

Specific Aims

Fluorescence microscopy is an extremely valuable tool in biology—by introducing a fluorescent probe into a live organism and measuring the position of the probe, researchers can watch cellular processes as they occur. An extraordinary amount of effort has been expended towards improving the spatial resolution of fluorescence microscopes, and recent breakthroughs have allowed microscopes to achieve resolutions below the diffraction limit which has enabled new biological insights [1].

Position is not the only property of fluorophores that can report on biological processes, though. Early studies have shown that the *orientation* of fluorophores can report valuable information as well [2]. Unfortunately, current live-cell techniques can only measure the transverse orientation of fluorophores in relatively thin specimens. These constraints severely limit the number of biological questions that can be answered using available orientation measurement techniques. In this work we propose the use of polarized multiview microscopes to measure the three-dimensional orientation of fluorophores in thick living specimens. We believe that this class of techniques will enable new insights in structural and functional biology.

Hypothesis: Three-dimensional fluorescence orientation microscopy is a valuable tool for investigating structural and functional biology in living cells.

Aim 1: Develop a signal processing pipeline for analyzing and visualizing polarized multiview fluorescence microscopy data.

The raw data collected by polarized multiview fluorescence microscopes is not easily interpreted in terms of fluorophore orientations. We propose a signal processing pipeline that can efficiently reconstruct fluorophore orientations from polarized multiview fluorescence microscopy data. An essential piece of this pipeline is the spherical Fourier transform—by analyzing the data in the angular frequency domain we can reconstruct fluorescence orientations much more efficiently than existing techniques.

Aim 2: Demonstrate and verify three-dimensional fluorescence orientation microscopy using a dual-view light-sheet microscope and a light-field microscope.

We propose two complementary three-dimensional fluorescence orientation microscopes—a dual-view light-sheet microscope and a light-field microscope. The dual-view light-sheet microscope has isotropic spatial resolution and a large field of view, but it suffers from long imaging times and it delivers a large light dose to the sample. The light-sheet microscope has complementary strengths and weaknesses—it images quickly and delivers a small light dose, but it suffers from anisotropic spatial resolution and has a relatively small field of view.

Aim 3: Demonstrate the value of three-dimensional fluorescence orientation microscopy for live-cell biology.

Our overarching goal is to develop useful tools that will enable biological discovery. To achieve this goal we will work directly with biologists who will propose specific questions and experiments for the techniques we are proposing. We expect that these interactions will inform and redirect our work in ways that will improve the likelihood of biological discovery.

Research Strategy

Background

A *fluorescence microscope* is an optical imaging system that can measure the position of fluorescent objects with a resolution of 1 μm or better. Fluorescence microscopes excite fluorophores in a sample using short-wavelength light and detect the long-wavelength light that the fluorophores emit as they relax. By focusing the emitted light onto a plane detector using a series of lenses, a fluorescence microscope creates a two-dimensional image of the fluorophores in a sample.

Fluorescence microscopes image fluorescent samples, so how can we attain a fluorescent sample? (1) *Find fluorescent samples in nature.* Most organisms create fluorescent molecules naturally. Chlorophyll, collagen, and melanin are examples of fluorescent molecules that are found in many plants and animals. (2) *Add a fluorescent dye to a sample.* There are hundreds of commercially-available fluorescent dyes that can be introduced into a sample. Researchers can choose a dye that will bind to a structure or process that they are interested in studying. (3) *Genetically modify an organism so that it creates fluorescent proteins.* Many organisms can be genetically modified so that a specific protein of interest displays fluorescence. These techniques can be used to image almost any biological process that involves proteins.

Most fluorescence microscopes only measure the position of fluorescent objects, but by adding *polarizing filters* to the microscope we can also measure the orientation of the fluorescent objects. If we place a polarizing filter in the excitation light path, then the light that is incident on the sample is polarized and it selectively excites fluorophores that are parallel to the light's polarization. If we place a polarizing filter in the detection path, then we only detect light of a specific polarization so we selectively detect fluorophores that are parallel to the detected polarization. By collecting images under several polarizing filter orientations and applying a reconstruction scheme, we can find the position and orientation of fluorophores in a sample.

Innovation

Table 1 summarizes state-of-the-art techniques for measuring the orientation of fluorophores. In this section we will briefly describe each technique and its strengths and weaknesses.

Polarized single-view microscopy [3] is the simplest fluorescence orientation measurement technique. A simple single-view fluorescence microscope can be modified into a polarized single-view microscope by adding a liquid-crystal polarizing filter to the illumination or detection path. After collecting intensity images under several polarizing filter orientations, the orientation of fluorophores can be reconstructed by applying simple image arithmetic to the set of images. Polarized single-view microscopes image quickly and gently—many live-cell biology applications already use these techniques—but they suffer from incomplete axial spatial and axial angular resolution.

Single-molecule localization techniques do not require any special imaging hardware—a plain fluorescence microscope can be used. Instead of special hardware, a photo-activatable fluorophore is used so that the concentration of excited fluorophores can be precisely controlled. By exciting and imaging fluorophores one at a time instead of all at once, the location and orientation of the fluorophores can be determined extremely precisely. Although these techniques can measure the position and orientation

Microscopy technique	Existing		Proposed	
	Polarized single-view	Single-molecule localization	Polarized dual-view light-sheet	Polarized light-field
Transverse spatial resolution	✓	✓✓✓	✓✓	✓
Axial spatial resolution	✗	✓✓✓	✓✓	✓
Transverse angular resolution	✓	✓	✓	✓
Axial angular resolution	✗	✓	✓	✓
Temporal resolution	✓	✗	✓	✓✓
Low dose	✓✓	✗	✓	✓✓
Inexpensive	✓✓	✓✓	✓	✓✓
Large field of view	✓	✓	✓✓	✓

Table 1: Comparison of existing and proposed fluorescence orientation microscopy techniques.

of fluorophores more precisely than any other light-microscopy technique, they require extremely long imaging times and large light doses. These constraints make localization techniques unsuitable for many applications in biology where fast and gentle imaging are essential for imaging live cells.

Figure 1 shows the imaging geometry for the proposed polarized dual-view light-sheet microscope. This technique uses two objectives instead of one, and it selectively excites planes of the sample to reduce phototoxicity. By using the images from both views, this technique can achieve isotropic spatial resolution, and it can measure the three-dimensional orientation of fluorophores throughout a large field of view. Although this technique does not achieve the high spatial resolution of single-molecule localization techniques, it can be applied to large-volume live-cell imaging.

Figure 2 shows an image collected by a light-field microscope. By replacing the usual detector plane with a microlens array and moving the detector to the focal plane of the microlenses, a light-field microscope captures many angular views of the sample at once. We can use these views and limited-angle tomography reconstruction techniques to determine the three-dimensional position of fluorophores throughout a sample. We propose the addition of polarizing filters to the light-field microscope to measure the three-dimensional orientation and position of the fluorophores. While the proposed light-field approach has poorer resolution than the dual-view light-sheet approach, the light-field approach is extremely fast and gentle, and it will allow us to study fast-moving processes for long periods.

Preliminary Results

We have completed a theoretical study that investigates the limits of orientation microscopy and the advantages of using multiple views [6]. In addition to finding that multiview microscopes can measure the orientation of fluorophores in all orientations instead of just transverse orientations, we also developed a set of practical design heuristics that we will apply to the design of our microscopes.

We have also collected preliminary data of a stained and fixed cell with a polarized dual-view light-sheet microscope. Figure 3 shows a prototype three-dimensional orientation reconstruction using a simplified model applied to real data, and the results match our expectations.

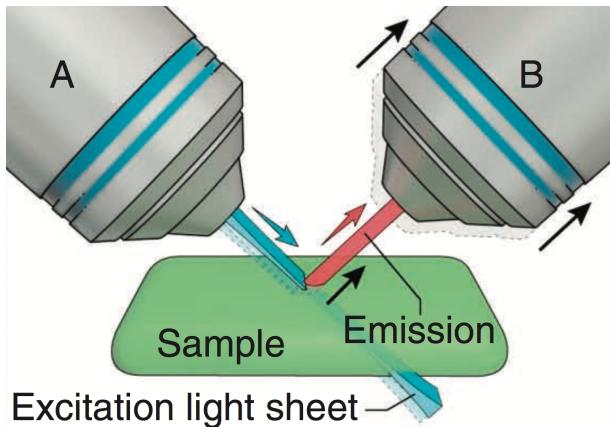


Figure 1: A dual-view light-sheet microscope excites the fluorophores in the sample with a light sheet originating from one objective, and it images the emitted light using the other objective as the light sheet sweeps through the sample. Next, the roles of the objectives are reversed and another set of images is acquired from the opposite view. We propose a dual-view light-sheet microscope outfitted with polarizing filters on each illumination arm. Figure from [4].

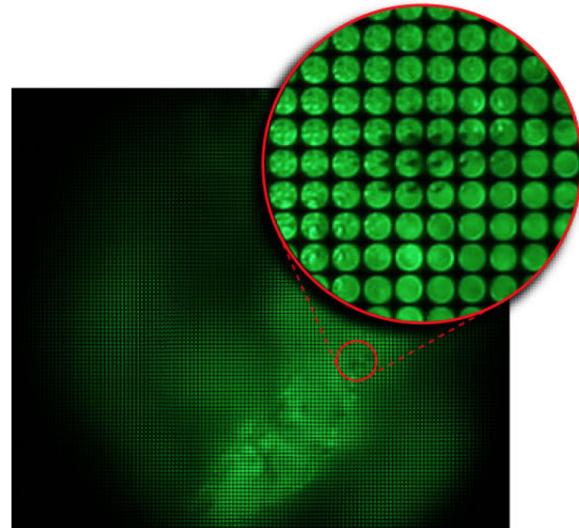


Figure 2: A light-sheet microscope is an ordinary single-view microscope with a microlens array in the usual detector plane and the detector displaced to the focal plane of the microlenses. The image collected by a light-field microscope consists of many angular views of the sample collected at once. Figure from [5].

Finally, we have collected preliminary images of several test specimens with known fluorophore position and orientation including oriented fluorescent fibers and giant unilamellar vesicles. These test specimens will be essential tools to help us verify the results of our reconstructions.

Approach

Aim 1: Develop a signal processing pipeline for analyzing and visualizing polarized multiview fluorescence microscopy data.

Methods: We will use physical modeling, linear systems theory, and optimization techniques to develop an efficient signal processing pipeline for the proposed microscopes. We have completed a prototype signal processing pipeline for reconstructing the three-dimensional orientation of fluorophores from polarized dual-view light-sheet microscope data, and we plan to improve this work by relaxing our assumptions and extending it to the light-field microscope.

We have also introduced the spherical Fourier transform for analyzing fluorescence orientation microscopes in the angular frequency domain—see Figures 4 and 5. These techniques allow us to use linear systems theory to understand our imaging systems, and we have already made large efficiency improvements by analyzing our microscopes in this way.

Expected outcome: A set of software tools that can be used to reconstruct, visualize, and understand fluorophore orientations from data collected by a wide class of polarized multiview microscopes.

Potential complications: We anticipate computationally expensive reconstructions and visualizations as

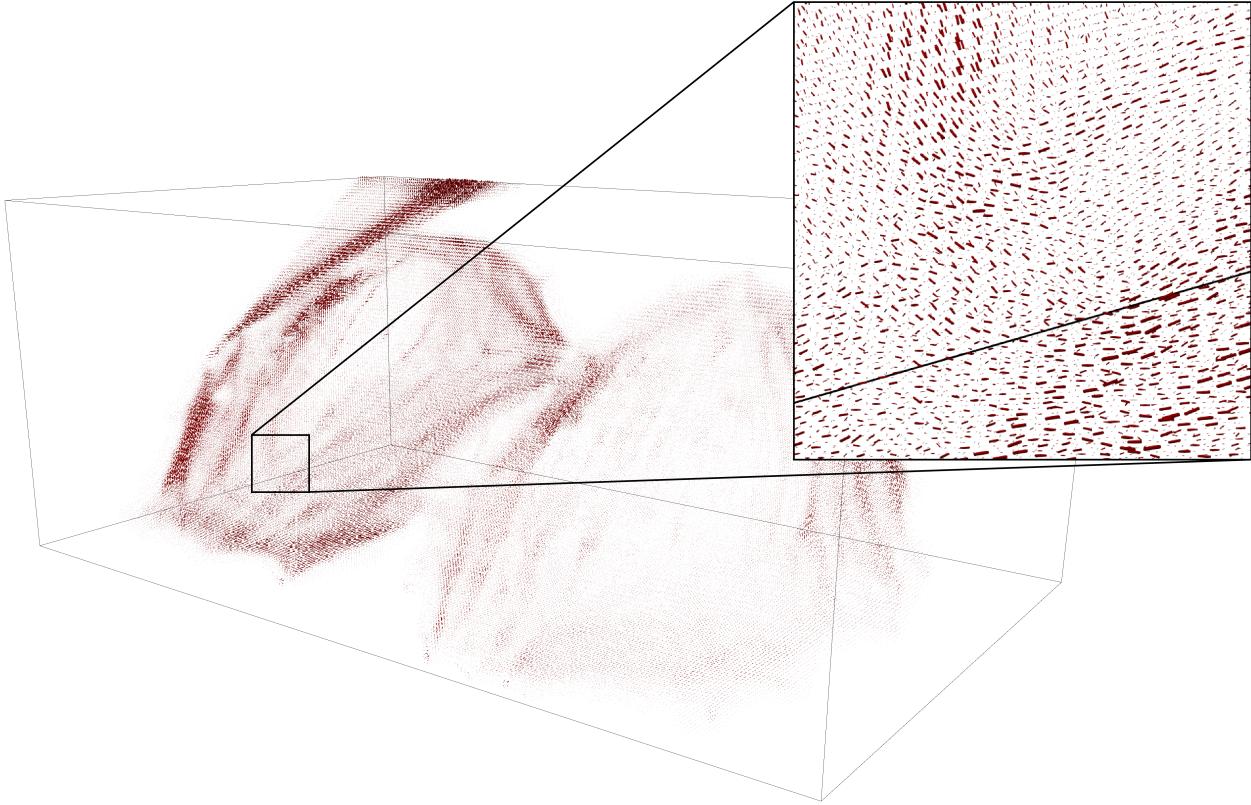


Figure 3: Orientation reconstruction of a $68 \times 108 \times 46 \mu\text{m}^3$ volume of fixed cells stained with Alexa Fluor 488 Phalloidin and imaged with an asymmetric 1.1/0.71 NA dual-view light-sheet microscope. We assign a scaled and oriented glyph to each voxel to indicate the quantity and orientation of fluorophores in that voxel.

we refine our pipeline with increasingly realistic physical models. We plan to employ graphical processing units (GPUs) and cluster computing to ease the burden.

Aim 2: Demonstrate and verify three-dimensional fluorescence orientation microscopy using a dual-view selective plane microscope and a light-field microscope.

Methods: To demonstrate the dual-view selective plane microscope we will use the dual inverted selective-plane illumination microscope (diSPIM) platform developed by collaborators at the National Institutes of Health (NIH). Prototype systems are available at the NIH and the Marine Biological Laboratory (MBL). To demonstrate the light-field microscope we will use a prototype system that is available at the MBL.

To verify our systems we will use several specimens with a known coupling between fluorophore position and orientation. We are currently evaluating several samples for this purpose—PBT [poly(1,4-phenylene-2,6-benzo-bis-thiazole)] film, giant unilamellar vesicles [7], and actin networks.

Expected outcomes: Clear evidence that our microscopes and reconstruction techniques can reconstruct the position and orientation of fluorophores in a known sample.

Potential complications: We expect initial disagreement between our results and our known samples due to our use of simplified linear models. We expect to be able to explain these discrepancies, and we plan to refine our models if it is computationally feasible.

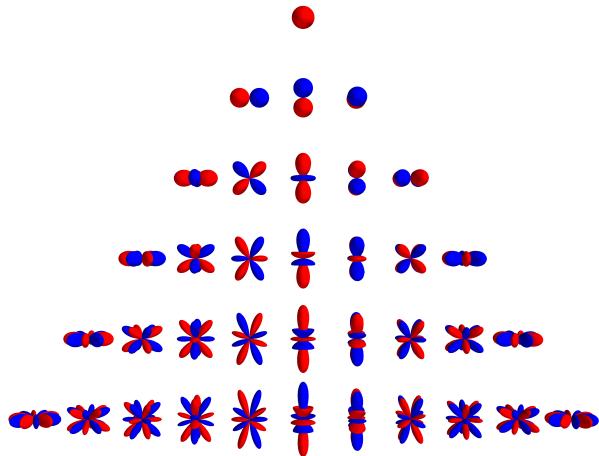


Figure 4: The spherical harmonic functions form an orthonormal basis for functions on the sphere. Red = positive, blue = negative.

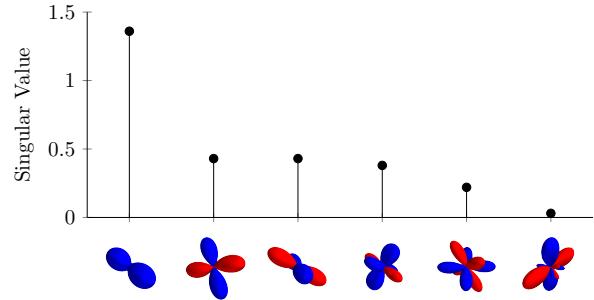


Figure 5: The angular singular value spectrum of a polarized dual-view selective plane microscope. In the same way that the modulation transfer function (MTF) characterizes the ability of an imaging system to transfer spatial harmonics, the angular singular value spectrum measures the ability of an imaging system to transfer spherical harmonics.

Aim 3: Demonstrate the value of three-dimensional fluorescence orientation microscopy for live-cell imaging.

Methods: We will collaborate with biologists at the Marine Biological Laboratory to find applications for our techniques. We have already identified several promising areas where the orientation of fluorophores in three dimensions could report useful information:

- Cellular migration—the dynamics of actin networks responsible for cellular migration have been successfully studied with two-dimensional fluorescence orientation microscopy [8]. We expect that more conclusions can be drawn using three-dimensional techniques.
- Cellular transport—motor protein dynamics have been studied extensively using single-molecule techniques [9]. Our proposed techniques may be able to improve on existing measurements.
- Protein-protein interactions—fluorescence resonance energy transfer (FRET) is a widely used technique for measuring nanometer-scale distances between proteins. Most FRET experiments make assumptions about the relative orientation of the fluorophores involved [10], and we expect that the proposed techniques could address these assumptions and improve the technique.

Expected outcomes: A biological research application for three-dimensional fluorescence orientation microscopy.

Potential complications: This aim depends on the previous two aims, and it requires a collaboration with a to-be-identified biologist. With our preliminary results in hand, we plan to start searching for a biological collaborator soon. During the summer the MBL acts as a hub for biologists and microscopists to test new techniques, so we expect to find a well-defined biological application in coming months.

Timeline

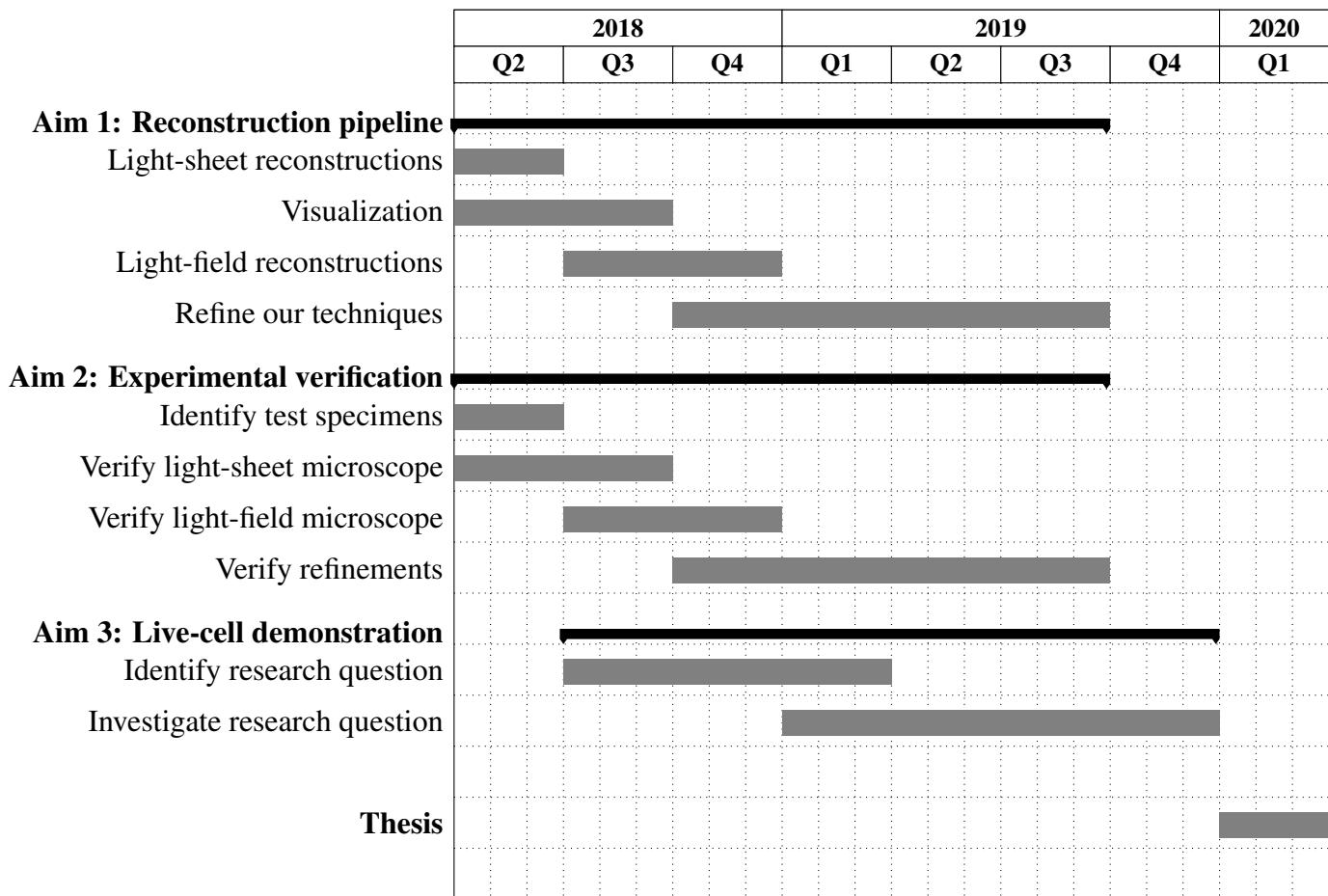


Table 2: Proposed project timeline.

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