Realistic Modeling of Spider Webs

Category: applications

Abstract

We present a system that creates models of spider webs by faithfully simulating their construction. We follow the specific procedures and subsequent phases of the construction, taking into account the natural constraints of the environment. The resulting geometries compare favorably to real-life webs. The rendered models provide insight into the typically complex structures and are visually pleasing.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling

1 Introduction

Spider webs are fascinating natural structures. While the spider builds a web as a living space and as a trap for insects, it appeals to us by its skillful construction, its geometrical intricacy and its natural beauty. In this paper we study the automatic modeling of spider webs. The techniques and procedures that spiders use to create their webs have been studied and documented extensively. Lougee [5] presents an informal introduction into the world of spiders and their webs. We have based our work primarily on the extensive study by Tilquin [8], who has specifically researched the construction and the structure of spider webs over a period of six years. Additional interesting information can be found in the work by Witt [9].

The modeling and visualization of spider webs serves several purposes. First of all, the process is educational. It shows that a spider web is more than just a few radial lines and a spiral thread, actually consisting of different elements and regions that are built in different phases. Although the result is highly intricate, each of the individual building steps is relatively simple. Even if individual spiders of the same species have their own styles [9, p. 20], important common features can be characterized. For arachnologists, the system provides a mechanism to verify theories on the construction of webs. The importance of understanding the construction is illustrated by Witt's study of the influence of chemical substances on spiders and the design of their webs [9].

Secondly, the simulation software provides a modeling tool for what would otherwise be a time-consuming task. With rendering systems becoming more powerful, the demand for detailed and accurate models increases. The complexity of the models greatly enhances the realism of the images. However, creating complex models requires a lot of expertise and time. Organic objects and natural phenomena are especially hard to recreate using the typical geometric primitives that modeling programs offer. Researchers have therefore studied the automatic modeling of structures such as trees [6], flowers [3] and lightning [7], and of textures, for instance due to weathering effects such as patina [1] and the flow of water [2]. These systems simplify and speed up the creation of convincing models. In our case, each web is similar but different, depending on the spider and on the environment. The system we present here automatically constructs highly intricate webs, based on statistical information about real webs and adapted to the environment.

The rest of this paper is structured as follows. In section 2 we present a few general facts about spiders and their webs. Section 3 provides details of the construction and the structure of a web. In section 4, we explain how our system simulates the different phases of the construction, eventually obtaining plausible models of webs. Results and conclusions are presented in section 5.

2 The Spider and its Web

Spiders belong to the class of *Arachnida*. A spider has two body parts: the cephalothorax and the abdomen, which are connected by a thin link, the pedicel. Its eight legs are attached to the cephalothorax. Depending on the species,

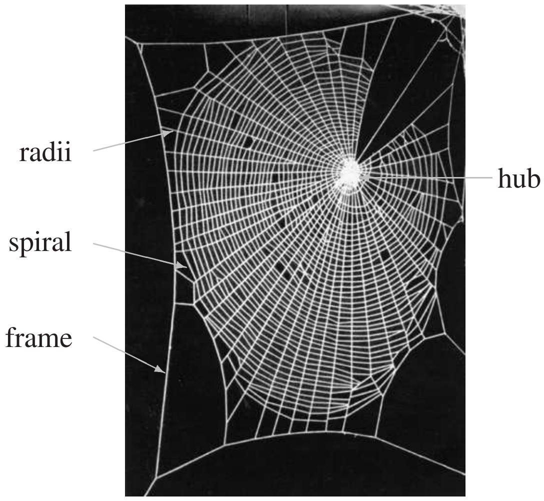

Figure 1: The typical orb web of a Zilla x-notata (from [9]).

Figure 2: Close-up of the central hub of a web (from [9]).

a spider has up to eight eyes. It has low visual ability, however, and most of its activities, such as building a web and catching insects, are directed kinesthaesically. The spider produces silk from its spinnerets, which are thin tubes at the underside of the abdomen. The spinnerets always produce at least a dragline, which is attached to the environment or to the web. It allows the spider to recover its previous position after having fled from a potential danger by dropping to the ground. According to the circumstances, the spinnerets can produce many other types of silk, e.g. dry silk for the supporting lines in the web, silk covered with a gluey substance for the capturing lines, and soft silk for a cocoon. By weight the silk lines are five times stronger than steel wire. We will therefore neglect their weight in our simulation. The lines can also stretch up to 10% without breaking. This is an important factor for the strength of the web and for its construction, as it allows lines to be retensioned to balance the structure.

There are many different types of webs: sheet webs, triangular webs, dome-shaped webs, etc. We are mainly interested in the classical orb-shaped web, as produced by the family of *Orbicularia*. Our simulations are based on the statistics gathered for the *Argiope Brünnichi* and the *Zilla x-notata*, which both build typical orb webs. The main difference lies in the missing sector in the web of the Zilla x-notata, as can be seen in Figure 1. During the daytime, the Zilla x-notata hides in a shelter outside the web, monitoring the warning thread in this open triangle. The main parts of the web are the radial lines, the frame, the gluey spiral, and the central hub, as indicated in Figure 1. The structure has a planar topology and a roughly planar geometry. The plane of the web is usually slightly oblique by 9 to 13 degrees [8, p. 407]. The spider normally resides on the underside of the hub, cephalothorax down, waiting for prey.

3 Construction of the Web

The spider constructs its web in distinct phases, which we will discuss in this section. Throughout the construction, the spider employs a few standard techniques. It constantly produces silk lines of the appropriate type. It drags the line behind it, always supporting it by one of its rear-most legs (pair IV) to make sure that the line does not stick to other structures or lines. Whenever required, the spider attaches the line by depressing its abdomen. The spider can strengthen lines by doubling them with an additional thread. It can retension or loosen existing lines by replacing it with a new line. It gathers the end of the old line in a knot (with pair III of its legs), advancing on this line in front (with pairs I and II) and tending a new line behind (with pair IV).

3.1 Primary Radial Lines

The construction of a web is started by laying a horizontal primary line between two fixed points in the environment. The spider either carries the line across or lets a strand float with the wind across a span until it gets entangled. The line is strengthened by overspinning. The spider then walks to the middle of the horizontal line and drops to the ground, creating a vertical primary line. The line is fastened at a suitable protuberance. The resulting fork largely determines the center and the maximum size of the eventual web. Figure 3 depicts this situation for a modeled web, within a simple square environment. The lines can be as short as a few times the size of the spider, but they can also easily span a small stream.

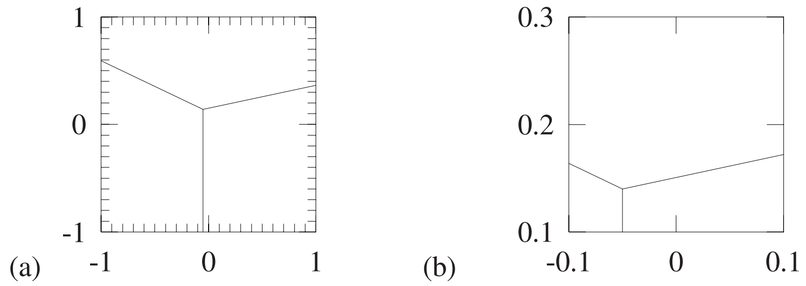

Figure 3: (a) The initial three primary radial threads of the web form a fork. (b) Close-up of the center of the web.

3.2 Secondary Radial Lines

In the next phase the spider regains the center. From there it walks along a primary line, producing a loose secondary radial line. At some point it attaches the secondary line to the primary line. It then walks back and attaches its dragline to the resulting loop. If the distance to the environment is small enough, the spider finds a suitable point of attachment, effectively creating a new primary line connected to the previous radial line by a frame line. Otherwise it walks back to the center and onto the neighboring radial line, attaching it near the outside of the web. The procedure then results in a frame line with a secondary radial line in between. In either case the lines are strengthened when returning to the center. The entire procedure is then repeated until a complete set of primary and secondary radial lines and the frame have been constructed, as shown in Figure 4.

The radial lines are not all attached to a single knot in the center, but rather at small distances on the existing lines (Figure 4b). The size and the shape of the outside frame are sometimes adapted and balanced, by linking the lines around the frame. Depending on the natural constraints, the web is usually slightly elongated vertically. In a controlled environment the elongation ratio is 1.28 on average [8, p. 407]. Additionally, radial lines in the upper part of the web are commonly shorter than those in the lower part of the web. Most webs are therefore more or less eccentric, on average by a factor of 0.63 [8, p. 407].

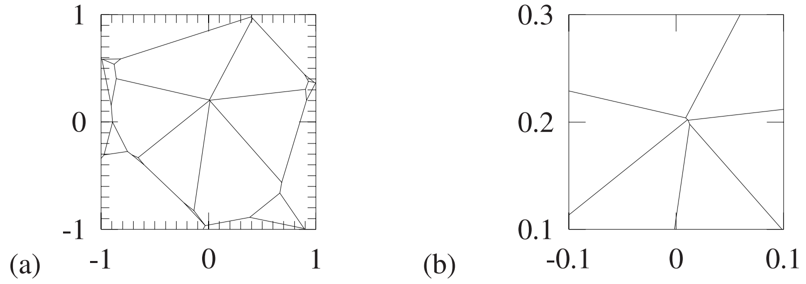

Figure 4: (a) The secondary radial threads are added in between the primary ones. Some of the lines are attached to the environment, while other lines are fastened to a newly created frame thread. (b) Close-up of the center, which is no longer a single point.

3.3 Tertiary Radial Lines

For creating tertiary radial lines, the spider rotates around its axis in the center of the web, sensing the angles between the existing radial lines with its front legs. If the angle is too large, the spider sets off along the line, drawing a tertiary line. This line is attached to the frame at a fixed distance from the radial line. As a side effect, the angles between the tertiary lines are often slightly larger in the upper part of the web due to its eccentricity.

The creation of secondary and tertiary lines actually alternates, depending on whether there already is a frame wire or not. The procedure of creating radial lines is repeated until the spider considers all angles between the radial lines sufficiently small. The web then has between 20 and 40 radii [8, p. 27], although this may vary strongly with the size of the web. Figure 5 depicts a situation with only a small number of radial threads.

During the creation of the secondary and tertiary lines, short random lines are laid down between the radial lines. This eventually results in an unstructured mesh that makes up the initial center of the web, as illustrated in Figure 5b. This is also visible in Figure 2, which shows the center of a real web.

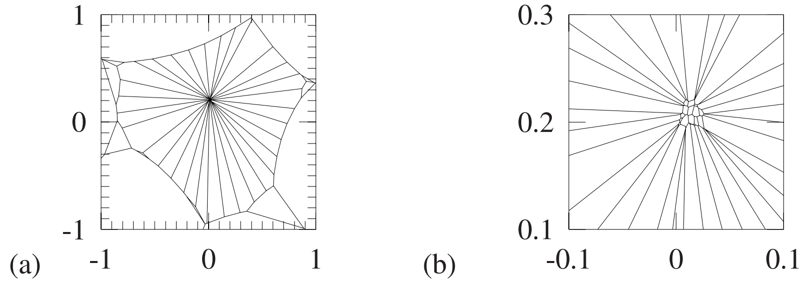

Figure 5: (a) The tertiary radial threads inserted wherever the angles are still too large. These lines are all attached to the frame. (b) Close-up of the center, which is now an unstructured mesh.

3.4 Hub and Preliminary Spiral

After the radial lines and the frame have been created, the spider starts completing the center hub. By walking around the unstructured center and laying down a spiral, it creates a mesh of quadrilaterals on the radial lines. The spiral is often attached to the lines over a small distance, thereby slightly distorting the mesh structure. This effect is clearly visible in the real web of Figure 2 and in Figure 6. The hub is only roughly disc-shaped. For the Argiope the hub consists of 7 to 15 spiral threads [8, p. 40]. When the hub has reached a certain size the spider suddenly increases the distance between the spiral threads. This spiral is continued until the spider reaches the frame of the web. It is still made of dry silk, as it will only serve as a temporary scaffold for constructing the gluey spiral in the next phase.

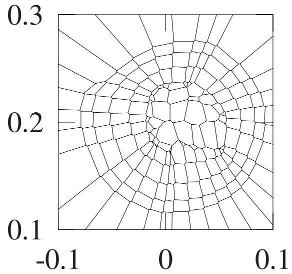

Figure 6: Close-up of the hub after it has been completed by means of a dry spiral. The spiral and the radii are distorted in a typical pattern at the attachment points.

3.5 Adhesive Spiral

When the spider kinesthaesically notices that it has nearly reached the outside of the web it stops laying the dry spiral. After a few seconds it reverses its direction and starts creating the actual capturing wires, now producing an elastic gluey silk strand. The adhesive spiral is thus constructed from the outside of the web towards the center. Near the outside of the web the spider tends to follow the frame, while towards the middle the spiral becomes more regular. The adhesive spiral is much tighter than the preliminary one, with the distances between the threads remaining approximately constant (3–5 mm [8, p. 50]). The spider each time checks the distance with the previous thread using one leg of pair IV.

The preliminary thread serves as a bridge between the radial lines and is cut while the spider progresses towards the center. The cut ends contract into tiny knots on the radial lines due to their elasticity.

Whenever the spider encounters the frame it does not attach the thread to it, but instead progresses over a small distance towards the center. It then reverses its direction and continues creating the spiral in this opposite rotational direction. This often results in the threads being coupled in pairs, with slightly varying mutual distances [8, p. 54]. Zilla x-notata avoids putting adhesive spiral on the radial warning thread of the web. It reverses it direction on or before the radial line before the warning thread.

When the spider has nearly reached the center, it returns to the hub at a faster pace. This leaves an open area between the hub and the spiral. Figure 7 depicts two resulting webs, for the Argiope Brünnichi and the Zilla x-notata respectively. The total number of spiral threads varies between 10 and 50 [8, p. 51].

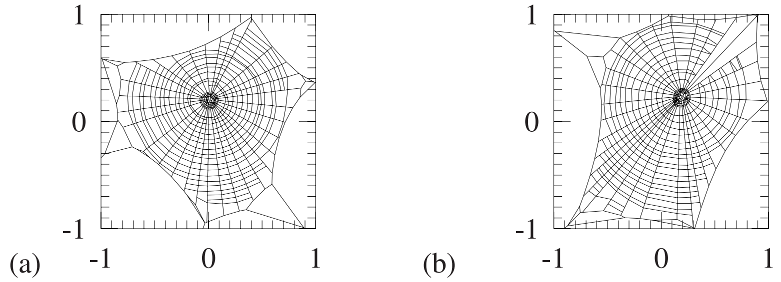

Figure 7: (a) A complete simulated web. The gluey spiral is constructed from the outside inwards, reversing its direction whenever the frame is encountered. (b) A complete simulated web of a Zilla x-notata. While laying down the spiral, this spider avoids covering the warning thread, leaving an empty slice in the web.

4 Simulation of the Construction

The input for our simulation is a model of the environment and an approximate position, orientation and size for the web. During the simulation, the intricate topology and geometry of the web are represented internally using data structures of lines and knots. The data structure has to be managed carefully, in order for the 'virtual spider' not to get lost. The output of the simulation is a set lines, which can be rendered in combination with the original model.

As we have seen in section 3, the spider does not implement a global design when building its web. Instead, it works locally, following its elementary instincts and acting in response to the environment and to the structure itself. We have applied this same principle in our simulation, in order to obtain a faithful simulation and plausible web models.

The next paragraph presents the procedure that simulates the mechanical equilibrium of the tensions in the web. We then go into the details of the actual construction, describing the most important assumptions that supplement the statistical and descriptive elements of Section 3.

4.1 Equilibrium of the Threads

Whenever threads are added, the dynamic equilibrium of the web is recomputed using an iterative relaxation procedure. The algorithm finds the new rest positions of the knots in the web. We assume that the tension of a silk line is linearly proportional to its length: $F = \sigma \times l$. The elasticity σ is constant for each given thread. Since frame lines are strengthened more than other lines, they are assigned a lower elasticity. On the other hand, the influence of the very elastic adhesive threads is considered negligible.

Figure 8 shows a knot $\mathbf{p}$ that is connected to three other knots $\mathbf{p}_1$, $\mathbf{p}_2$ and $\mathbf{p}_3$. It is locally balanced if the vector sum of the tensions in the connecting lines is 0. One can easily derive that this condition is met if

$$\mathbf{p} = \frac{\sigma_1\mathbf{p}_1 + \sigma_2\mathbf{p}_2 + \sigma_3\mathbf{p}_3}{\sigma_1 + \sigma_2 + \sigma_3}.$$

The iterative procedure loops over all knots $\mathbf{p}$ and computes their new local balance position $\mathbf{p}'$ using this equation. As the new positions may mutually influence other knots, this is repeated until the positions converge to a global equilibrium.

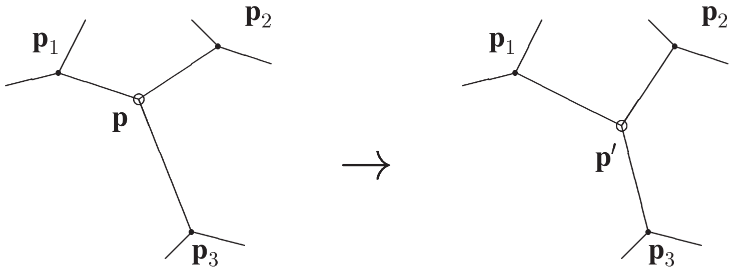

Figure 8: In the relaxation algorithm, each knot is repositioned such that the tensions in its lines are balanced. This procedure is repeated iteratively until the positions have converged to a global equilibrium.

4.2 Simulation of the Construction

The primary radial lines are constructed according the indicated position and orientation of the web. In order to find points to which to attach the silk lines, the algorithm traces geometric rays in the selected directions and computes their closest intersections with the geometry. This technique has proven to be versatile, as it is applicable to practically all possible types of geometry. In a first step the algorithm finds an object in the general direction by sampling the environment. In a second step the position is refined using a steepest descent method, so as to find a suitable protuberance. The algorithm thus creates webs that are adapted to the environment.

The secondary radial lines are connected nearby the center, between radial lines that span a certain minimum angle. If the raytracing procedure can find a nearby point to attach a line to the environment, the line is attached and a frame line is created. Otherwise it is attached to a newly created frame thread between the existing radial lines. If necessary, the frame is tightened using short links. The center mesh is constructed by incrementally adding short random threads that balance the structure. If distance to the frame along a radial line exceeds the desired size of the web, the radial line is connected to the frame thread by means of a link, thereby reducing the size of the frame. This procedure results in the short curved segments inside the frame.

The tertiary radial lines are constructed in a similar way. They are always fastened to the already existing frame. Their tensions cause the typical curves in the frame threads.

The hub is then created in a tight spiral around the unstructured center mesh. In our simulation we do not construct the preliminary spiral, as it only serves as a support when creating the final spiral, without influencing its structure.

Construction of the capturing spiral is started near the frame, spiraling inward across the radial threads. The position $\mathbf{p}$ for attaching the thread on a radial line is a weighted average of two positions. On the one hand the spider tends to follow an ideal spiral around an imaginary center of the web. This would lead to the position $\mathbf{p}_{\text{spiral}}$, which is computed with respect to the previous point of attachment. On the other hand the spider strives to maintain the ideal inter-distance from the frame or the previous spiral thread, corresponding to the position $\mathbf{p}_{\text{distance}}$. The weight w for combining these positions varies proportionally to the distance to the center d: $w = A \times d/D$, where D is the radius of the web and A is a factor that expresses the attraction to the frame. The point for attaching the spiral is thus expressed as

$$\mathbf{p} = (1 - w)\, \mathbf{p}_{\text{spiral}} + w\, \mathbf{p}_{\text{distance}}.$$

This functional approximation is simple, but it produces satisfactory results in our simulations for attraction factors A around 0.2.

Whenever the line comes too close to the frame or the warning thread, the direction of the spiral is reversed. The spiral ends when it comes within a given distance of the hub, thus leaving some space between the hub and the spiral.

The realism of the result is further improved by including small random variations during the construction. After the construction of the web insects and other environmental influences may still affect its structure. We simulate the destruction of spiral threads by randomly cutting a few, leaving small gaps in the web.

5 Results and Conclusions

Figures 9 and 10 show more examples of webs in different settings, in various sizes and shapes. The silk wires are modeled thicker than in real life to make them better visible. Still, the webs are relatively hard to render, as noted in [4, p.173]. We have rendered these images using a stochastic raytracing program, taking a large number of samples per pixel to avoid aliasing effects. Alternatively, with the proper precautions, other scanline algorithms or scene-based rendering algorithms might be used.

Our system models spider webs, based on arachnological studies and statistical data of real webs. The real-life construction procedures are incremental and act locally. A faithful simulation of these procedures successfully produces plausible models. The models are adapted to the environment in which they are placed. The success of a design partly depends on the position indicated by the modeler. The virtual spider will always attempt to construct a web, the best it can. If the location is not really suitable the web may look poor, which is just as in nature.

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Figure 9: A forest at dawn.

Figure 10: A teapot in a cupboard, covered by spider webs.