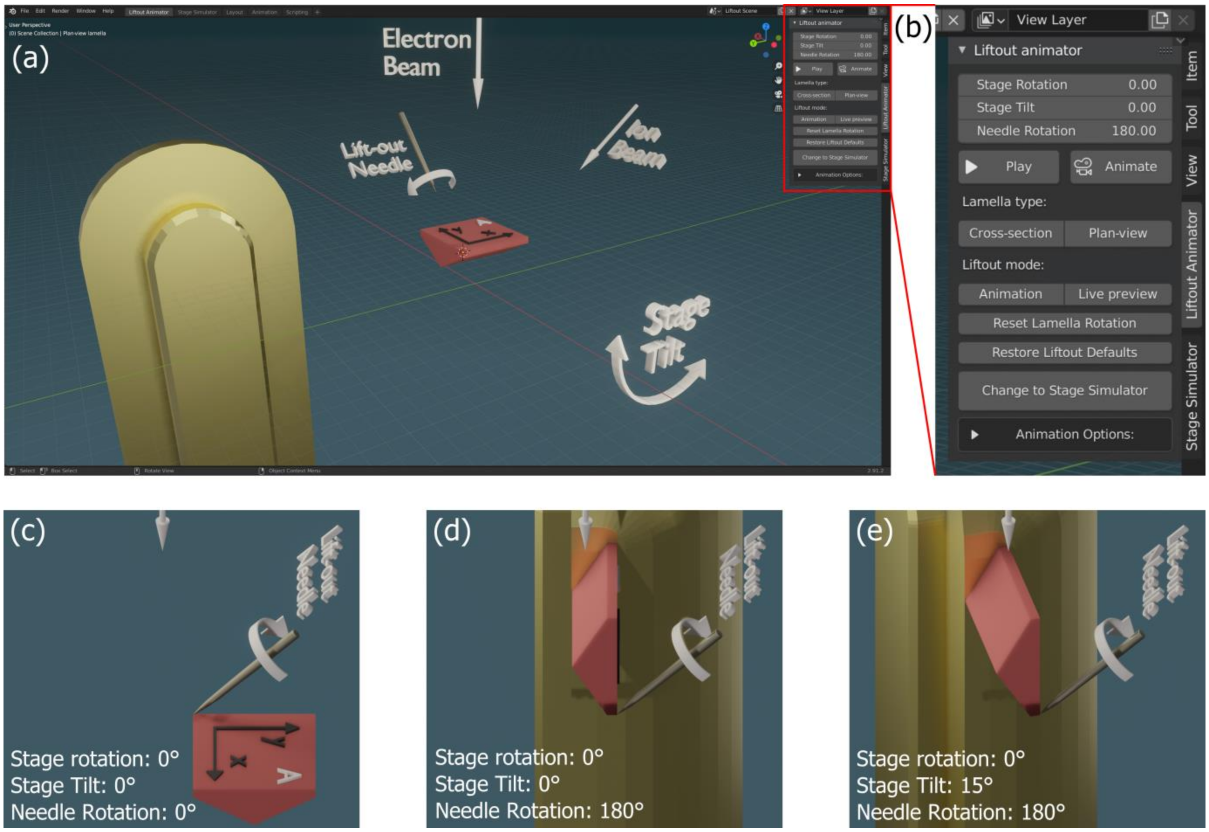


Figure 1. Degrees of freedom in FIB. (a) Schematic of 5-axis stage for FIB-SEM. (b) Blender render of FIB chamber with 5-axis stage and door-mounted rotating lift-out needle. (c) Render with examples of two currently available solutions for triple-beam systems, an argon polisher beam or femtosecond laser beam.



Stage Rotation 0.00
Stage Tilt 0.00
Needle Rotation 180.00

(c)
Stage rotation: 0°
Stage Tilt: 0°
Needle Rotation: 0°

(d)
Stage rotation: 0°
Stage Tilt: 0°
Needle Rotation: 180°

(e)
Stage rotation: 0°
Stage Tilt: 15°
Needle Rotation: 180°

Figure 2. Example use case for lift-out animator. (a) 3D model of plan-view specimen (red), half-grid post (gold) and lift-out needle, with (b) specific lift-out animator interface. (c-e) Specimen as seen by the ion beam, (c) with needle attached, before needle rotation and (d) after needle rotation, ready to be welded to the post. (e) Final lamella orientation if stage is tilted to 15° when lifting out, the top surface is now protected from the ion beam when welding to the post.

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[8] The Norwegian University of Science and Technology and NorFab are acknowledged for support through the Enabling technologies: NTNU Nano program. SuperSTEM is the UK National Research Facility for Advanced Electron Microscopy, supported by the Engineering and Physical Sciences Research Council (EPSRC).