Navigation is a fundamental behavior that has evolved multiple times during the course of evolution. This is not a trivial task, because the environment is not uniform. Obstacles, changing terrain, and physical dangers constrain an animal’s choices, and require constant behavioral adjustment to decide optimal trajectory and limb placement. Like a dog choosing to carefully place its paws on the white strips of a crosswalk on a hot day, animals alter their innate motor programs to mitigate environmental constraints. A unique motor program where this is exceptionally important is climbing. Unlike crawling/walking, climbing requires the animal to suspend itself by a substrate that is not as uniform as the ground. An incorrect step while walking may lead an animal to fall a short distance, but a misstep while climbing can be potentially disastrous. Nocturnal orb-weaving spiders are an excellent example of this behavior. They live for most of their lives on their webs, and they must navigate the web’s variable geometry to capture their prey. The web itself provides a uniquely advantageous substrate for experimentation, because its geometry is easy to quantify and is behaviorally relevant to the spider. It also serves as the primary source of sensory input (vibration) used for navigation. Many other climbing animals, such as primates, evolved to climb variable environments; however, these organisms are often not tractable for experiments. Artificial environments with known parameters can be created but have dubious behavioral relevance. Model organisms such as mice can climb variable substrates, but this is often a learned behavior, and not their primary mode of locomotion. However, orb-weaving spiders are small, with brains that evolved to primarily navigate on webs.

Despite considerable research into web geometry, web biomaterial and web-building behavior, the biomechanics and ethology of spider limb movement along the web are poorly understood. An improved understanding of this behavior will help inform not only how animals adjust their behaviors to accommodate their environment, but also help inform how we can use this knowledge to build robots that can climb along suspended substrates. Such robots can be useful for dangerous tasks such as high voltage cable inspection and maintenance, bridge and tower construction and maintenance, etc.

**Hypothesis**: Spiders sense and actively filter vibrational frequencies detected by their legs and use this information for web navigation and object localization.

**Nature of Collaboration**

Chen Li has extensive experience in biomechanics and the modeling of animal locomotion in complex environments. Andrew Gordus has extensive experience in invertebrate behavioral neuroscience, has maintained a spider colony of several hundred individuals, and has developed a research program focusing on uncovering the underlying neuronal mechanisms that encode orb-weaving behavior. The combination of defining underlying biological mechanisms of navigation with biomechanical modeling will enable a new understanding of the principles of optimal navigation and object localization on suspended substrates.

**Aim 1: Define vibrational sensory field detected by spider limbs. (Gordus)**

**Aim 2: Define action sequences for sensory gain and locomotion. (Gordus & Li)**

**Aim 3: Define physical landscape of the web and constraints of limb movement. (Li)**

**Aim 1: Define vibrational sensory field detected by spider limbs.**

The primary sensory input for orb-weaving spiders is tactile. Spiders sense substrate vibrations through the displacement of their legs that are detected by sensory sensilla in their joints. Vision and olfaction play negligible roles, because the prey and web itself are most often not within the visual field of the animal and spiders have limited olfactory capabilities. However, spiders have incredibly sensitive tactile sensing capabilities, on par with the energy equivalent of the retina detecting single photons. While the vibrational sensitivities of single legs have been studied in other spider species, a full investigation of all limbs and their vibrational sensitivities has not been performed. This is essential for knowing the full sensory field detected by the spider. Because the vibrational landscape is the primary sensory input for their behavior, understanding the bounds of this will enable a full understanding of how spider behavior is a direct function of vibrational input.

The primary sensory organs for web vibration are the sensory sensilla that lie in the joints of spider legs. These organs detect strain in the cuticle, and their sensitivity is a direct function of limb posture CITE Biorxiv. This means that the spider can alter their sensory gain by adjusting their limb posture to optimize frequency detection in a vibrating web. Different sensilla have different strain sensing capabilities, and this is reflected in how the slits in the organ stretch in response to posture.

Prior research in this field have used white light interferometers to measure slit displacement as a function of limb posture. Our first goal will be to define the different strain capabilities of each sensilla along each leg as a function of joint posture using interferometers in the Whiting School of Engineering. A comprehensive map of sensilla sensitivity will enable us to correlate spider posture in the web with the sensitivity of each sensilla that serve as the primary sensory inputs into behavior.

Prior web-modeling in the field has shown that the web radii are the primary sources of vibrational dissipation in the web. Spiders spend most of their time in the center of the web, which is the optimal location in the web for determining the source of an intruding object in the web. However, this capability relies on synthesizing the information detected by each leg. Object localization is not a passive behavior; once the web is vibrated, the spider changes its posture, and performs silk-plucking behaviors. It is thought that these behaviors serve two functions. One, changing posture modulates the gain in detecting different frequencies. Two, plucking the lines provides known vibrational input into the web to serve as reinforced feedback for prey localization.

The Gordus lab has performed preliminary observations of web vibrations using high speed cameras with the spider present or absent. Vibrations were manually provided with defined frequencies, or by placing a live fly on the web which struggled and produced web vibrations. The goal is to continue this work with defined web vibrations and prey placement and monitor how the spider’s posture changes as a function of different spatial vibrations. Performing this experiment in the absence and presence of the spider will uncover how the spider itself can actively modify the vibrational landscape. By combining posture with known sensilla sensitivities, we will be able to build a model of gain capabilities as a function of spider posture. We expect that the spider alters its posture to maximize sensory gain of SOMETHING?.

**Aim 2: Define action sequences for sensory gain and locomotion. (Gordus & Li)**

Once an object is detected on the web, the spider navigates toward the object. Because the web and its legs are not within the visual field of its eyes, a spider must perform this action blindly on the web. This is not a trivial task, because web geometry places constraints on where the spider can place its legs. The Gordus lab has already established an experimental setup for tracking limb-movement of a spider while it builds and navigates a web. We will add cameras to track the limbs and determine their placement on the web in three dimensions.

The Gordus lab has used limb-tracking to define web-building action sequences. Several of these action sequences are performed for navigating during web construction. Once the limbs are tracked in three-dimensions, current ethological analysis used for defining web-building behavior will be applied to this experiment to define common action sequences performed by the spider while localizing an object and navigating toward it. Because the limbs are also the primary sensory organs, correlating limb posture with known sensory gain (from **Aim 1**) will provide a map of the sensory field.

We expect that the spider will alter its posture to maximize sensory gain and then execute action sequences that enable it to efficiently navigate toward prey on the web. Spiders are able to perform these actions even when the web has been altered due to damage. By damaging the web at specific locations, we will test how the spider can update its knowledge of the sensory field and alter its action sequences to navigate toward prey.

**Aim 3: Define physical constraints of limb movement and choice. (Li)**

The legs gather the primary sensory input and generate behavioral output of the system. The physical forces acting on the web directly alter the physical forces of the legs. By measuring and modeling changes in the web, we can directly model the impact on the legs, and define this system as a closed-loop set of action sequences that themselves alter the sensory input.

**Expected Impact**

Many organisms such as bats and snakes localize prey using vibrations sensed in different environment such as the air and ground. However, these behaviors require the use of a complex and separate set of sensory organs and body movements. With the spider, we have a constrained system where almost all sensory input and behavioral output are executed by the legs, which can be easily tracked. By defining a closed loop system for vibrational navigation, we can develop optimized strategies for the design of robotics to perform similar functions.

**Potential Sources of Funding**

Li and Gordus plan to apply for funding through the NSF and the Air Force Office of Scientific Research (AFOSR). The NSF Division of Integrative Organismal Systems has two programs devoted to behavioral morphology. The Physiological Mechanisms and Biomechanics Program (PMB) funds research that uncovers biomechanical mechanisms that operate at the whole-organism level. The Behavioral Systems Cluster supports animal behavior research devoted to uncovering fundamental principles of animal behavior. The proposed research program is ideally suited for both. The AFOSR funds research that improves our understanding of biological sensory and behavioral systems used for navigation. They have a funding program specifically devoted to acoustics and vibrational sensory integration. The integrative approach used in the proposed research program is well within the scope of the goals of this funding source.