Biomemetic Research

Observation and Analysis of the Water Spider

Contents

Introduction

Part 1. Introduction of the biological role model

Part 2. Development of experimental set-up

Part 3. Biomimetic investigations

3.1. System

3.2. Behavior (of the spider and the system)

3.4. Hierarchy of fibres

3.5. Micro details

Part 4. Application of biomimetic principles

Introduction
Architecture and biomimetics

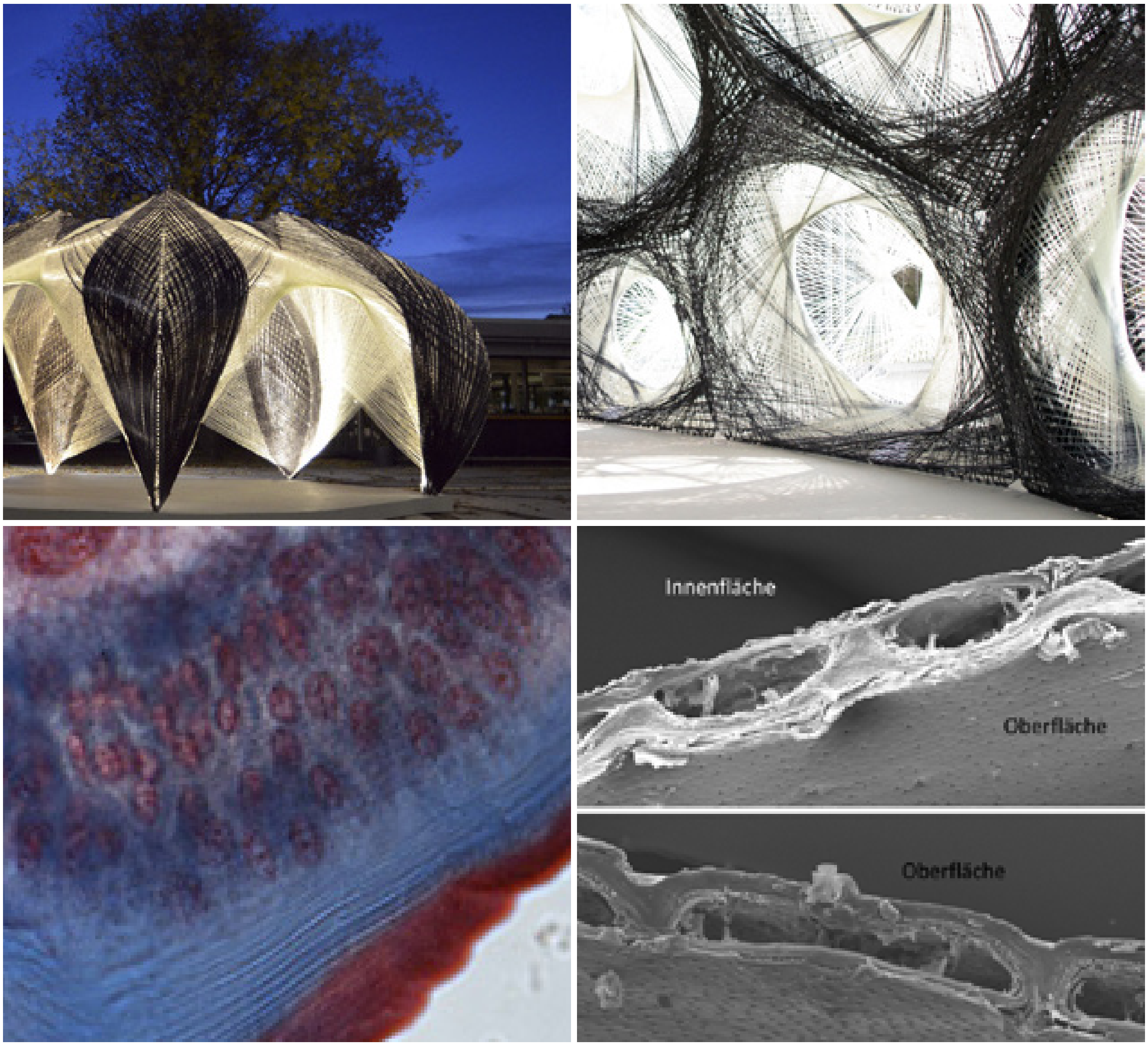


FIGURE 01: The 2012-13 ICD/ITKE pavilion used the lobster claw as its biological role model. The 2013-14 pavilion principle was inspired by Beetle Elytra. (Source: ICD, ITKE)

INTRODUCTION. ARCHITECTURE AND BIOMIMETICS

Biomimetic research has a lot of interesting precedents in history of Stuttgart and Tübingen University. It is a modern history, starting from the middle of 20-th century, but reach with findings and directions of development. Many of this research branches are currently developed in the ICD, ITKE, and ILEK – institutes of Stuttgart in cooperation with the University of Tübingen. In many ways this up-to-date development (big part of it is computational design and analysis) is based on the research headed by Frei Otto in 60-70-ies (pneus, membranes, grid-shells, minimal surfaces, water tension in fibrous wet aggregations). Those years estimations were mainly done with the help of models, numeric analysis was used only in several cases, while now computational techniques is one of the main tools.

ICD-ITKE collaboration is advancing the field of the research with new approaches and applications.

In the ITECH master programme's (headed by ICD and ITKE) first year we have been looking into the topic of pneumatic constructions and fibrous morphologies. By year 2014 the research in the field of fibrous morphologies has resulted in two experimental pavilions.

Biomimetic research can offer new perspectives in architecture, engineering and related sciences. Every organism has evolved over a long time period and has become more and more adapted to their environments, resulting in highly specialized morphologies by using a minimum amount of energy including materials and efficient techniques. Those techniques and materials, as well as body structures, can be analysed and abstracted into architecture and engineering disciplines.

FIGURE 02: Water spider bubble.(Source: M.Helmreich, Yassmin Al-Khasawneh)

Biomimetics can be categorized into two groups: the top-down approach solves an existing problem with the aid of a biological role model; the second category is the bottom-up approach which investigates a biological technique or structural logic and then applies the research to a technical question.
The research of the water spider for the 2013-14 ITECH pavilion takes a top-down approach: in order to construct a robotically produced demonstrator using lightweight materials including glass and carbon fibres the water spider's fibre placement and water bubble were analysed.
In case of the current research, the material and construction process parts were advanced with new technique- usage of pneu as scaffolding and as part of the composite material.
From the computational part, the advancement and the challenge of the project is an application of spider behavior on the rules of agent behavior. It is the first pavilion to be made in which design the object-oriented programming is used. The most ultimate case would be if the robot as an agent would interactively react on changing environment, changing its behavior in real time. This could be the next step of research, and though we made attempts to create such a system, it still needs to be further developed.
In terms of interactivity, in the current pavilion, the system with pressure sensor will be used. I will not adjust the pattern of laid fibers, but will adjust the path- with the data from sensor robot will push the membrane more or less according to the critical values. The pattern of fiber layout is created by the agent, but it will not be given to a robot in real time, but as a pre-defined path.

Part 1. Introduction of the biological role model

FIGURE 03: The water spider in the undewater bubble.(Source: Yassmin Al-Khasawneh)

01. ROLE MODEL - THE WATER SPIDER

Architectural and biological interest

The base of the project concept is a biomimetic research on a water spider *Agyroneda aquatica* behavior and its masterpiece- underwater bubble held by the web.
Initially, several biological systems where analysed, including spider and water spider webs, cocoons, insect shells, fibre reinforced plants, algae, corals and self-organization. After researching a variety of systems, it was determined that the water spider's web had the most appropriate output regarding fabrication techniques and materials. Thus, the water spider's web was chosen for biomimetic research.

The water spider constructs a fibrous nest under water and reinforces it from the interior. The aim of this research was to understand the water spider's fabrication processes in order to abstract its techniques and implement them in architectural and engineering systems. The goal was to discover novel architectural fabrication techniques as well as to combine both pneumatic and membrane systems in fabrication. Possible research output for fibrous reinforcement systems may then provide a new method for designing enclosed lightweight structures.

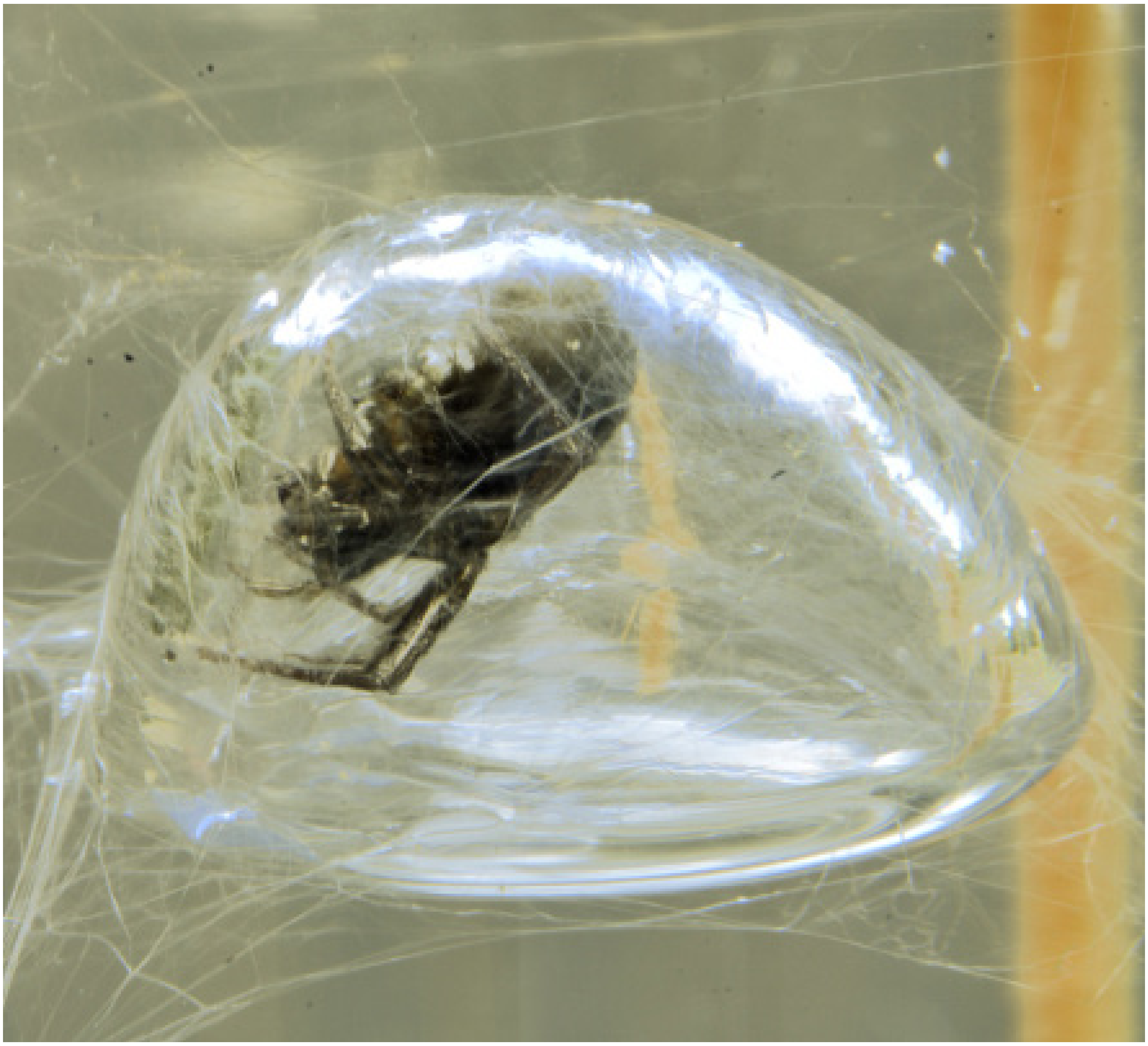


FIGURE 04: The water spider in the undewater bubble.(Source: M.Helmreich, Yassmin Al-Khasawneh)

02. BIOLOGY OF THE WATER SPIDER

Argyroneta aquatica

The water spider *Argyroneta aquatica* (Cybaeidae, Araneae, Arachnida, Arthropoda; Figure 03, 04) is the only known spider that lives its entire live under water. The spider cannot, however, naturally breathe in water since it, like terrestrial spiders, respires with book-lungs and a tracheal system. In order to live an entirely aquatic life, the arachnid developed two air holding systems: the physical gills and a diving bell.

Physical Gill

A physical gill is a thin air layer around the spiders abdomen held and stabilized by two hair typologies on the spider's ophistosoma, ventral prosoma side and legs including short, massively pinnated hairs (Figure 05). The hairs in the gaps in-between the hairs are too small for water molecules to migrate. Gaps between hairs, additionally, result in a capillary effect that holds the air body in place. Both effects create a hydrophobic body surface. The second hair type differs in that it is longer and less pinnated (Figure 05). The longer hairs support and stabilize the air layer around the body and protect the smaller hairs from interacting with water. Thus, spiders can carry surface air for respiration under the water.

This thin air layer is not, however, stable over time: gases, including oxygen, nitrogen and carbondioxyd, can pass through the layer. Due to breathing activities, the spider consumes oxygen while producing carbondioxyd. With respect to the gases partial pressures, oxygen migrates from the water into the air layer and carbondioxyd moves into the water. The partial pressure of nitrogen, however, is higher in the air layer

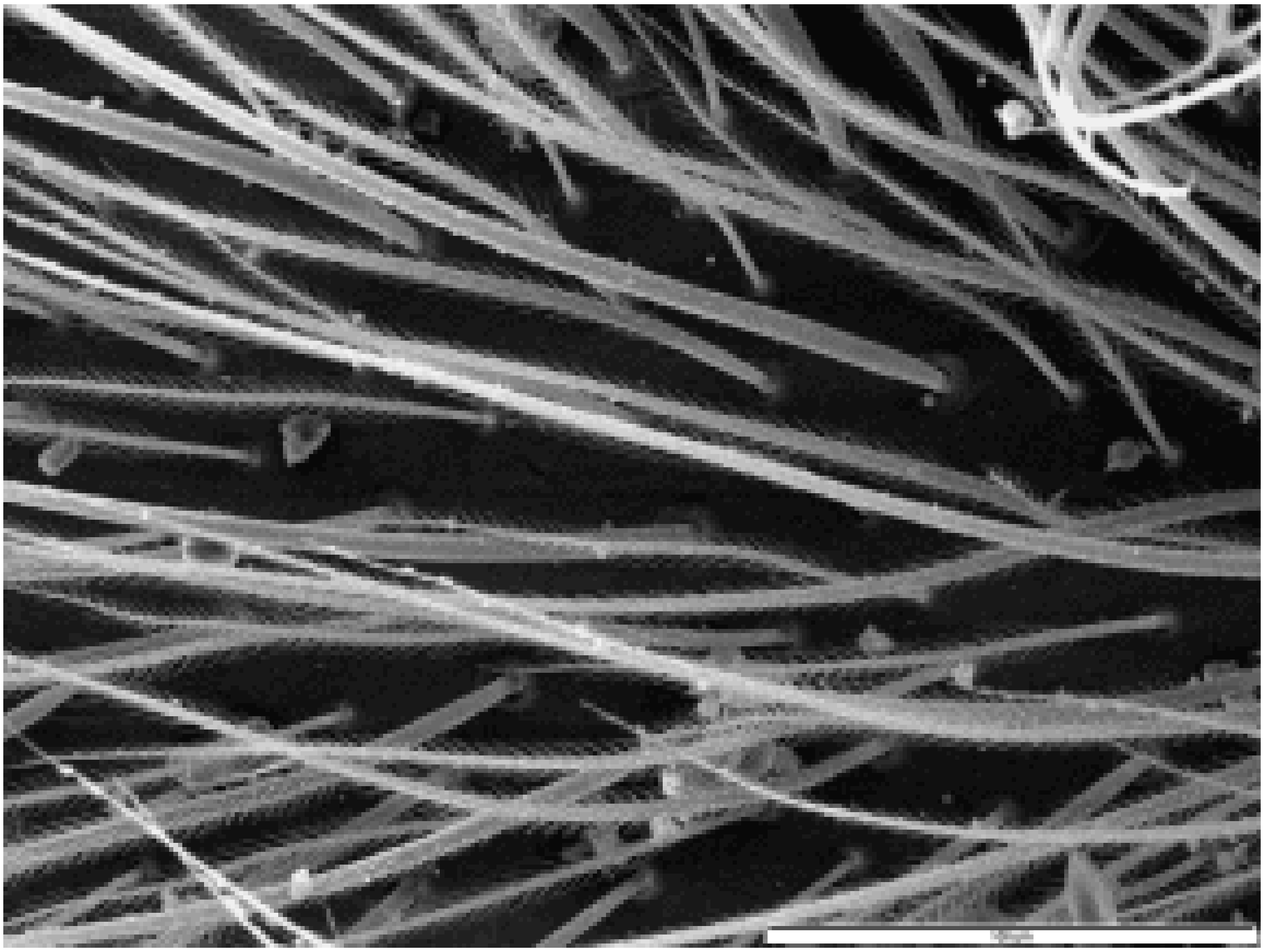


FIGURE 05: Micrograph of spider's short, massively pinned hairs and longer, less pinned hairs on the ophistosoma. Short pinned hairs can interact with surface air in that the air adheres to the hairs which make it impossible for water molecules to migrate between the hairs and wet them. The thin layer of surface air (plastron) enables the spider to breath under water. Longer hairs in contrast stabilizes the air bubble around the body. (Source: Dr. Armin Kureck)

than in the water which results in a high nitrogen movement from the air layer into the water. This nitrogen movement causes a permanent shrinking of the air layer around the spider's body. In contrast to the spider's physical gill, which is supported by fine hairs, the diving bell is a surface-air filled, bell shaped bubble wherein the spider lives. The diving bell also acts as a physical gill that has to deal with the same shrinking effects due to gas exchange like the physical gill on the spider's abdomen. To prevent the bubble from shrinking as well as for initial bubble construction, the spider fills the bell by successively retrieving air from the surface and carrying it to the bubble via its abdomen‘s fine hairs.

Diving Bell

Argyroneta aquatica is able to construct silken under water webs between a variety of water plants and substrates. The water spider web, therefore, features a wide range of specialized characteristics in order to deal with environmental settings, including currents and plant movement. The water spider and its behavior are well analyzed, but there is in fact a lack of data regarding fiber yarning, laying techniques and laying patterns. Existing publications and research does include a description of the six steps of nest construction.

In step one, anchor points are set and anchor threads are spun. These anchor threads are 1.05 - 1.15 µm in diameter. They are the thickest threads in the water spider's web in order to deal with tensile forces of water currents and the buoyancy of the air bubble. Second, the spider spins thinner threads that are up to five times thinner than the anchor threads. These thinner threads are placed in between the anchor threads and

FIGURE 06: World map: the water spider occurs in palearctic ecozones (shown here in dark gray). (*Source:* Open Source Map, edited)

are called bell threads. The bell threads are laid more or less horizontally, producing an almost two dimensional sheet web. In the third step, the spider places a drop of hydrogel on the bottom side of the web. Hydrogel consists of the same proteinous material as the threads but in contrast to the almost solid threads, the hydrogel shows a significant lower viscosity and works as a surface-active agent, thus, it can lower the water's surface tension. The hydrogel also enlarges the contact area between water and air, resulting in a stabilized air bubble position and holding. Fourthly, the spider brings in air from the surface under the sheet web, with the aid of the ophistosomal hairs, next to the hydrogel patch where it releases the bubble followed by the fifth step, where the spider goes into the bubble and reinforces it from the interior and attaches additional hydrogel between the web and the bubble. In the sixth step, the spider repeats step four and five until the diving bell is large enough for the spider's entire body to fit inside.

The diving bell itself has an essential meaning for the water spider: it is the environment in which the spider spends most of its time. The spider mainly lives in its diving bell, leaving it only for hunting and bringing new surface air to refill the air reservoir within the diving bell. Males will also leave their diving bells in order to mate. They visit females within the female diving bell.

Distribution and Habitat

The distribution of *Argyroneta aquatica* is restricted to the palearctic ecozone, reaching from polar to temperate ecozones of Europe to the Bering Sea (Walder 1995, Masumoto et al. 1998b, Neumann et Kureck 2013, Figure 05) . The spider lives in non or slow moving fresh water bodies such as ditches, ponds, bomb

FIGURE 07: The map of the area where the spiders were collected. (Source: Google Maps)

craters, lakes and rivers with a preferred water temperature ranging from 20 to 23°C (Crome 1951, Walder 1995, Masumoto et al. 1998 a et b, De Bakker et al. 2006, Schütz et al. 2007, Seyyar et Demir 2009). Due to environmental changes including an increase of agricultural use and land reutilization, the water spider's abundance decreased in Germany and has been considered endangered locally. The spider, however, was recorded in past years in water bodies and rivers around Vienna, Austria 8, in different areas in Turkey 9 and in middle and northern Germany 10. Occurrences in southern parts of Germany are rare and were documented for the first time in 2010 by Christopher Allgaier (University of Tübingen) in the Federsee (Bad Buchau).

Crome (1951) reported that *Argyroneta* prefer dark and covered areas for nest building. Also, nest building predominantly takes place during dusk. The water should have an optimal temperature between 20°C to 23°C (Crome 1951). Water temperatures between 12°C and 15°C cause a sluggish movement and temperatures below 6°C lead to a minimum amount of movement. With temperatures lower than 4°C *Argyroneta* is indolent.

Hunting

The water spider is a sit-and-wait predator: once it finishes its nest, the spider sits inside, sticking out one pair of legs. The web diving bell is surrounded by supporting threads including walking threads (Debaker et al., 2006). The spider legs that are stuck out of the bubble are attached to the walking thread. When possible prey is within reach, it produces vibrations due to its movement. These vibrations are then transferred to the spiders web and can be perceived by the spi-

FIGURE 08: Hunting for the water spider.(Source: Elena Chiridnik)

der. *Argyroneta* then leave its nest and catches its prey by paralyzing it with a toxin. Hunting behavior can differ between sexes (Chrome 1951). After paralyzing its prey, the spider carries it into the nest and consumes it. The spider's hunting behavior, however, can change during captivity: spiders sometimes leave the water and consume the prey outside. (Chrome 1951), a behavior that has never been observed in the natural environment. *Argyroneta* is an insectivore and carnivore predator that predominantly feeds on invertebrates including *Asellus aquaticus*, *Daphnia* sp., *Culex* sp., *Chaoborus* sp., *Branchipus* sp. *Chironimus* sp., *Tubifex* sp. as well as on small fish (e.g. Crome 1951 and De Bakker et al. 2006).

Gender Determination

Differentiation between males and females requires looking at a variety of sex specific characteristics (Crome 1951): the most important features are the (1) pedipalps; pedipalps of males are thickened on the top, forming a copulation structure whereas pedipalps of females are uniform. The (2) second pair of legs are longer in males than in females, additionally (3) the ophistosoma in males are long and fusiform, in contrast, females ophistosoma are more spherical and (4) males are more haired than females. Coloration is, according to several authors, not an usable evidence: coloration of males is described as light brown whereas coloration of females is significantly darker. This may be correct in its natural environment but in captivity coloration of all genders is light brown (Crome 1951).

Capture

Water spiders were collected (permission is present) in a canal "Ringkanal" in Flemhude, Quenbeck, Northern

FIGURE 09: Hunting for the water spider.(Source: Elena Chiridnik)

Germany according to evidential records by Seymour and Hertz (2011). The Ringkanal is a slow moving canal with a variety of environmental settings ranging from well vegetated and natural edges to artificial straightened margins with rare vegetation. The Canal floor is mostly muddy and precipitous from the edges. Possible sample sites were approached with inflatable boats by wading through shallow water zones and from land. Wading seems to be the most efficient method since the collector is flexible and versatile. Sampling started under the Highway 210 Bridge where favourable areas were systematically approached. Vegetation in shallow water areas (< 50 cm in depth) were trawled using 1 mm fine mashed entomological steel ring nets with an opening of 30 cm and a grasp of 180 cm. Spiders were caught in two ways (personal communication with Dolores Schütz, February 2014): firstly by trawling the nets from the ground through the vegetation to the surface or by disturbing the habitat and waiting until the water spiders rose to capture surface air for refilling their diving bell. Spiders are easily recognizable by as they stick out their abdomen at the surface of the water. This method is highly selective and environmental protective in contrast to the non-selective net trawling and is preferred.

10 specimens were caught and separately stored in containers with plant fragments. Specimens were brought to the University of Stuttgart, Institute for Computational Design, Kepplerstraße 11, 70174 Stuttgart, Germany for further observation and research.

Spiders were kept in the basement of the University of Stuttgart with a constant room temperature and 12 hours of artificial light. Spiders were kept separately in 2/3 filled 1 L glasses which contained wooden sticks for them to build their webs around. All spiders were fed ad libitum with Daphnia sp. and Chironimus sp. One couple (male and female) was separated out and kept together in a 5 L tank with black course quartz sand, Elodea sp. and Alisma sp. Water pumps were not installed in the tank nor the glass jars.

Optical analyses were conducted using a transmitted light photo microscope (TLM) and the LEO 1450VP scanning electron microscope (SEM). Samples for SEM micrographs were prepared and recorded at the University of Tübingen, Institute for Geosciences, Hölderlinstraße 12, 72076 Tübingen, Germany.

Most authors keep water spiders in small canning jars or bottles (e.g. De Bakker et al. 2006). Light time is similar to natural day-night rhythm.

Part 2. Development of experimental set-up

Chapter 03:
Pilot experiments

FIGURE 10: First successful set-up where the spider is visible (*Source:* Elena Chiridnik)

03. PILOT EXPERIMENTS

Aquarium

For convenience of documentation, the spider was put into the parallelepiped aquarium. If there were plants, the spider would make a web in their leaves, but if there were no plants, the spider would make a web in the corner, even if there were vertical or straight sticks. That is how it was decided to use cylindrical glasses.

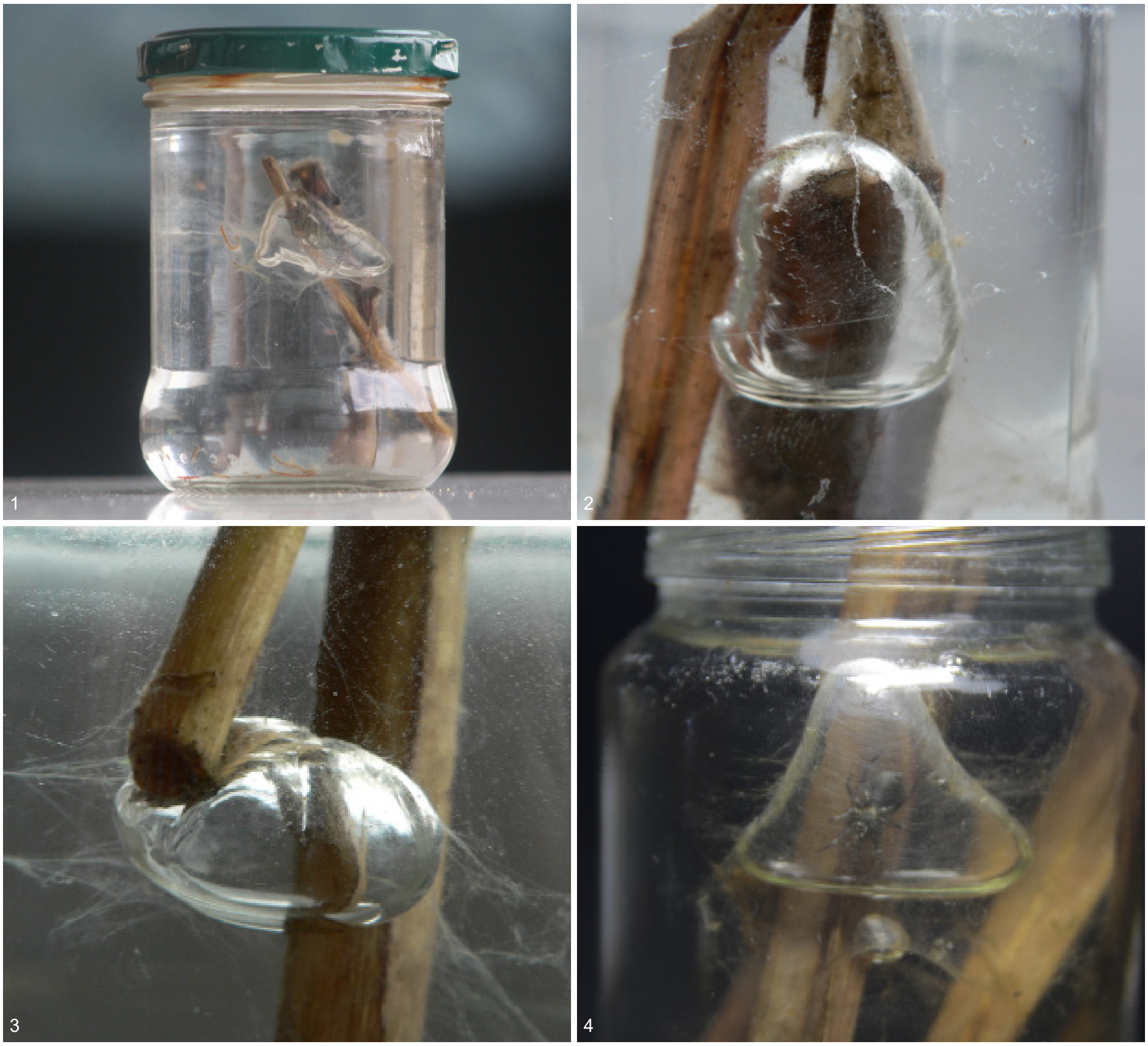


FIGURE 11: Glasses with hatural sticks (*Source:* Elena Chiridnik)

Glasses with natural sticks

We brought the spider with the sticks and leaves from their natural habitat. It was a comfortable surrounding for them, but we could not conduct clearly visible experiments with those set-ups. It should be mentioned, though, that only in one of these set-ups we have seen the bubble of so strongly articulated bell shape (4).
It was decided to take very thin sticks for the next set-ups.

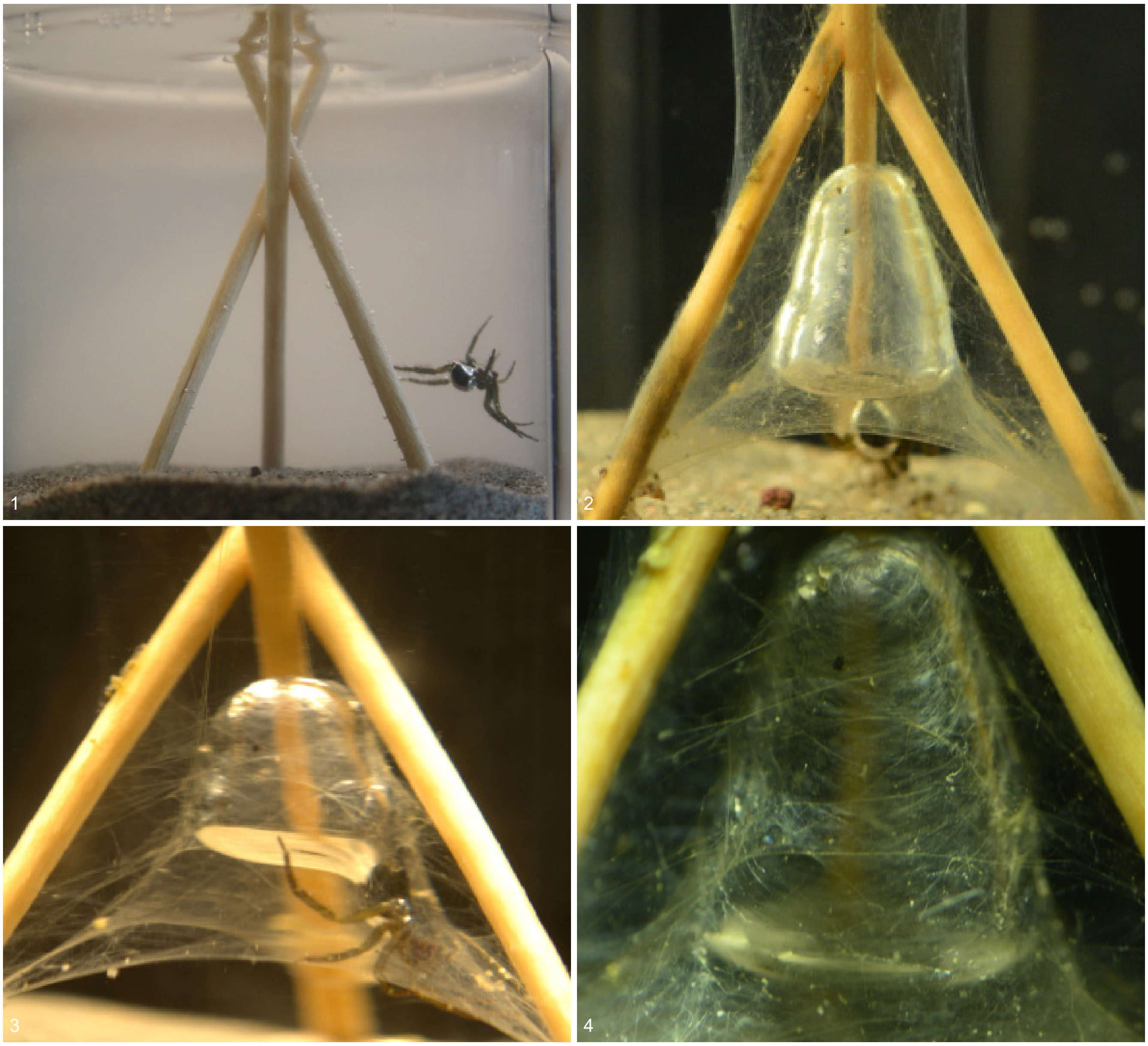


FIGURE 12: Glas jar with three angled sticks (Source: Elena Chiridnik)

Glas jar with three angled sticks

Among the sticks set-ups these ones were the most comfortable for spiders, as they could construct the bubble very quickly- in few hours, whether with the other set-ups it took at least one night.
With these set-ups we could not view from the top and could not identify whether the shape of the bubble if pre-defined by the position of sticks. That is why we changed to parallel sticks set-ups.

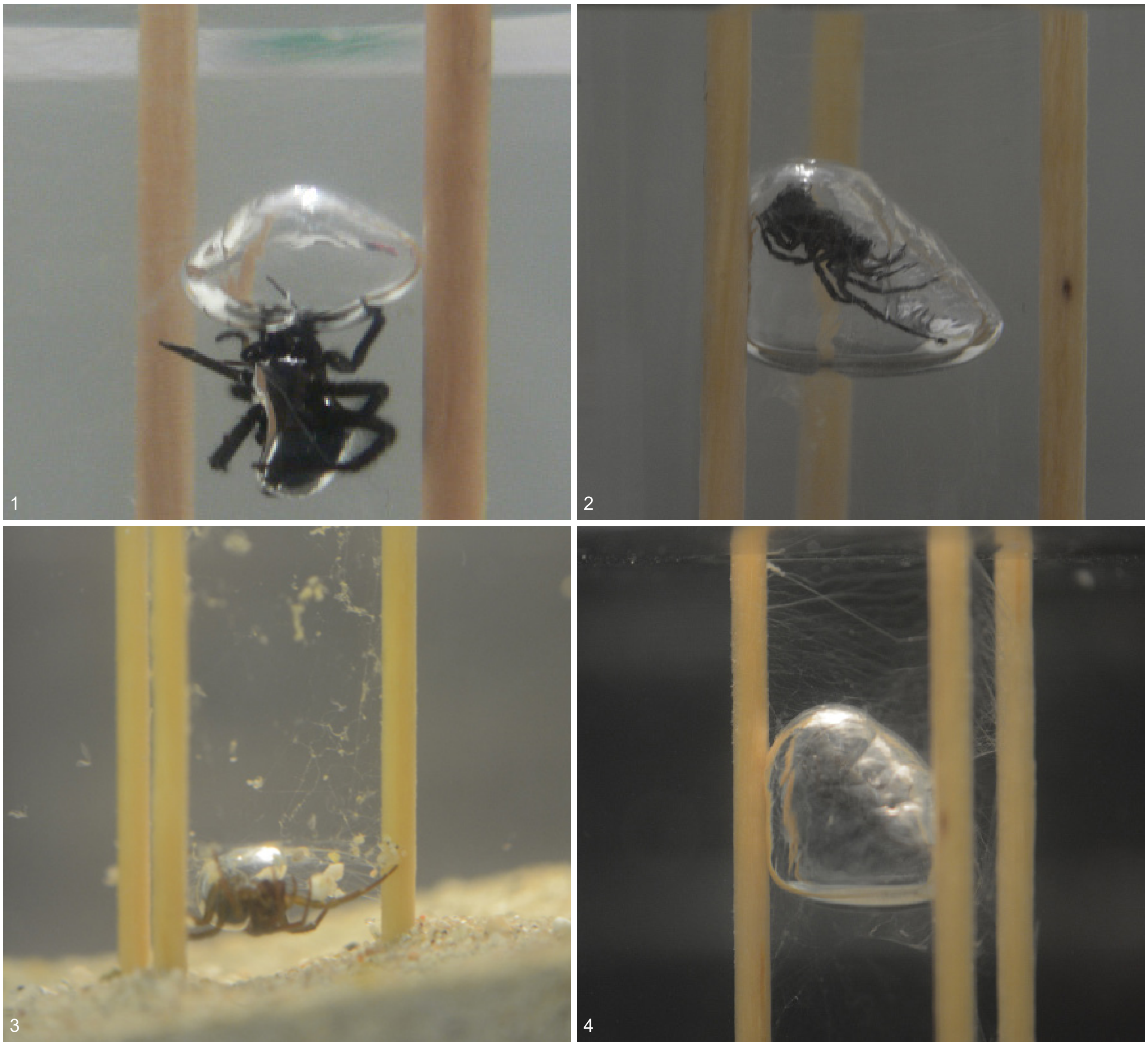


FIGURE 13: Glas jar with three parallel sticks (Source: Elena Chiridnik)

Glas jar with three parallel sticks

To reduce the distortion, the cylindrical glasses were put into the aquarium for documentation.

Documentation itself was a challenge, because taking photographs or videos of an object in water had a problem of diffraction or the problem of placing inventor into the water. We have chosen the first option, as we only had available instruments of required quality only for “dry” documentation . Thus, we were solving the problem of diffraction. We had cylindrical glass for the spiders, because in any other “unsmooth” shape they were making webs in the corners. Cylindrical glasses, at the same time, had much stronger diffraction, than planar shapes (standart aquariums). We placed cylindrical glass with water into aquarium with water, so the picture was clear. Also we always had to position the camera perpendicularly to the surface of the aquarium to avoid distortion.

These are the set-up types that were chosen for further development.

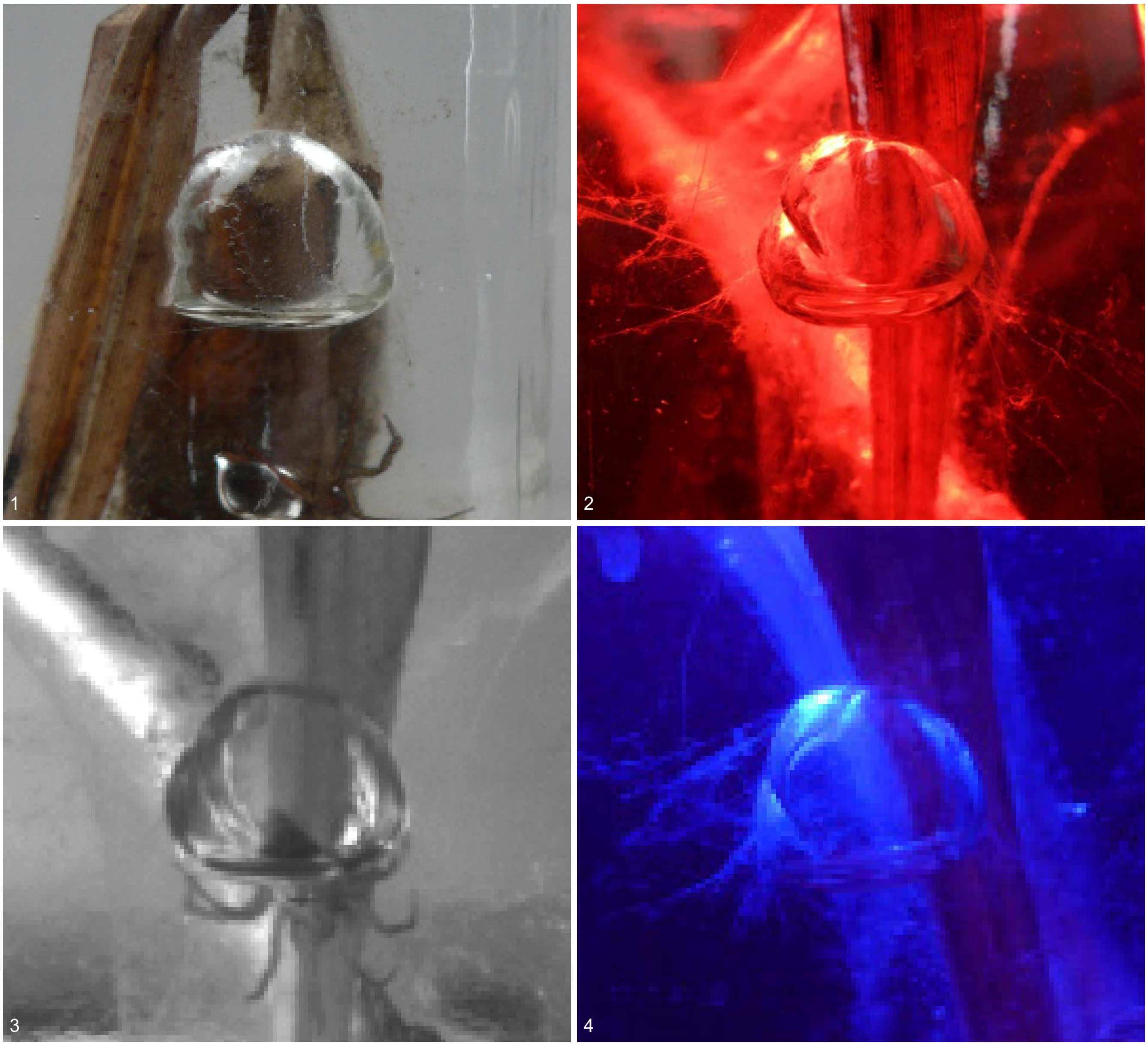


FIGURE 14: Using coloured light and ultraviolet light to enhance spider web visibility (Source: Elena Chiridnik)

Lighting

To increase visibility of webs, we tried different lightning.
The challenge was transparency of web and bubble wall. We tried coloured light, various strengths of light, directed light. In the end what helped best is increasing the quality of picture with dissolved light, and making the best possible pictures of the web and the bubble in its natural state.

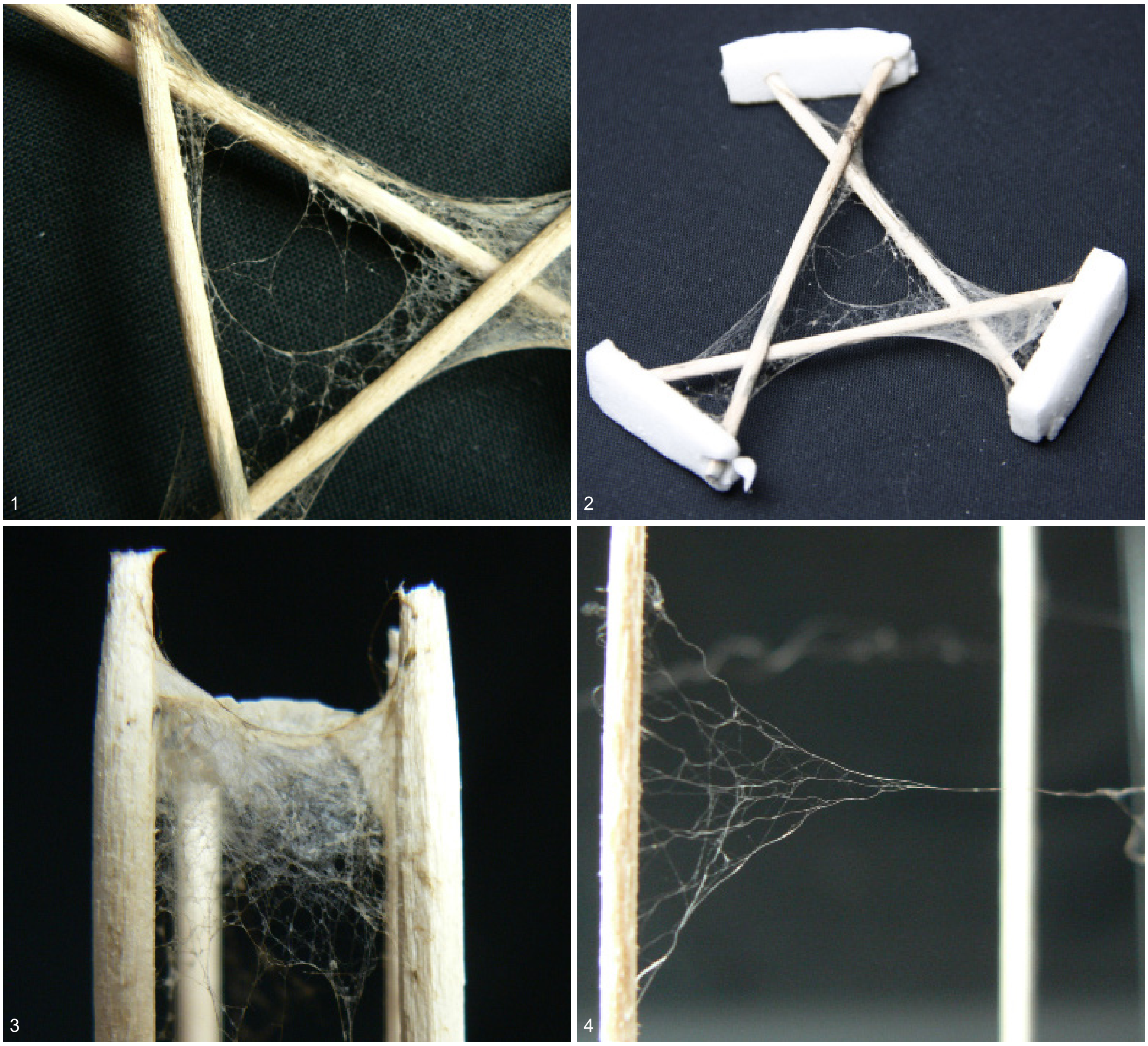


FIGURE 15: Drying web behaviour. (Source: Elena Chiridnik)

Dry webs

Fibrous structures of dry webs deal not so much with the behaviour of spider, but more with the behaviour of fibres. When the web is drying, the micro-tension of water makes fibres aggregate in a certain way. That reminded us aboul Frei Otto's wool experiments.

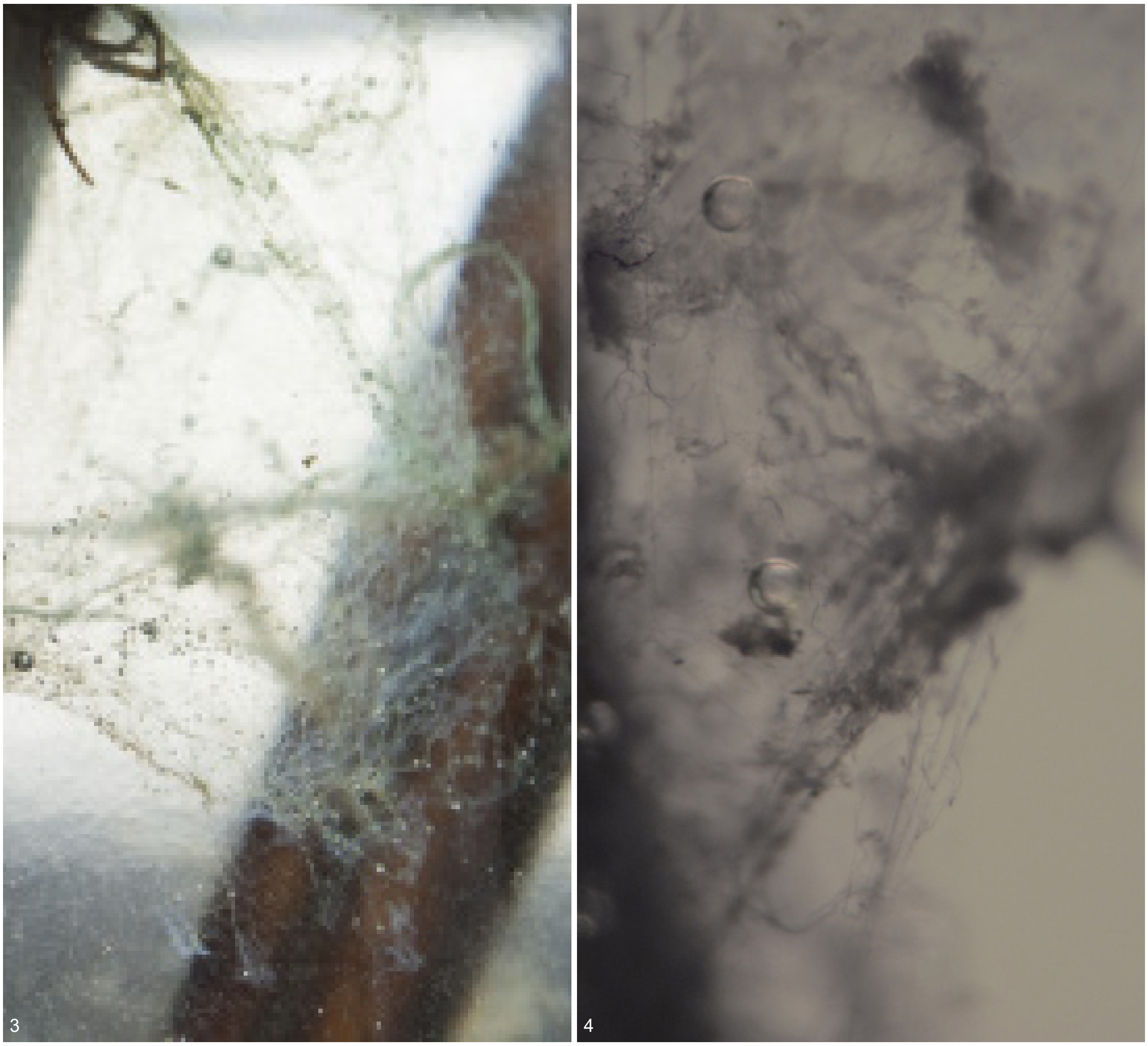


FIGURE 16: Colouring of the web (Source: Elena Chiridnik)

Colouring of the web

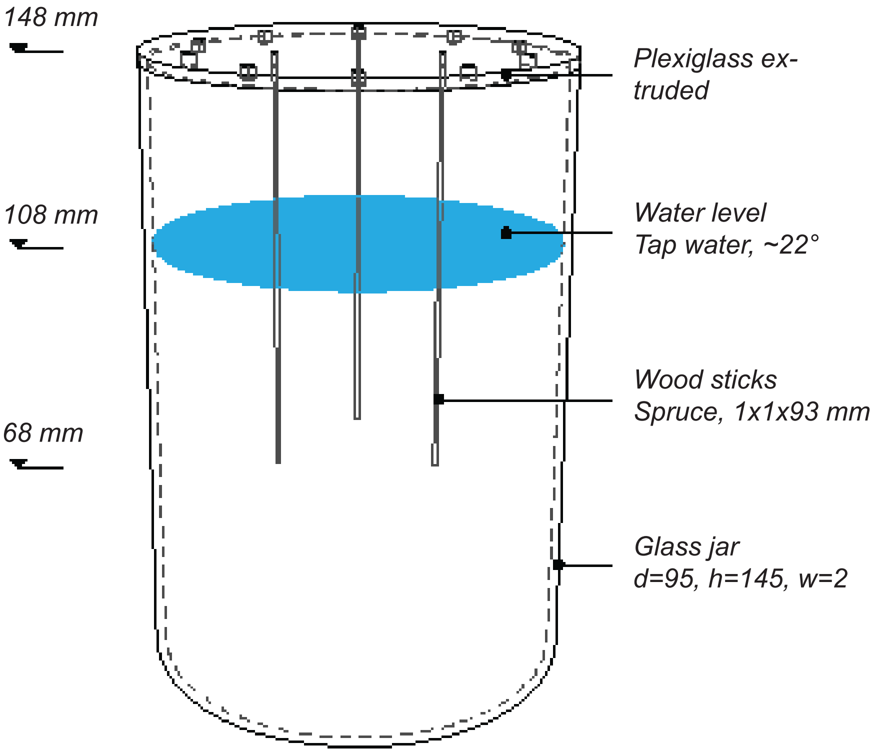
We made experiments colouring the web. Experiment with brilliant green was successful, as web is sensitive to protein-colouring substances.
Is the end we were much more looking into the process, not the result, so colouring of the web could not help, as we would not colour web during the process of construction.

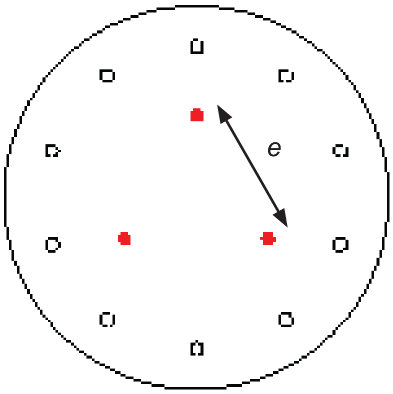
FIGURE 17: Web with the cocoon (Source: Matthias Helmreich)

Reproduction

The male and female were put in the aquarium. The offspring was about 20 little spider. Unfortunately, the food we had (daphnias) seems to be not suitable for them. The old male spider died after fertilization. Made a cocoon and in couple of weeks offspring appeared.
The amazing fact is that a month later the female spider gave one more offspring without another contact with the male.

Chapter 04
Final experimental set-up





Top view of Set-up A010,
e = 35.4 mm

FIGURE 18: Perspective diagram of Set-up A010 (Source: Matthias Helmreich)

EXPERIMENT SET-UP

Materials and Methods

The water spider is placed in an artificial set-up (Figure 18) to observe the construction of its bubble. The wood sticks are fixed from the top and reach down to 68 mm from the bottom of the jar. The wood sticks are clamped into a 3 mm plexiglasss cover and oriented perpendicular to the cover. Due to the tension of the fibers and the influence of water, each stick will bend towards the centre about 3-5mm. After five days, the sticks and the water are be replaced. The glasss jar must be cleaned with extreme care each time to avoid the water spider anchoring onto the surface of the jar.

The area the water spider can build its bubble in is limited to 5cm in height which allowed for closeup photography. Images were taken with a NIKON D7100 body and NIKON AF-S Micro Nikkor DX 85mm 1:3.5G ED VR lens. Standard flurocent lights provided the lighting for the experiments. A black matte background and dull grey bottom paper (120g) were placed behind and beneath the jars. The glass jar was placed in a larger aquarium to avoid relfection and minimize distortion. The camera was focused on the center of the three stick set-up, but slighty angled from the above to best obsere the reinforcement of the bubble. The sticks were rotated so we could observe on which stick the fibers were placed.

Various types of sticks were tested to see which one performed best in terms of remaining straight and visibility in photodocumentaiton. Additionally, the sticks had to resist water oxidation, non-toxic and non-chemical consistency and not color the water.

FIGURE 06: Glasss jar with set-up and water spider

FIGURE 06: Spruce, lark, cherry; plastic tube, carbon fibre, steel (from left)

FIGURE 19: Perspective diagram of Set-up A010 (Source: Matthias Helmreich)

The cherry wood was making the water a brownish color and lark wood became very flexible under influence of water. Jaw wood showed the best performance in terms of water resistance and stiffness. Each wood stick had a profile of 1x1mm.

The steel metal sticks were oxidating in the water. Aluminum sticks of the same size were not stiff enough to hold the tension force. The carbon fibre test was skipped due to the toxic attribute of resin.

A 1x1mm jaw wood stick was chosen for the experiment.

Water spider Anna (female) showed best construction performances in speed and design in previous experiments and was therefore chosen for the experiment.

Data was transmitted to a 1TB Trancend solid state harddrive via USB 3.0. The camera was connected to a power source so photos could be taken over long periods of time.

Resolution of each image: 6000x4000px at 300dpi, F-stop: f/9, Exposure time: 2sec, ISO speed: ISO-100, Focal length: 85mm, image size 6.34mb.

The time-laps sequence was set to take an image every 4sec. 35 585 images were taken from 03.07.2014 (10:56:45 am) till 05.07.2014 (7:22:19 am).

Chapter 05
Case study experiments

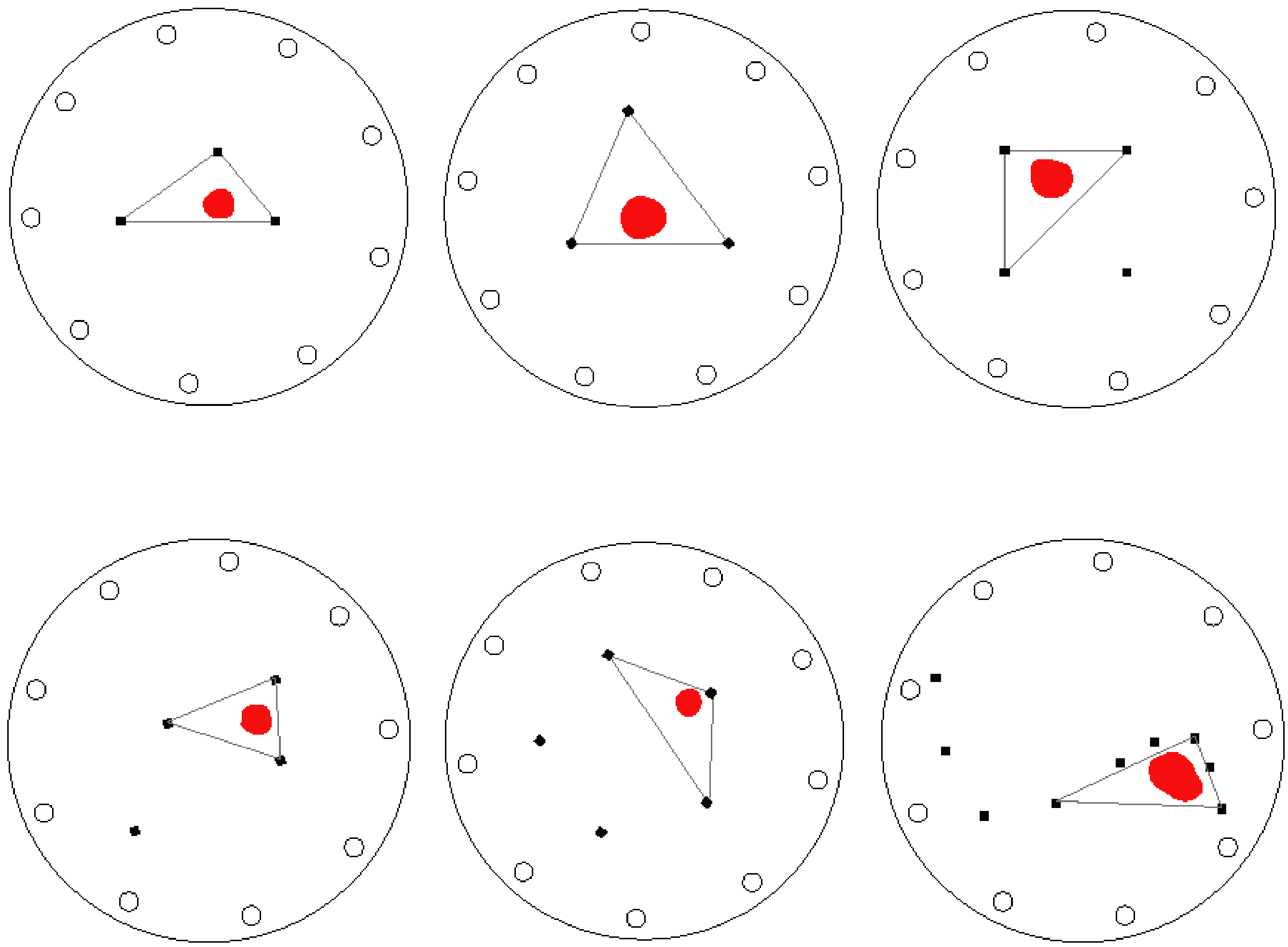


FIGURE 20: Stick configurations and bubble placement for original stick variation tests (Source: Matthias Helmreich)

PART B_STICK VARIATION

Setup:
The lids of each jar, made of plexiglass, were laser cut with a different pattern and number of holes. The holes were cut to the precise size that would allow the sticks to fit in and be secure enough to support the spider's movement and the bubble.

Six setups were tested using varies configurarions of 3, 4, 5 and 9 sticks.

Purpose:
After the correct stick type and jar setup was determined, it was necessary to test how many sticks were required for the water spider to successfully build its web.

Both regular and irregular patterns were chosen in order to observe the various ways the spider would build its bubble and to determine if the number of sticks changed the fibre laying pattern or the water spiders overall behavior. For example, we wanted to see if the spider would ever build more than one bubble, where the main fibres were laid when many sticks were available for construction, and if the bubble would be placed centrally or at the perimeter of the stick area.

Waterspider Anna (Female)

Set-up af-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	3

Bubble:

Area	510.0 mm2
Height	10.9 mm
Length	13.4 mm
Stage	48 hours

Top View:

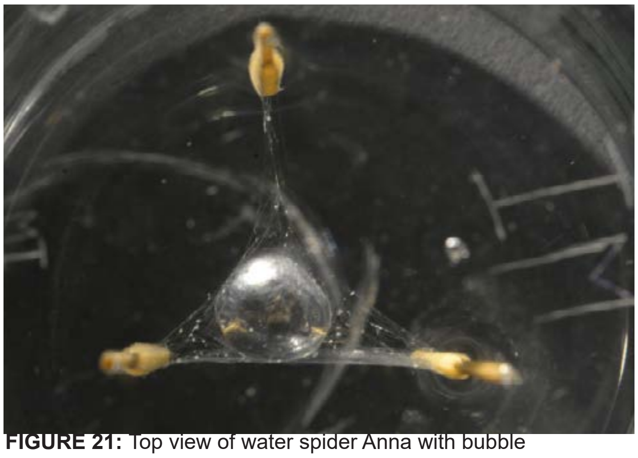
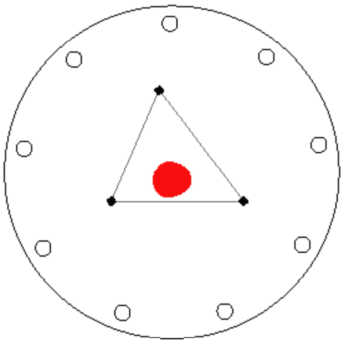
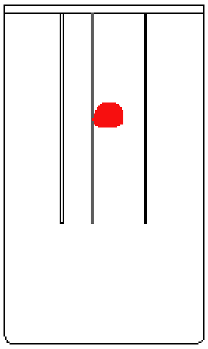


FIGURE 21: Top view of water spider Anna with bubble

Plan:



Elevation:



Side Views:

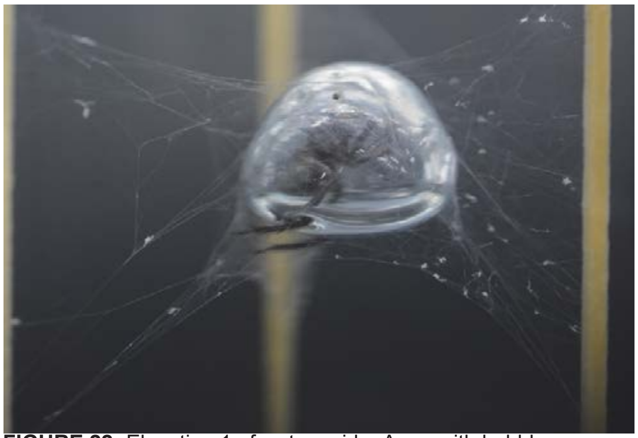


FIGURE 22: Elevation 1 of water spider Anna with bubble

FIGURE 23: Elevation 3 of water spider Anna with bubble

FIGURE 24: Elevation 2 of water spider Anna with bubble
(Source of photos on this page: Jessica Jorge)

FIGURE 25: Elevation 4 of water spider Anna with bubble

Waterspide Freddy (Male)

Set-Up bf-001:

Jar diameter	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	3

Bubble:

Area	207.1 mm2
Height	6.7 mm
Length	8.6 mm
Stage	48 hours

Top View:

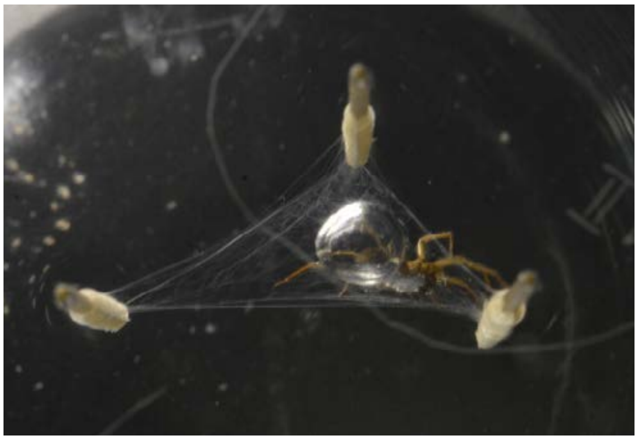
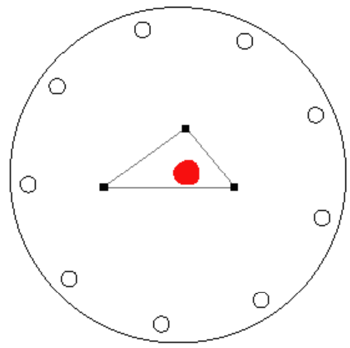
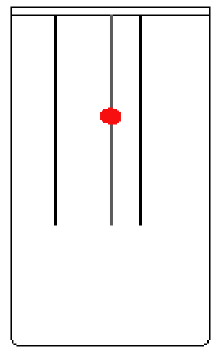


FIGURE 26: Top view of water spider Freddy with bubble

Plan:



Elevation:



Side Views:

FIGURE 27: Elevation 1 of water spider Freddy with bubble

FIGURE 28: Elevation 3 of water spider Freddy with bubble

FIGURE 29: Elevation 2 of water spider Freddy with bubble
(Source of photos on this page: Jessica Jorge)

FIGURE 30: Elevation 4 of water spiderFreddy with bubble

Waterspide Bruce (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	4

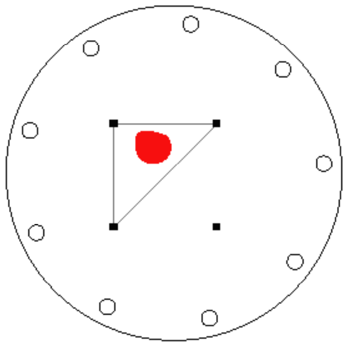
Bubble:

Area	337.3 mm2
Height	8.1 mm
Length	11.3 mm
Stage	48 hours

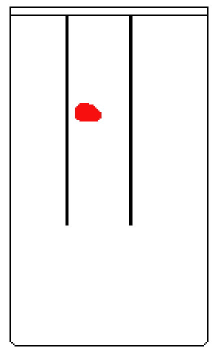
Top View:

FIGURE 31: Top view of water spider Bruce with bubble

Plan:



Elevation:



Side Views:

FIGURE 32: Elevation 1 of water spider Bruce with bubble

FIGURE 33: Elevation 3 of water spider Bruce with bubble

FIGURE 34: Elevation 2 of water spider Bruce with bubble

FIGURE 35: Elevation 4 of water spider Bruce with bubble

(Source of photos on this page: Jessica Jorge)

Waterspider #5 (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	4

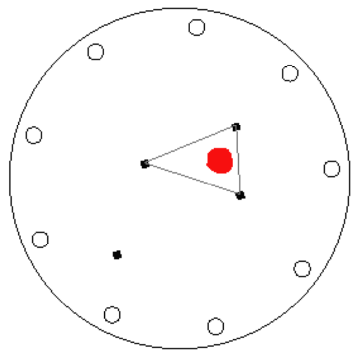
Bubble:

Area	? mm2
Height	? mm
Length	? mm
Stage	9 days

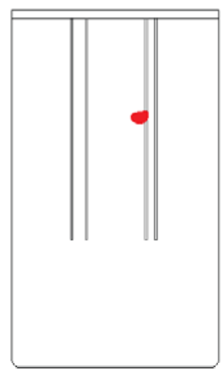
Top View:

FIGURE 36: Top view of water spider #5 with bubble

Plan:



Elevation:



Side Views:

FIGURE 37: Elevation 1 of water spider Female #5 with bubble

FIGURE 38: Elevation 3 of water spider Female #5 with bubble

FIGURE 39: Elevation 2 of water spider Female #5 with bubble

FIGURE 40: Elevation 4 of water spider Female #5 with bubble

(Source of photos on this page: Jessica Jorge)

Waterspider #4 (Female)

Set-Up 4f-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	5

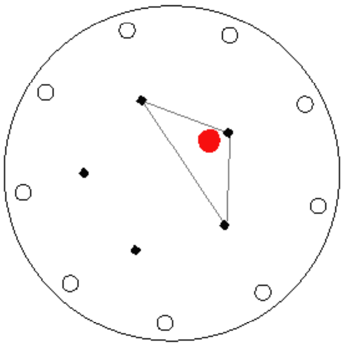
Bubble:

Area	177.3 mm2
Height	7.2 mm
Length	10.1 mm
Stage	48 hours

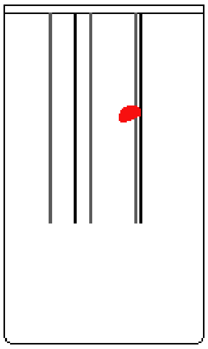
Top View:

FIGURE 41: Top view of water spider #4 with bubble

Plan:



Elevation:



Side Views:

FIGURE 42: Elevation 1 of water spider Female #4 with bubble

FIGURE 43: Elevation 3 of water spider Female #4 with bubble

FIGURE 44: Elevation 2 of water spider Female #4 with bubble
(Source of photos on this page: Jessica Jorge)

FIGURE 45: Elevation 4 of water spider Female #4 with bubble

Waterspider Big Momma (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	9

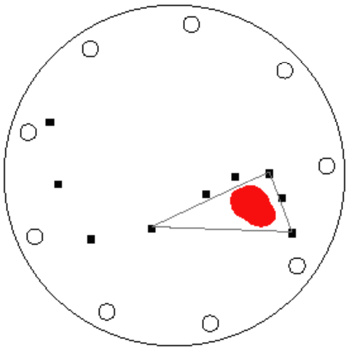
Bubble:

Area	? mm2
Height	? mm
Length	? mm
Stage	9 days

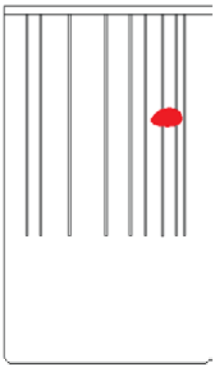
Top View:

FIGURE 46: Top view of water spider Big Momma with bubble

Plan:



Elevation:



Side Views:

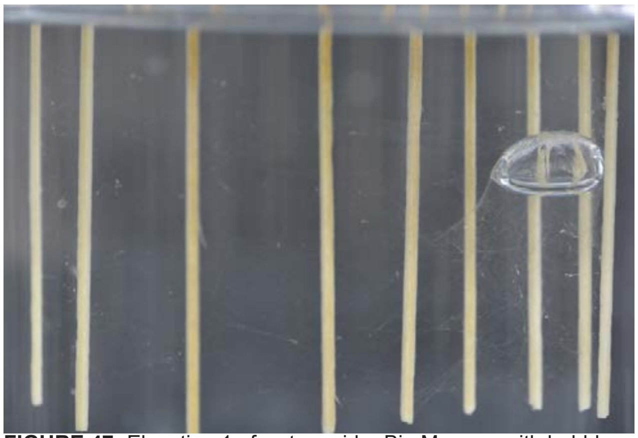


FIGURE 47: Elevation 1 of water spider Big Momma with bubble

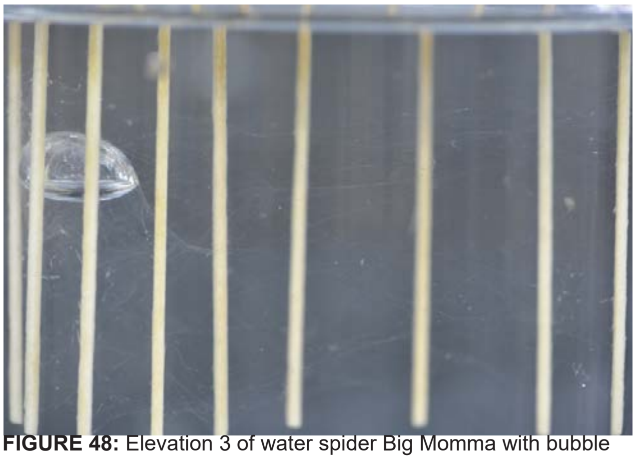


FIGURE 48: Elevation 3 of water spider Big Momma with bubble

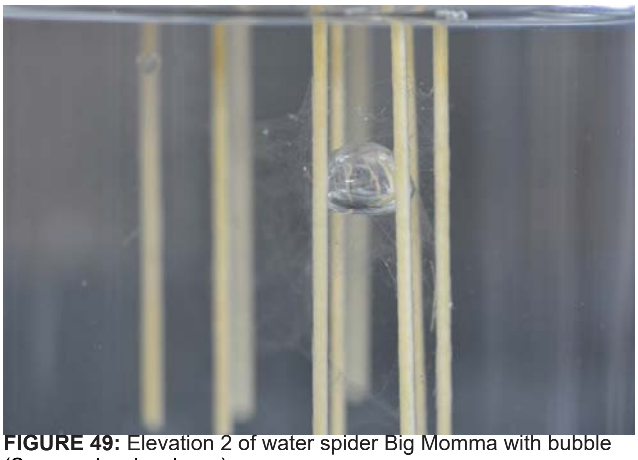


FIGURE 49: Elevation 2 of water spider Big Momma with bubble
(Source: Jessica Jorge)

FIGURE 50: Elevation 4 of water spider Big Momma with bubble

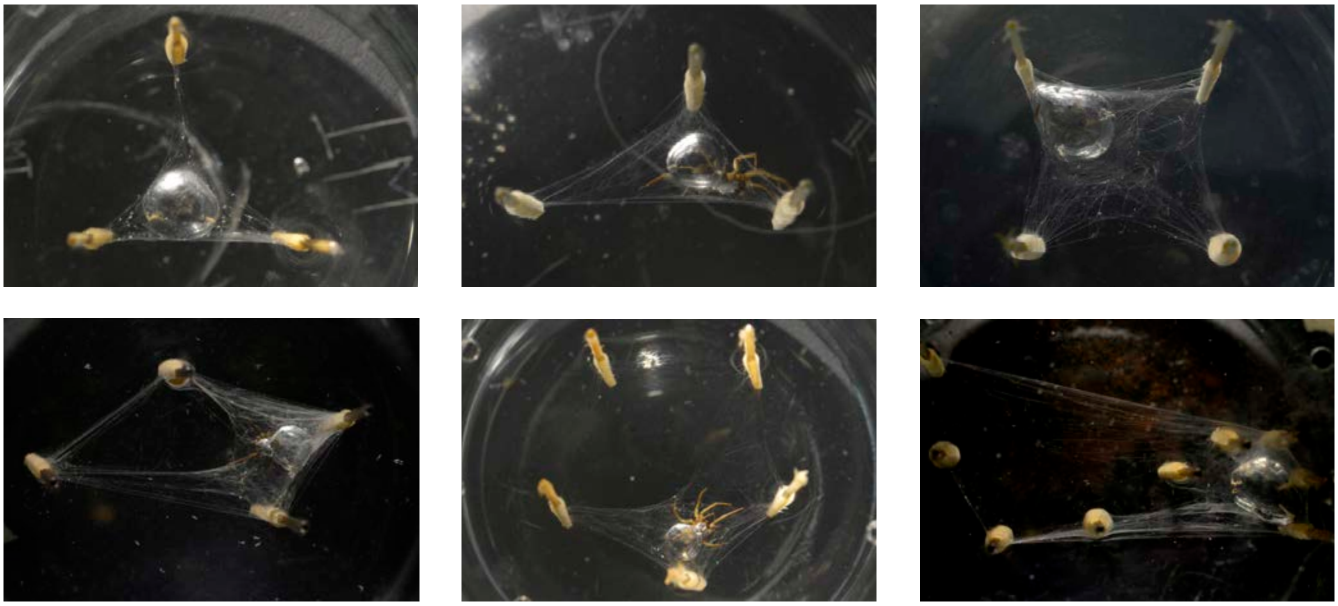


FIGURE 51: Summary of stick position and bubble placement (Source: Jessica Jorge)

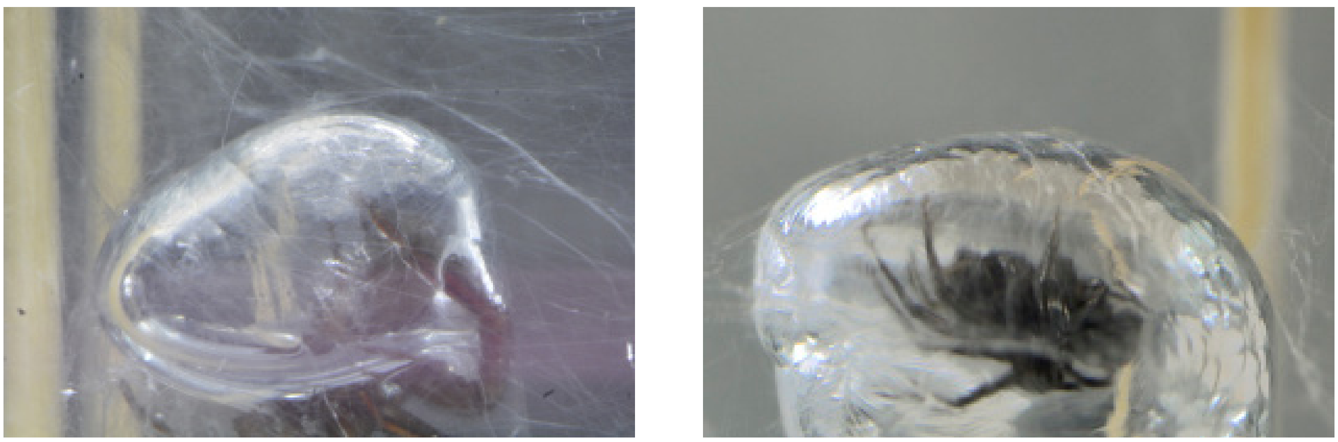


FIGURE 52: Detail images of crease on the surface of the bubble created by tension of the fibres (Source: Jessica Jorge)

CONCLUSIONS

Crease Created by Tension:
External fibers which connect to the sticks also cross the top of the bubble. As the bubble is inflated from below, the external fibers stay in place thus creating a visible crease between the surface of the bubble and the fiber.

Position and Number of Sticks:
From observing the six setups with different stick numbers and arrangements, we could conclude that the water spider requires only 3 sticks to successfully make a bubble. When more sticks were added, the bubble was still placed close to the sticks (not in the center area) and the main fibres were connected to three sticks. In other words, increasing the number of sticks did not change the spider’s method of laying fibres.

Thus, moving forward, the 3 stick setup was used to make further observations.

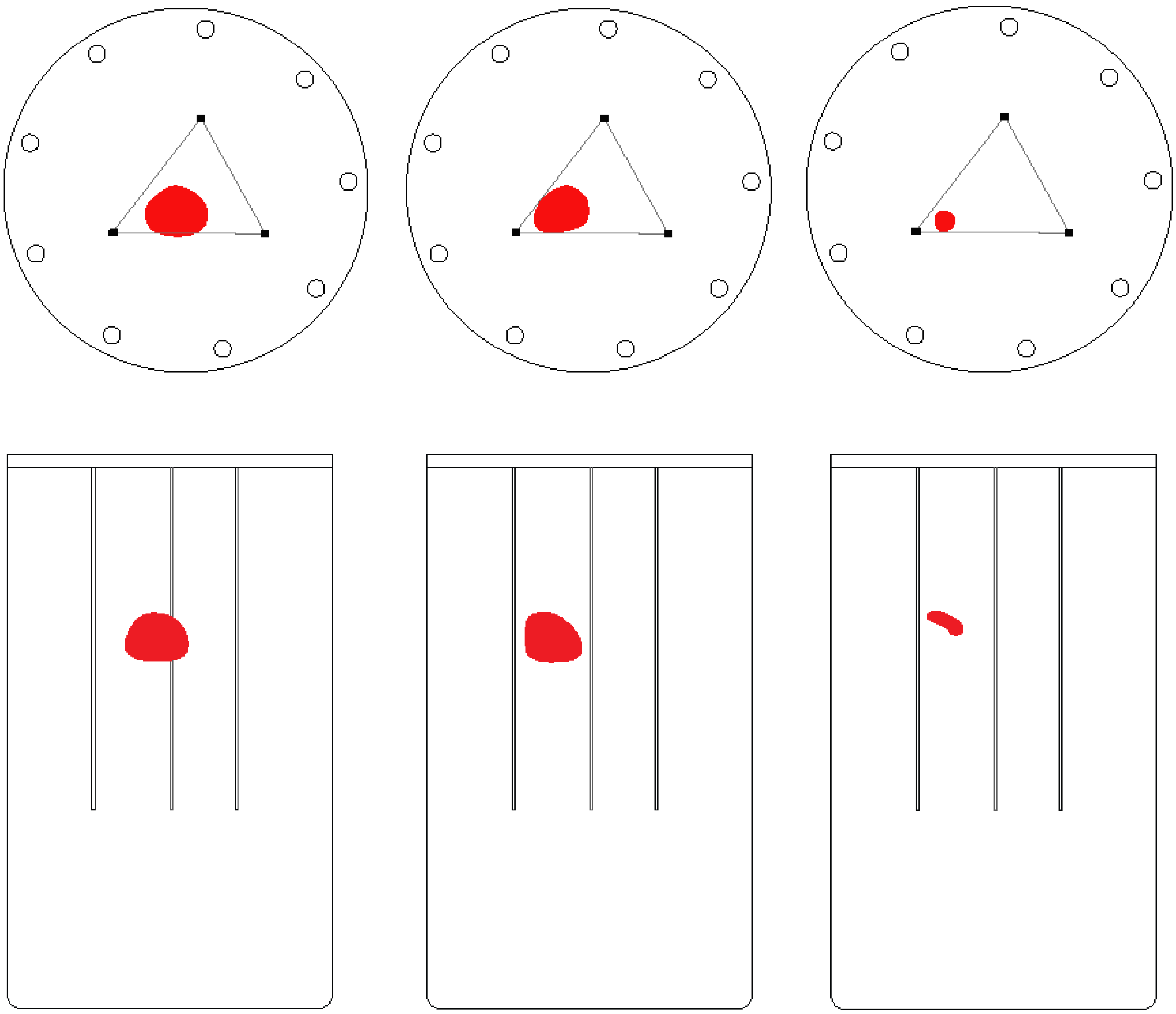


FIGURE 53: Three 3-stick setups were made to compare how and where the water spider builds its bubble. (Source: Matthias Helmreich)

PART C_3 STICK SETUP

Setup:
3 sticks were inserted into the plexiglass jar lids as with other experiements. The sticks were placed in an equilateral triangle 37mm apart. The jars were made on the same day and the water spiders were placed into the new setups at the same time as well. The setups were left for 9 days in order to allow the spiders time to fully lay fibres and begin bubble inflation.

Purpose:
While we concluded that only 3 sticks were necessary for each setup, we wanted to observe identical setups to see if different water spiders would lay fibres and inflate their bubble in a similar or different fashion. We also wanted to compare the rate at which different spiders would build their bubble.

CONCLUSIONS

Waterspider Bruce (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	3

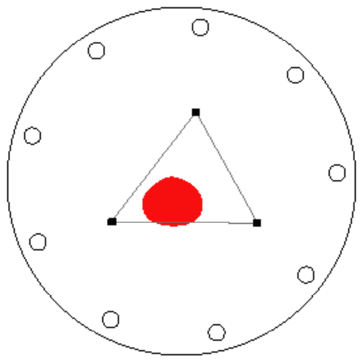
Bubble:

Area	824.4 mm2
Height	13.4 mm
Length	17.2 mm
Stage	9 days

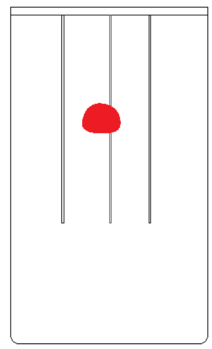
Top View:

FIGURE 54: Top view of water spider Female #4 with bubble

Plan:



Elevation:



Side Views:

FIGURE 55: Elevation 1 of water spider Female #4 with bubble

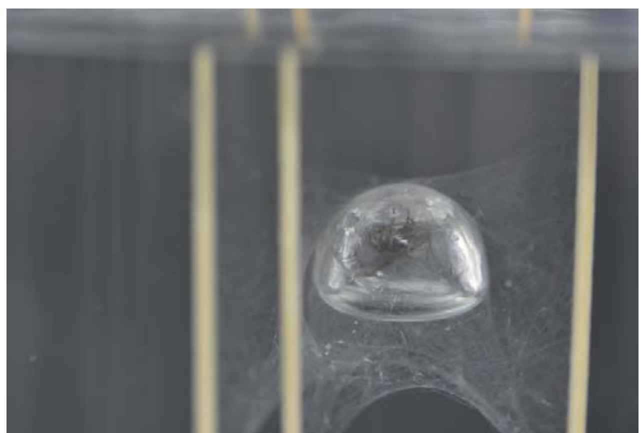


FIGURE 56: Elevation 3 of water spider Female #4 with bubble

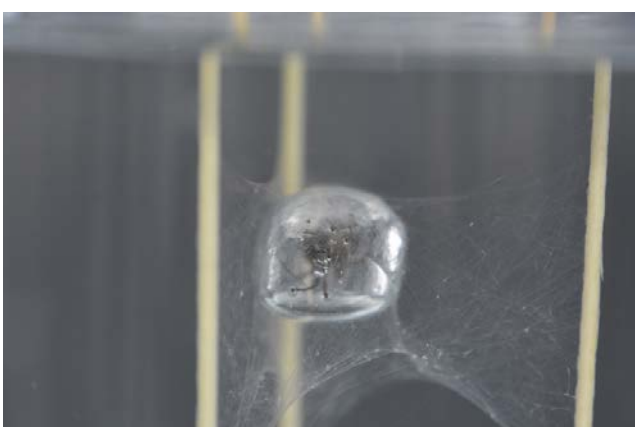


FIGURE 57: Elevation 2 of water spider Female #4 with bubble

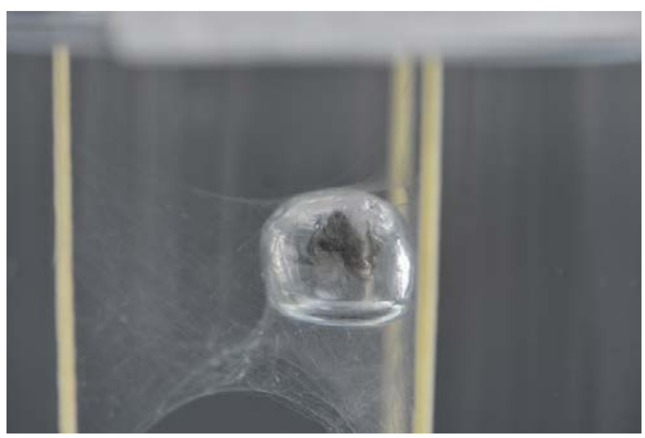


FIGURE 58: Elevation 4 of water spider Female #4 with bubble

(Source of photos on this page: Jessica Jorge)

Waterspider Anna (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	3

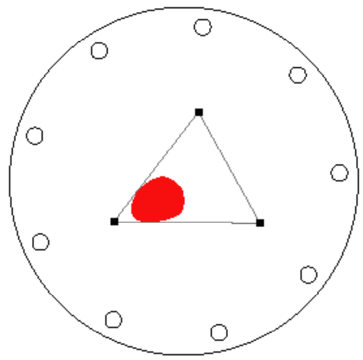
Bubble:

Area	734.8 mm2
Height	13.6 mm
Length	15.5 mm
Stage	9 days

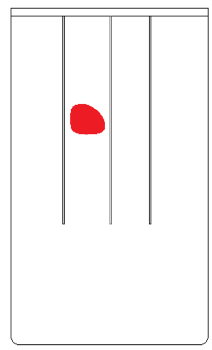
Top View:

FIGURE 59: Top view of water spider Female #4 with bubble

Plan:



Elevation:



Side Views:

FIGURE 60: Elevation 1 of water spider Female #4 with bubble

FIGURE 61: Elevation 3 of water spider Female #4 with bubble

FIGURE 62: Elevation 2 of water spider Female #4 with bubble

FIGURE 63: Elevation 4 of water spider Female #4 with bubble

(Source: Jessica Jorge)

Waterspider #4 (Female)

Set-Up bf-001:

Jar dimension	150 mm x 90 mm
Stick dimension	2 mm x 2 mm x 90 mm
Number of sticks	3

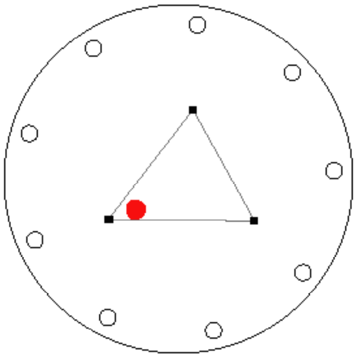
Bubble:

Area	116.5 mm2
Height	6.5 mm
Length	9.7 mm
Stage	9 days

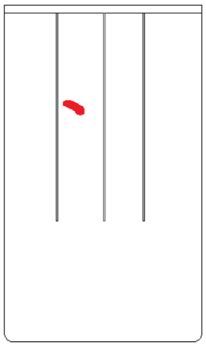
Top View:

FIGURE 64: Top view of water spider Female #4 with bubble

Plan:



Elevation:



Side Views:

FIGURE 65: Elevation 1 of water spider Female #4 with bubble

FIGURE 66: Elevation 3 of water spider Female #4 with bubble

FIGURE 67: Elevation 2 of water spider Female #4 with bubble
(Source: Jessica Jorge)

FIGURE 68: Elevation 4 of water spider Female #4 with bubble

Chapter 06
Web analysis with microscope

FIBER ANALYSIS WITH MICROSCOPE

Setup and Method:

When the bubble reached full inflation (aka when the spider could comfortably sit and breath in the bubble), the bubble was removed from the glass jar setup and placed in an alcohol mixture to stabilze the bubble and fibres.

After the bubble stablized in the alcohol bath, the anchor threads were cut away from the sticks and the bubble was placed flat on a glass slide for observation.

We were most interested in observing the fibres on the top of the bubble because the top is the most dense part of the bubble and we wanted to observe the path of the spdier as it reinforces the bubble from the interior. Therefore, careful attention was paid to avoid any distortion or moving of the top of the bubble when it was placed on the glass slide.

When under the microscope, only the center area of the web, where we were certain no distortion of the fibres had occured, was documented and observed.

The microscope allowed for magnificaiton at three levels: 4x, 10x and 40x.

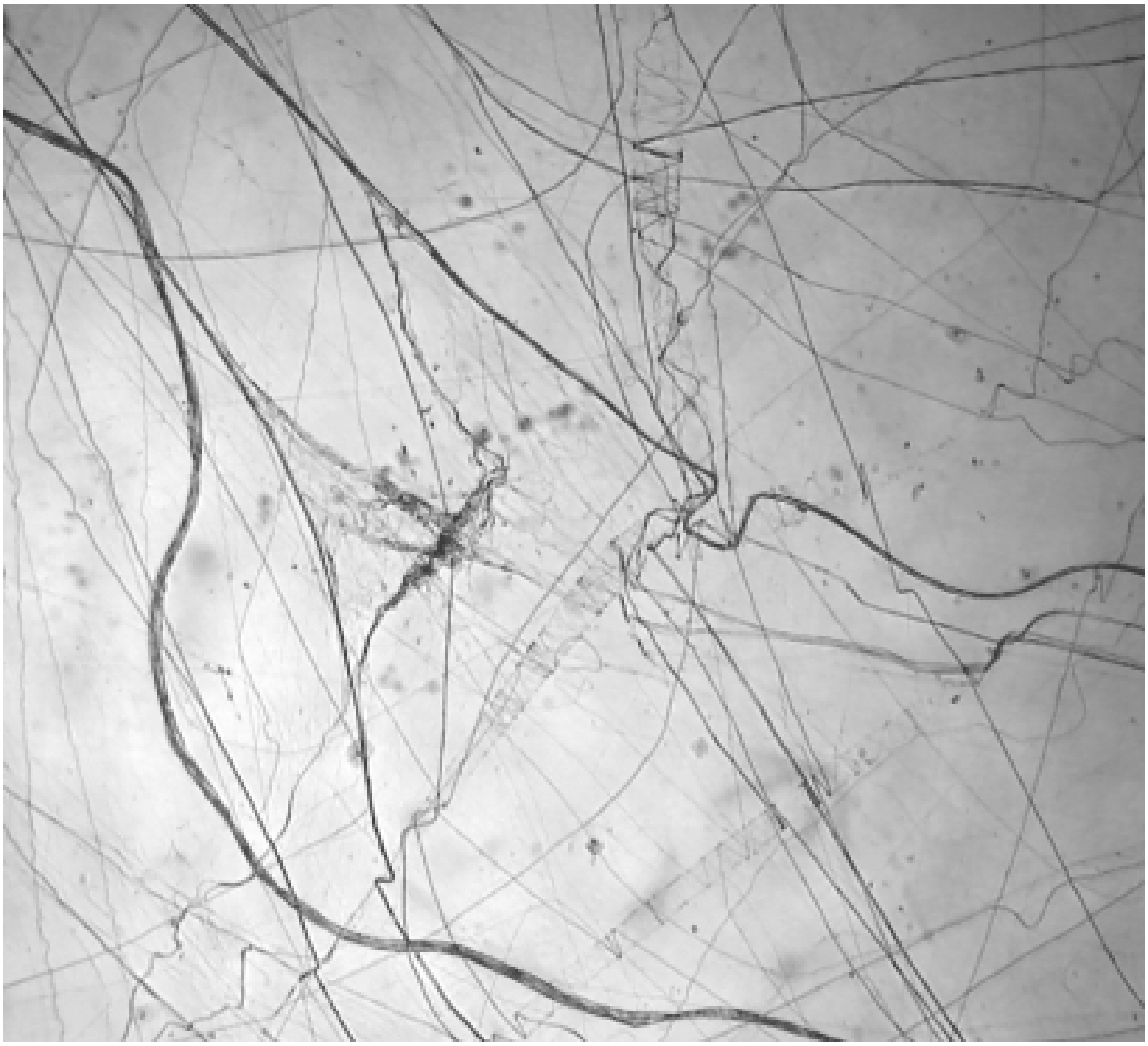


FIGURE 69: 4x magnification (Source: Elena Chiridnik, Tobias Grun, Jessica Jorge)

4x MAGNIFICATION

Observations:

We see threads of various thicknesses going in various directions.
Thick trads are only few items, while thin threads are aggregations.

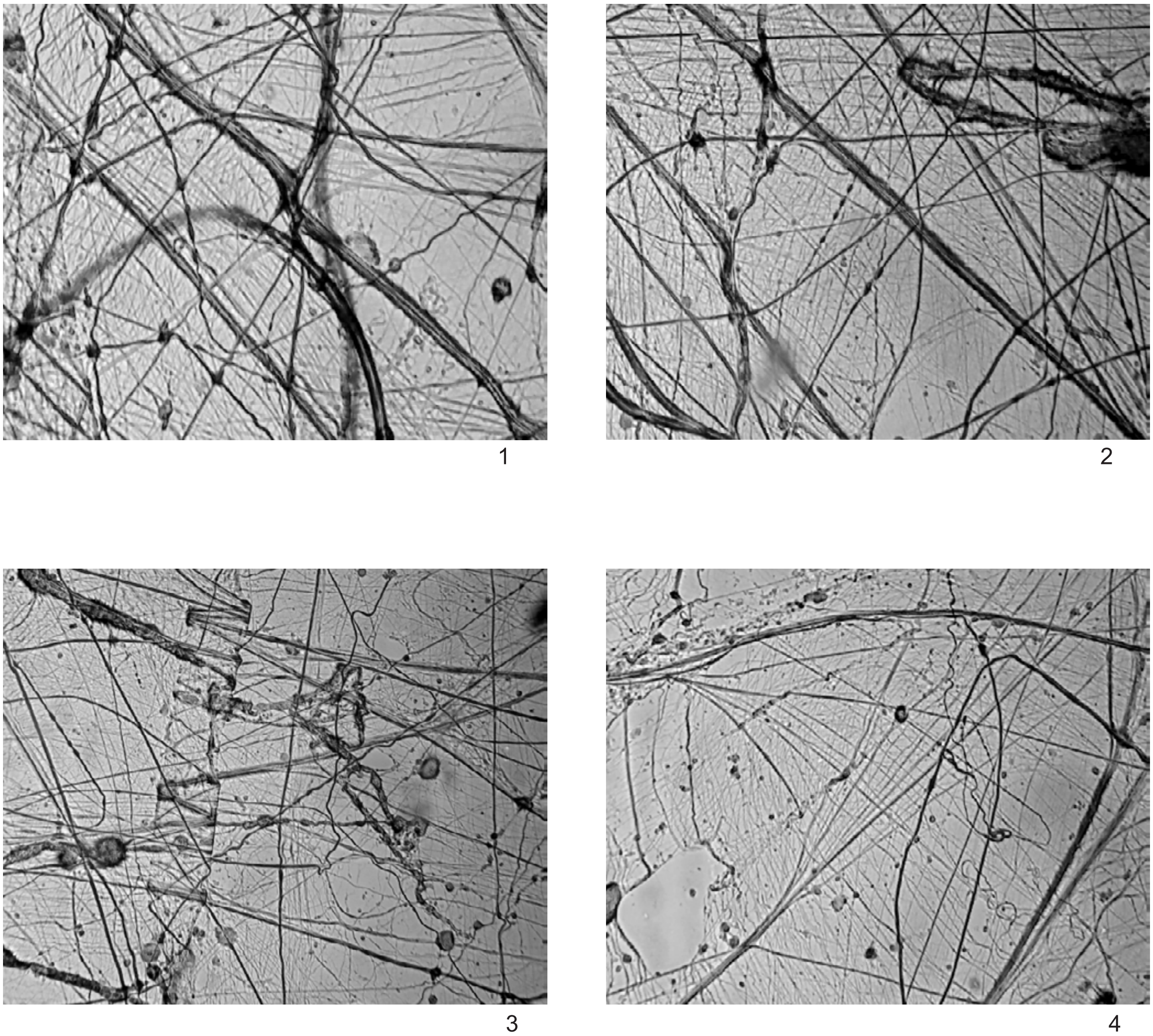


FIGURE 70: 10x magnification (Source: Elena Chiridnik, Tobias Grun, Jessica Jorge)

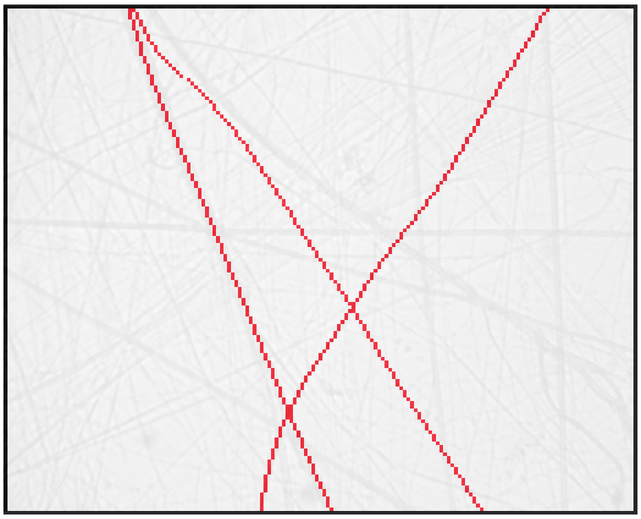
10x MAGNIFICATION

Observations:

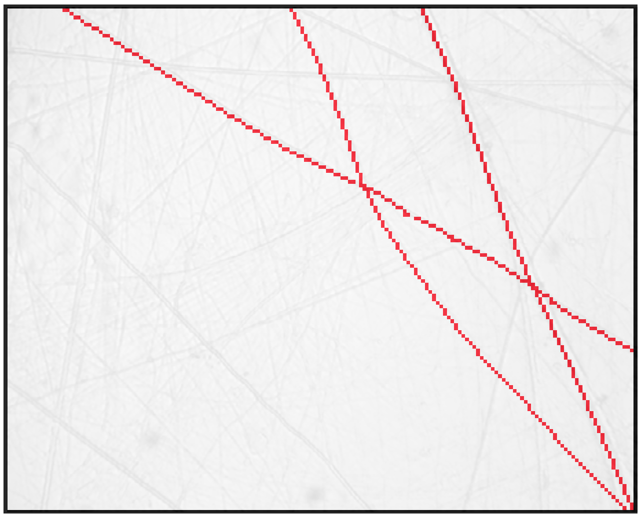
Minor-Major: A minor fibre will temporarily join a major fibre path before breaking away and taking on a new direction. Two or more minor fibres come together to produce a major fibre section and then slit and disperse again (Image 1 and 2).

Dendritic Branching: A tree-like branching network is produced when a major fibre splits at one point into its smaller fibres (Image 4).

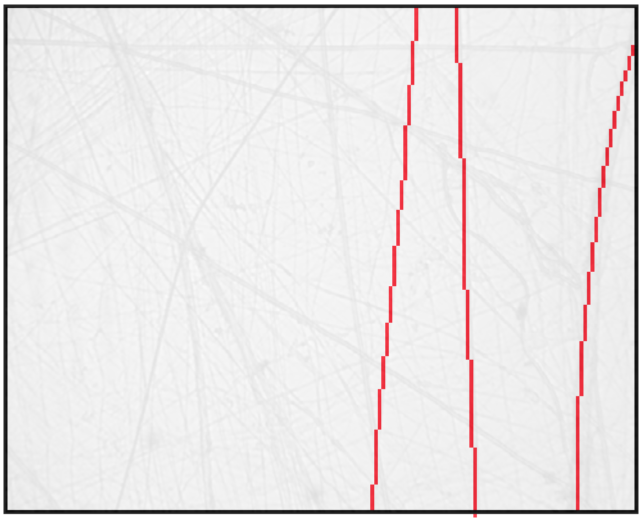
Zig-zag: At the micro scale, a zig-zag path is created for seemingly random durations and in unpredictable directions (Image 3).



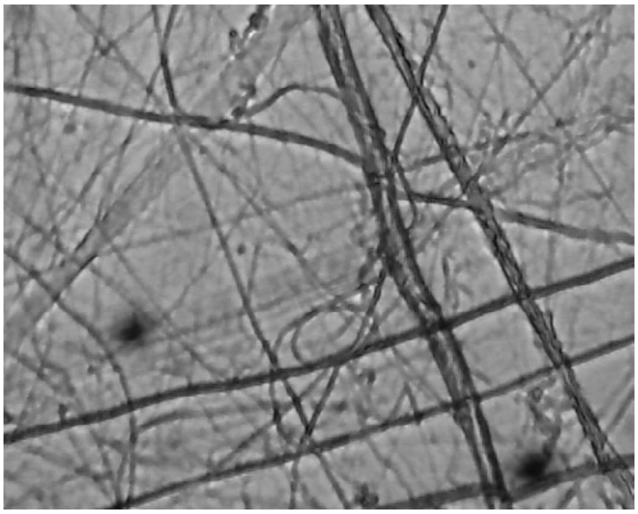
5



6



7



8

FIGURE 71: 40x magnification (Source: Elena Chiridnik, Tobias Grun, Jessica Jorge)

40x MAGNIFICATION

Observations:

Branching: Unlike with dendritic branching, these minor fibers never layer to create a major fiber path. Instead, the minor fibers maintain their singularity and stay on their own track. After running parallel for a short time, they branch. (Image 5 and 6)

Loop: Within the system of minor fibers, closed loops are produced often adjacent or tangent to a major fiber or an intersection of two major fibers (Image 8).

Fiber Thickness:

When magnifying the web at the 40x level, three heirarchies of fibres are clearly visible.

Image 5: minor thread 1 unit; 1.562; 6.353
Image 6: minor thread 1 unit; 1.21; 4.462
Image 7: minor thread 1 unit; 2.175; 5.190

Part 3. Biomimetic investigations

Chapter 07
Fields of research

Summary of Research Areas

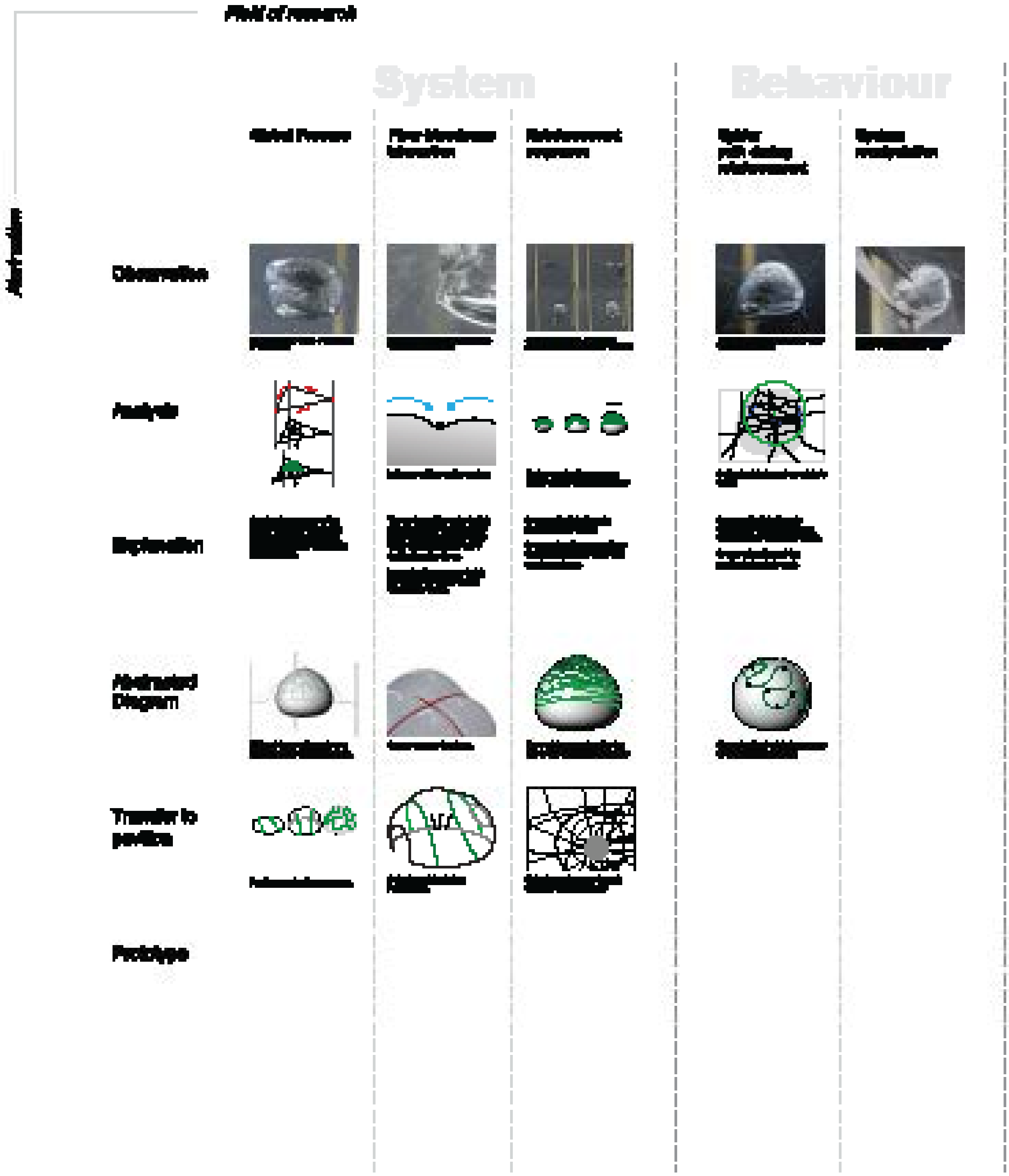
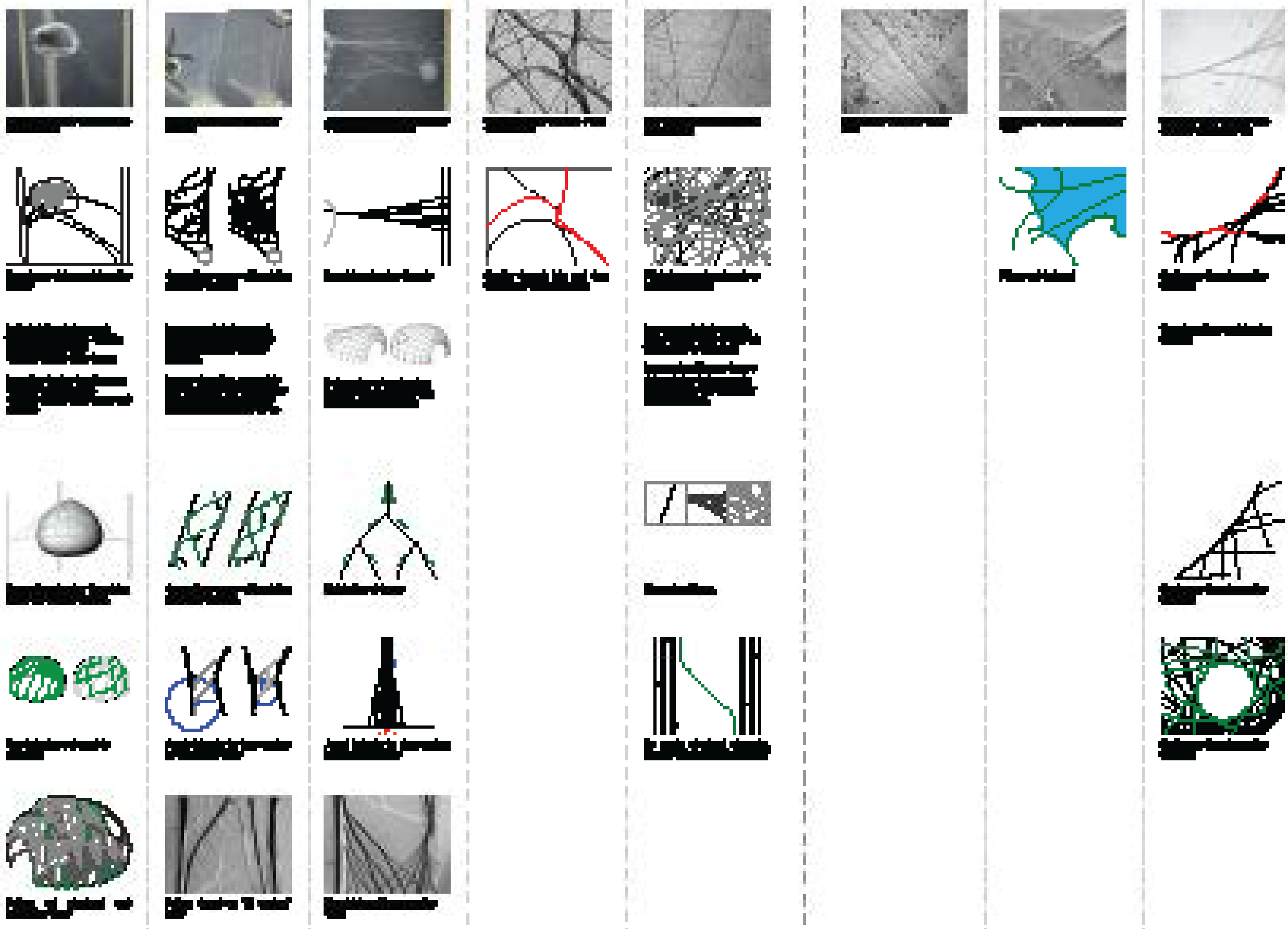


FIGURE 72: Areas of research.(Source: Elena Chiridnik, Mandy Moore, Matthias Helmreich)

Fibres

Micro details

Hierarchy of fibres, function and order | Connection of threads | Anchor points | Fibre-Fibre interaction | Fibre bundling and thickness | Density on micro scale | Hydro-gel | Edge condition of external fibres



3.1. System

Chapter 08
Global process

FIGURE 73: Process of bubble construction (Source: Elena Chiridnik)

OBSERVATION CONSTRUCTION OF AIR-BUBBLE

Introduction

The water spider first finds a suitable environment at about 10cm under the surface to start placing anchor threads. Anchor threads help the water spider to walk under water and are the base for the horizontal sheet web. In a secondary stage, the water spider weaves a horizontal sheet web on the anchor thread. The horizontal sheet web will help keep the air bubble in place once the bubble is constructed.

After a certain density of fibers has been reached, the spider moves to the surface of the water to get air for the bubble. It then places an air bubble under the horizontal sheet web. While holding the bubble in place, the spider glues the bubble onto the horizontal sheet web with hydrogel. Additionally, the hydrogel functions as the connector between the interior fibers that are woven onto the interior of the bubble for reinforcement. This method of laying interior and exterior fibres, both glued using the hydrogel, keep the bubble in place.

Once the initial bubble is put in place, the spider continues to move back to the top surface to gather more air and add it to the bubble. With each inflation step the spider continues to reinforce the bubble from the inside in order to keep the structure stable. At certain inflation stages more or less fibres are added from the inside.

FIGURE 74: Process of bubble construction (Source: Elena Chiridnik)

BUILD-UP PROCESS OF BUBBLE

Process

The time-laps images were processed in Adobe After Effects and compiled into a quick time movie. The movie gave a general overview of how the spider was building the bubble. Images in which the spider was actively constructing the bubble have been selected, observed an compiled into a movie, length 46sec. The movie gave a general impression of how the construction process develops and what its main characteristics are. The water spider reinforces and inflades the bubble in a top-down process. It only reinforces and connects the extended surface of the bubble to the outer threads after each inflation step. The process of inflation was categorized into 16 inflation steps. A step was defined when the spider went up to gather more air and placed it in the bubble. After the inflation step the spider either reinforced the bubble at the extended surface or continued the inflation streight. Figure xx and xx show the key images for each inflation step. The shown track of the spider was generated through the time laps images. 613 images have been imported into Rhinoceros to track the spiders movement. A point was placed at the water spiders abdomen on each image. The images have been overlaid and the path could be generated. Before the water spider placed another inlation step the image was taken and the fibers redrawn. It was difficult to draw the exact fiber layout due to the qualtiy loss of th eimage after importing it into Rhinoceros. As well not all fibers were visible in the images. Increasing the volume of the bubble created a higher upflow force, which caused the bubble to move upwards. Due to a higher density of the horizontal sheet web on the left the bubble

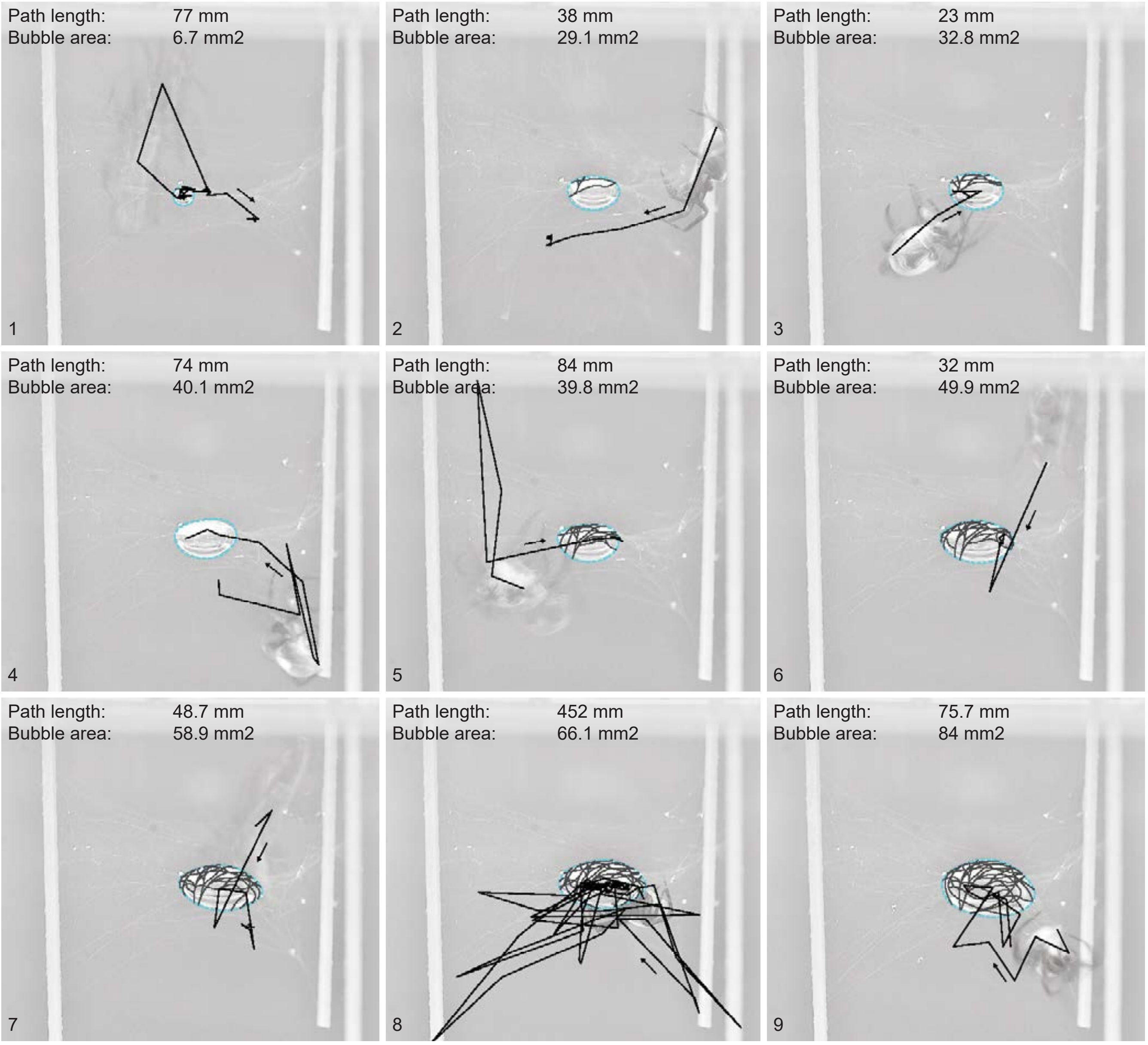


FIGURE 75: Process of bubble construction with spider path (Source: Matthias Helmreich)

tended to move right while the volume was encreased. The border of the bubble was redrawn in its elevation from which we could calculate the elevation area.

Image 1

Initial bubble placement and the reinforcement right after it has been placed. The inital bubble had a size of about 155mm3. The size is estimated by revolving the elevation of the bubble. To fix the bubble to the horizontal sheet web the water spider mainly fixed and reinforced it on the top.

Image 2 - 7

Reinforcement and fixation of the extended surface of the bubble on the horizontal sheet web. The reinforcement is relatively small and we assume that most of the fibers that are visible on the bubble surface are from the horizontal sheet web. Sequencially the reinforcement starts from the horizontal sheet web and the water spider pulls the fibre onto the bubble surface.

Image 8

The horizontal sheet web is subsequently reinforced as well as the lower sides of the bubble surface are heavily reinforced. This shows that the water spider will at a certain stage of the bubble put more fibres rather than placing the same amount of fibres each time after inflation.

Image 9-10

Water spider continues to reinforce the lower part of the bubble, subsequently connecting the interior fibres to the horizontal sheet web.

Image 11- 12

Once the bubble has reached a certain height the water spider will start to place fibres again on the top part of the bubble. Though the main reinforcement takes place at the lower part of the bubble. To connect the interior fibres to the horizontal sheet the female pushes the bubble surface about 4 mm out until it reaches

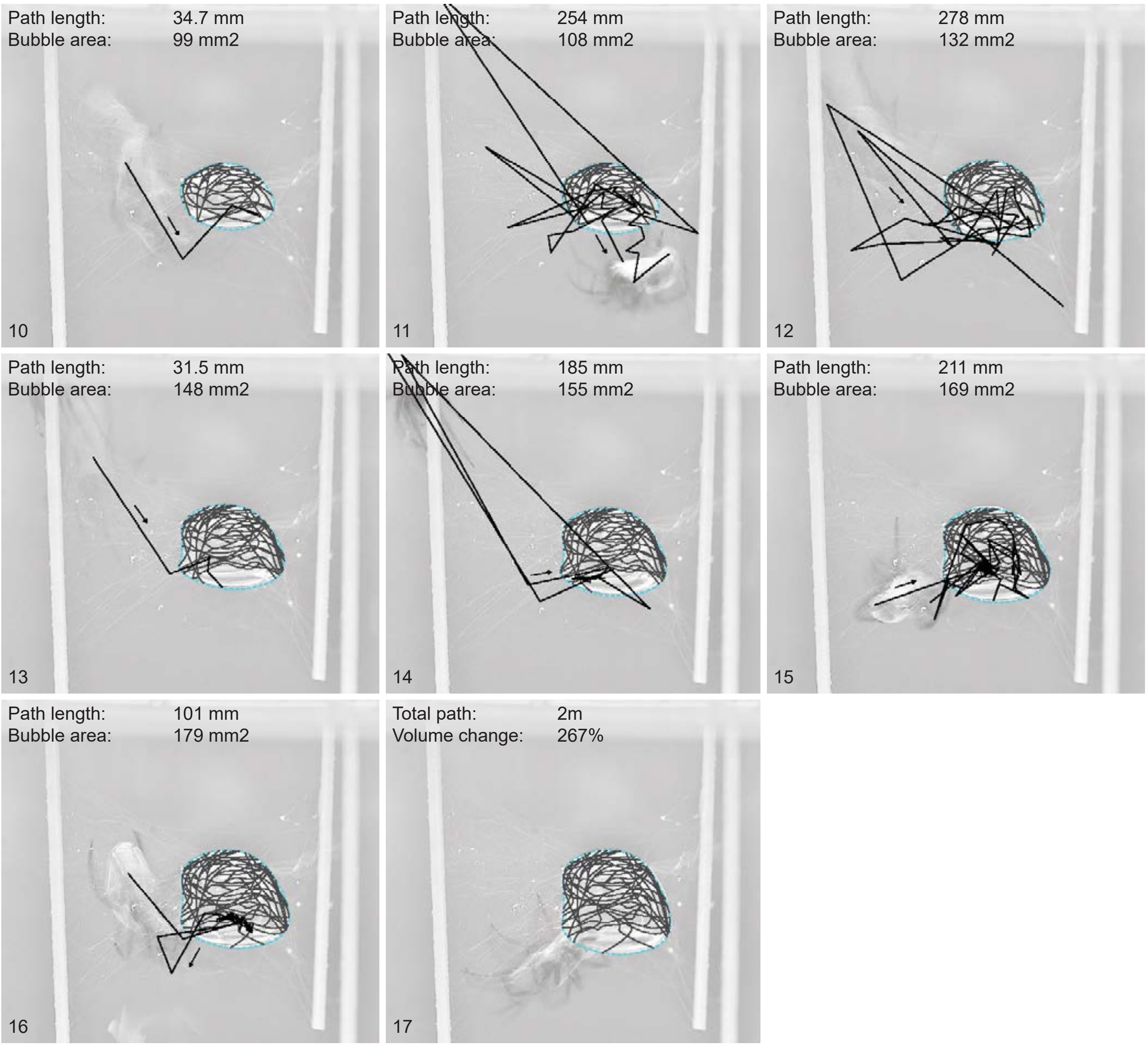


FIGURE 76: Process of bubble construction with spider path (Source: Matthias Helmreich)

one main fibre of the horizontal sheet web.

Image 13 - 14

Repeating the sequence of images 9-10

Image 15 - 16

Again reinforcement of the lower part of the bubble while connecting the fibres to the higher part. The weaving process results in a quite homogeneous density of the fibre pattern on the surface. After its last inflation stages the spider greatly reinforces the edge of the bubble. We assume this is to reinforce the entrance area and secure the edge onto the horizontal sheet web. Also we could observe a reinforcement movement in where the water spider travels from the lower right part of the bubble over the top to the lower left part of the bubble.

In total the spider placed about 2m of fibres on a final bubble surface area of 169mm2. The volume of the bubble is about 2696mm3. The water spider increased the volume to about 267% of its original size. No fibres have been placed at the bottom of the bubble. This allows the spider to enter and exit the bubble.

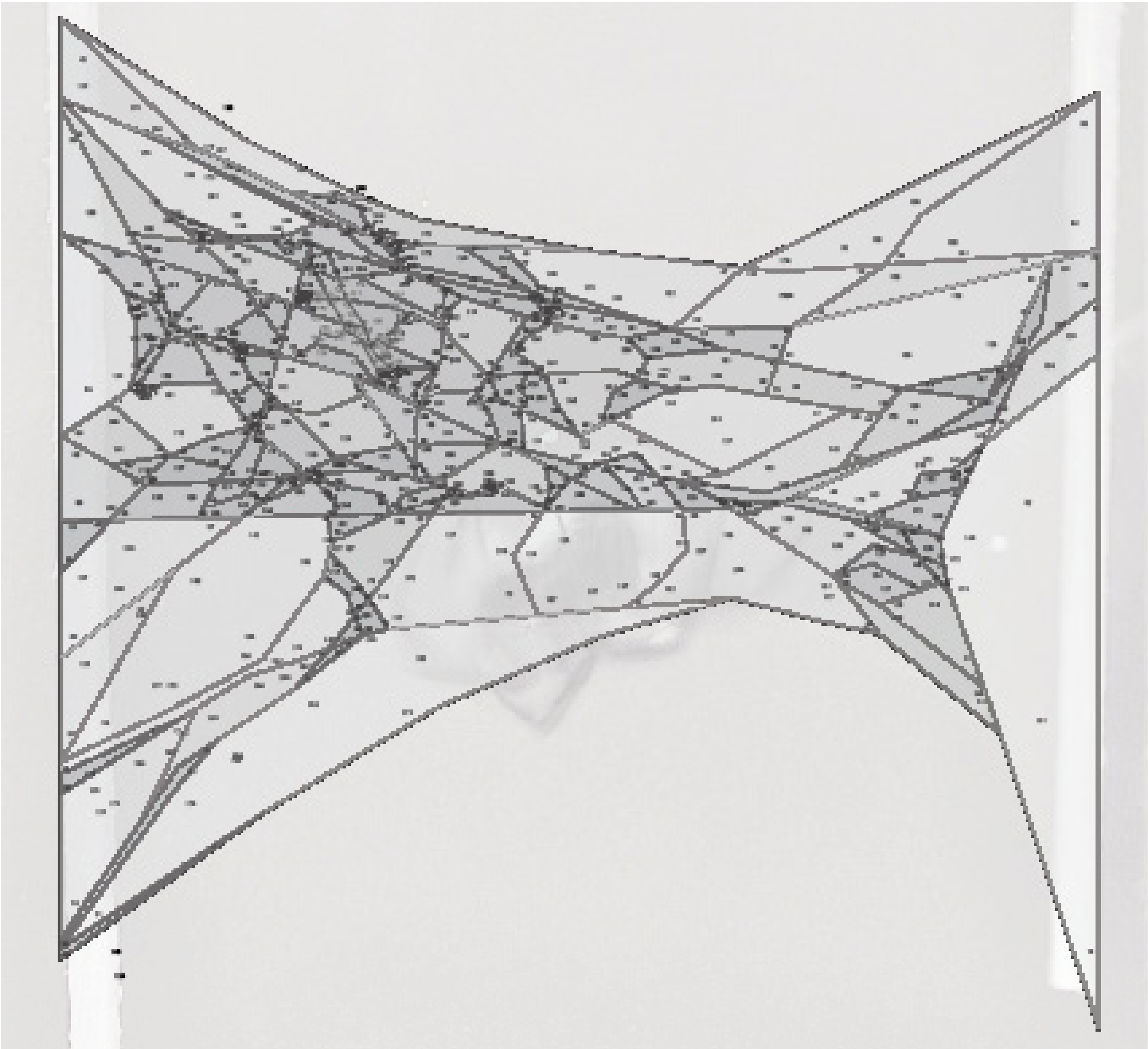


FIGURE 77: Density analysis (Source: Matthias Helmreich)

HORIZONTAL SHEET WEB - ANALYSIS

Method

All images were taken perpendicular to the wood sticks. The elevation gave us the possibility to analyse the horizontal sheet web from XZ-axis. 3D intersections have been neglected in this analysis. The last image of the horizontal sheet web construction shows the final stage of the web before the inital bubble has been placed. The image was prepared and sharpened in Photoshop and imported to Rhinoceros 5.0. Importing the image reduced the quality of the image, even though most of the fibers remained visible.

The images were placed in the background of the drawing program and all visible fibers were redrawn upon the image with polylines.

The single polylines were converted into close polylines. The web was then analysed with Grasshopper to estimate the average angles in which the fibers meet each other. The data was processed and the angles categorized according to their frequency:

Fibres tracked:	88 Fibres
0° < α > 30°:	10%
30° < α > 60°:	18%
60° < α > 80°:	11%
100° < α > 120°:	12%
120° < α > 160°:	35%
160° < α > 180°:	0 %

FIGURE 78a: The water spider begins by attaching anchor points to a solid substrate (i.e. water plants), from where it begins to construct the web's anchor threads.

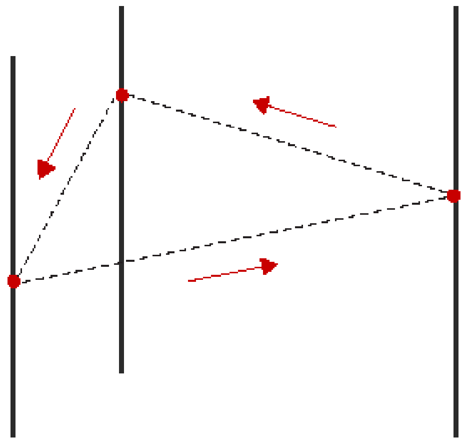


FIGURE 78b: The spider then interconnects anchor threads with bell threads.

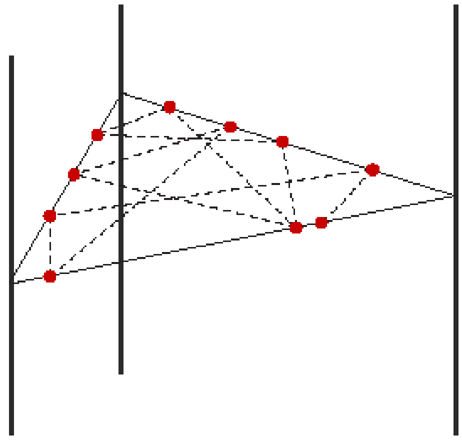


FIGURE 78c: The spider places a drop of hydrogel on the bell web to position the air bubble.

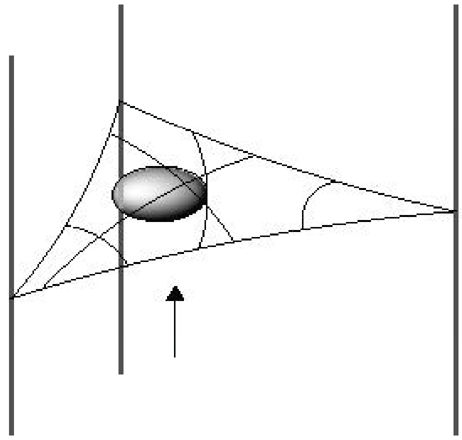
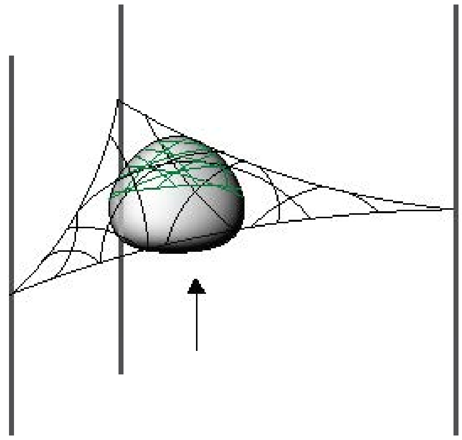


FIGURE 78d: The waterspider continues to inflate the air bubble with surface air until it reaches a certain size. Simultanesously, it reinforces the top of the bubble from the inside.

(Source of the diagrams on this page: Mandy Moore)



Chapter 09
Level of control

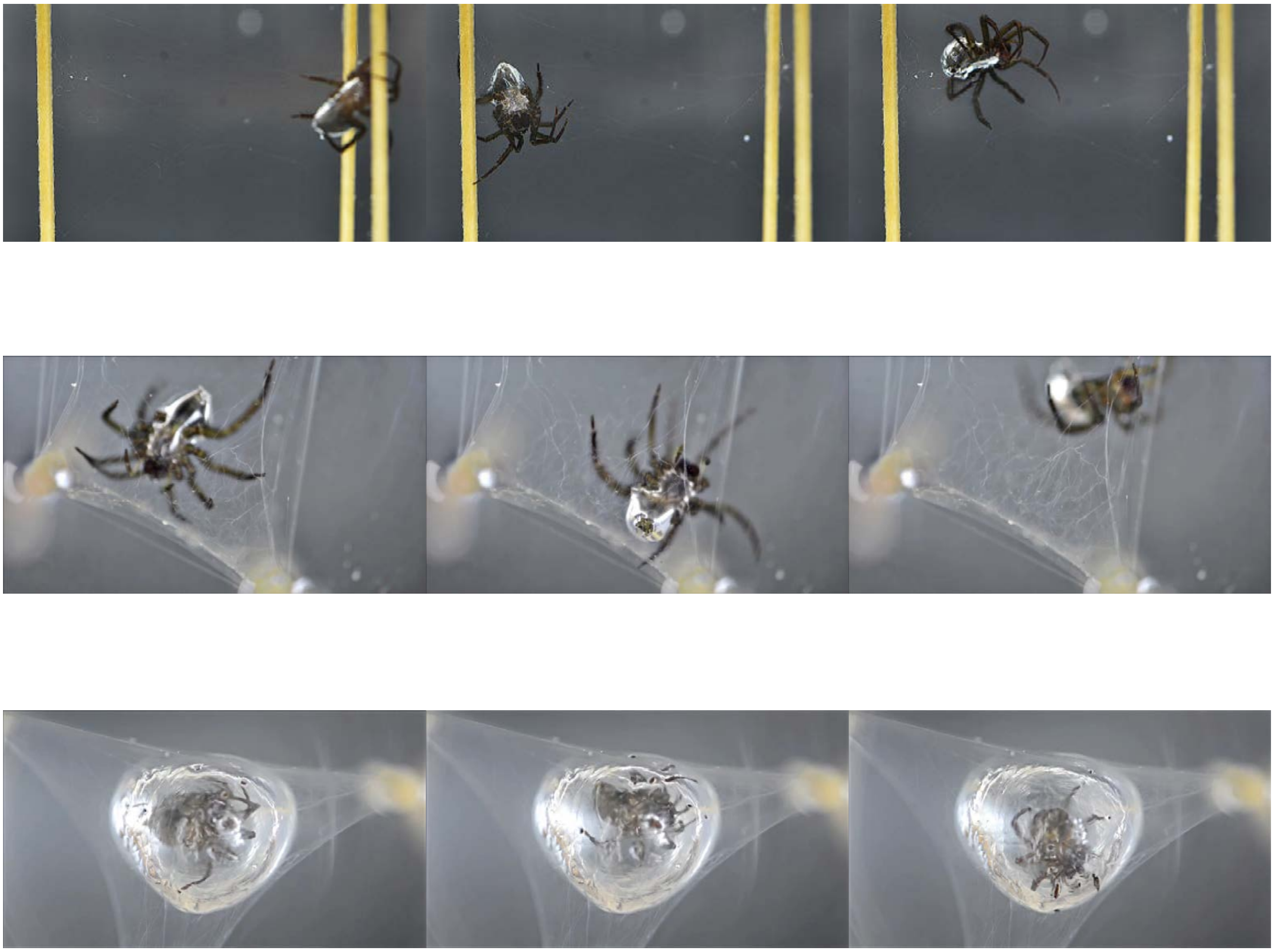


FIGURE 78: Fibre laying behaviours of the waterspider.(Source: Elena Chiridnik)

LEVEL OF CONTROL. ABSTRACTING FIBRE LAYING STRATEGIES

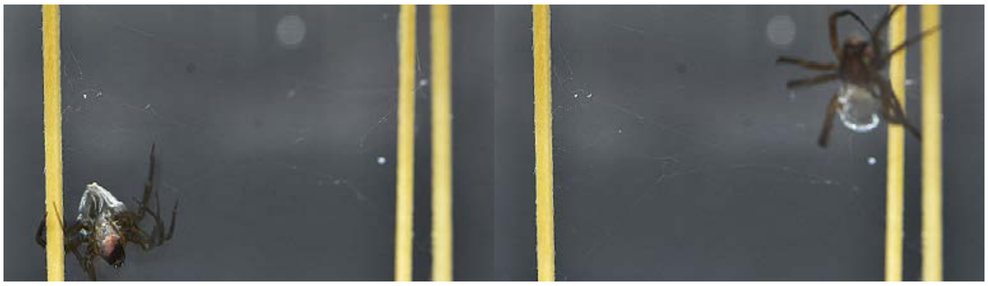
The ultimate case for the robotic fabrication field in this project would be to identify behaviour (behaviours) of the spider, abstract them to the agent behaviour, and set the interactive loop with the robot recieving data from the environment and reacting as an agent on the environment changes. There are two options for environment changes: robot is changing the environment and adjusting to that accordingly, or there are changes coming from outside the system- from human.

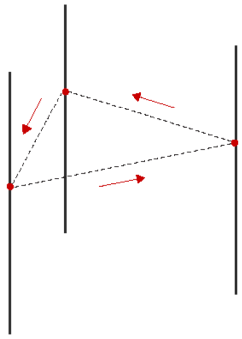
For the fibrous pavilion the role model gives us the order of construction, the hierarchy of fibres, and rules for the behaviours resulting in a fibre layout. These behaviours have a different level of control over the system. There is a “gradient” of predefined and emergent paths in spider actions and our agent (=robot) actions. Researching the biological role model, we have discovered that during time of construction spider conducts different action over certain periods of time, resulting in fiber layouts with different layouts, functionality, connections, and thicknesses of fibres.

The first fibre layout is anchor threads arrangement. This layout is pre-defined by the substrate and possibility to fix anchor points. This is the most top-down controlled behaviour os setting the boundaries.

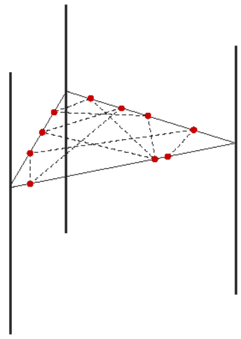
Second fibre layout is a construction of a sheet- web or a structural network which will hold the bubble. The sheet-web threads are fixed carefully in many points to the anchor threads, thus path is still partly pre-defined by the position of anchor threads. The connections of this layout are of a strong “interwoven” type.

In the third fibre layout the connections are just a crossing of fibre over each other, they are not so strong. On

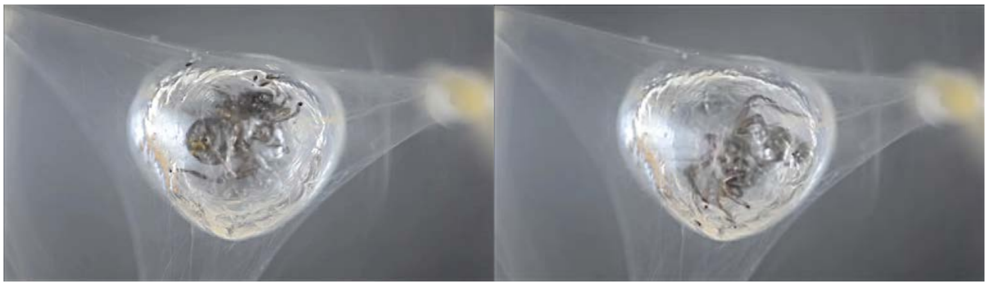


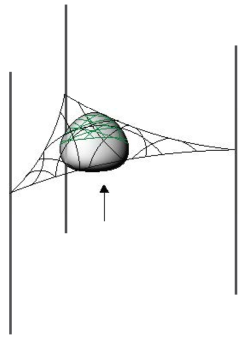


Construction of anchor threads



Construction of horizontal sheet web

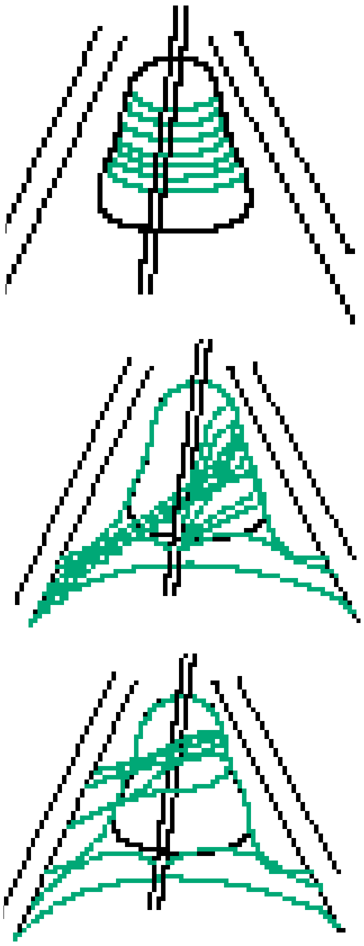




Internal reinforcement of bubble

this stage the reinforcement should be even, so the certain density should be reached on the internal surface of the bubble. Performing this tast, spider moves freely according to its morphology from one side of the bubble interior to the other. We consider this behaviour as the least controlled as there is no certain spot to be reinforced emergently, there is a task to fill the surface with fibres.

Chapter 10
Fibre-Membrane Interaction



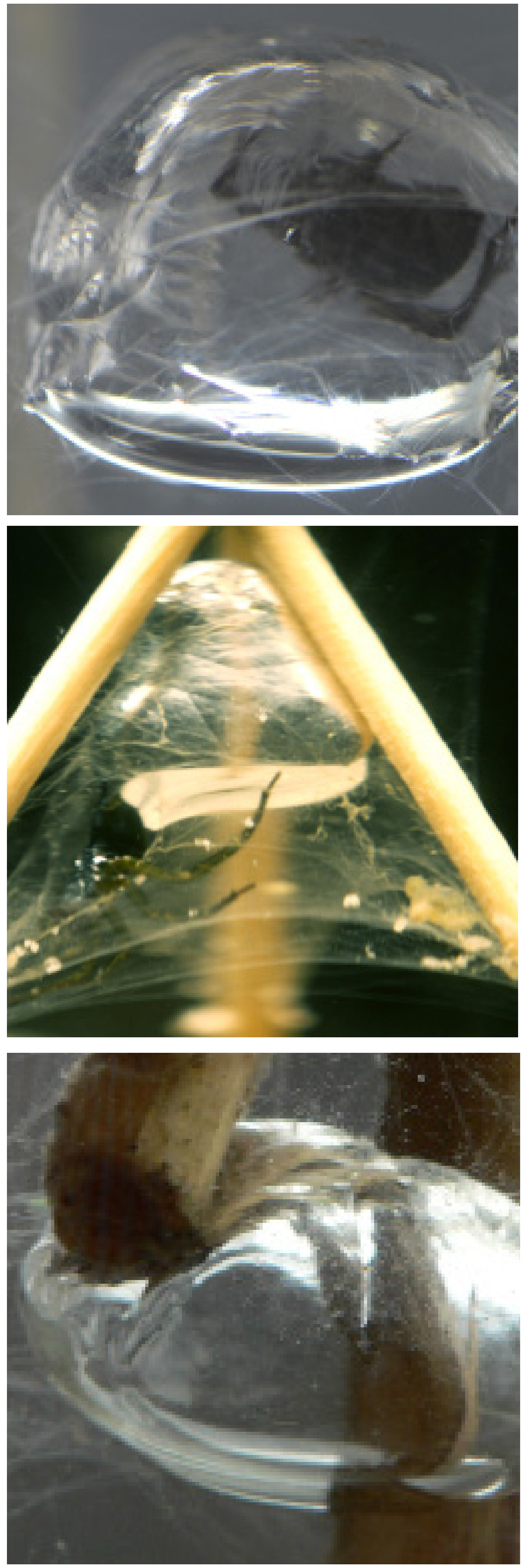


FIGURE 79: Outer threads and the membrane (Source: Elena Chiridnik)

INFLUENCE OF OUTER THREADS ON THE SHAPE OF THE BUBBLE (IN BIOLOGICAL ROLE MODEL)

On the earlier stages of construction outer threads play significant role in shaping the bubble.Later after inflation shape is mostly formed by internal reinforcement. It was noticed that rarely spider goes out of the bubble and puts additional outer threads. Thus, the most important thing considering outer threads after the bubble is fixed in its position is how the inner reinforcement interacts with the outer threads.

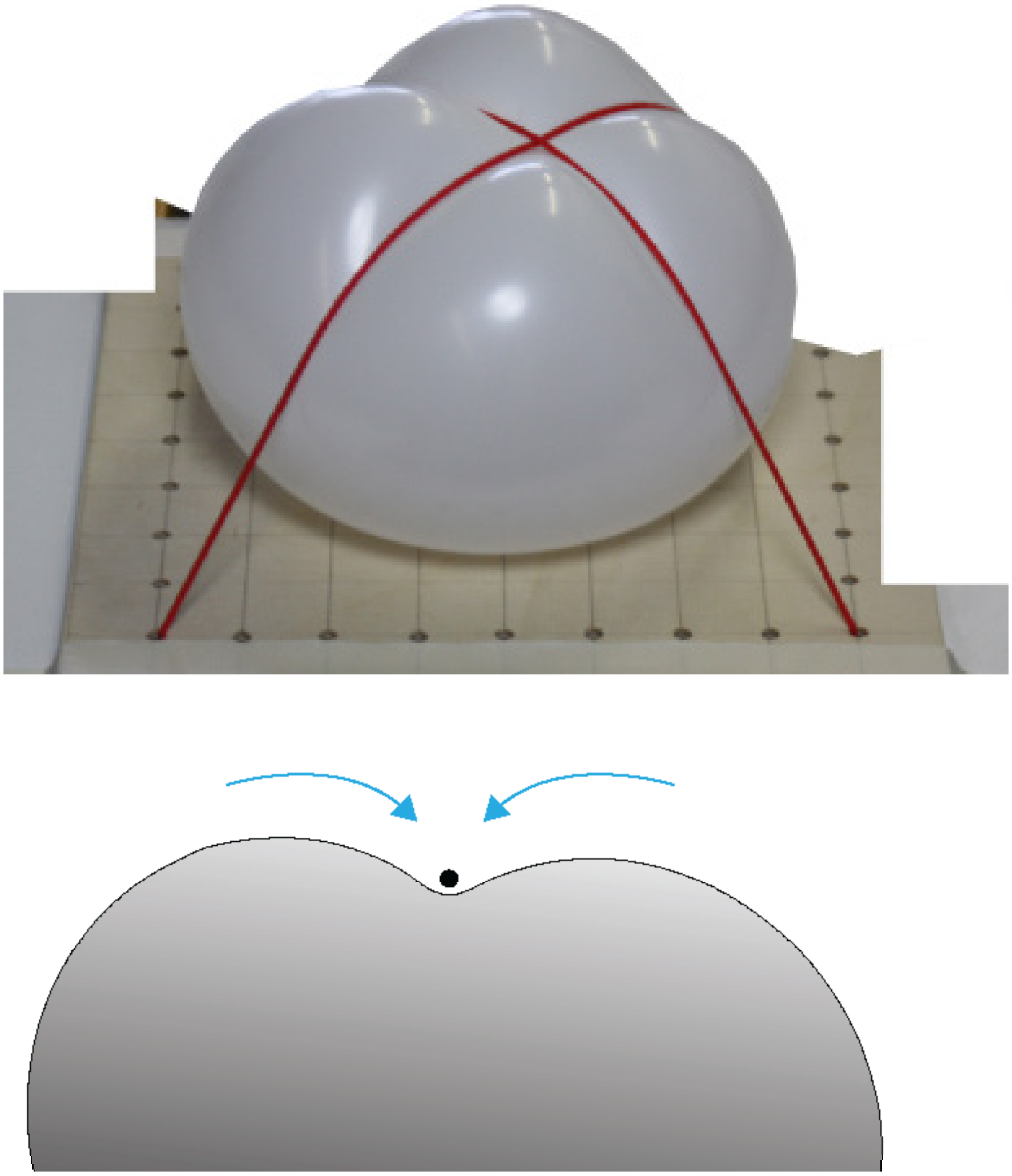


FIGURE 80: Outer threads shape elastic membrane. (*Source:* Matthias Helmreich)

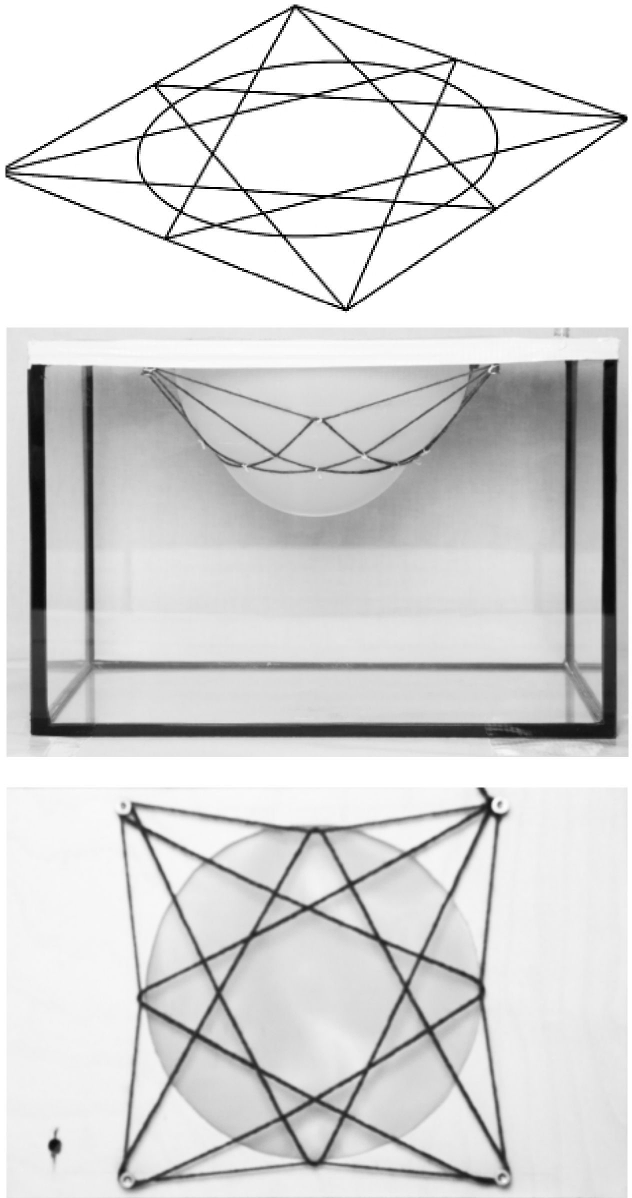


FIGURE 81: Fibres shaping the membrane. (*Source:* Matthias Helmreich, Elena Chiridnik)

INFLUENCE OF OUTER THREADS ON THE SHAPE OF THE BUBBLE

It was noticed that sheet- web threads limit extension of bubble in certain areas (where threads have higher density). In the model we experimented with density of fibres and how thy create bell-shabe in comparison with perfect sphere latex bubble tends to be.

In this model fibre-membrane interaction experiment is based on the density of fibres near anchor points.

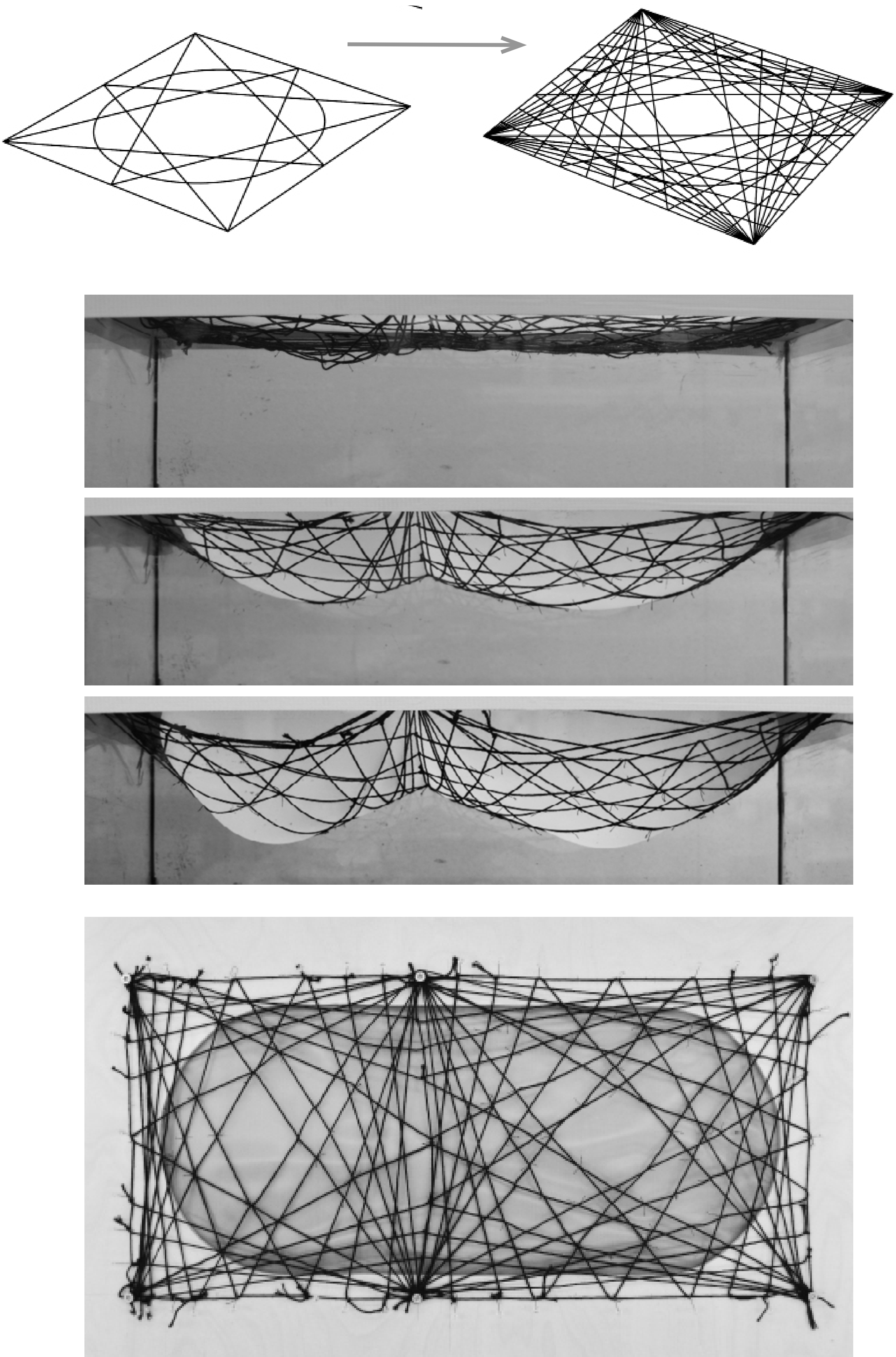
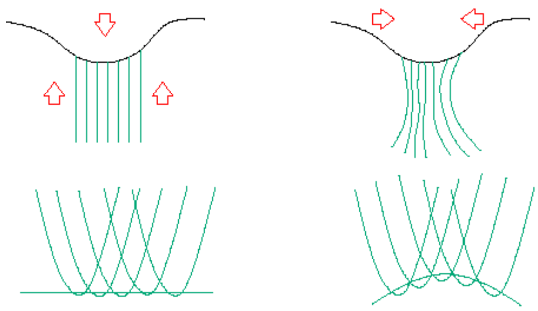


FIGURE 81: Fibres shaping the membrane. Additional density and variable angularity of fibres (*Source:* Matthias Helmreich, Elena Chiridnik)

Chapter 11
Fibre-Fibre Interaction



Threads shape the bubble, bubble shapes the curvature of threads

Plain web of anchor threads

Inflated membrane is shaped by anchor threads

FIGURE 82: Models based on spider web fibre-fibre joints and how it influences the shape. (Source: Elena Chiridnik)

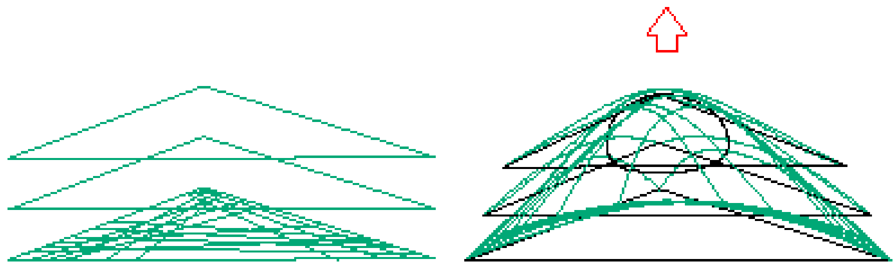
FIBRE-FIBRE INTERACTION

On early stages of web construction fibre-fibre interaction in sheet web is set up. Later the shape of the bubble is influenced by this interactions and suface they create. When the spider puts sheet web threads, it wraps them around anchor threads - it is one of the connection types of the web (as well as when it wraps anchor threads around sticks).

Two pictures show the flat and volumetric states of the net. In the biological role model bubble the sheet web is constructed prior inflation, and has and influence on the surface shape.

This model explores the influence of the connections between the threads on the direction of fibres in the process of change from one state to another: from flat to volumetric.

If there were no fibred wraped around straight ones, the straight would aggregate in one line in the middle of the bubble and create the crease on it. In this case straight lines change to zig-zag, but they still create the surface holding the bubble.



Process of construction- initial sheet. Dependance of fibre position.on the opsition of sticks.

Plain web of anchor threads

Inflated membrane is shaped by anchor threads

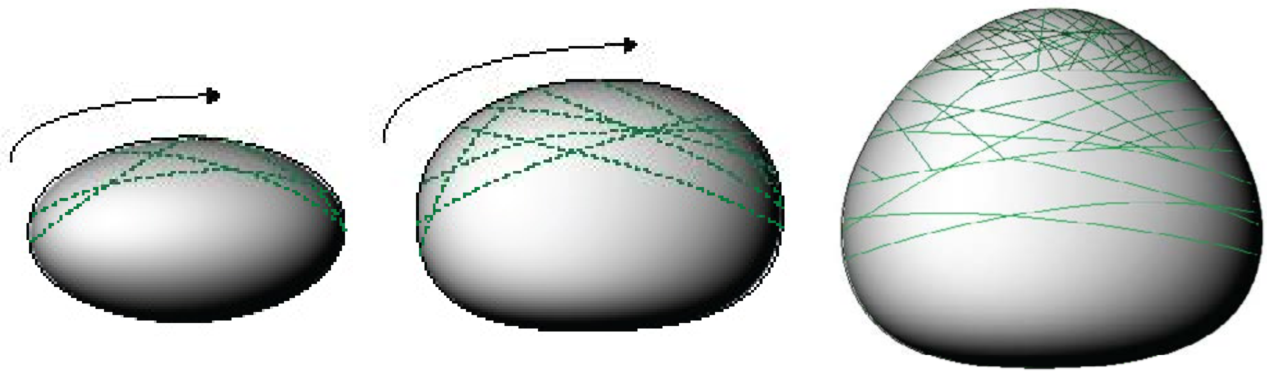
FIGURE 83: Models based on spider web fibre-fibre joints and how it influences the shape (Source: Elena Chiridnik)

Anchor points

In the current model the position of anchor threads and its influence on the form is explored.

It was noticed, that in the waterspider bubble There are upper and lower threads connected to the vertical sticks, except the main and the most visible sheet web.
The model explores what kind of shape we would get if we had anchor threads fixed in horizontal and vertical position.
Position of sticks defines the position of fibres,and transition from vertical to horizontal surface of the bubble.

Chapter 12
Density



Interior reinforcement of bubble creates variable densities on surface.
The proportion of threads and hydrogel in determined area is not equal

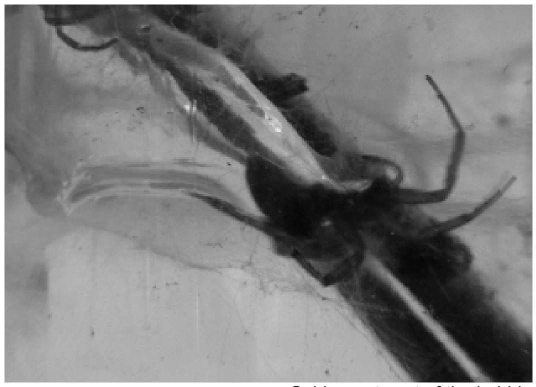
Bubble without interior reinforcement

Spider reinforcing the bell-shaped bubble from the inside

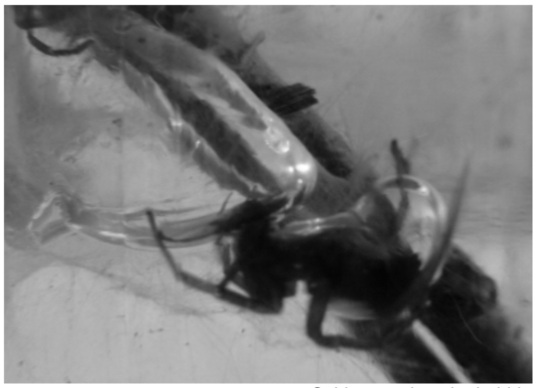
FIGURE 84: Density of threads. (*Source:* Elena Chiridnik)

DENSITY

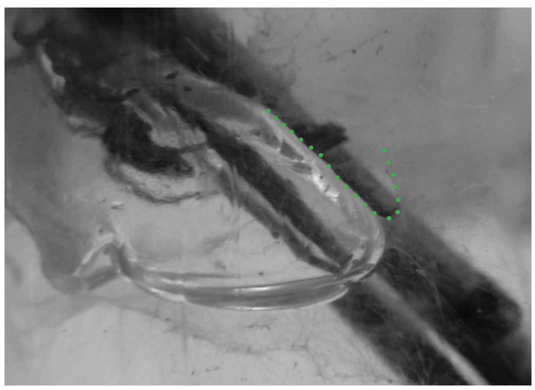
It was noticed, that spider creates more density on the top of the bubble.
Later careful observations showed that it occurs due to the process of bubble construction: as the bubble gets bigger, at every stage spider reinforces perimeter and top center of the bubble.
When bubble grows, we see repeatedly new iterations of the behaviours that lead to even distribution of reinforcement.
In the process of research two states of density on the surface of the bubble were noticed. Certainly when the bubble is small, only its area is reinforced. In the process it gets bigger. There is a time when new areas of bigger bubble are not that much reinforced as initial bubble (its top and sides). From this at some point we concluded, that there is differentiation in reinforcement of the bubble according to te distribution of forces- from top to bottom.
Later we realized this is just a stage of the process, not the final “goal”. We have tracked the spider and concluded, that the spider reinforces the new area more then the old one, going through existing one, though. We did not have appropriate equipment to measure the final thicknesses of the bubble wall in different areas, but it would be interesting to find out. From our observation and microscopic pictures we conclude in result the reinforcement density is equal on the surface of the bubble.
What we transfer from this part of the research is that the task is to create certain density going through the whole surface gradually, not doing if in pieces, part by part. Then if there is necessity to reinforce some particular zone it is done with bending with other zones to preserve the continuity and integrity of fibre layout.



Spider gets out of the bubble



Spider gets into the bubble



Formation of entrance

FIGURE 85: *Spider creates local reinforsement and change of surface curvature in the areas of higher stresses.* (*Source:* Elena Chiridnik)

Local density was noticed in one of the earliest set-ups in the area of the entrance to the bubble.

3.2. Behavior (of the spider and the system)

Chapter 13
Spider Movement
During Reinforcement

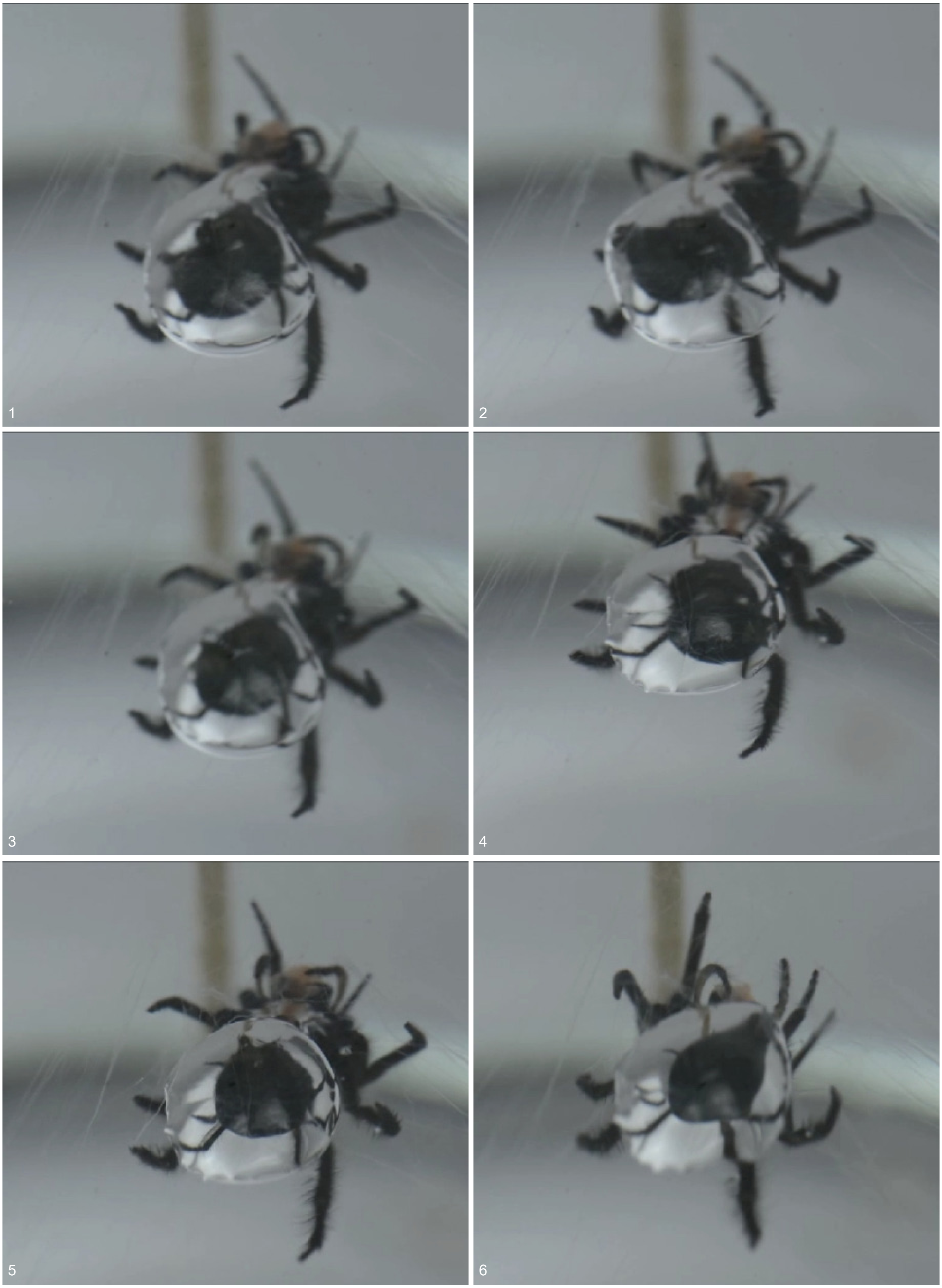


FIGURE 86: Spider movements during internal reinforcement of the bubble (*Source:* Elena Chiridnik)

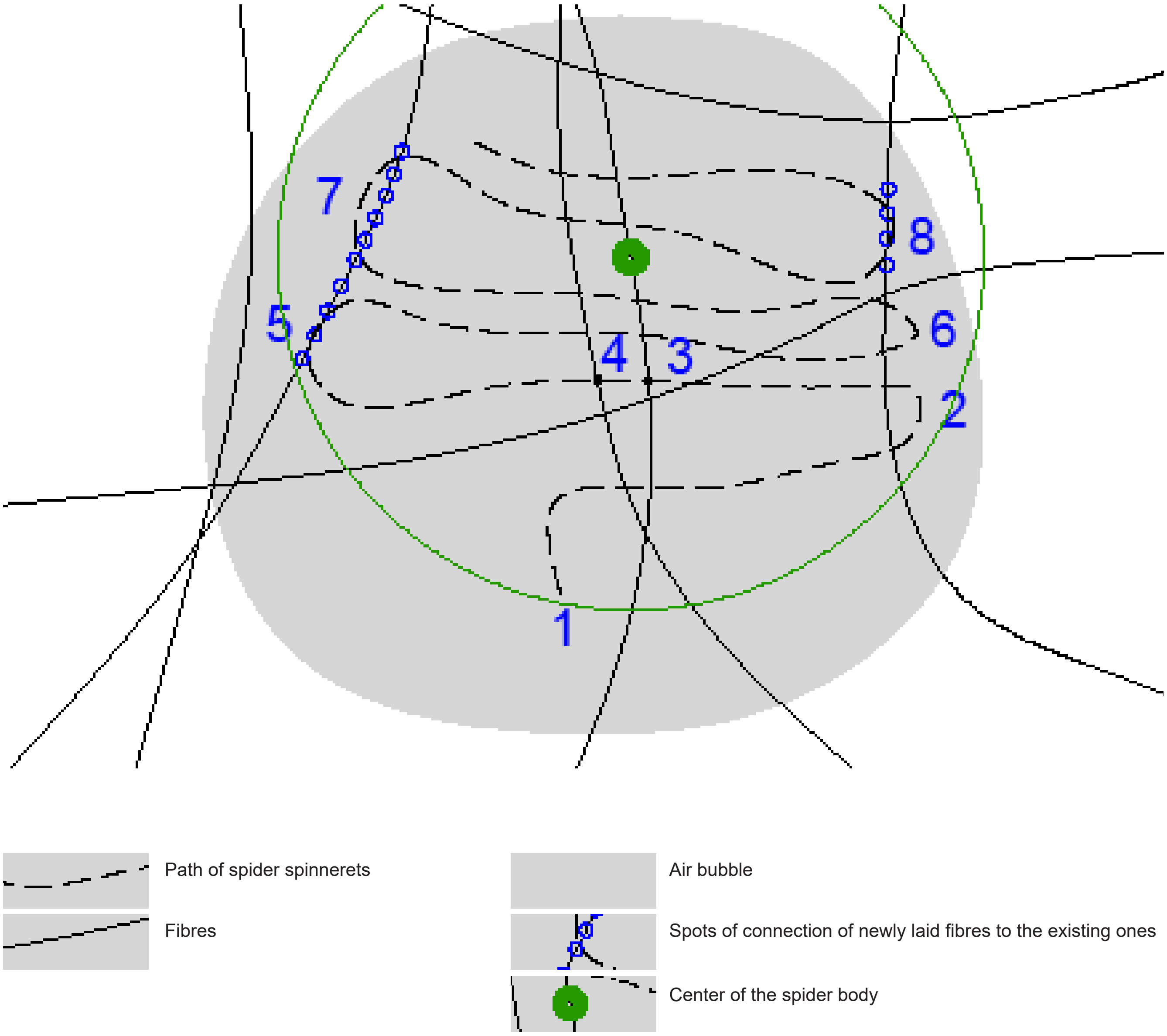


FIGURE 87: Spider movements during internal reinforcement of the bubble. Diagram. (*Source:* Elena Chiridnik)

SPIDER MOVEMENT DURING REINFORCEMENT

Spider movement depends on the size- the reach of the spider.

In case of bubble, there is minimal movement, maximum reinforcement with spider reach. Spider stays in the same position and reinforces to the left and to the right from its center, and then moves forward to the othe side of the bubble.

In case of the design proposal, all the pavilion is in robot reach, so the spider movement is not fully applicable. The principle which should be transferred is reinforcement should be created through the bubble from one side to the other, so the integrity of the fibre layout is guaranteed.

Chapter 14
System Manipulation

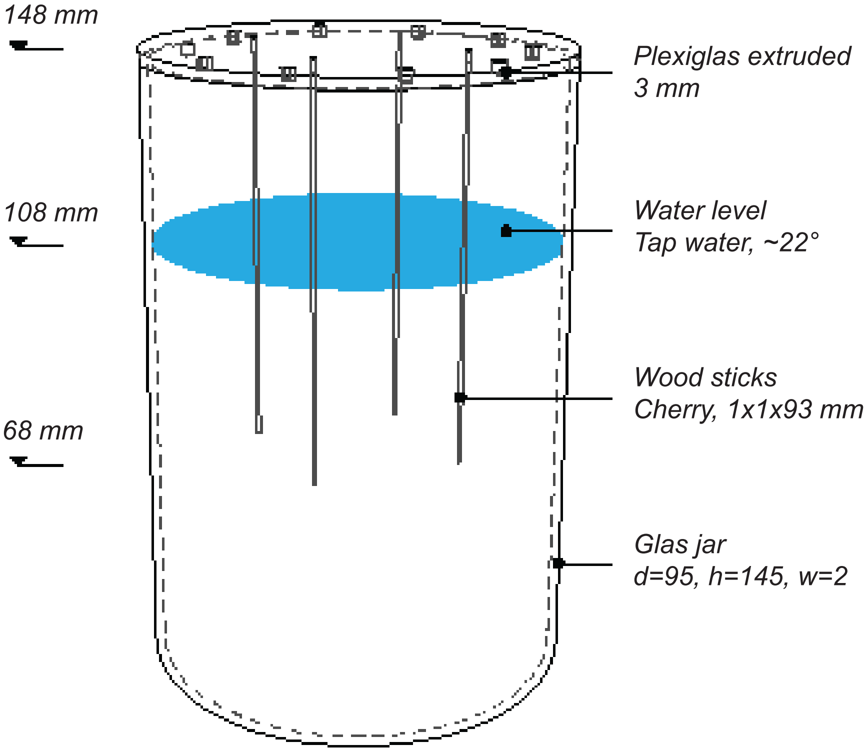
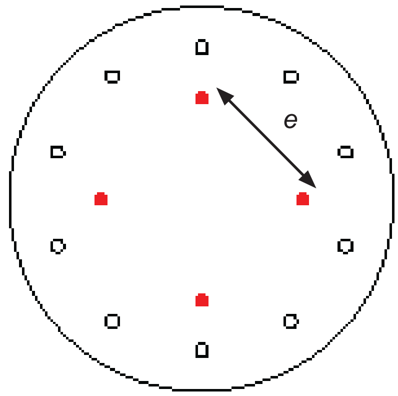


FIGURE 88: Perspective diagram of Set-up A009 (Source: Matthias Helmreich)



Top view of Set-up A009,
e = 35.4 mm

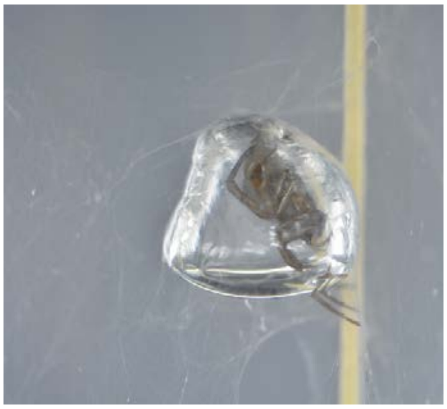


FIGURE 89: Elevation of bubble in its original shape within set-up A010 (Source: Matthias Helmreich)

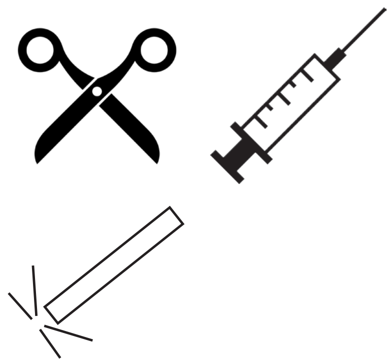


FIGURE 90: Tools for surface manipulation, Scissor, syringe, tube (Source: Matthias Helmreich)

Surface manipulation

Interactive behaviour

We have expected the interactive behavior of the spider and conducted few experiments: with needle, inflation, cutting the fibres, waterflow. The spider reacted in one case of four, when the anchor thread wsas damaged. It started repairing the wweb from outside and continued inside. In most of other cases spider left the bubble and waited outside until the disturbance was over.

Method

Set-up A009 and set-up A010 each with a four day old bubble and the same female water spider were used to test the surface properties of the reinforced bubble. Set-up A009 consited of four cherry wood sticks, A010 of three spruce wood sticks. The water spider had completed its reinforcement process at the time the experiments took place. Figure shows the original bubble in the set-up A010. Videos were take with a NIKON D7100, lense NIKON AF-S Micro Nikkor DX 85mm 1:3.5G ED VR.

The bubble surface was manipulated with several tools. A standard plastic tube was used to observe the surface attributes of the bubble when a hard object impacts into it. A laboratory scissor was used to chop specific fibres of the bubble and see whether the system collapses. With the syringe we blow air into the bubble to observe the flexibility of the composite surface.

Purpose

Applying outer forces allow to test the efficiency and characteristic of the system and cause the water spider to take immediate action.

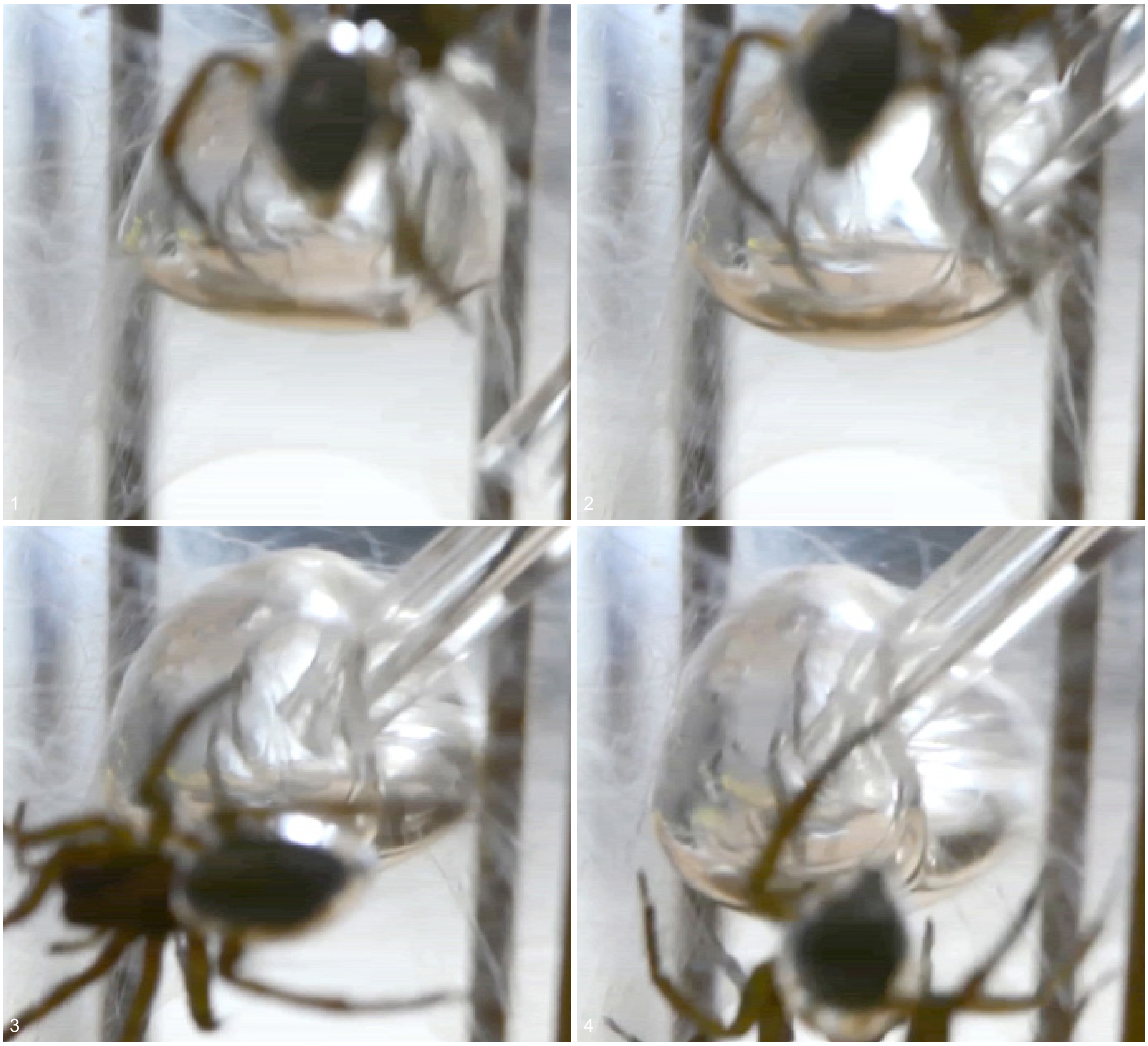


FIGURE 91: Disturbing the bubble. (Source: Matthias Helmreich)

Surface manipulation, object impact

Method

Experiment were done within set-up A009. A plastic tube was taken by hand and fair pressure was applied to the surface of the bubble. To reach the surface several fibres of the horizontal sheet web that were holding the bubble in place were damaged and ripped of. The tube was than pressed on the bubble surface until roughly 1cm to the inside.

Observation

The surface was elasticly deformed to the inside and showed a certain flexibilty comparable to a standard PE-foil membrane that is pushed inside. Foldings accured around the impact but the surface could not be sticked through. The main fibres that were placed on the surface were pulled inside and caused sharp edges on the surface. Figure xx. The volume of the bubble changed when pushing the surface to the inside. The changed volume was counterbalanced on the bottom part of the bubble. It did not extend towards the sides. This leads to the assumption that the composite surface is tenshioned through the fibres and the system can only extend towards the bottom. After removing the stick the bubble snapped back its original shape. The shape of the bubble changed at the point of impact. Realizing the bubble was being damaged the water spider immediately went out of the bubble and attacked the plastic tube. After the experiment it began to place new fibres at the damaged area. She especially repaired the anchor threads that had been ripped of.

Conclusion

The surface tension of the bubble, laid fibres and the hydrogel create a composite that during impact remain flexible but have a PE foil like wrinkling effect.

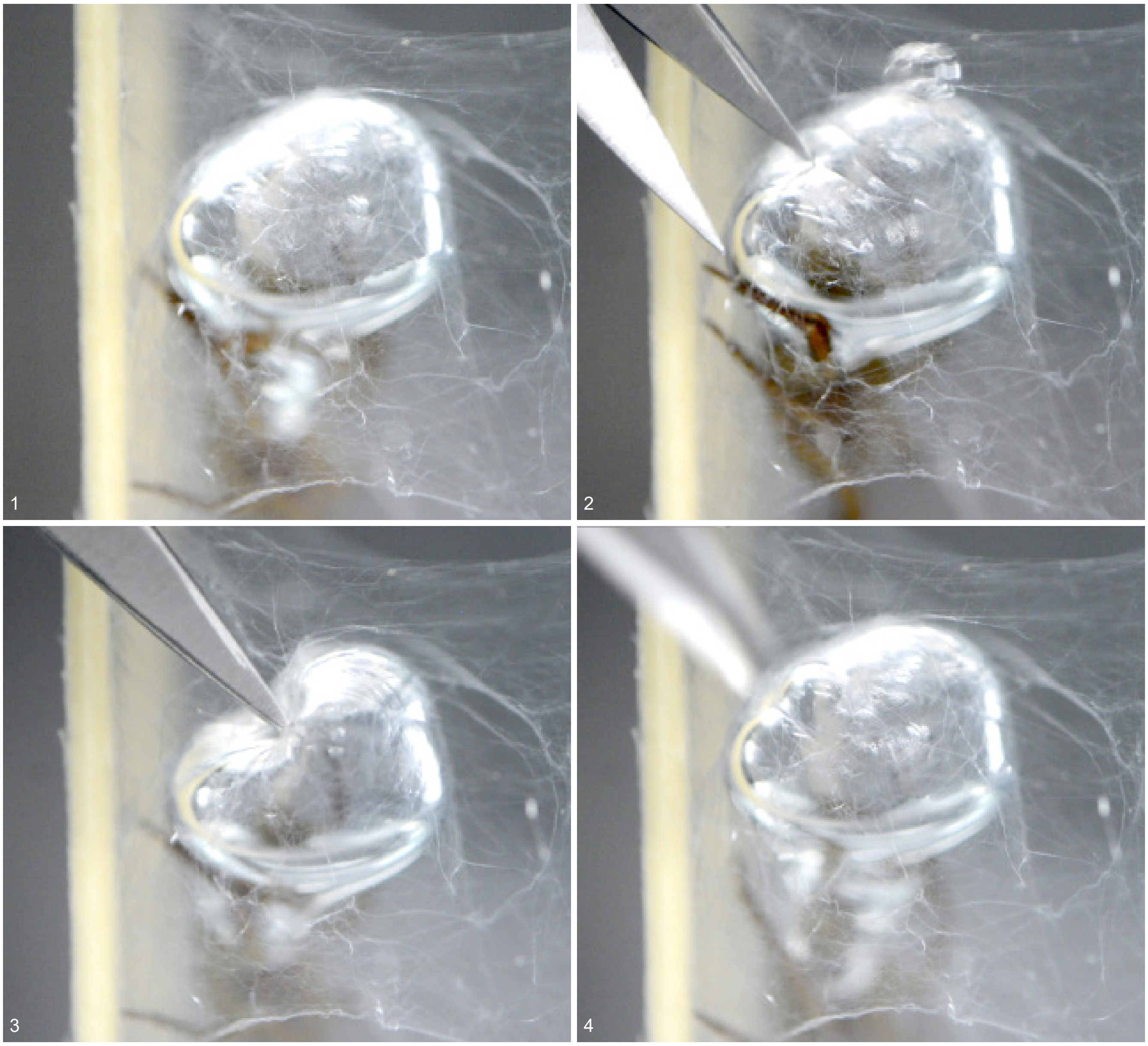


FIGURE 92: Disturbing the bubble with scissors. (Source: Matthias Helmreich)

Surface manipulation, Snipping fibres

Method

Experiments took place within set-up A010. A preparation scissor was used to chop a structural fibre on the surface and see how the system will behave. Observatoin was taken after the cut to see whether the water spider will take action on repairing it. Video was taken with the NIKON D7100 (Macrolense) during the experiment itself and a image time-laps for 12 hours to document whether the spider will repair the destroyed parts. Approaching the bubble surface with the instrument it was not possible to chop a single fibre but scissor an about 5mm wide area. After the cut the scissor was removed and some parts of the surface were stuck to the scissor but ripped at about a distance of about 10mm.
Images have been taken from the video at a consistent angle, overlaid and compared to each other.

Observation

Image 1 shows the bubble after the first approach with the scissor. The surface has already been slightly damaged. The bubble surface tension itself is less stiff than the fibre-composite, therefore it bulbs out. This leads to the assumption that the fibre-hydrogel composite is tensioning the bubble surface together. The characteristic of the bubble surface is much different in terms of flexibility than the composite surface.
A second cut was placed above the first one to observe the occurrence at another spot. About two visible main fibres have been chopped within the cut area. As the surface is very slippery a fair pressure was applied while cutting.
Chopping the second area created the same affect bumping out effect than below.
The water spider remained calm first than went out-

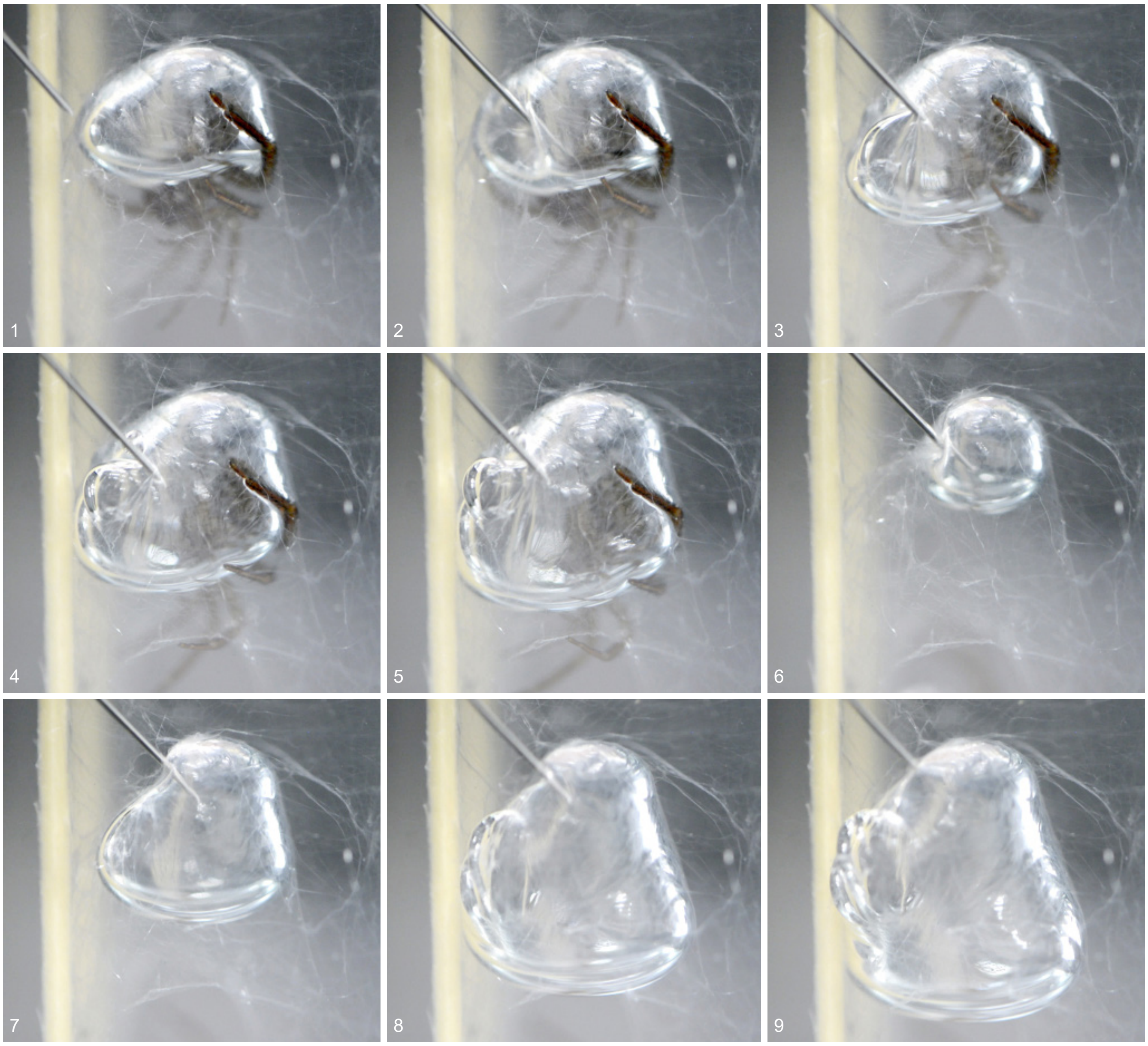


FIGURE 93: Disturbing the bubble with a needle. (Source: Matthias Helmreich)

side of the bubble but did not make any attempts to attack the scissor unlike we observed in the first experiment with the tube. Within the 12 hours of observation after scissoring the bubble the spider did not make any attempts to repair the area.

Conclusion

Cutting the composite surface did not cause the system to collapse. Also the fact that the water spider did not repair the damage showed that the system could not have been heavily in danger. In a later stage we added air to the inside of the bubble to observe the characteristic of the bubble under tension.

Surface manipulation, In-/ Deflation

Method

Same set-up, water spider and bubble was used in this experiment than in the experiment with the scissor. To blow air inside the bubble we used a standard injection with 5 ml volume.

Observation

The bubble was stitched through the area that has been damaged by the scissor. To get through the composite surface a fair pressure had to be applied and the bubble deformed. It was not possible to get through the composite surface so we had to stitch at the area where the fibres already had been removed. Adding air to the bubble extended the volume towards the bottom. The original shape of the bubble was remaining the same with slight extension to the

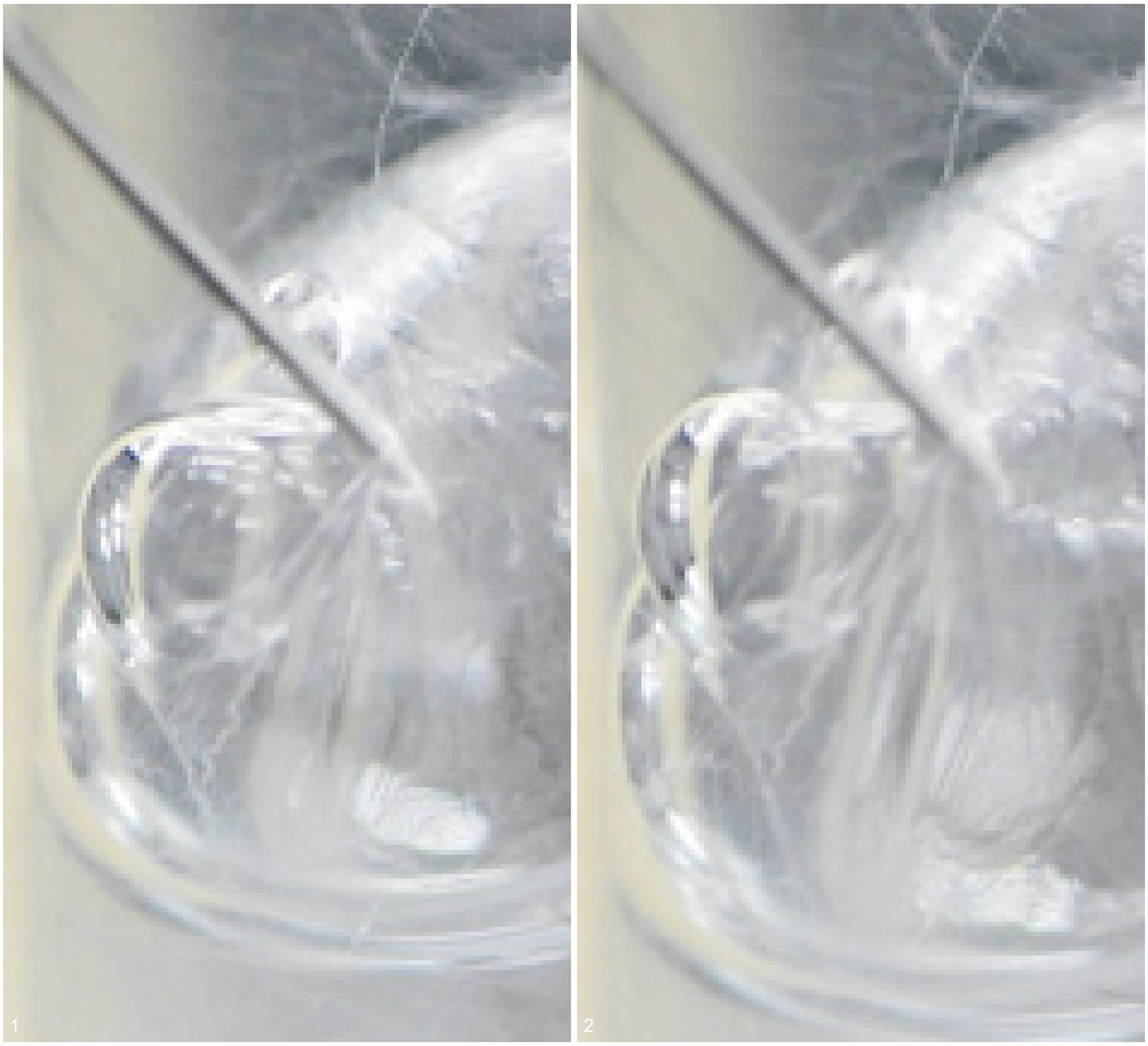


FIGURE 94: Disturbing the bubble with scissors. (Source: Matthias Helmreich)

sides. Putting the full amount of air of 5ml caused the bubble to extend through the bottom and escape the construction from there, Figure XX (image 5). The fibre composite stayed fairly in its original shape and position. Fibres slightly moved to the inside. Air was added into the left bubble to see whether the volume and shape of the bubble can be reproduced by adding the lost air. Overlaying the images showed that bubble went back into its original shape. The fibre composite didn't extend while adding more air into it than the water spider originally did. At the area where the surface was damaged the bubble surface was bumping out.

Comparing the images of figure 1 and 2 shows that the composite surface has a very low elasticity value.

Conclusion

The water spider creates a fibre-hydrogel composite on the surface of the bubble. It uses the bubble as mold. Removing or adding air to the bubble doesnt affect its shape. The composite surface has a very low elasticity value in comparison to the pressure that is applied upon it.

Air will bump out of the are where the composite has been damaged. There is a clear border visible.

3.4. Hierarchy of fibres

Chapter 15
Functional, geometrical, sequential hierarchy

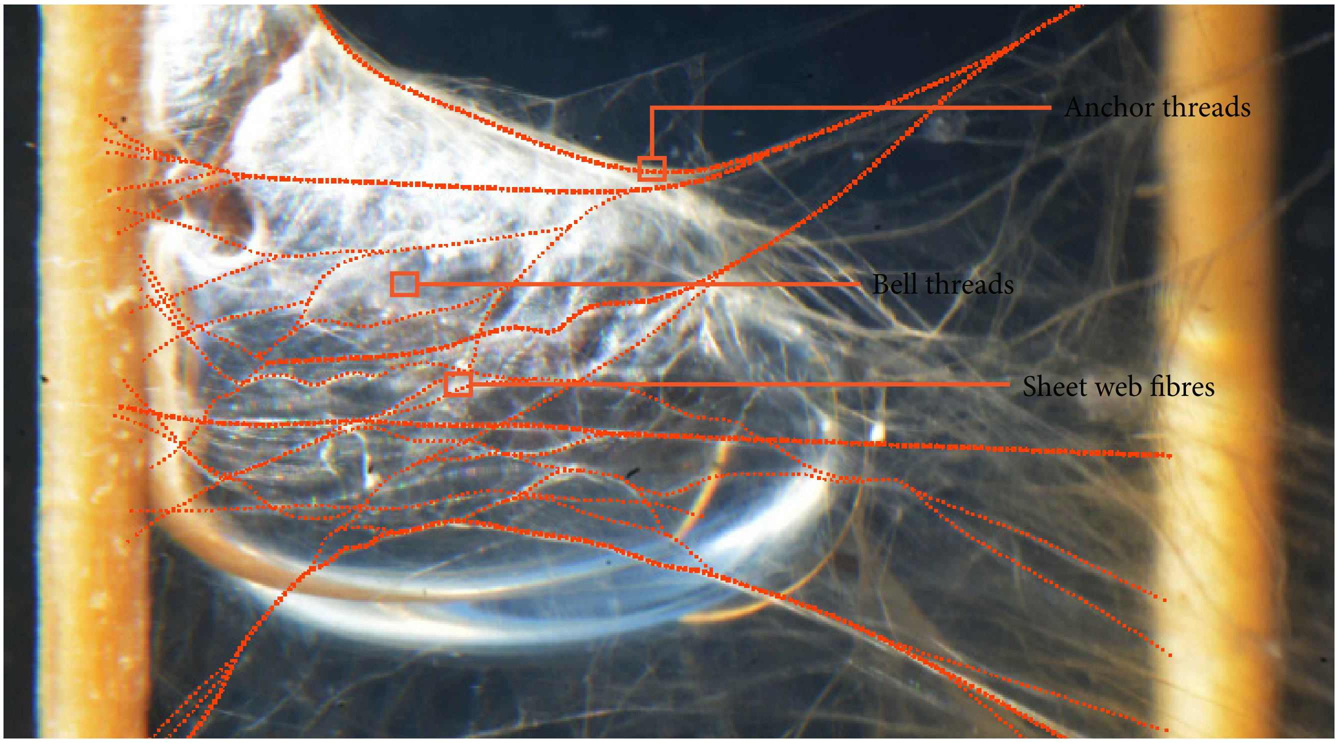


FIGURE 95: Parameters of different types of threads (Source: Elena Chiridnik)

PROCESS WHICH CREATES HIERARCHY OF FIBRES

On the surface of the bubble there are three types of threads. We do not consider walking threads as they are outside the bubble.
The bubble fibres are laid in three main stages, which creates geometrical (thickness of fibres), functional (fibres working against different loads) and sequential (fibres are laid in different matter with different connection in different stages of construction) hierarchy.
The interconnection details are significant for different stages of construction as well.
In three stages also the differentiation of quantity of fibres is identified. Anchor threads are only few elements, sheet threads are more but still can be distinguished as elements, bell threads are more like a layer or shell of fibres.

TYPES OF FIBRES.

Anchor threads fix the sheet web to the anchor points, they create the perimeter and few crossing lines inside perimeter to be connected by sheet web.
Sheet web threads are fixed to anchor threads and create a surface which is later covered with hydrogel and hosts the bubble.
Bell threads are surface-filling threads inside the bubble which are connected in few points to anchor threads and glued through hydrogel to outer sheet web threads.
To research the topic we summarized tree main questions: 1. Why do spiders do what they do; 2. How they do this ; And 3.In which order they do this. Answering these questions, we were surprised to discover , that the answers for these questions are different on different stages of web construction. Thus, purpose, method and microplan of spider would be

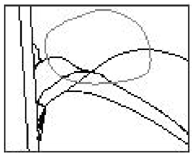
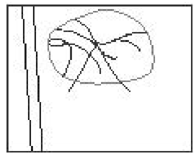
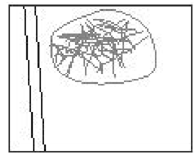
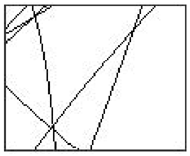
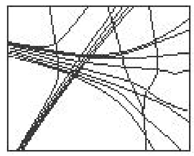
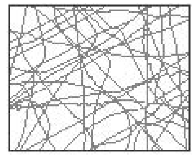
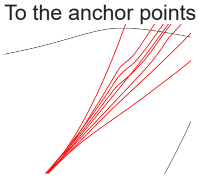
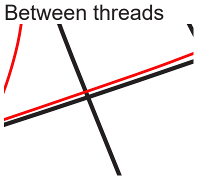
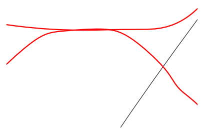
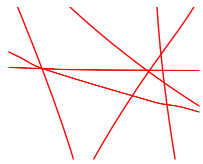
Hierarchy	Anchor threads	Sheet web threads	Bell threads
General description	Perimeter to hold the sheet web	Surface to host the bubble	Shell inside the bubble
Order of construction	1	2	3
Functional	Main structure stabilization	Main structure stabilization+connection	Connection+surface filling
Thickness	1,8 μm	1 μm	0,34 μm
Position in a bubble system			
Typical layout			
The most frequently occurring connection	To the anchor points  Between threads 		
Application	Outer cables	Structural layout	Surface filling against sagging layout

FIGURE 96: Parameters of different types of threads (Source: Elena Chiridnik, Jessica Jorge)

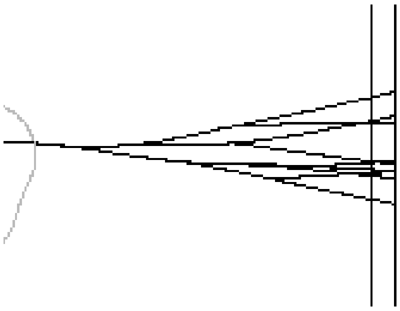
different for construction stages.
Even if, for example, during construction of sheet web (second behavior) spider returns to reinforcing anchor threads (first behavior), the percentage of dominant behavior is so high, that we can identify it a a long stage.
In the process of our investigation it was noticed that in the web there are various connections. It was noticed both in photos and microscopic pictures.
In the beginning we have been mostly focusing on the last behaviour- internal reinforcement, but we could not find the process of “winding” connections creation. That meant they are created on the other stage. Later we noticed they are created on the sheet web construction stage, and it is very important in the overall process. We understood that we can not analyze only one winding stage, that different winding stages create hierarchy of fibres which serve different functions.
Static pictures gave us questions and observations and videos gave us answers. That is how we found out how patterns and connections are produced.
After observing a number of construction cases, we could clearly identify stages of construction.

1. Anchor threads. Connections: binding-branching near anchor points and crossing on the top.
2. Sheet web. Connections: binding(weaving) and crossing.
3. Internal reinforcement. Connections: Cross-ing , weaving only to anchor threads.overlapping glued connections are typical.

Sometimes these stages could take more or less time, but this certain order of behaviors took place in every construction case.
Every behavior will be explained in-depth , including duration+thickness, purpose, method and microplan, duration.typical fibre layout.transfer
Later tere is an overview of the spider behaviours in parallel to fibre layout on the pavilion and agent behaviours producing this layout.

Chapter 16
Anchor threads. Branching.

Anchoring of water bubble to stick set-up (Photo: Jorge, Al-Khasawneh)



Branching of anchor threads. (Chiridnik)

Branching of anchor threads. Model. (Chiridnik)

FIGURE 97, 98, 99: Branching

ANCHOR THREADS. BRANCHING

1. Construction of anchor threads takes few hours (from one to six). Thickness- 1,7 μm. Hold sheet web threads which are fixed between anchor threads. Method- going around the sticks winding around them. Creating bunches of threads near anchor points by adding fibres and separating existing ones into several threads.
In the pavilion it is a controlled pre-defined layout of outer cables.

Anchor threads are wound as a bundle of multiple fibres. It was noticed, that spider literally separates the anchor thread near the anchor point with its leg. “Branching” near anchor thread is a typical detail of anchor thread.

Deformation of construction near the base is smaller with branching anchor points.

Dispatching of fibres near the edge

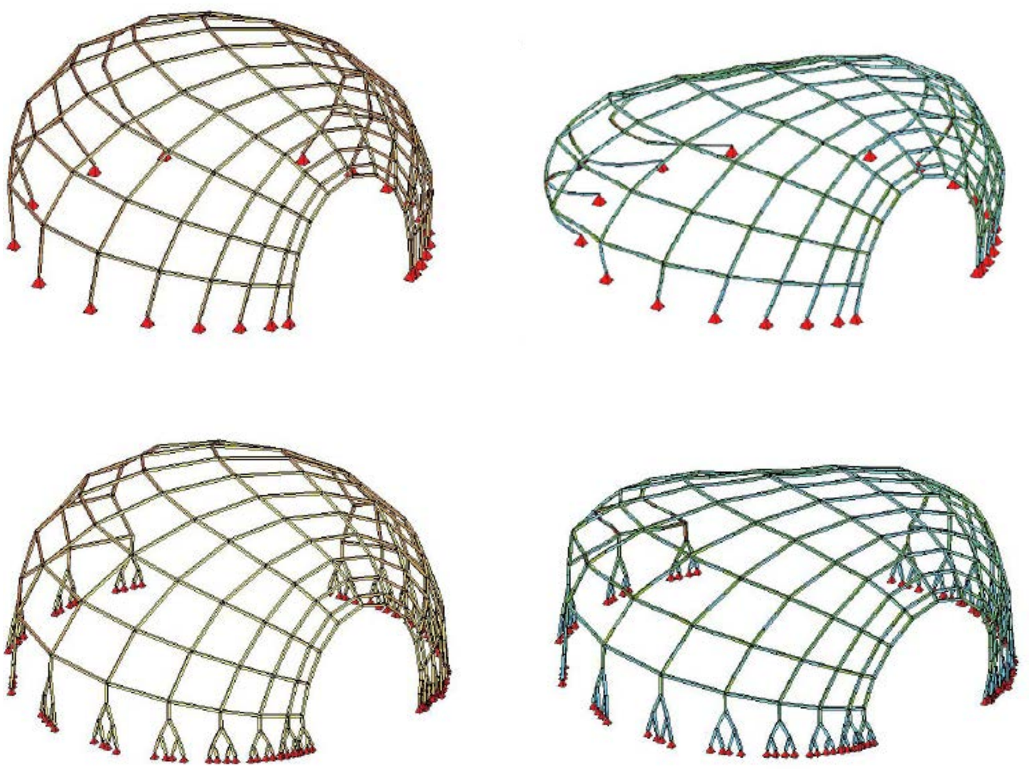
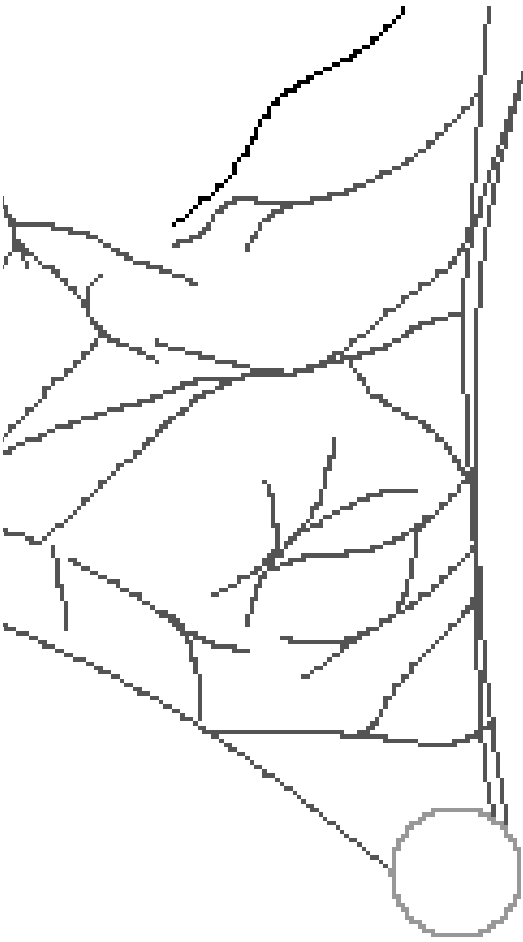


FIGURE 100: Evaluation of branching on anchor points principle. Structural analysis of point anchoring connection in comparison with branching anchoring connection. (*Source:* Emily Scoones, Elena Chiridnik)

Chapter 17

Sheet web threads. Connections and layout. Proposal for agent behaviour based on spider logic

FIGURE 101: Construction of sheet web and placement of the bubble (Source: Elena Chiridnik)



Sheet-web construction at early stage

Sheet-web construction at later stage

FIGURE 102: Density and position of threads on different stages (Source: Elena Chiridnik)

SHEET WEB THREADS. CONNECTIONS AND LAYOUT

2. Construction of the sheet web can be very fast – few minutes if the spider has the food, and few hours if there is no food. General remark is that if spider catches food, it constructs the web very fast – in several minutes. So there are only few threads holding the bubble. If there is no food at the moment the sheet web can be sophisticated and its construction can take few hours.
Thickness -1 μm. Purpose- to hold the bubble from floating up. Method is to fix the new thread to the existing one , the length of connection is few diameters of fibre, several μm. The typical layout is a net with y-connections.

In a pavilion it will be a layout produced by agent following stress lines and producing repeated paths with fibres next to each other- beams structural calculations.

Sheet web threads are interwoven with anchor threads and between each other. Connection is a segment of interwoven fibres. Probably, this connection is used in sheet web to create stronger connection, than just overlaying or gluing. Creating a sheet web, spider identifies somehow empty (or covered with hydrogel, this we could not exactly identify) areas, and puts a fiber across it , connecting with existing fibres.
Interconnection of threads with merging detail starts on anchor threads stage, continues on sheet-web and a little –on internal reinforcement. As soon as stability and certain density is reached, spider lays the threads across, gluing to each other.
"Surface filling" behavior continues on the internal reinforcement stage. At this stage interwoven connections are noticed only to anchor threads outside the bubble. Inside the bubble the fibers are laid over each other.

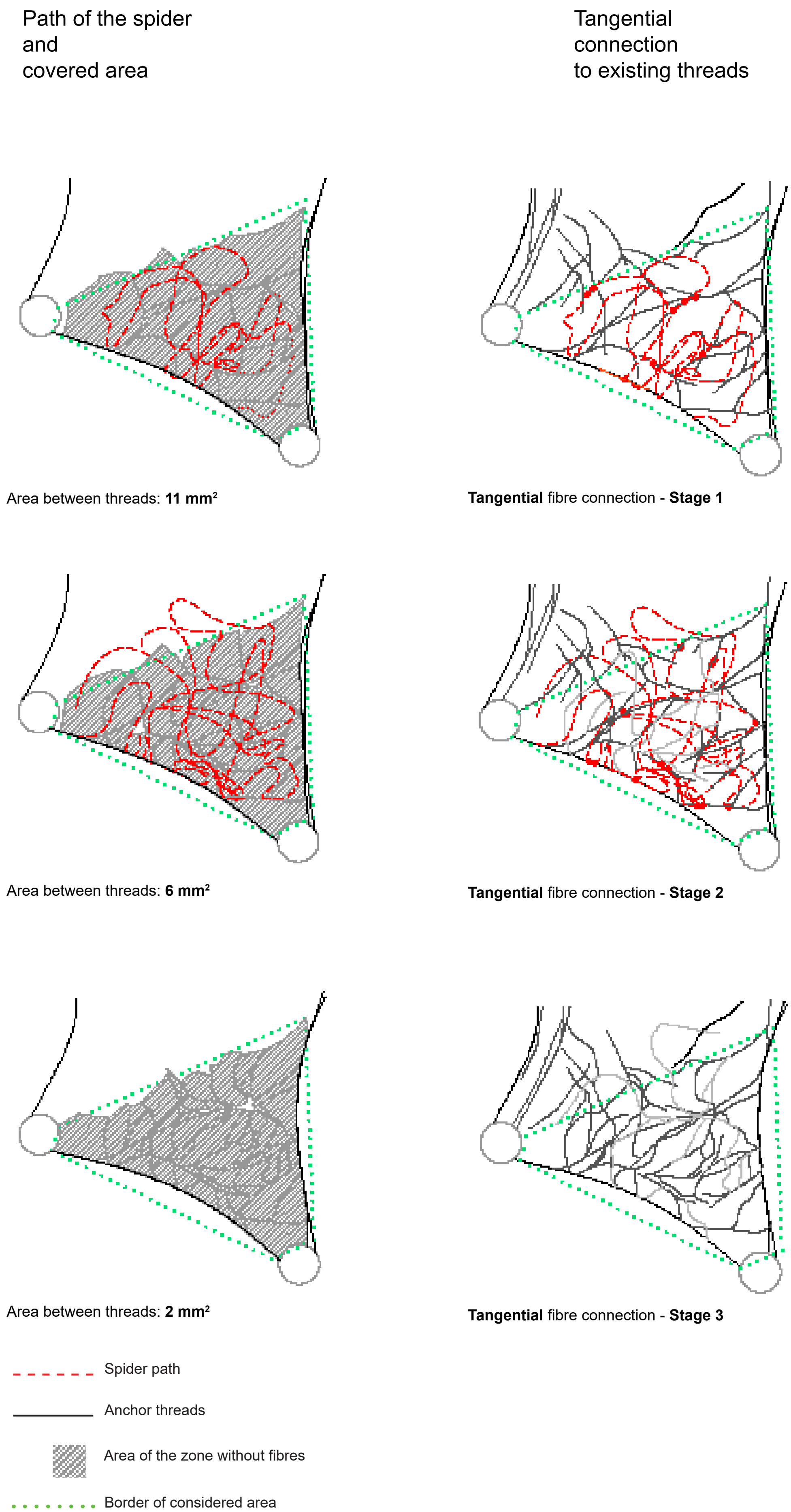


FIGURE 103: Stages of interconnection of fibres (Source: Elena Chiridnik)

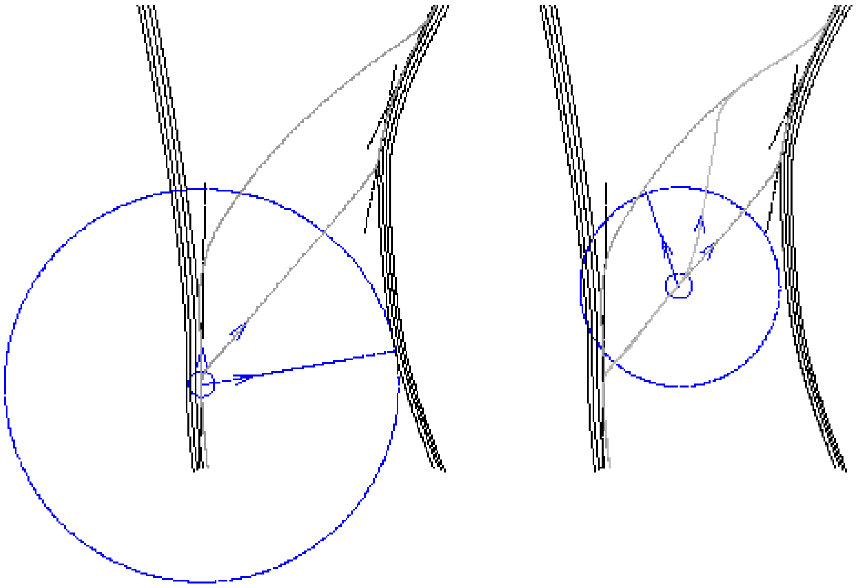


FIGURE 104: Proposal for agent behaviour (Source: Elena Chiridnik)

FIGURE 105: Proposal for agent behaviour-result (Source: Elena Chiridnik)

AGENT SURFACE FILLING BEHAVIOUR PROPOSAL FOR CONNECTING THE FIBRES

Rules for agent behavior:

1. Measure distance to neighbor bundle of structural fibres.
2. If distance is larger than x, add steering vector to current velocity.
3. Approach the fibre so that tangents of curves in fixation point are parallel

Chapter 18
Bell threads. Internal reinforcement. Functional hierarchy

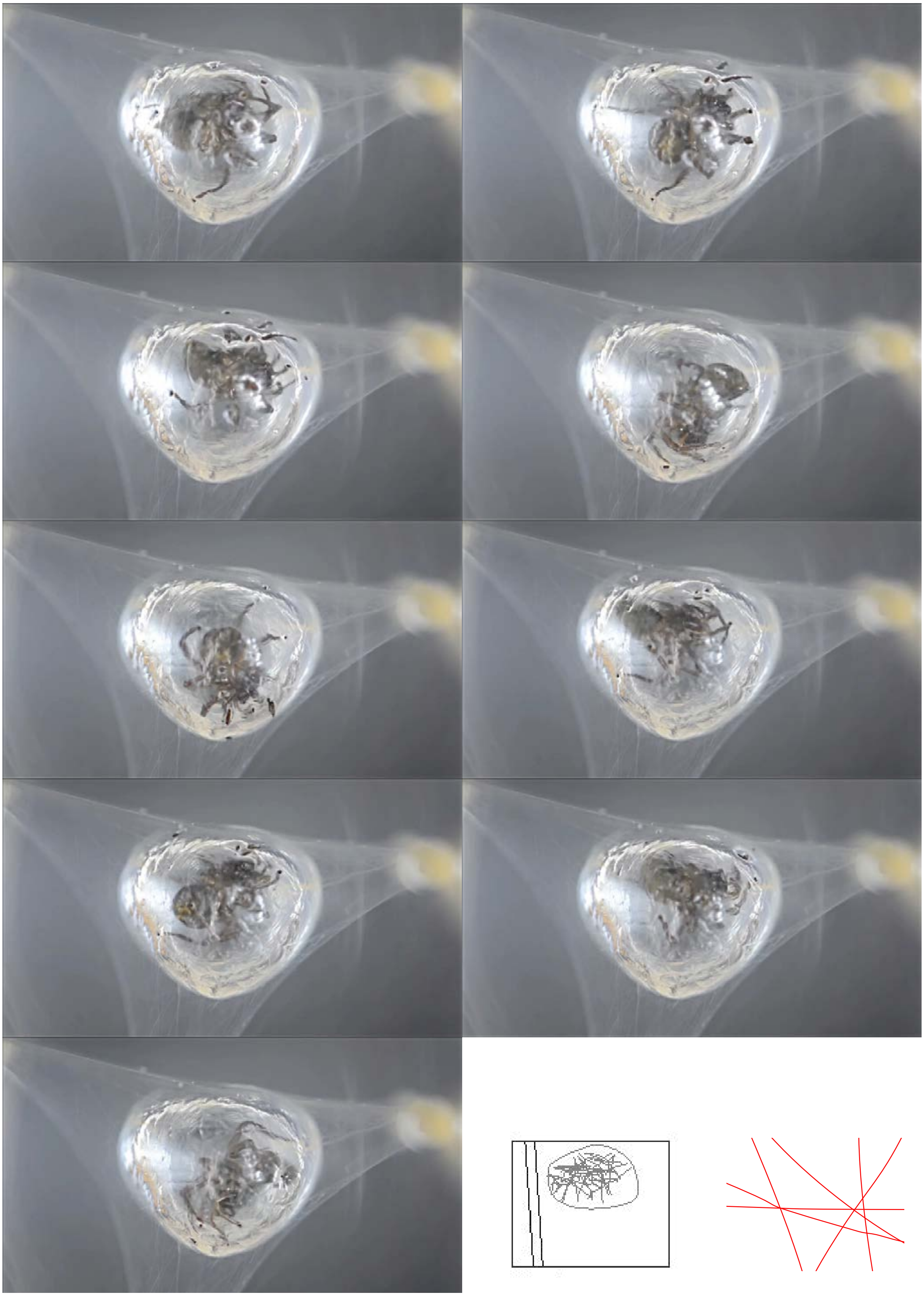
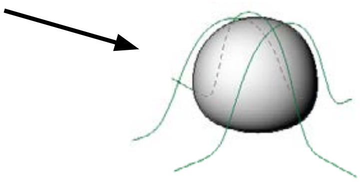


FIGURE 106: Construction of internal reinforcement (Source: Elena Chiridnik)

One-day old bubble with only anchor threads and sheet web is blown away by the stream



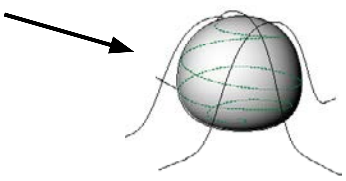
Water flow test (Image: Chiridnik)

Before

Water flow test (Image: Chiridnik)

After

Two days old bubble with internal reinforcement is more stable



Water flow test (Image: Chiridnik)

Before

Water flow test (Image: Chiridnik)

After

FIGURE 107: Comparison of bubbles with and without internal reinforcement (Source: Elena Chiridnik)

BELL THREADS. INTERNAL REINFORCEMENT. FUNCTIONAL HIERARCHY

3. Internal reinforcement. Can take place up to several days (5 as we observed) until the web is destroyed or in about 10 days gets to old and can not hold a bubble anymore. Thickness- 0,3. Purpose – to hold the bubble in place in case of disturbance from the side, possibility to enlarge the bubble by adding air. Method- to fix the thread to the anchor thread by “winding” Y-connection and then go along the surface inside the bubble with crossing X-connections.
X-connections are dominant in this type of reinforcement.

Fibre layout which sustains the shape of the bubble, creates a shell, connects previously laid “beam” fibres between each other.

Anchor threads hold sheet web from going up.
Sheet web holds the bubble from floating up.
With these two types of fibres bubble is already in place, but the system is not stable. As experiment with waterflow showed, the one day old bubble without internal reinforcement is blown away by side waterflow, while two-days old bubble with internal reinforcement remained in place. Thus, internal fibres serve as reinforcement against any other forces occurring except buoyancy forces.

Chapter 19
Types of bundling

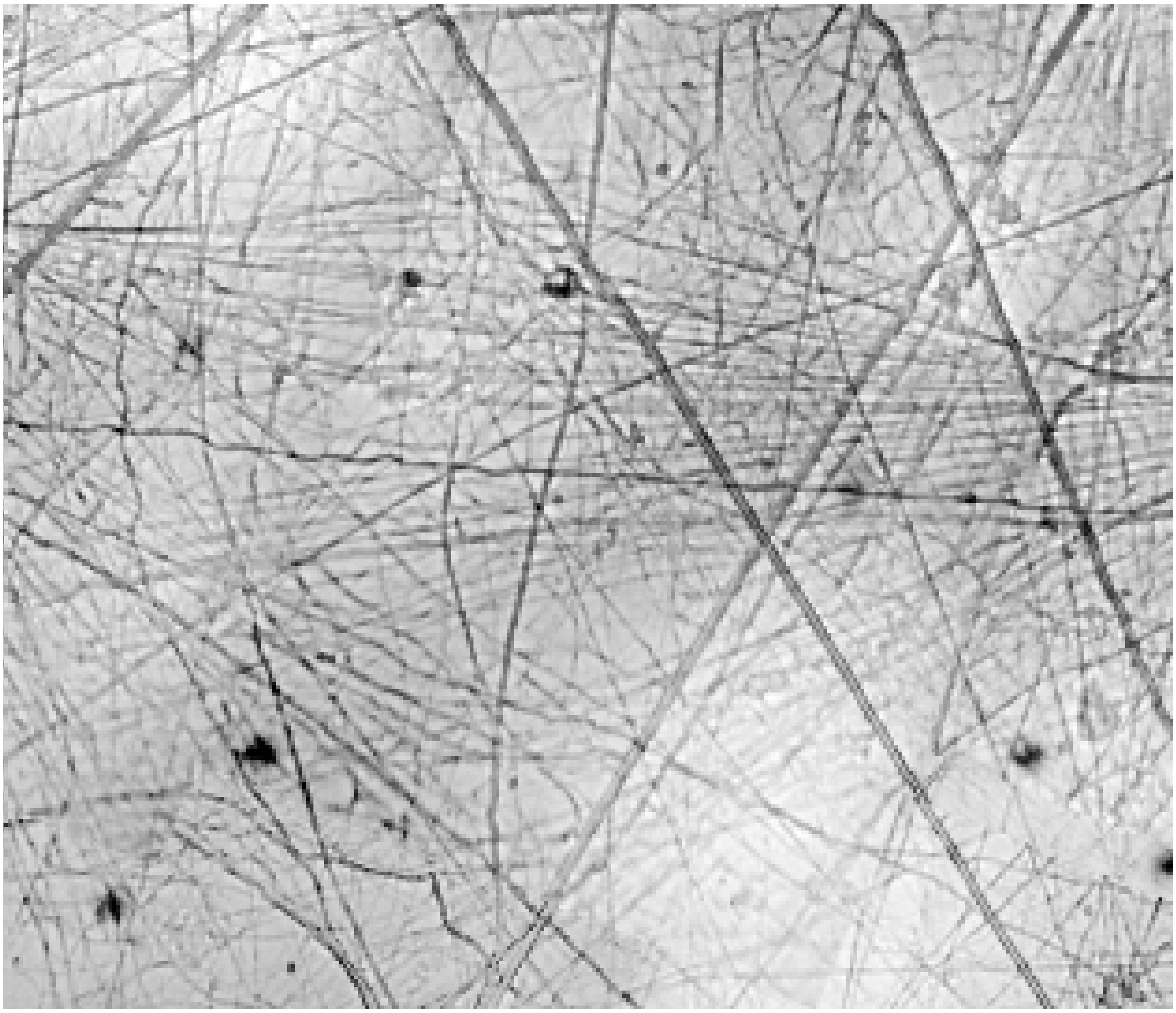
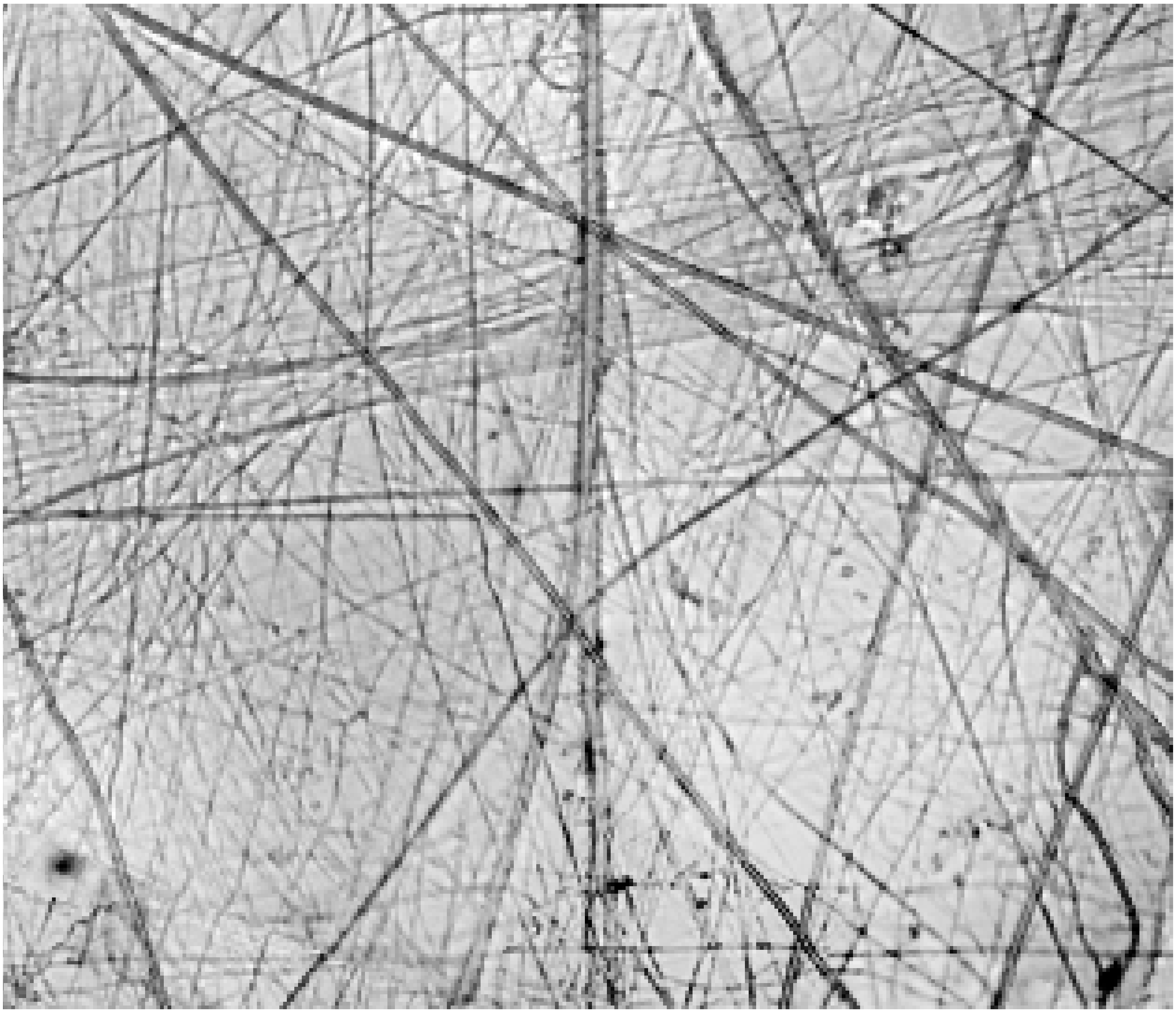


FIGURE 108: Microscopic picture. Magnification 40x (Source: Elena Chiridnik, Jessica Jorge)



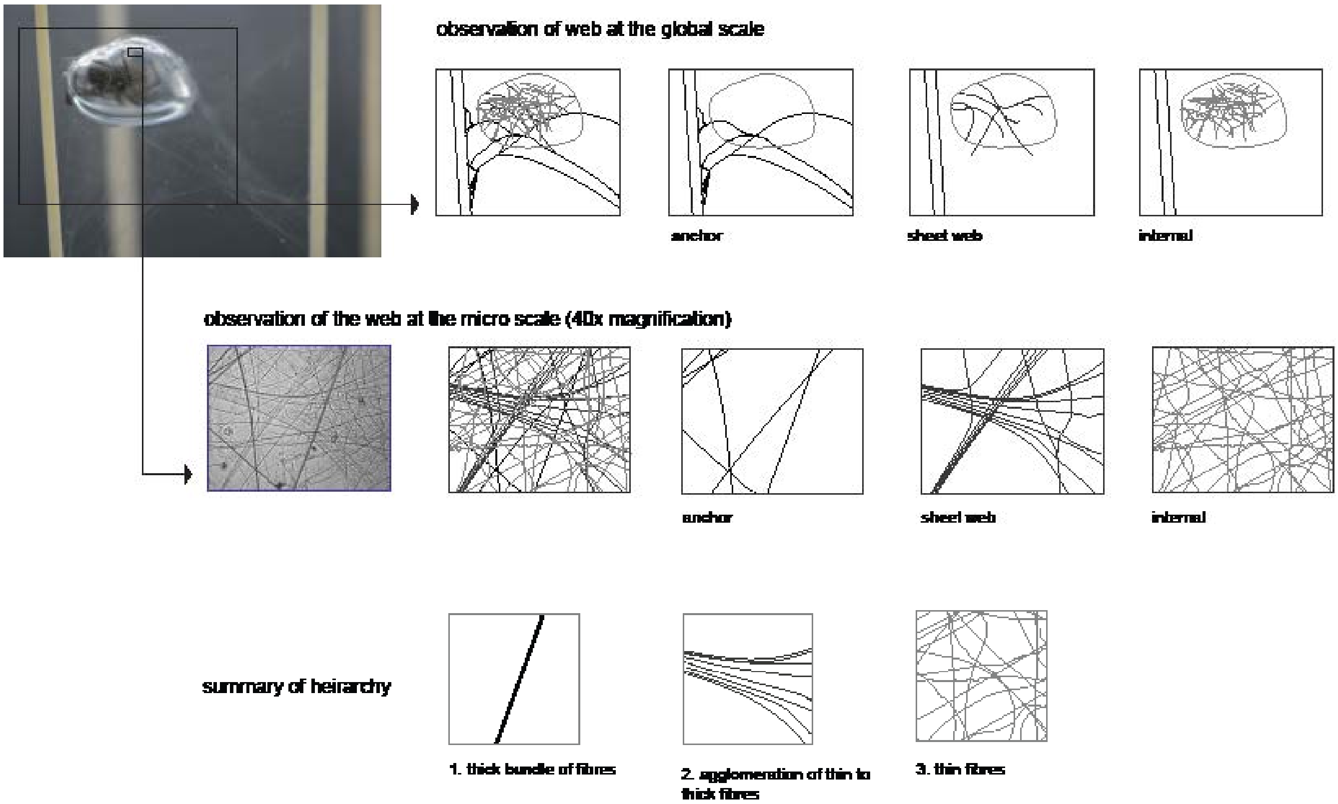


FIGURE 109: Types of threads (Source: Elena Chiridnik, Jessica Jorge)

BUNDLING

Fibres can be collected in one very thick fibre or create parallel aggregations of fibres.

From literature(///), our observations and microscopic pictures we can conclude that spider web has sevetal types of fibre placement.

Anchor threds bounding.
In the article /// it is said that anchor threads branching is either a result of adding fibres or separating fibres. We have noticed, that spider separates the thick anchor threads with its foot.

On microscopic pictures we have noticed a considerable aggredation of thin fibres.

3.5. Micro details

Chapter 20
Fibre behaviour in hydrogel on microscale

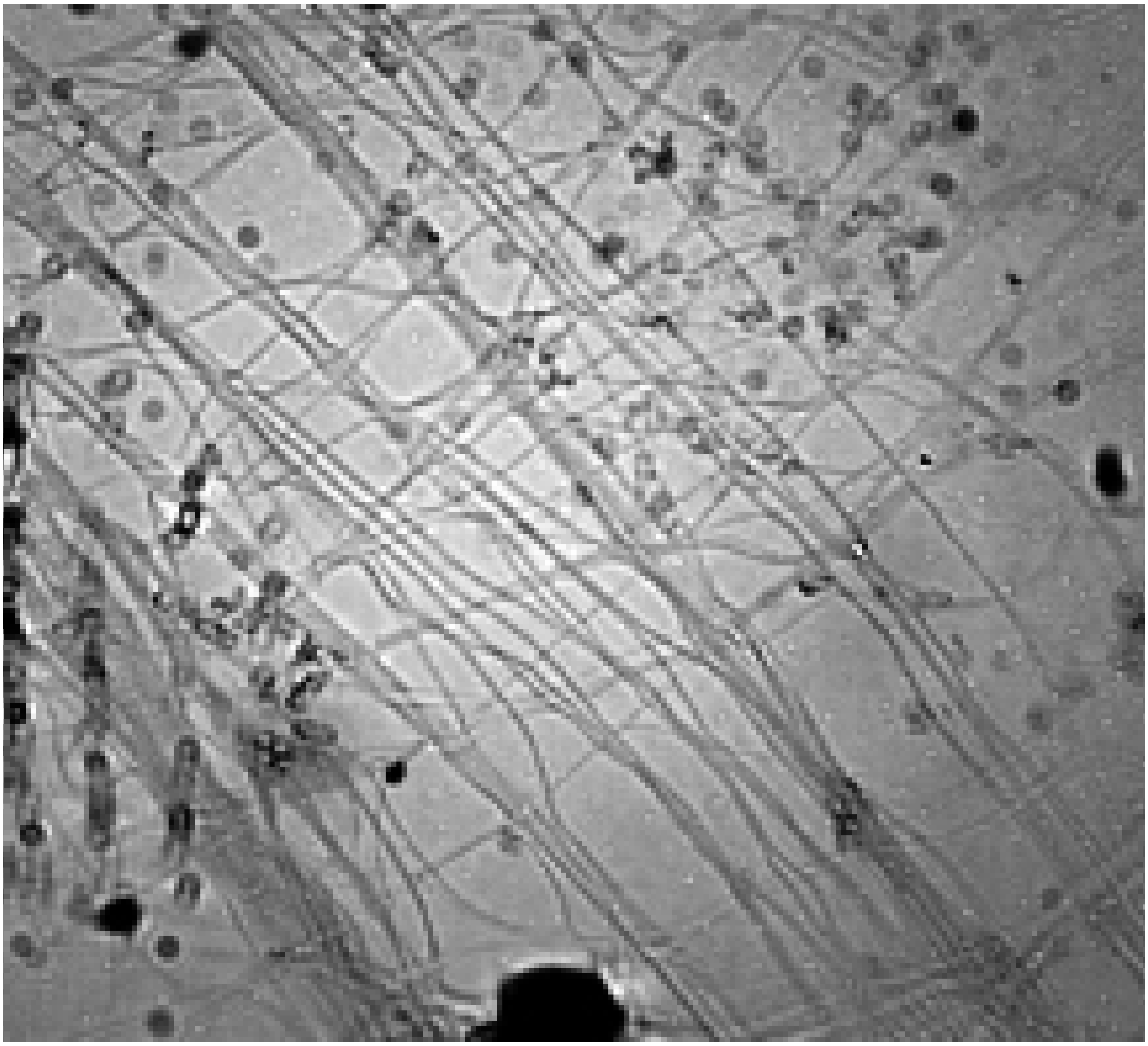


FIGURE 110: Microscopic picture of a half-dry web (*Source:* Tobias Grun)

FIBRE BEHAVIOUR

Undertitel

It was noticed that fibres create fibres of checkmate bounding. There are two reasons for it: spider behaviour and fibre behaviour.

By first we state that spider moves in a zigzag motion and sequentially fixes threads on different sides from himself.

By second we state that fibres in the hydrogel got deformed when the piece is cut out to be placed under microscope, and then ,when drying, the tension of water and hydrogel creates a pattern similar to wool experiments patterns by Frei Otto.

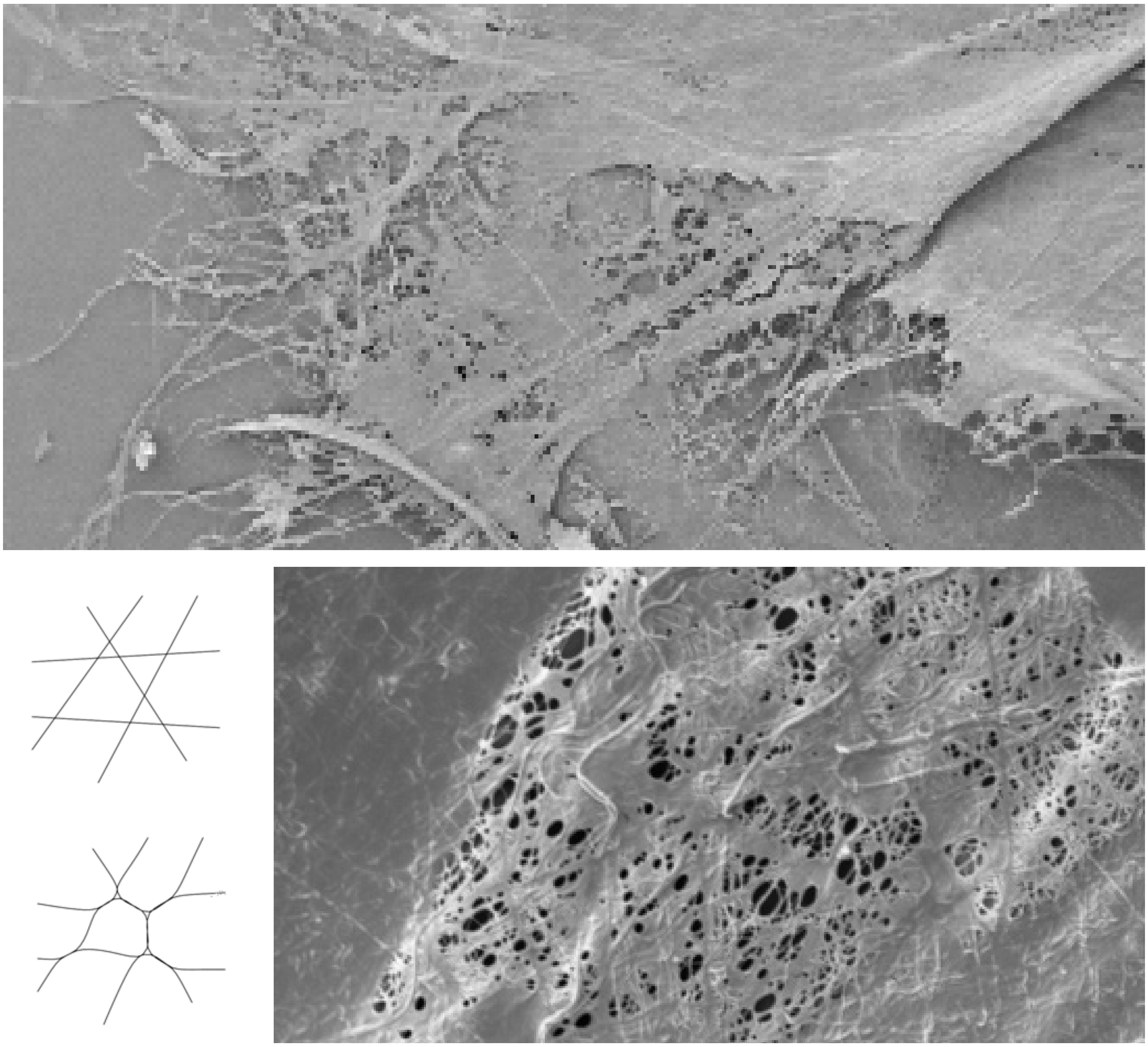
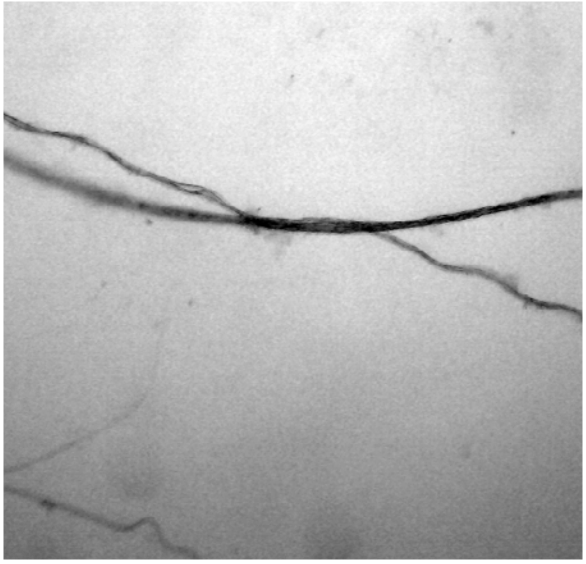


FIGURE 111: SEM scan picture of a dry web (*Source:* Tobias Grun)

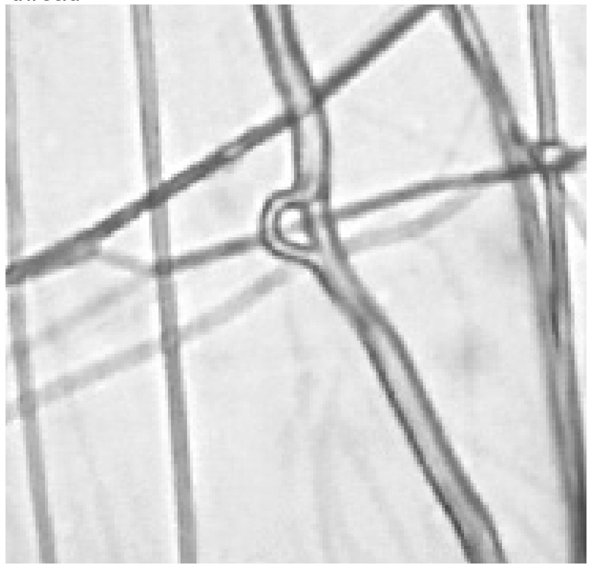
HYDROGEL

On the macroscale the zig-zag pattern is created on the stage of sheet-web building, but on microscale the origin of this pattern in most certainly the material behavior.
When the hydrogel is drying it creates tension and deforms fibres, creating pattern visible on the pictures from SEM-scanning above.

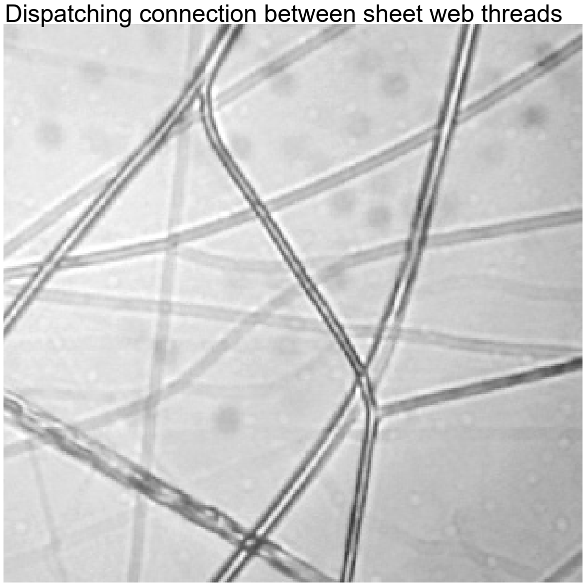
Twisting connection between sheet web thread and bell thread



Twisting connection between anchor thread and bell thread



Dispatching connection between sheet web threads



Glued connection between sheet web threads

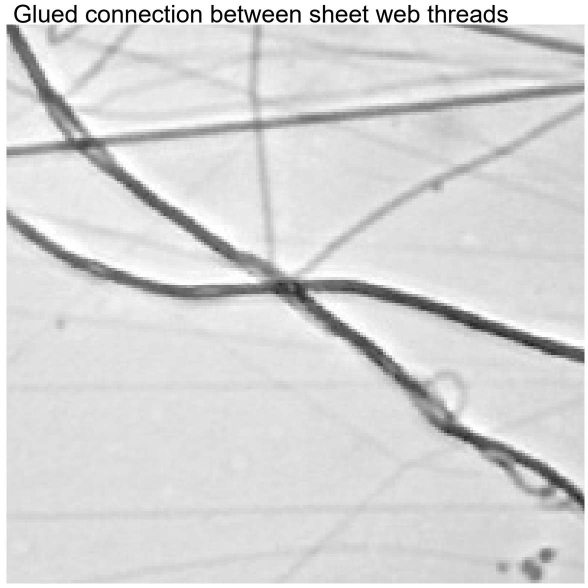


FIGURE 112: Macroscopic pictures of joints (*Source:* Tobias Grun)

INTERCONNECTION BETWEEN INNER AND OUTER THREADS IN HYDROGEL

Inner threads are connected to outer in waterspider web (they are interweaving, melding, overlapping, looping)

Outer threads are a net, holding bubble from floating up. They are sunk in hydrogel from exterior side. Inner reinforcement is also placed “in” the layer of hydrogel from interior side. This processes already create a composite. This “glued” connection is the most frequent. Except this, there is a variety of other connections. That action of spider going along the existing fibre with spinnareds results into interwoven connection. We could not identify how loops are created.

The particular feature of the WS web and the bubble is that all the fibres and all the types of connections are in the hydrogel, they are not outside or inside the bubble. Physically all the fibres are in the matrix. For the order of construction abstraction we consider them as “outer” and “inner” threads.

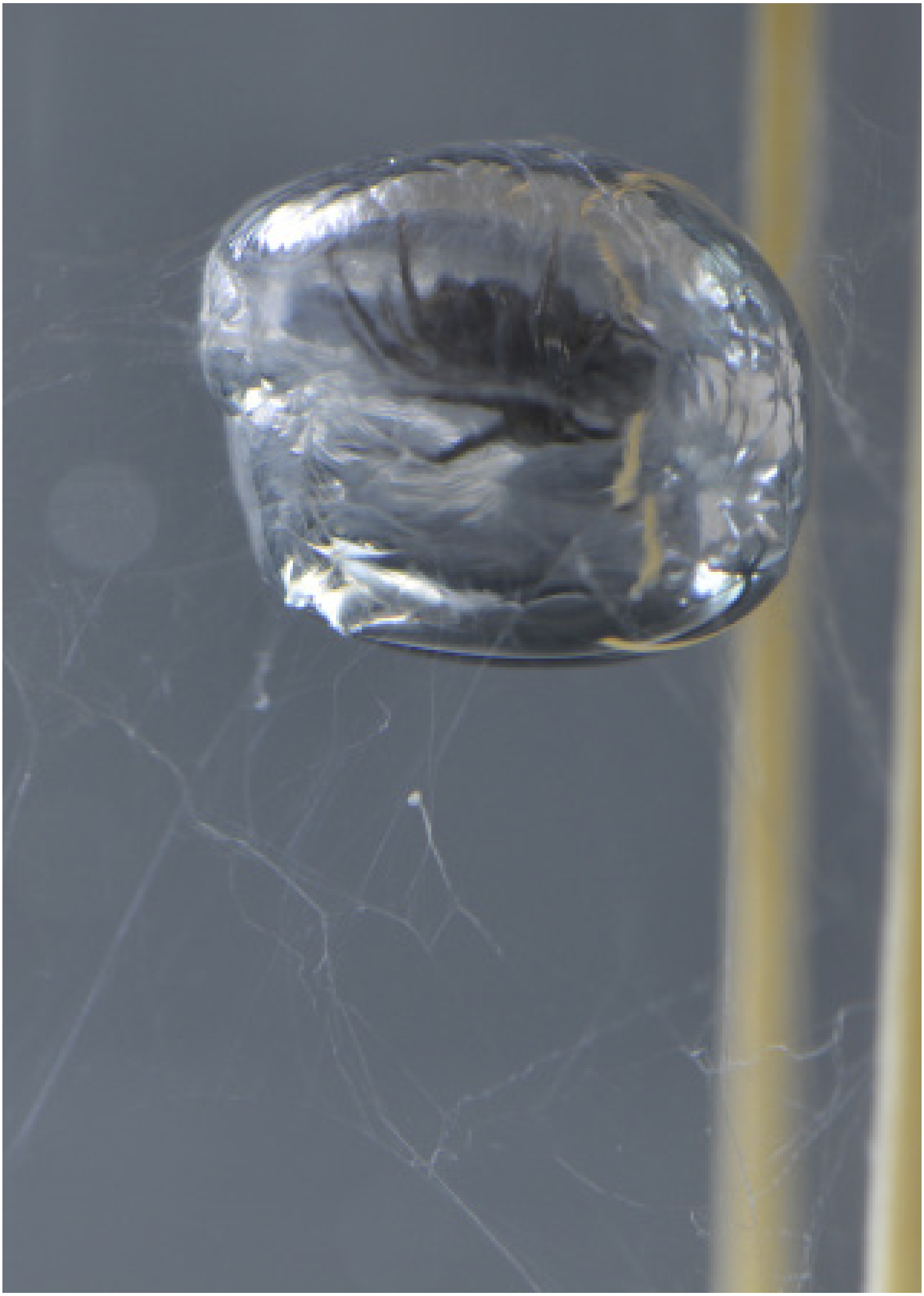


FIGURE 113: Picture with visible hydrogel (Source: M.Helmreich, Yassmin Al-Khasawneh)

Chapter 21
Edge Condition

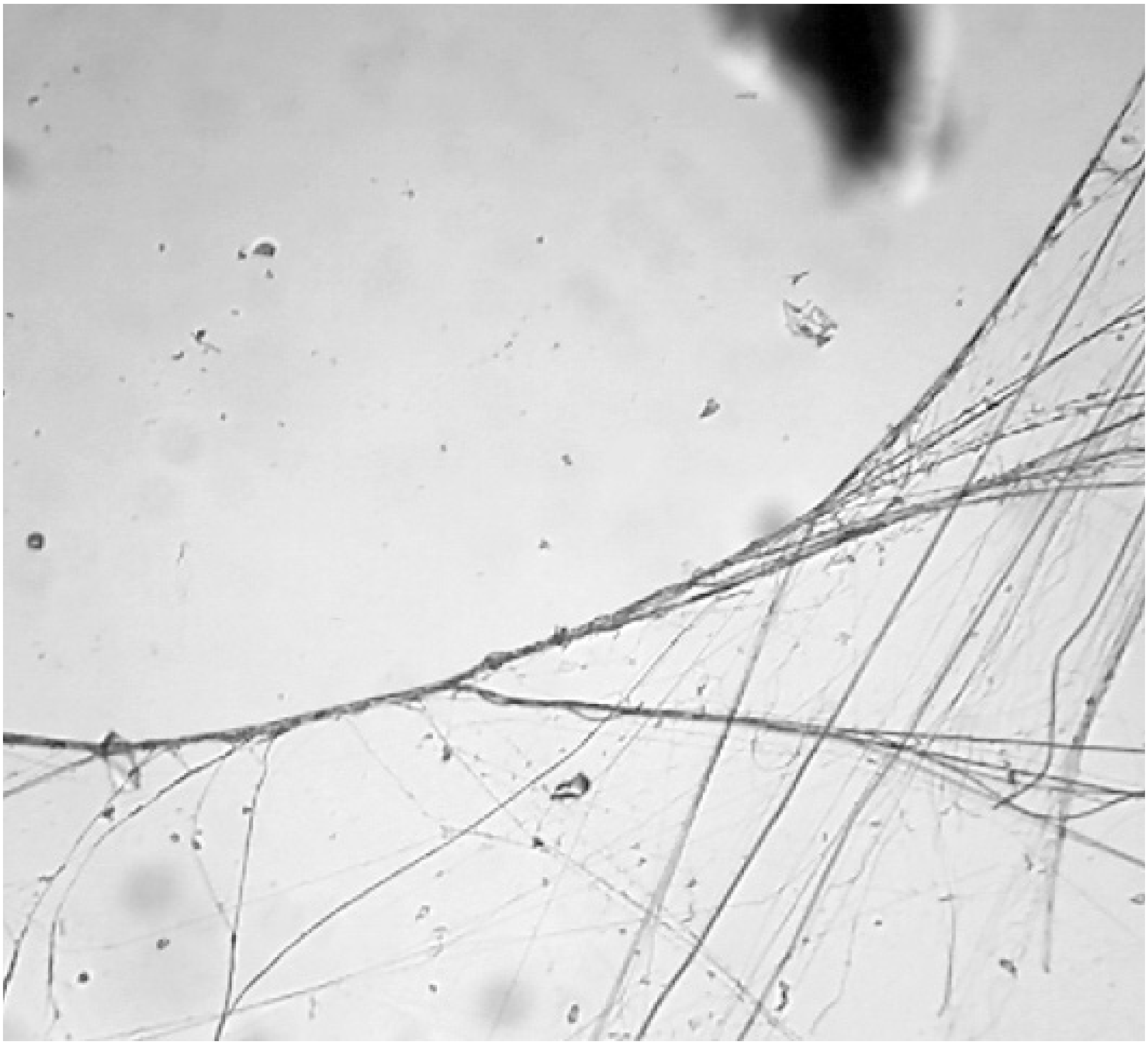


FIGURE 114: Edge of the Water Spider bubble. (*Source:* Tobias Grun)

EDGE CONDITIONS

Edge condition of the bubble involves the anchor threds which form the edge, and sheet web and bell threads which are fixed to this anchor. These latter threads are fixed to the main one tangentially, and on significant length of few millimeters they form a single line. That is defined by the type of connection (Y-connection as it is called in this booklet), produced by spinning along the existing fibre, thus reinforcing it.

In case of pavilion, the fibres come to the edge tangentially and go along the existing fibre repeating the logic of the spider web.

Part 4. Application of biomimetic principles

Chapter 22
Methods of transfer and application

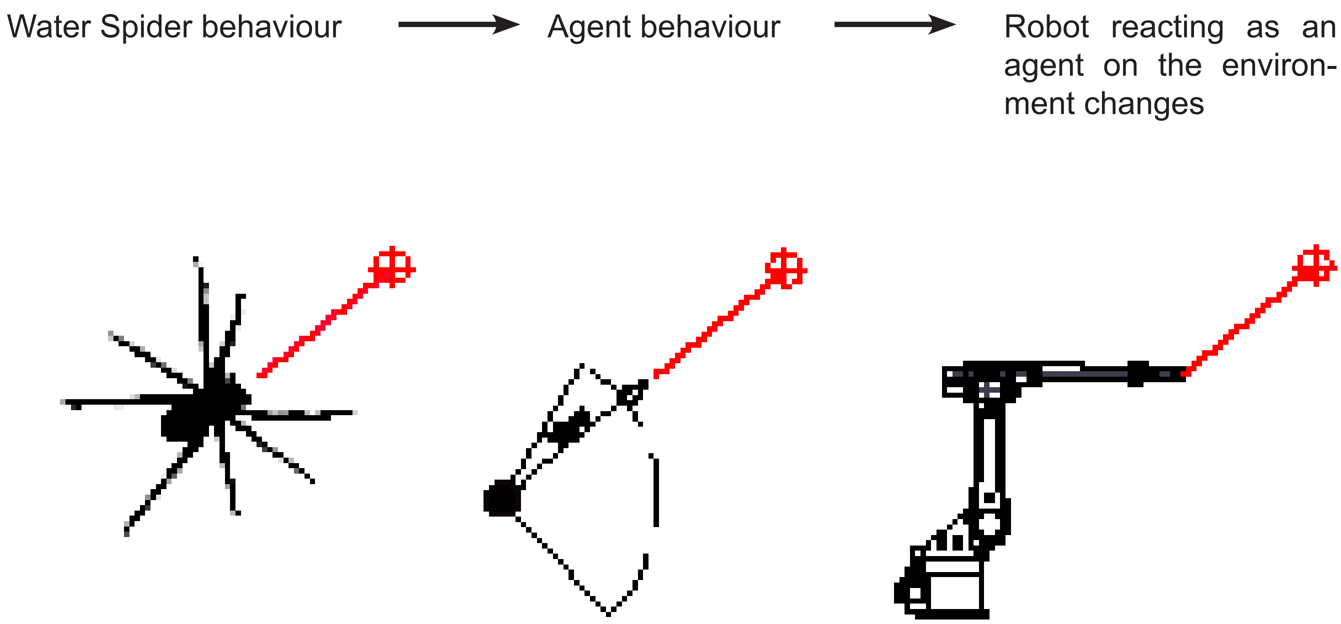


FIGURE 115: Transfer from the spider behaviours to agent behaviours and the robot acting as an agent. (*Source:* Elena Chiridnik)

TRANSFER AND APPLICATION TO THE DESIGN

We have seen several behaviours of the Water Spider. The fist behaviour -laying the external fibres before the bubble is abstracted as laying of the main structural "arches", and was used in formfinding of the pavilion shape with the halp of Rhino Membrane.
The result of second and third behaviours (reinforcing the main cables from the inside and creation of the uniform shell) is an imput for the agent system which is producing the fiber layout paths. We have several goals, such as: "create thicker beams" and "create uniform shell". These goals will be achieved with combinations of agent behaviours.
There are several adent behaviours, such as: "Follow path" to create thicker beams and "follow vector field" to create shell layers.

The digital paths are materialized with the ETFE membrane, fibre and epoxy glues, and carbon and glass fibres.
Robotic fabrication is performed with the help of Kuka robot KR 120 r3900 k.

FIGURE 116: Materialization of the concept. (*Source:* http://www.easycomposites.co.uk/, http://www.easycomposites.co.uk/)

Summary of Research Areas

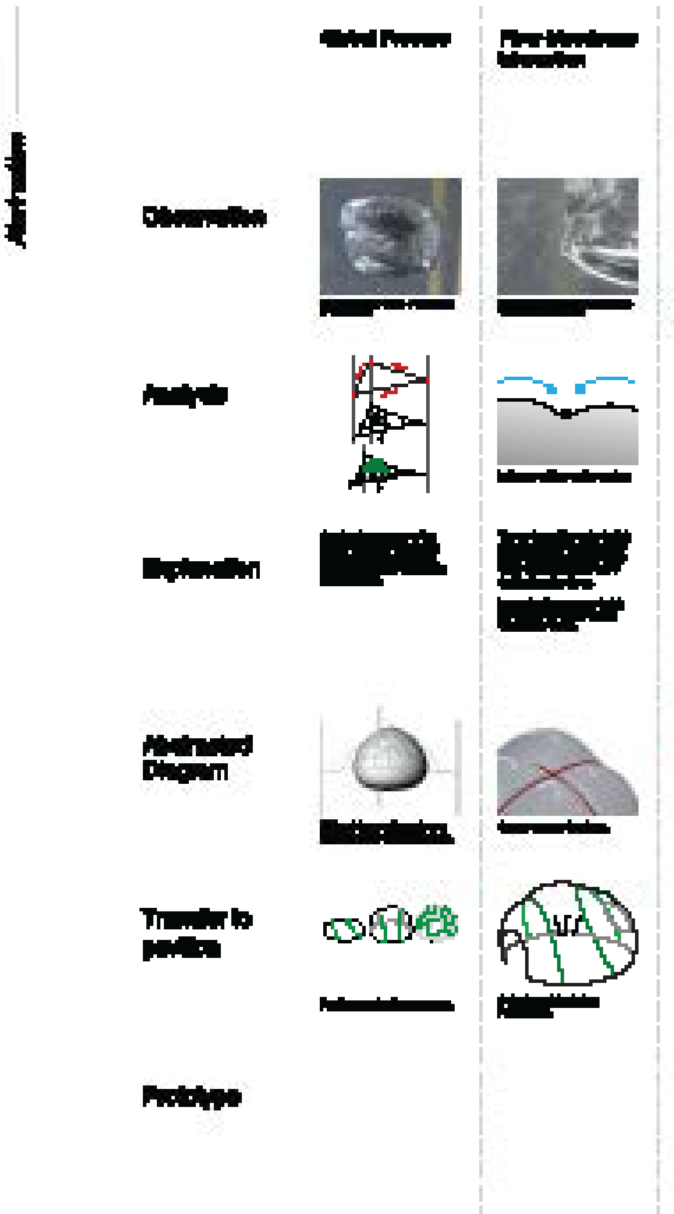
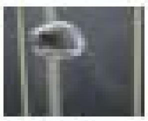


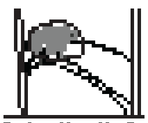
FIGURE 117: Areas of research selected for further development (Source: Elena Chiridnik, Mandy Moore, Matthias Helmreich)

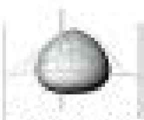
AREAS OF RESEARCH SELECTED FOR FURTHER DEVELOPMENT

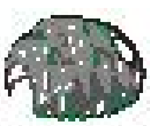
In the current design general order, fibre-membrane interaction (in the stage of form-finding), the hierarchy of fibres, different types of fibres bundling, and edge condition are implemented.

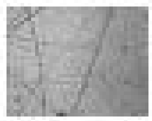
The level of control concept is brought to reality as an interactive method only partly, so it is a part of an outlook of this project.

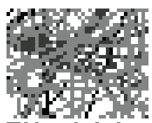


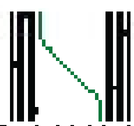


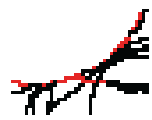


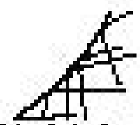




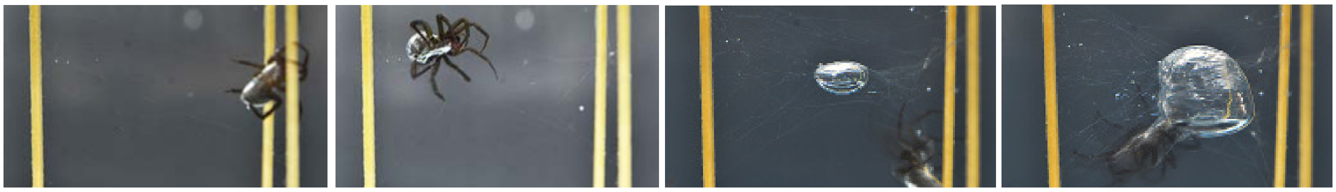








Chapter 23
Features to be applied



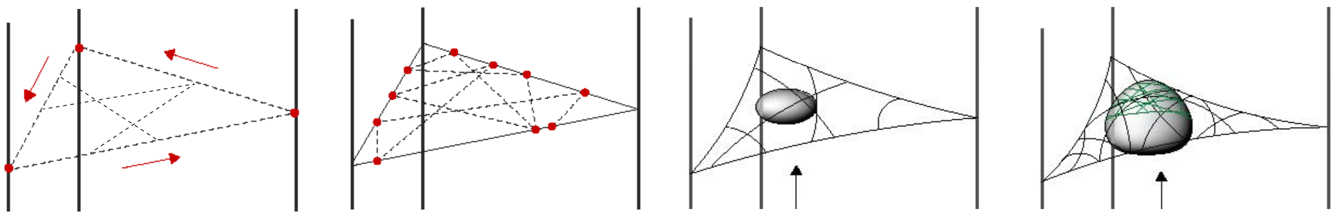
OBSERVATION

Anchor threads (1-st type of fibres)

Horizontal sheet web (2-nd type of fibres)

Initial bubble placement

Internal reinforcement of bubble (3-d type of fibres)



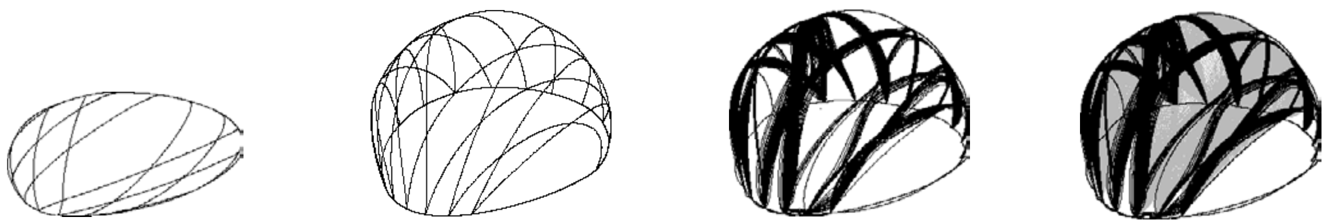
ABSTRACTION

Anchor threads (1-st type of fibres)

Horizontal sheet web (2-nd type of fibres)

Initial bubble placement

Internal reinforcement of bubble (3-d type of fibres)



APPLICATION

Exterior Fibres (1-st type of fibres)

Inflation of Membrane

Placement of main structure and path of outer threads (2-nd type of fibres)

Reinforcement of the surface (3-d type of fibres)

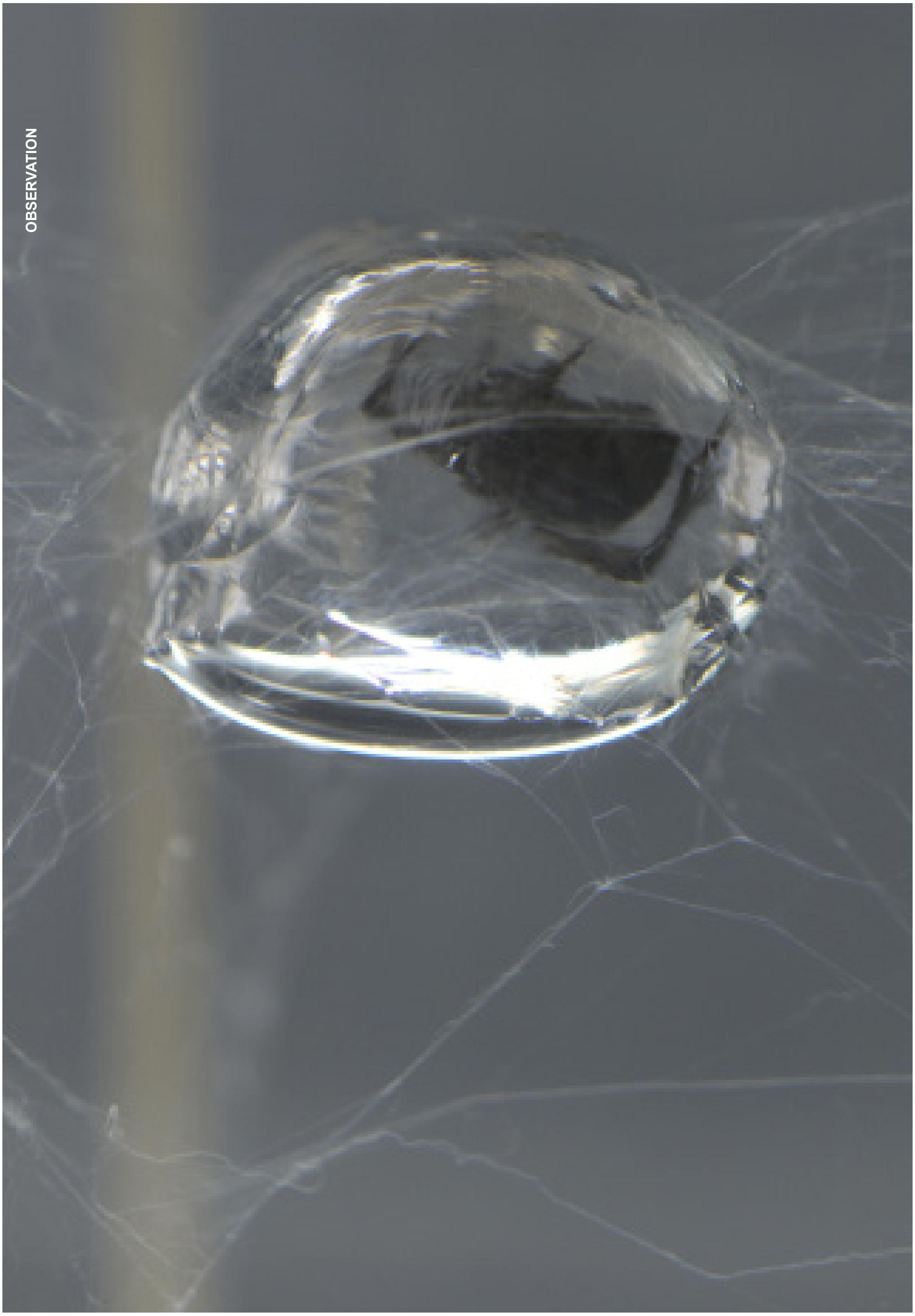
FIGURE 118: Sequence of water spider bubble construction. (*Source:* Elena Chiridnik)
FIGURE 119: Sequence of water spider bubble construction. Diagram. (*Source:*Mandy Moore)
FIGURE 120: Sequence of pavilion construction. (*Source:* Paup Poinet, Kenryo Takahashi)

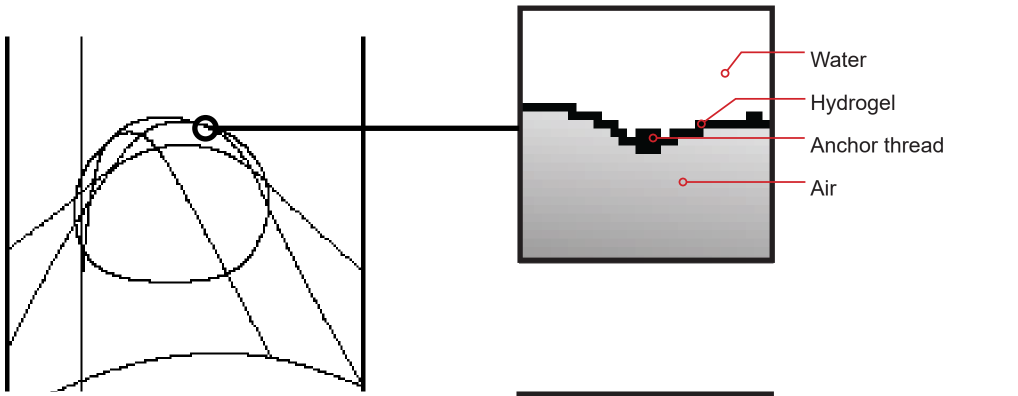
GENERAL ORDER OF CONSTRUCTION

1. External cables
2. Inflation
3. Internal fibres: main structural arches
4. Internal fibres: shell condition

In case of second types of fibres, there is a difference in their position in relationship to the membrane. In the spider bubble the sheet web threads are outside the bubble (placed before the air) and has the function of holding the bubble from floating up.Structural fibres in the bubble act against buoyancy forces. In our design sheet web is transferred as structural beams and they have the function to resist gravity forces when the air pressure inside the bubble is gone. As well as on sheet web, the structural layer fibres will bundle to create thickness of “beams” . This behavior of fiber layout is decided to depend on structural analysis input.

The third stage of fibrous reinforcement has similar functionality in biological role model and in design. The reinforcement acts against additional side forces and interconnects existing fibres as a shell.





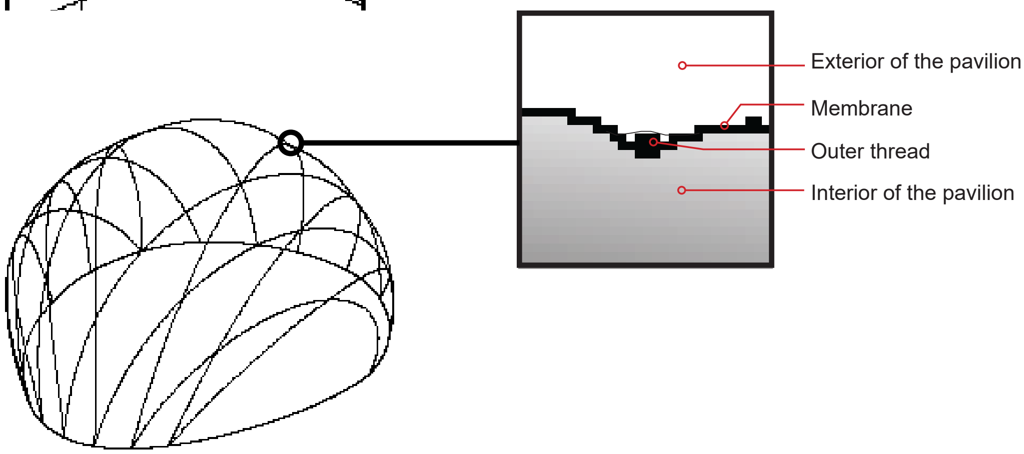
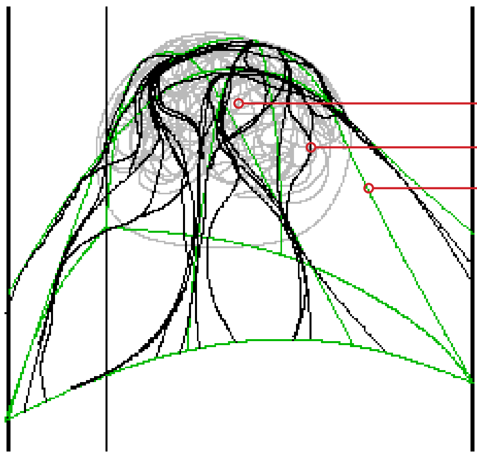


FIGURE 121: Water spider and air-filled underwater-web (Source: Al-Khasawneh, Jorge)
FIGURE 122: Outer cables influencing the surface of the bubble (Source: Mandy Moore)
FIGURE 123: Outer threads in the process of pavilion fromfinding with Rhino Membrane software (Source: Paul Poinet)

OUTER CABLES

In both biological role model and design play stabilizing role. In both cases they are necessary in the process of construction not only to resist outer environmental deformations, but also inner pressure of the spider or robot on the membrane.
Except that outer cables have a feature of defining a surface shape of the bubble on early stages of construction. This crease feature has been implemented on form-finding stage in Kangaroo and Rhino Membrane software, when the shape is inflated digitally as if it was from flexible material, and, as a sequence, has a crease which will host external stabilizing cables in the pavilion shape, which finally will be produced from non-flexible material.



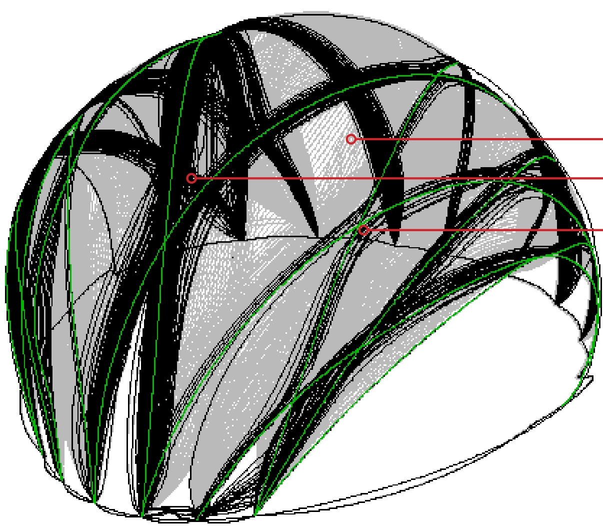


FIGURE 124: Biological role model of fibre hierarchy. Water spider and air-filled underwater-web (Source: Al-Khasawneh, Jorge)
FIGURE 125: Fibre hierarchy in the ware spider bubble (Source: Mandy Moore)
FIGURE 126: Design proposal of fibre hierarchy (Source: Kenryo Takahashi, Mart Besalu)

HIERARCHY APPLICATION TO THE DESIGN

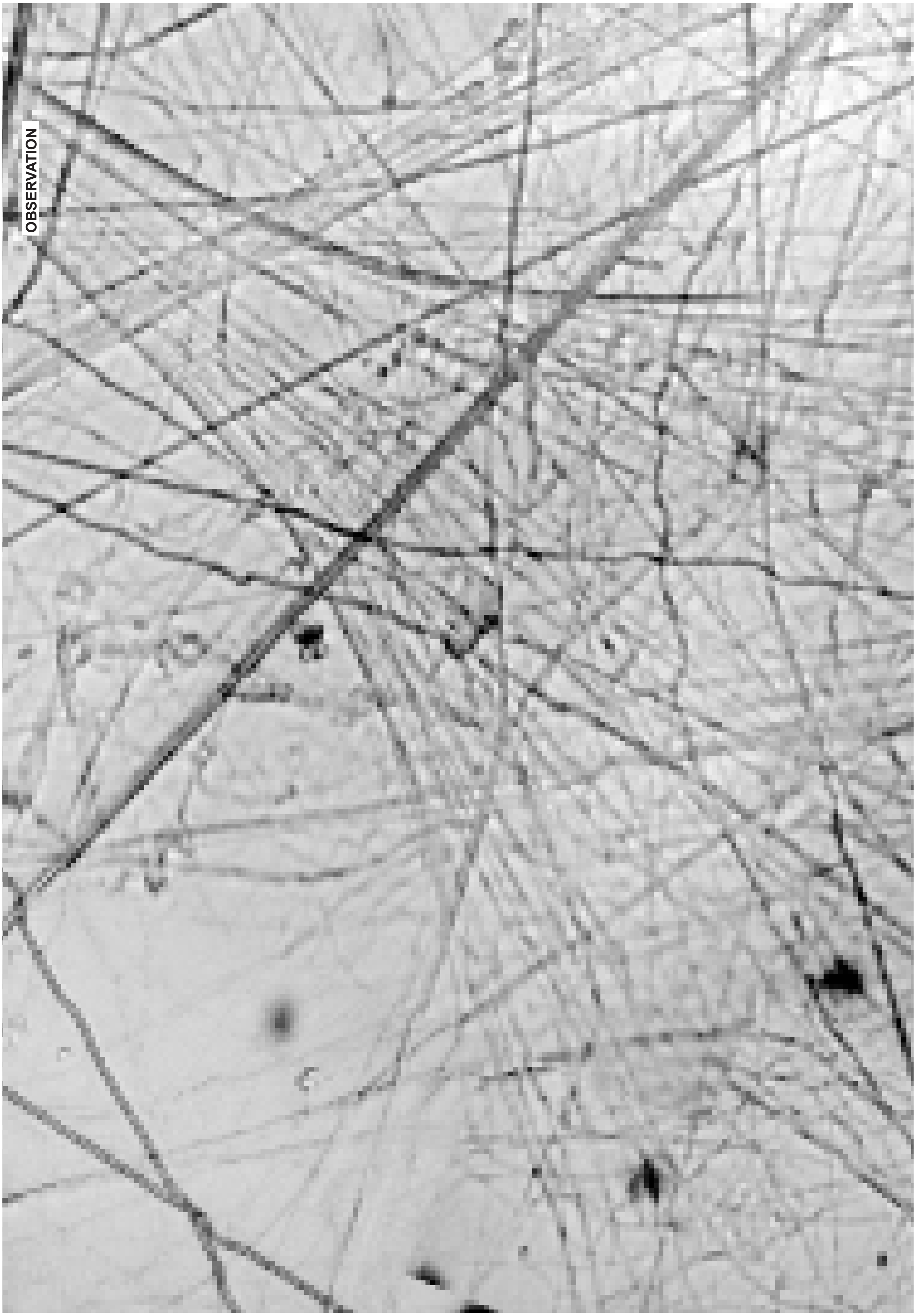
Hierarchy of fibres is going to be applied in the design of the pavilion.
Few outer cables will stabilize the membrane from outside. External cables play their role in formfinding.
Internal fibre layout is going to be created with the help of several agent behaviours. Two main behaviors are structural fibres layout and surface filling layout, protecting membrane from sagging.

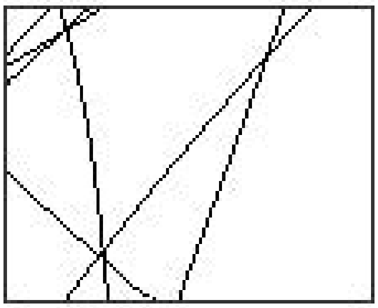
1. In the pavilion it is a controlled pre-defined layout of outer cables.

2. The typical layout is a net with y-connections.
In a pavilion it will be a layout produced by agent following stress lines and producing repeated paths with fibres next to each other- beams structural calculations.

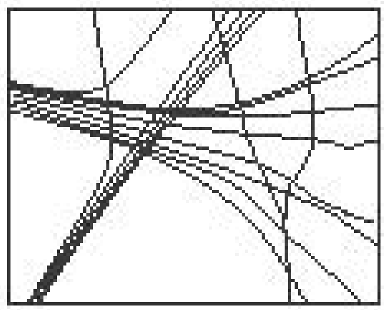
3. X-connections are dominant in this type of reinforcement.
Fibre layout which sustains the shape of the bubble, creates a shell, connects previously laid “beam” fibres between each other.

Two main functions we take from from the spider and transfer to the pavilion robotic fibre layout (not discussing the outer cables now- 1st stage described before). Structural and surface-sustaining fibres. The structural are more controlled and beam-like, their position should be calculated and exact. The surface sustaining are less controlled and more shell-like, their thickness should be calculated.

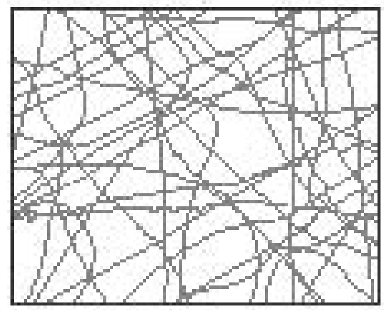




Anchor threads.
Few thick bundles of threads.

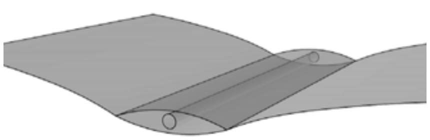


Sheet web threads.
Aggregations of threads.

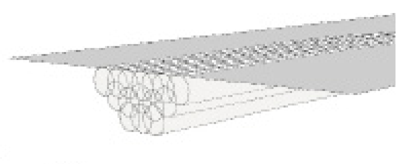


Bell (internal) threads.
Multiple thin treads in various directions

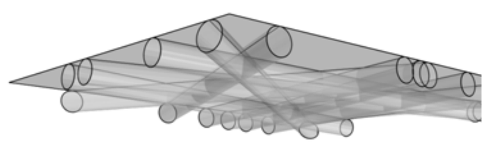
ABSTRACTION



External cables



Structural aggregations of fibres



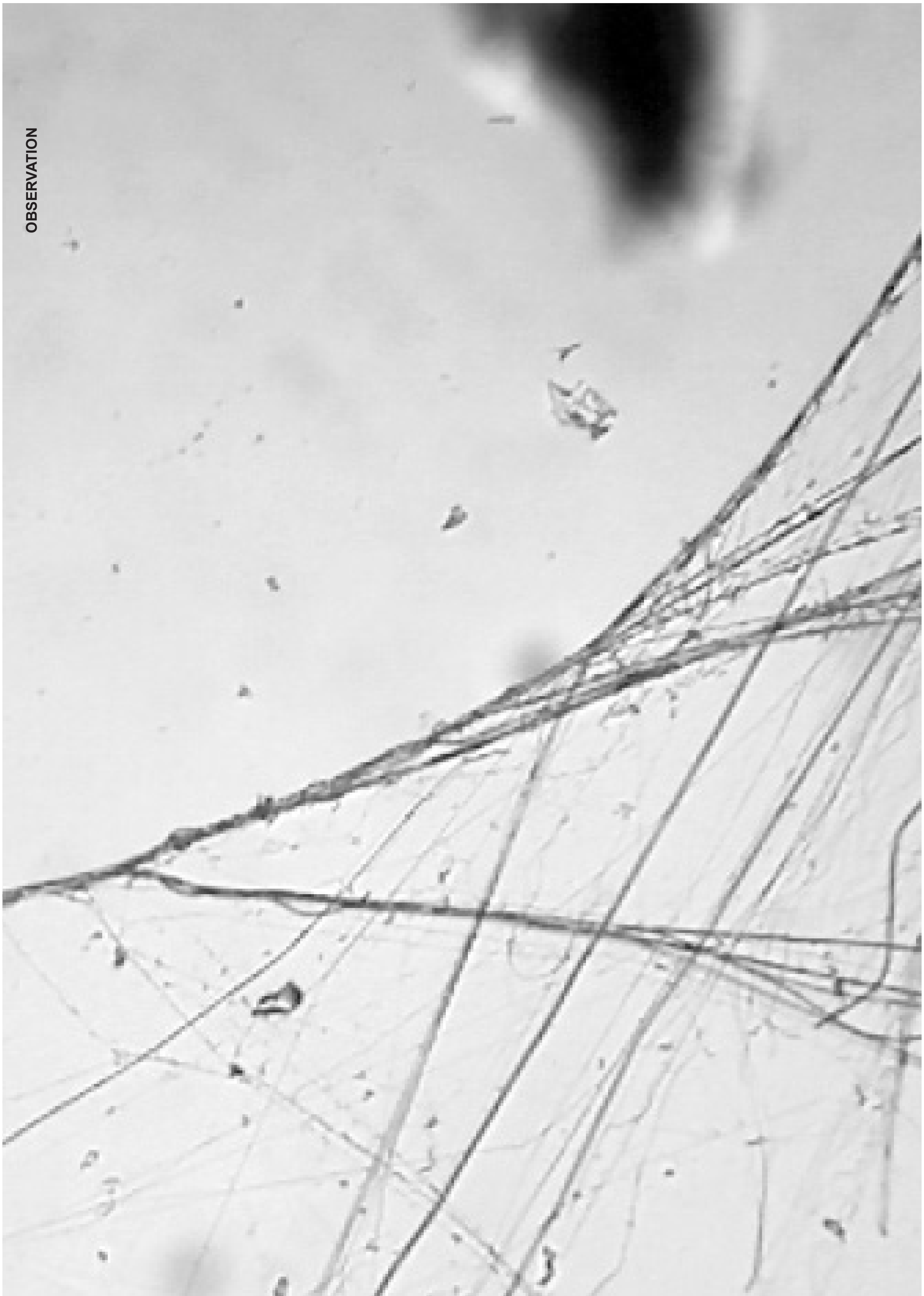
Surface- sustaining fibres

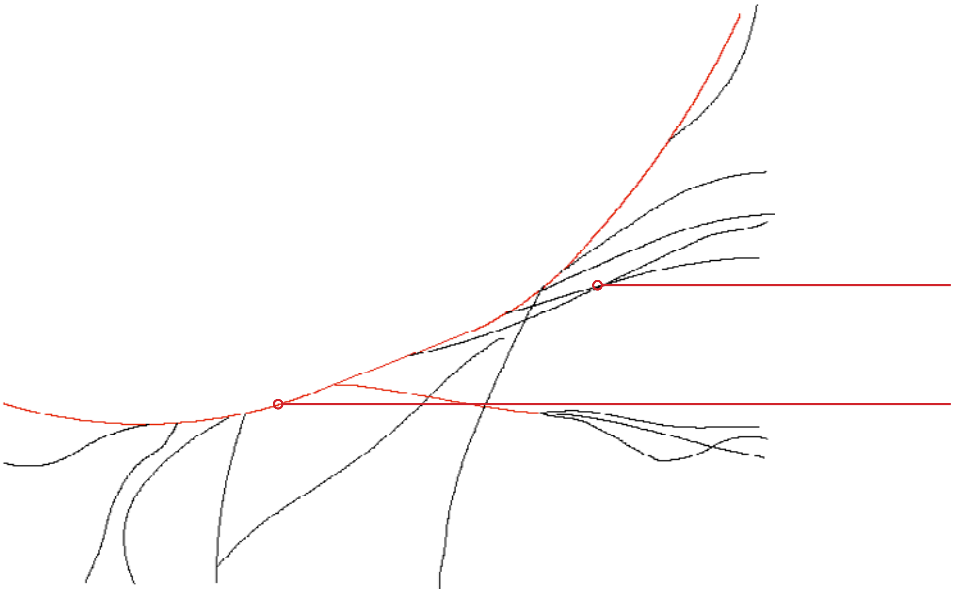
APPLICATION

FIGURE 127: Microscopic picture of three days old bubble surface (Source: Chiridnik, Jorge)
FIGURE 128: Parameters of different types of threads in a spider bubble (Source: Jorge)
FIGURE 129: Types of threads for pavilion fibre layout (Source: Chiridnik, Al-Khasawneh)

TYPES OF LAYOUT

External cables
Outside the membrane. in the pavilion will be adding stability on the site during construction.
Beams
Structural fibres in the bubble act against buoyancy forces. In our design sheet web is transferred as structural beams and they have the function to resist gravity forces when the air pressure inside the bubble is gone. As well as on sheet web, the structural layer fibres will bundle to create thickness of “beams” . This behavior of fiber layout is decided to depend on structural analysis input.
Shell
The reinforcement acts against additional side forces and interconnects existing fibres as a shell, preventing the surface from sagging





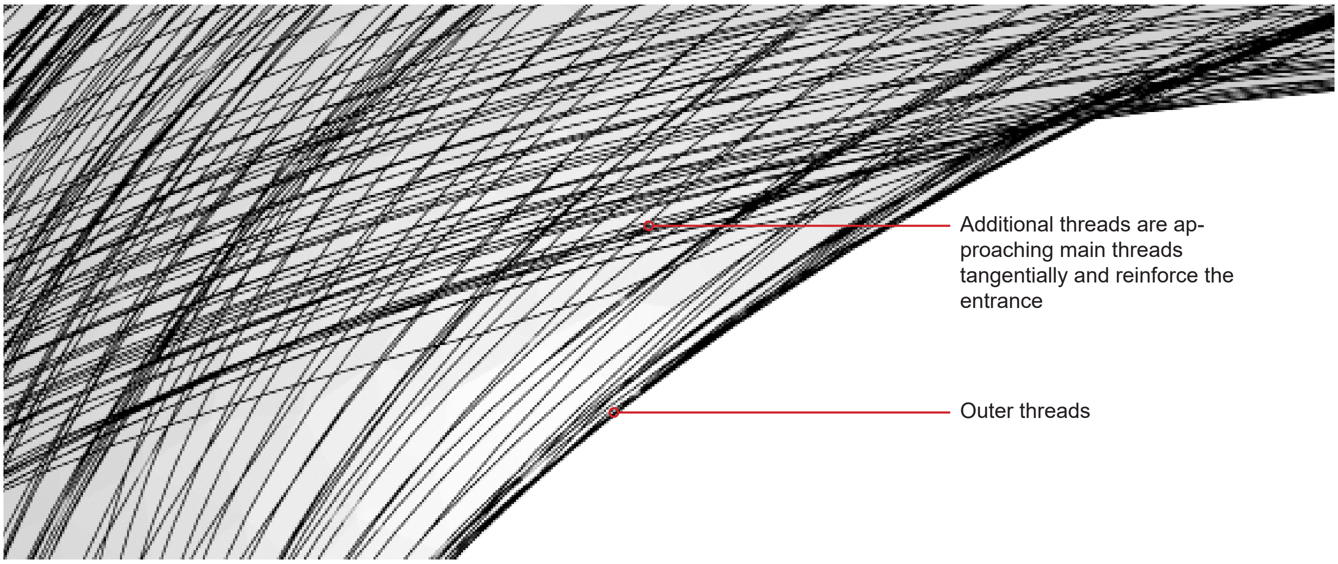


FIGURE 131: Edge of the Water Spider bubble. (*Source:* Tobias Grun)
FIGURE 132: Edge of the Water Spider bubble.Diagram (*Source:* Mandy Moore)
FIGURE 133: Edge of the pavilion entrance. (*Source:* Kenryo Takahashi, Marta Besalu)

EDGE CONDITIONS

Edge condition of the bubble involves the anchor threds which form the edge, and sheet web and bell threads which are fixed to this anchor. These latter threads are fixed to the main one tangentially, and on significant length of few millimeters they form a single line. That is defined by the type of connection (Y-connection as it is called in this booklet), produced by spinning along the existing fibre, thus reinforcing it.

In case of pavilion, the fibres come to the edge tangentially and go along the existing fibre repeating the logic of the spider web.

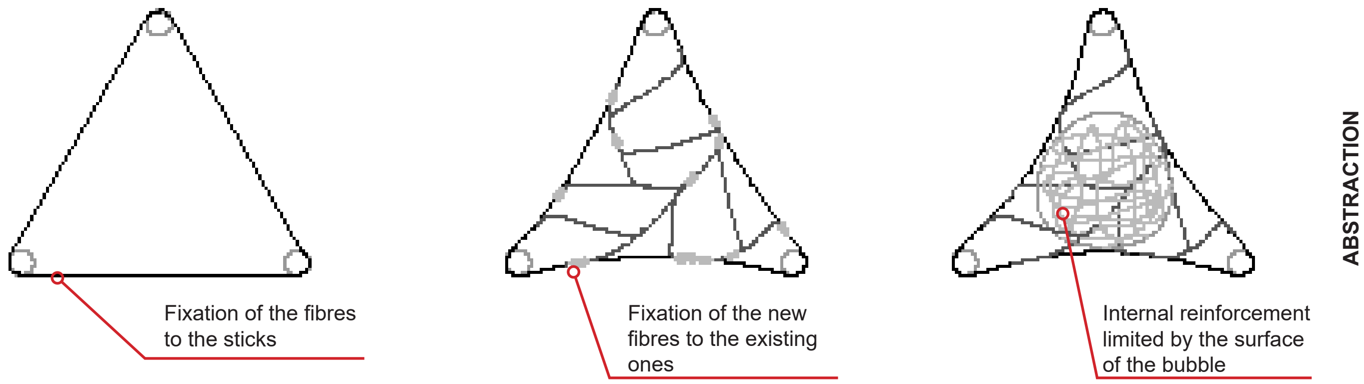
Chapter 24
Outlook

BEHAVIOURS FOR THE AGENT

For the first option of environment change (when robot is changing the environment and adjusting to that accordingly) we have abstracted three levels of behaviour control.
First level of control is predifined boundaries of the sheet we are painting.
Second level of control is a behaviour where the agent should reach the anchor point. In this case agent has an initial vector of movement, which is influenced partly by the change of the environment which occurs because of its movement.
Third level of control: non-controlled behaviour. The task is to fill the surface between the border. The only steering behaviour is a constantly changing according to the previous path vector.

The common feature of the behaviors is to create a web with certain density. What varies in a sheet web and bell reinforcement is area between laid fibres.This “filling the surface” spider behaviour can be translated to the agent behaviour as estimation of a free surfaces in the closest environment and going througth them.

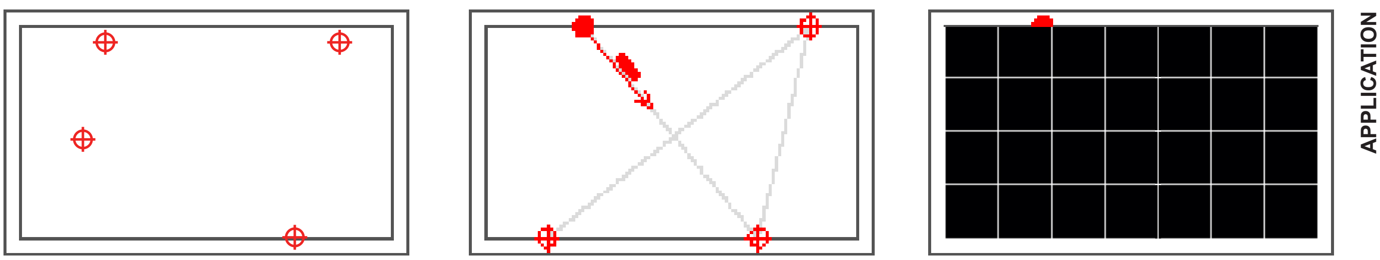
In the other case of environment change - coming from outside the system, from human (if we add the paint), agent should recalculate the path avoiding the spot that has alredy been painted.



Pre-defined conditions

Adjust to existing fibres filling the surface

Adjust to environment filling the surface



Anchor points as pre-defined conditions

Follow path behaviour

React to the environment

FIGURE 134: Different levels of control in spider behaviour. (Source: Elena Chiridnik, Matthias Helmreich)
FIGURE 135: Different levels of control in spider behaviour. Diagram. (Source: Elena Chiridnik)
FIGURE 136: Different levels of control in agent behaviour. (Source: Elena Chiridnik, David Andres, Matthias Helmreich)

CONTROL

The idea ordering the behaviours is level of control over the system. What we implement is functionality of behaviours.

In the beginning of construction the spider would repeat its path reinforcing the same thread more often . Further in the process it is not so careful about fixing new treads to existing ones. We assume, that this facts deals with the level of control. In the beginning of construction the connections should be stronger in particular spots and lines. It seems like for this task (anchor threads) spider knows exactly were to go. Constructing the web, the spider identifies weak zones (supposedly) with its feet. Connections are shorter but still of a strong interwove type. In the final internal reinforcement stage the connections do not have to be so strong. The reinforcement should be even. To perform this task the spider does not have to go to some particular spot urgently, so there is freedom in time and space to reinforce.

Chapter 25
Appendix

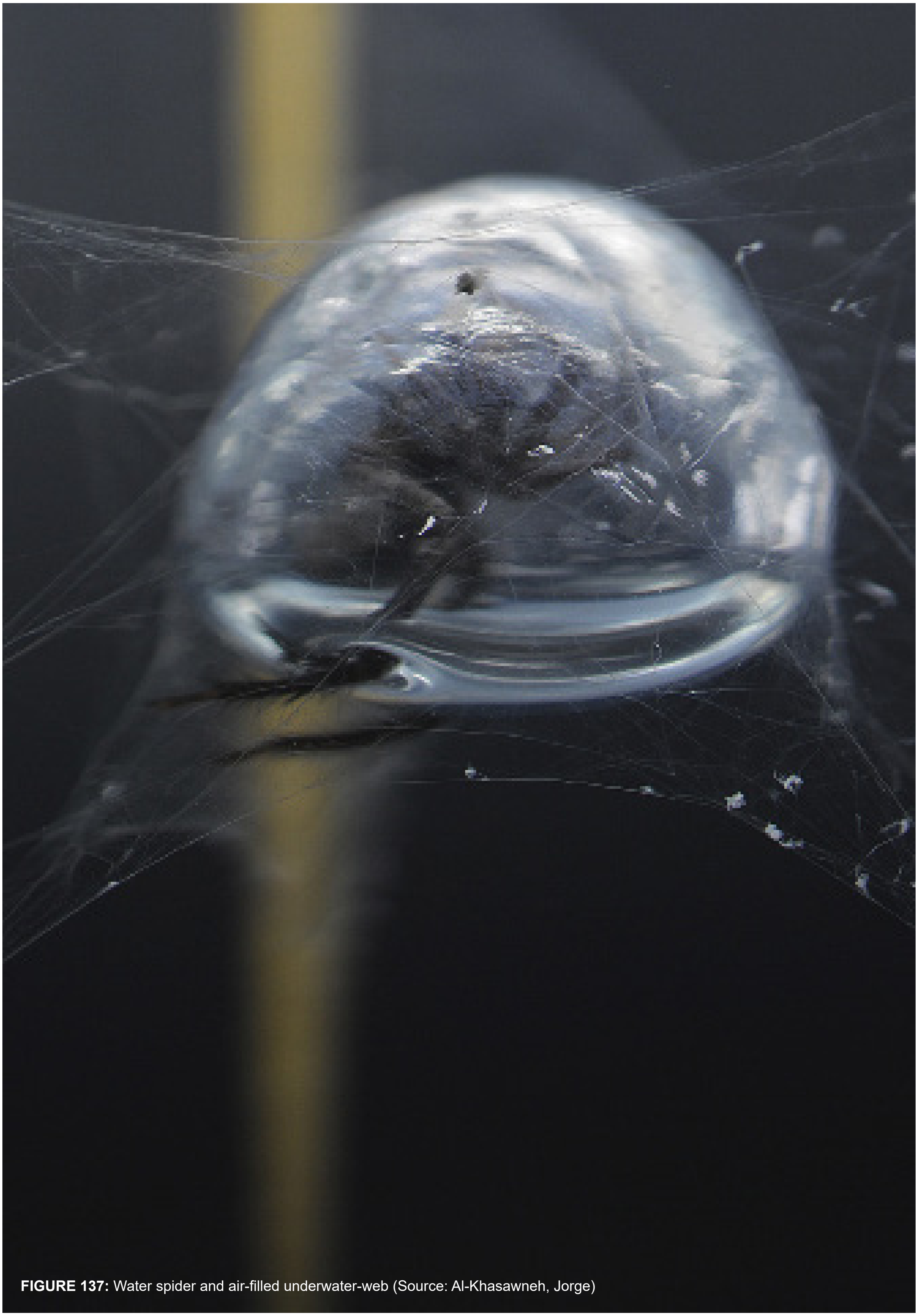


FIGURE 137: Water spider and air-filled underwater-web (Source: Al-Khasawneh, Jorge)

Bibliography

Chaui-Berlinck, Jose´ Guilherme and others. The oxygen gain of diving insects. Elsevier. 24 July 2001.

De Bakker, Domir, and others. Description of the structure of different silk threads produced by the water spider *Argyroneta aquatica* (Clerck, 1757) (Araneae : Cybaeidae). Belg. J. Zool., 136 (2) : 137-143. July 2006.

Neumann, Dietrich, and Kureck, Armin. Composite structure of silken threads and a proteinaceous hydrogel which form the diving bell wall of the water spider Agyroneta aquatica. SpringerPlus. 2013.

Seymour, Roger S.,* and Hetz, Stefan K. The diving bell and the spider: the physical gill of *Argyroneta aquatica*. The Journal of Experimental Biology 214, 2175-2181. Published by The Company of Biologists Ltd. 2011.

Shiffman, Daniel. The nature of code. 2012. Available from: http://natureofcode.com/book/.