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Studies on the Geometrical Design of Spider Webs for Reinforced Composite Structures

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Abstract: Spider silk is an astonishingly tough biomaterial that consists almost entirely of large proteins. Studying the secrets behind the high strength nature of spider webs is very challenging due to their miniature size. In spite of their complex nature, researchers have always been inspired to mimic Nature for developing new products or enhancing the performance of existing technologies. Accordingly, the spider web can be taken as a model for optimal fiber orientation for composite materials to be used in critical structural applications. In this study an attempt is made to analyze the geometrical characteristics of the web construction building units such as spirals and radials. As a measurement tool, we have used a developed MATLAB algorithm code for measuring the node to node of rings and radials angle of orientation. Spider web image samples were collected randomly from an ecological niche with black background sample collection tools. The study shows that the radial angle of orientation is 12.7 degrees with 5 mm distance for the spirals' mesh size. The extracted geometrical numeric values from the spider web show moderately skewed statistical data. The study sheds light on spider web utilization to develop an optimized fiber orientation reinforced composite structure for constructing, for instance, shell structures, pressure vessels and fuselage cones for the aviation industry.

Keywords: composite design; fiber orientation; image processing; nature-inspired design; orb web

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1. Introduction

The co-evolution of spider web arrangements and silks began about 400 million years ago, at first possibly as a protein cover to protect the animal's eggs and young. Webs then evolved different functions, including acting as a wallpaper for the animals' tunnels and modifying holes into simple traps by radiating triplines that inform the lurking spider about things beetling around outside. Mimicking the silk production of a spider requires copying its silk extrusion and spinning system; for manufacturing silks 'the spider' way, we need atomic force microscopy that provides information about the surface of silks, and polarizing microscopy that informs about the internal order of silk structures that can accelerate the research on decoding the secrets behind spider netting. For the sake of survival in different situations, spiders have adjusted and changed their web architecture by providing casing, guards, and an efficient tool for trapping prey [1]. The web of spiders is composed of radial and spiral threads each with their own characteristics. Spider webs are a distinctive example of high-performance bio-material design in Nature.

Biomaterials are the construction materials used by Nature to build all living creatures. The structures of most of these biomaterials have evolved to maximize the performance of the function provided. Engineers often produce a biomaterial or process through emulating natural phenomena. The silks that form spiders' webs are an excellent example of these natural biomaterials that contribute to early human fishing net production. Spider silk is the model for engineering materials for its exceptional properties combining unique strength and toughness. Apart from their notable material properties, spider webs are natural models of a particular class of pre-stressed structures that are termed as tensional integrity (tensegrity) structures [2]. Such structures are characterized by unique geometries and mechanics that are used for making very efficient structures because of their geometry with optimal distribution of structural mass and play a significant role for the presentation as well as the toughness of a derived tensegrity creation. A self-stressing nature, which offers inelasticity, provides spider webs with a mechanism for a competent and economical means of harmonizing induced stresses. An understanding of the interactions between material properties and structural geometry may shed light on our ability to design the next generation of ultra-lightweight, large area space structures. Orb-weaving spiders construct orb webs by depositing protein-based silk materials through their spinnerets for catching prey, sensing vibrations and protecting their offspring. They are primarily collections of structural radial filaments and gluey spiral threads with circular geometry with different functional design objectives [1].

Furthermore, spider web arrangements have inspired numerous biomimetic material and structural designs in fields as diverse as art [3], architecture [4], batteries [5], and acoustics [6]. Several research laboratories are working on decoding the nature of spider webs' secrets [1]. The decoded nature of spider web arrangements can be applied for designing spider-web-inspired structures and arrangements. Such nature-tailored fibre arrangements can be used for composite product design, where the requirements of high-performance and light weight are needed like for long-span structures, vertical and horizontal pressure vessels, air radome retrofitting and construction, shell structure construction, renewable energy construction of dome reactors and wind turbine blade, the automotive industry, space science hardware construction and safety nets, among others [4].

Studies are reported on new methods to trace spider webs in an automatic, rapid, and precise way using image processing techniques via developing algorithms for extracting their geometrical features. Image processing is a technique used to carry out the specific processes needed to acquire an improved image or generate valuable data from processed images. It is a type of signal processing in which the input is an image and the output may be an image or some characteristics/features associated with that image [4,7].

Currently, image processing is among the most rapidly growing technologies, and artificial intelligence (AI) and computer vision techniques are the main core research areas that integrate engineering with computer science disciplines, which is the evidence for this research output. Image-processing of computer vision-based algorithm techniques can generate the geometrical features of the spider web. There are three general stages that all types of data have to undergo when using a digital image processing technique [7]:

1) Pre-processing: Importing the image via image acquisition tools with excellent pixel size,
2) Enhancement: Analyzing and manipulating the picture, and
3) Output reporting: imaging display attributes or features of information extraction.

With these stages, it is possible to perform image processing, analysis, and visualization by developing a purposeful algorithm used for image segmentation, image enhancement, noise reduction, geometric transformations, and image registration of 2D, 3D, and arbitrarily large images.

Several works have studied spiders' behavior. Some of them focus on using the way spiders build their webs as a source of information for species identification. AI systems have proven to be of incalculable value for these systems [8]. In [9], a model for spider behavior modeling, which provides simulations of how specific spider species build their webs, has been proposed and how spiders make their webs in a controlled scenario for further spatiotemporal analysis was recorded.

Spider webs convey an extraordinary amount of information that can be used by designers and material engineers [10]. Natural materials are acknowledged for their extremely improved structure and functions. They often exceed man-made materials in strength and toughness. They have grown into a source of inspiration for high-performance material design. Silk has become a pattern for up-grading molecular properties to the macro scale [8].

This article presents a study of geometrical features for orb species-made spider webs. The geometrical analysis for physical data extraction of point to point (node to node) distance, radial/mesh size and variation among them, and total spiral size and opening angle from x-axis are discussed. The study results are intended to be used in Nature-inspired design as a basis for fiber orientation in composite engineering for the design of an optimized composite structure.

2. State-of-the-Art on Spider Web Construction and Property

Spiders are abundantly available species in most ecological niches of this planet due to their evolutionary success for over 380 million years [11]. Undeniably, spiders have survived and succeeded in diverse environments due to their adaptive talents made possible because of their silk [12]. As indicated in Figure 1, spiders can swirl up to seven different types of silk with diverse characteristics and functions, such as flexibility and stickiness of viscid silk to catch prey or to provide strength and stiffness of dragline silk to make the web frame or as a safety line.

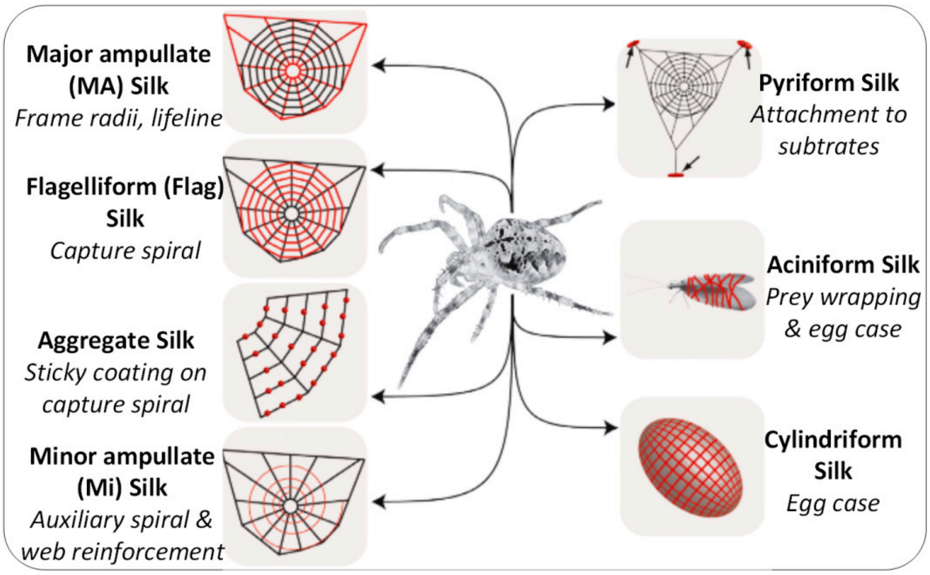

Figure 1. Different design of spider silks and their specific purpose as a web, adapted from [1].

All-embracing investigation has examined the mechanics of spider orb-webs, typically for two-dimensional (2D) webs built from stiff radial silk and extensible and sticky spiral threads to catch flying prey. The robustness of 2D orb webs results from the non-linear material behavior (dragline silk) that localizes the deformation and ruptures caused by a point [3]. In addition to the effect of non-linear mechanics of silk, the spider webs' geometry, which defines how the individual silk fibers are connected and anchored to substrates, plays a vital role in carrying out its biological functions of housing, protection, and prey capture. Ecologists believe that spiders needed a 3D barrier to protect themselves from predators [12]. To fully understand the structure-function relationship of webs, the intricate architecture of 2D or 3D webs needs to be revealed precisely with existing knowledge. The complex and irregular network of the silk fibers with micro-scale thickness is limited to the imaging toolkit to quantify web structures' topology [4]. Indeed, the thickness of silk fibers (approx. 1 mm) are only visible to human eyes under appropriate lighting conditions and angles [8]. Although it is possible to distinguish the fibers and visualize the web by dusting the web or spraying water, these methods are not suitable for precise imaging because they apply unknown loads that can generate deformations and contraction of up to 50% from water [13]. Non-destructive testing techniques such as computed tomography (CT) scans or ultrasound imaging do not work for webs because the fibers are too thin to be captured [4].

A spider web's architecture can be described by a confocal microscope with a limited sample and very close observation for its 2D projection. The 3D type of spider web could be imagined by micro-CT machines with high resolution with limited sample sizes and is not suitable for capturing the entire spider web [14]. Due to these confines, different authors have designed image processing by edge detection techniques. The wide application of image processing for a medical sector that successfully sense for very thin arteries and other organs to quantify and extract special features for prescription [15] have inspired scholars to extend image processing applications like Nature-based engineering design.

Orb weaving spiders build webs to act as traps for gathering prey. Once constructed, these webs also aid as a means to convey vibrational information to the spider and physical understanding of the web helps us use these geometrical structures for optimized design concepts [16]. Commonly spider webs' geometry is oriented perpendicular to the plane of the net—prey bearing impact occurs in the capture spiral portion of the web. The spiral strands are better impedance-matched to the radial strands in the out-of-plane direction and transmit more energy to them in these modes [17]. Such a model of capturing air-borne insects motivates investigating the spider web's geometrical features to implement them for engineering fiber orientations for structural design and production.

The appropriate fiber orientation is primarily determined by the loading condition of either uniaxial, biaxial, shear, or impact state of loading on the structures [18]. Countless scholars have carried out experimental studies to explore the outcome of fiber orientation impact on fibers [19]. Reported studies [20] showed the mechanical behavior of plain knitted and twill weaved fiber and revealed that a twill woven fiber ensures excellent mechanical properties as compared to the woven 0/90 mat. Woven mat fibers afford a proper equilibrium between mechanical properties, and it is the favorite form of standard fiber mats for an engineered composite product made by hand layup methods. Nevertheless, the impact of hybrid fiber orientation for ultimate tensile strength (UTS) of unidirectional and biaxial strength of fiber reinforcements is not sufficiently studied yet. Hybrid fiber orientation promotes a composite with high strength for different loading conditions and headway for composite structure reliability. Fiber orientations with 0°, 90°, +45°, and/or –45° is a standard method for designing fiber orientations and is a common practice to produce composite structures. Among these, 0°/90°, +45°/–45° orientation types are frequently used, but none of them are a Nature-inspired form of orientation [20].

Nature-inspired innovative composite design approaches are becoming interesting research and development areas to overcome the design limitations of fiber reinforced composite products. Fiber orientation is one of the parameters that determines the working stress of composite products to perform at their design load. Composites made in cylindrical form are extensively used in the aerospace, aeronautical, energy and marine industries. Cylindrical shells are exposed to different axial and lateral loads [21]. The pressure for enhanced product requirements from those industries are driving researchers to develop different optimization techniques for cylindrical shells. The Direct Fiber Path Optimization (DFPO) protocol is one of the recent works that promote the use DFPO as a method of tailoring the stiffness properties by fiber routing on the surface of composite cylinders for enhancing their precise linear buckling load under axial compression that is used to obtain non-symmetric buckling patterns [22]. Such research work can be extended to Nature-inspired optimization for tailoring stiffened engineering products via spider web arrangement fiber reinforcement for composite design.

The importance of process parameters concerning the merits and demerits of manufacturing methods for the better-quality performance was reported by different scholars [21]. Particularly, the rapid growth of fibre reinforced polymer (FRP) composite pipes has potentially attracted the attention of the oil and gas industry due to the benefits of corrosion resistance and structural flexibility of composite-made pipes. Fiber reinforcement of such pipes and pressure vessels practice conventional fiber orientation that has to be extended to replace the existing fiber orientation to new practices like Nature-inspired design of spider web-based reinforcements for enhanced design of those products. There are many techniques to optimize fiber orientation. A variable (angle-tow and stiffness) design under axial compression is a method adopted for design space, loads and boundary conditions. The use of such novel optimization concept based on the custom-made fiber placement method is one of the techniques used to optimize composite cylinders' thickness and fiber angle [22,23].

There is a practice to enhance the strength of composite structures to avoid fiber breakage and delamination by orienting the fibers following a patterned track around holes. Recently manufacturing method developments have led to the option of routing fibers in the plane of a sheet, thus manufacturing variable-axial (VA) laminates and expressively growing the design space offered to engineers. Automated fiber assignment (AFA), continuous tow steering and custom-made fiber assignment are the most widely used and appropriate procedures to yield such tow-steered paths. AFA is mainly suitable for the construction of shell-like structures with high productivity. However, local fiber folding, tow holes and overlays are the most frequent flaws observed in parts made by AFA. Such fiber arrangements can be used to mitigate the stress concentrations around holes that can be used for cut-out structures of engineering products [24].

In this study, an approach to extended optimization techniques by Nature-inspired methods of optimization is used that starts by decoding the natural web arrangement through image analysis of existing natural examples. The spider web geometrical architecture images analysis aims to generate figures for point to point distance on the spiral mesh, radial orientation of angle, counting the number of radial threads, and the relation of spiral and radial threads. Understanding of 3D spider webs can add new modalities for fiber orientation for mechanical strength optimization in composite structure design for pressure vessels, fuselages and small modular reactor products by Nature-inspired design methods.

3. Methods

3.1. Image Capture

In the preprocessing phase, which is a vital step to isolate the spider webs and remove possible effects of background in the system, the spider web images from uncontrolled environments were taken. Once the image capturing tool has captured the spider web image, the proportional ratio adjustment was necessary to obtain a balanced square image for image pixels' calibration to linear distance.

3.2. Data Extraction of Opening and Mesh Element Size of Spider Web

This is an approach used to collect data or real picture of the web and prepare the study samples, and it involved the following:

1) Collecting real pictures for orb webs as a study sample.
2) Developing an algorithm/use a pre-made one that helps measure the required geometry.

3) Data manipulation (loading pictures, calibrating the algorithm working systems for equating the size of pixels to the linear distance or measurement (distance and angle in cm/mm)).
4) Conducting measurements of the theta and p2p distance with the developed MATLAB algorithm.
5) Generating reports for mean, mode, variance, min and maximum.
6) Reporting the extracted features.

After collecting real pictures of webs as study samples, the MATLAB algorithms extracted each radial opening angle and mesh size of the spider web that radiated from center to tip. The original pictures of the examined spider webs were taken using an Infinix Note 7 Lite smart phone camera as picture capturing tool that is designed with an autofocus camera and an embedded artificial intelligence (AI) system and a black background was used to enhance the quality the images of the specimens. After running the developed MATLAB algorithm for measuring purposes, there should be a calibration of the image pixels to the linear measurement of real spider web pictures and processing for further feature extraction.

3.3. Methods for Coding the MATLAB Measurement Algorithm

To measure the angle and linear distance of the fibers with invisible size for the naked eye, a MATLAB code algorithm was developed in house and modified to calibrate pixels to linear or angular translations of the spider web images. The coding work involves the following steps:

Step 1: Calculation of the actual dimensions to pixel ratio by measuring the background distance and the pixel dimensions.

Step 2: Writing a code using MATLAB that can measure the distance between two points on an image using pixel distances. Every point in an image is represented by a color value at that row and column. Hence, to measure the distance between the two points, it just needs to record the row and column position of the two points and calculate the Euclidean distance between them. This will give the distance between the two points in pixels and the angle between two lines will be calculated geometrically in the same way explained for linear measurement.

Step 3: The pixel distance was converted into a actual measurement by using the ratio calculated in Step 1.

This study collected original spider web pictures from a 110 mm × 150 mm sized office window grid at our university (Addis Ababa Science and Technology University, AASTU). Thus, except for one sample, all samples contained 580.2 pixels used for calibration for 110 mm of actual web size. The extraction of radial opening angles was conducted based on the ratio of pixels to actual captured pictures size as the fundamental measuring parameter and the obtained result are discussed in the following section.

4. Discussion of Results

By using the developed MATLAB algorithm, the extraction process of the geometrical features has been done on five different types of spider web images that were collected from AAST windows of steel frame construction by a random selection method from an existing niche. The process of obtaining numerical values via measuring the photo of the spider web for its angle of opening and point to point distance data required the calibration of the pixels to linear measurement ratio. By using the MATLAB 2020 tool kit, the spider web photos were loaded independently for extraction of opening angles, and the generated data analyzed by Microsoft Excel and descriptive statistical data thus obtained.

4.1. Methods for Extraction of Spider Web Radials Orientation

After careful collection of geometrical data for radial orientation through the MATLAB measuring tools algorithm, data was generated independently from the selected spider web images calibrated at 580.1 pixel with 110 mm distance (Figure 2) The measured opening angle of spirals in Figure 2b show that the mean of the radial orientation is 13.7°, i.e., approximately 14°, and the frequently used radials orientation in web construction of samples, designated as SP1, is 11.04°. Thus, there is an indication of a 11° −14° range as radial orientation angles favorable for such tight web building.

The unmeasured and measured images of five samples, designated as SP1, SP2, SP3, SP4 and SP5, are depicted in Figures 2–6, respectively. A summary of the statistical description of the images is presented in Table 1.

Figure 2. (**a**) Unmeasured image (**b**) measured image of SP1.

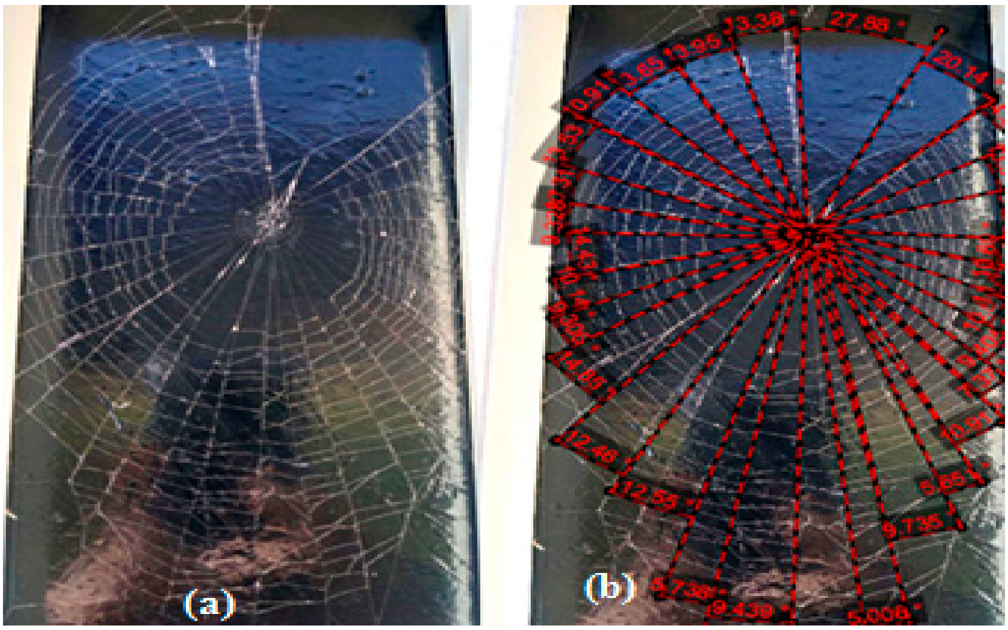

Figure 3. (**a**) Unmeasured image (**b**) measured image of SP2.

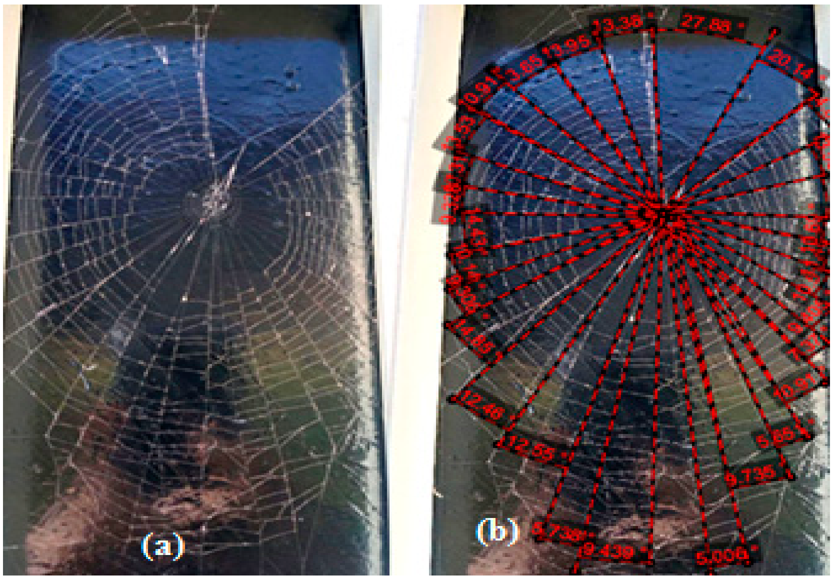

Figure 4. (**a**) Unmeasured image (**b**) measured image of SP3.

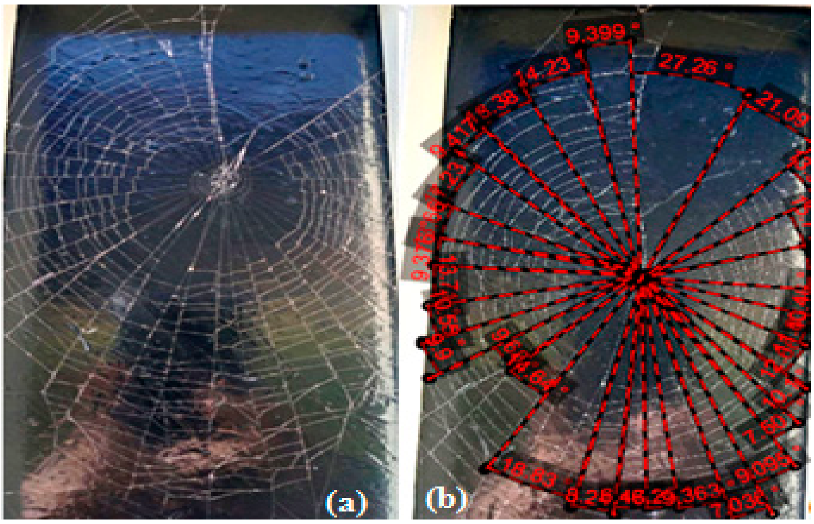

Figure 5. (**a**) Unmeasured image (**b**) measured image of SP4.

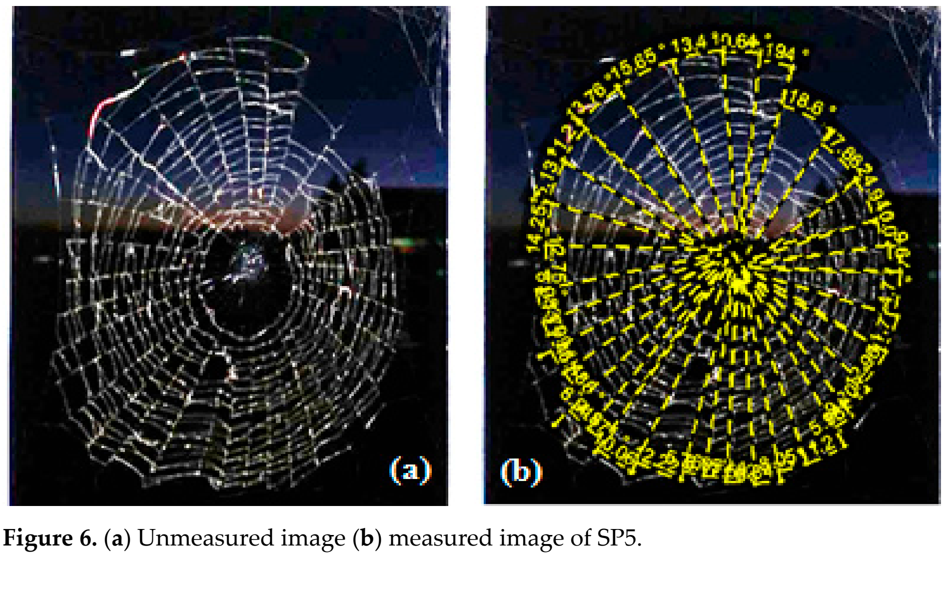

Figure 6. (**a**) Unmeasured image (**b**) measured image of SP5.

Table 1. Summary of measured angle (θ) of spider webs radials for five images.

Extracted Data for the Opening Angle of Spider Web Radials from the Sampled Image					
Statistics Descriptive	**Sample SP1**	**Sample SP2**	**Sample SP3**	**Sample SP4**	**Sample SP5**
	$\theta_{1\text{–}26\ \text{radials}}$	$\theta_{1\text{–}31\ \text{radials}}$	$\theta_{1\text{–}25\ \text{radials}}$	$\theta_{1\text{–}28\ \text{radials}}$	$\theta_{1\text{–}32\ \text{radials}}$
Mean	13.70	11.87	14.52	12.47	11.13
Standard Error	0.87	0.78	1.89	0.92	0.77
Median	12.72	10.69	12.57	11.19	10.35
Mode	11.04	9.33	No	No	11.20
Standard Deviation	4.46	4.37	9.44	4.85	4.35
Sample Variance	19.90	19.09	89.09	23.55	18.91
Kurtosis	−0.93	5.17	9.59	1.82	1.89
Skewness	0.29	1.86	2.81	1.22	1.10
Range	15.34	22.67	45.29	20.97	20.07
Minimum theta	7.31	5.21	6.01	6.29	4.87
Maximum theta	22.65	27.88	51.30	27.26	24.94
Sum of angle for web	356.24	368.04	362.91	349.06	356.07
Qty of spirals in web	26.00	31.00	25.00	28.00	32.00

As the values in Table 1 show, there are different quantities of spirals used for web construction ranging from 25 for sample SP3 to 32 for SP5. Accordingly, the opening angle ranged from 11°–13° (Figure 7). The statistical results in Table 1 also depict that there is tight opening angle utilization by the spider for web construction, and the cumulative mean of all collected samples shows that the favorable angle of the spider for orientation in web construction is 12.7°. The radial orientation is also observed to be asymmetrical with an appropriate skew.

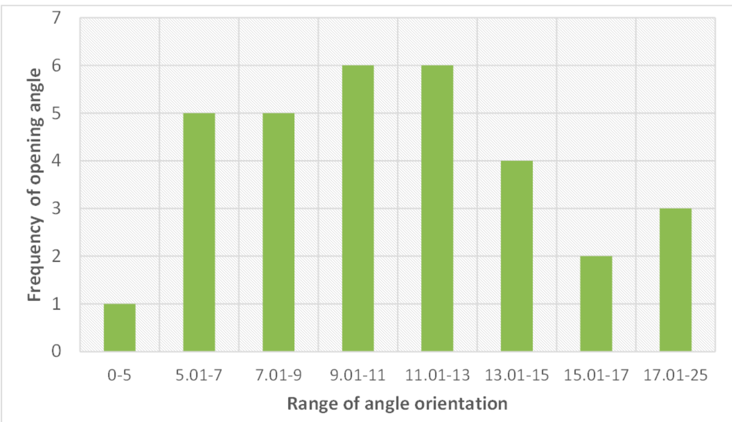

Figure 7. Histogram of spider web opening angle for sample SP5.

4.2. Extraction of Spider Web Node to Node Distance by Element-Wise Measurement

The node to node distance was extracted from three samples of 545 elements that were collected independently to extract the statistical data for obtaining the trends of mesh element size distribution in the construction of spider webs. The cumulative data indicates that there are acceptable values of skew and kurtosis among the extracted data. The mean values of the 545 extracted data for mesh element size show that 5 mm liner distance between node to node distances of the spirals. However, spiders weaves their web spirals asymmetrically, i.e., there is a tight spacing between a mesh of web building elements in the spirals.

For a generalization of the point to point distance measurement along with the seven samples of spider, web spirals have been detected, and measurement has been taken through the developed algorithm in which the statistical description is summarized in Table 2.

Table 2. Summary of extracted data for a spiral distance of sample SP1.

Descriptive Statistics	Node to Node Distance Extracted Data for Sample SP1						
	Spiral 1	**Spiral 2**	**Spiral 3**	**Spiral 4**	**Spiral 5**	**Spiral 6**	**Spiral 7**
Mean	14.88	3.97	3.36	2.55	3	2.94	2.64
Standard Error	1.14	0.31	0.22	0.25	0.24	0.24	0.18
Median	13.13	3.76	3.65	2.32	3.12	2.9	2.61
Standard Dev.	5.7	1.59	1.14	1.27	1.21	1.22	0.94
Sample Variance	32.59	2.55	1.3	1.62	1.48	1.49	0.89
Kurtosis	−1.18	7.23	4.81	6.62	2.17	3.35	1.09
Skewness	0.37	1.31	−2.12	1.73	−0.83	0.53	−0.5
Range	18.24	9.62	4.61	7.14	5.72	6.6	4.21
Maximum	24.21	9.62	4.61	7.14	5.72	6.6	4.21
Sum off used yarn	372.15	99.33	84.06	63.93	75.18	73.66	66
No. of Elements	25	25	25	25	25	25	25

As indicated in the table's right side, the spider's real picture web located at 110 mm grid spacing, and the photograph accounts for 580.2 pixels, and is used as a calibration standard for the developed algorithm and facilitated the data extraction process.

In data analysis, skewness is a measure of the irregularity of the probability spreading of an arbitrary variable about its mean [25,26]. The skewness value can be positive or negative. If skewness is 0, the data are perfectly symmetrical, although it is quite unlikely for real-world data. As a general rule of thumb [27]:

- If skewness is < −1 or > 1, the distribution is highly skewed,
- If skewness is between −1 and −0.5 or between 0.5 and 1, the distribution is moderately skewed and
- If skewness is between −0.5 and 0.5, the distribution is approximately symmetric.

According to this rule of thumb, Figure 8 depicts that symmetrical measure of point to point distance in construction of the first spiral of orb web unit and Figure 9 (see also Table 3) indicates that except the central or first spirals all measures of point to point weaving by orb web accounts for moderate skewness.

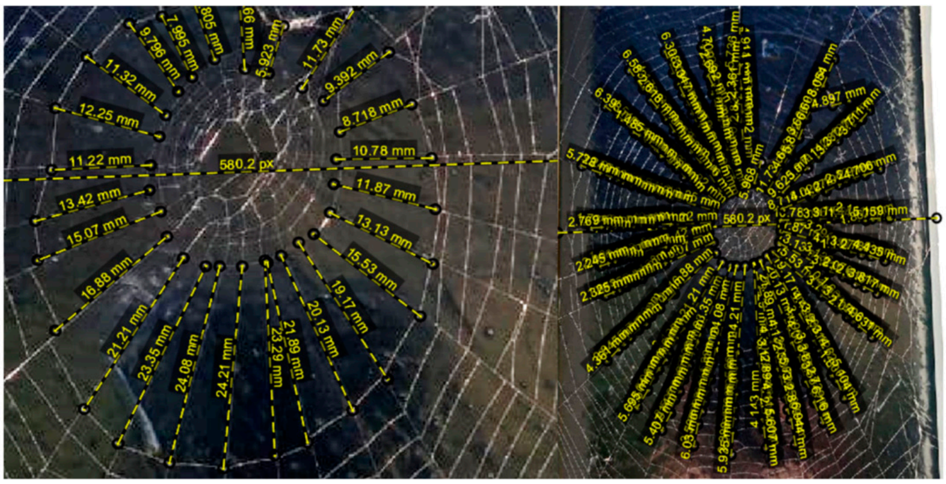

Figure 8. First spiral statistical geometric data and point of location indication.

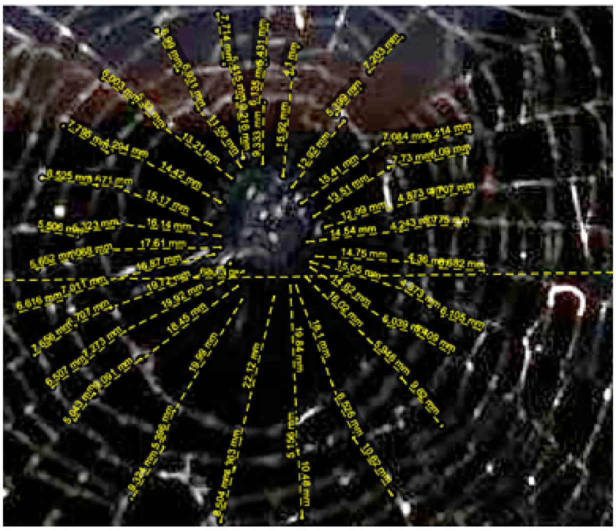

Figure 9. Geometrical measure of orb image of spider web and its statistical data report.

Table 3. Geometrical extracted data of node to node size for sample SP5.

Statistics Descriptive	Spiral 1	Spiral 2	Spiral 3	Spiral 4	Spiral 5	Spiral 7	Spiral 7
Mean	15.66	5.59	7.02	7.62	7.76	7.84	8.07
Standard Error	0.66	0.26	0.34	0.30	0.30	0.44	0.54
Median	15.17	5.33	6.62	7.32	7.30	8.10	7.60
Mode	NA	NA	NA	NA	7.30	5.00	5.30
Standard Deviation	3.32	1.31	1.70	1.48	1.52	2.22	2.70
Sample Variance	11.04	1.73	2.89	2.18	2.32	4.95	7.32
Kurtosis	−0.32	0.55	−0.35	1.60	−0.59	−0.71	−0.88
Skewness	−0.09	0.87	0.73	0.97	0.55	0.41	0.42
Range	12.90	5.42	5.91	6.85	5.60	7.35	9.20
Minimum distance	9.22	3.67	4.71	5.04	5.20	4.90	3.90
Maximum distance	22.12	9.09	10.62	11.89	10.80	12.25	13.10
Sum of yam used	391.52	139.75	175.56	190.45	194.00	195.94	201.80
No. of elements	25.00	25.00	25.00	25.00	25.00	25.00	25.00

5. Conclusions

The motivation for the research reported in this article is that spider silk exhibits exceptional properties, such as strength, toughness, elasticity and robustness, which make it to surpass other biological and engineering materials. Spider silk as a natural fiber has long been recognized as a wonder fiber for its unique combination of high strength and elongation before rupture. An earlier study indicated that spider silk has strength as high as 1.75 GPa at a breaking elongation of over 26%, with toughness more than three times that of Aramid and other industrial fibers [17]. Spider silk continues to attract the attention of fiber scientists and hobbyists alike. In addition to the effect of nonlinear mechanics of silk, the geometry of spider web, which defines how the individual silk fibres are connected and how they are anchored to substrates, plays an important role in carrying out its biological functions such as housing, protection and prey capture [10] which have to be mimicked for reverse engineering.

This work reports the geometrical study of spider webs by measurements processed by a developed MATLAB algorithm. Using appropriate picture capturing tools, the distance of the spiral meshes and angle of radial orientations of the spider webs were quantified from real captured images.

Analysis of the collected images of the spider web weas performed by a measurement tool in MATLAB package. The extracted data for 994 radial opening angles from five images indicated that the mean opening angle of the spider web is 12.7°, which can be approximated to 13°, that indicates the radial angle distribution is approximately symmetric. Furthermore, the extracted data for 545 elements that were collected from three purposely selected sample images depicted that the elemental (node to node) mean distance amounts to about 5 mm and the total silk used for the construction of web mesh took about an average of 1250 mm for the whole node to node building in the captured image with 580.2 pixels. It is also observed that the distance measurement on the node to the node of the spider i.e., the mean values of all the first center to outwards are larger than the rest of all elements that are used to build the web. The study described here presents a new method to trace spider webs quickly and precisely to quantify the size of spider meshes for further exploration. Moreover, this 2D image-based geometrical study will be instrumental to expand our understanding of measuring any captured image via calibration of the pixels to the linear distance through developed algorithms. Furthermore, it is essential to evaluate if and how localization of fiber orientation built across the web occurs, which can be used as a platform to create a refined localized angles of orientation to design optimized structures that function in real-time.

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References

1. Eisoldt, L.; Smith, A.; Scheibel, T. Decoding the secrets of spider silk. *Mater. Today* **2011**, *14*, 80–86.
2. Hesselberg, T.; Vollrath, F. The mechanical properties of the non-sticky spiral in *Nephila orb* webs (Araneae, Nephilidae). *J. Exp. Biol.* **2012**, *215*, 3362–3369.
3. Cranford, S.W.; Tarakanova, A.; Pugno, N.M.; Buehler, M.J. Nonlinear material behaviour of spider silk yields robust webs. *Nat. Cell Biol.* **2012**, *482*, 72–76.
4. Su, I.; Qin, Z.; Saraceno, T.; Krell, A.; Mühlethasler, R.; Bisshop, A.; Buehler, M.J. Imaging and analysis of a three- dimensional spider web architecture. *J. R. Soc. Interface* **2018**, *15*, 1–11.
5. Zhang, Y.; Guo, L.; Yang, S. Three-dimensional spider-web architecture assembled from Na2Ti3O7 nanotubes as a high-performance anode for a sodium-ion battery. *Chem. Commun.* **2014**, *50*, 14029–14032.
6. Su, I.; Buehler, M. Dynamic mechanics. *Nat. Mater.* **2016**, *15*, 1054–1055.
7. Ticay-Rivas, J.R.; del Pozo-Baños, M.; Gutiérrez-Ramos, M.A.; Eberhard, W.G.; Travieso, C.M.; Jesús, A.B. Image Processing for Spider Classification. In *Biodiversity Conservation and Utilization in a Diverse World*; IntechOpen: Rijeka, Croatia, 2012.
8. Su, I.; Buehler, M.J. Nanomechanics of silk: the fundamentals of a strong, tough and versatile material. *Nanotechnololgy* **2016**, *27*, 1–15.
9. Qin, Z.; Compton, B.G.; Lewis, J.A.; Buehler, M.J. Structural optimization of 3D-printed synthetic spider webs for high strength. *Nat. Commun.* **2015**, *6*, 1–7.
10. Harmer, A.M.T.; Blackledge, T.A.; Madin, J.S.; Herberstein, M.E. High-performance spider webs: integrating biomechanics, ecology and behaviour. *J. R. Soc. Interface* **2011**, *8*, 457–471.
11. Blackledge, T.A.; Scharff, N.; Coddington, J.A.; Szu, T. Reconstructing web evolution and spider diversification in the molecular era. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 5229–5234.
12. Smith, M. Condition-dependent spider web architecture in the western black widow. *Latrodectus Hesperus*. *Anim. Behav.* **2007**, *73*, 855–864.
13. Madrigal-Brenes, R.; Barrantes, G. Construction and function of the web of *Tidarren sisyphoides* (Araneae: Theridiidae). *J. Archeol.* **2009**, *37*, 306–311.
14. Saint Martin, J.-P.; Saint Saint, S.; Bolte, S.; Nèraudeau, D. Spider web in Late Cretaceous French amber (Vendée): The contribution of 3D image microscopy. *C. R. Palevol.* **2014**, *13*, 463–472.
15. Debelee, T.G.; Kebede, S.R.; Schwenker, F.; Shewarega, Z.M. Deep learning in selected cancers' image analysis—A survey. *J. Imaging* **2020**, *6*, 121.

16. Jiang, Y.; Nayeb-hashemi, H. Dynamic response of spider orb webs subject to prey impact. *Int. J. Mech. Sci.* **2020**, *186*, 105899.
17. Ko, F.K.; Jovicic, J. Modeling of mechanical properties and structural design of spider web. *Biomacromolecules* **2004**, *5*, 780–785.
18. Yang, I.-Y.; Im, K.-H.; Hsu, D.K.; Dayal, V.; Barnard, D.; Kim, J.-H.; Cha, C.-S.; Cho, Y.-T.; Kim, D.-J. Feasibility on fiber orientation detection of unidirectional CFRP composite laminates using one-sided pitch—Catch ultrasonic technique. *Compos. Sci. Technol.* **2009**, *69*, 2042–2047.
19. Köbler, J.; Schneider, M.; Ospald, F.; Andrä, H.; Müller, R. Fiber orientation interpolation for the multiscale analysis of short fiber reinforced composite parts. *Comput. Mech.* **2018**, *61*, 729–750.
20. Moakher, M.; Basser, P.J. Fiber orientation distribution functions and orientation tensors for different material symmetries. In Visualization and Processing of Higher Order Descriptors for Multi-Valued Data; Hotz, I., Schultz, T., Eds.; Mathematics and Visualization; Springer Switzerland: 2015 ; pp. 37–71.
21. Prabhakar, M.M.; Rajini, N.; Ayrilmis, N.; Mayandi, K.; Siengchin, S.; Senthilkumar, K.; Karthikeyan, S.; Ismail, S.O. An overview of burst, buckling, durability and corrosion analysis of lightweight FRP composite pipes and their applicability. *Compos. Struct.* **2019**, *230*, 111419.
22. Almeida, J.H.S., Jr.; Bittrich, L.; Jansen, E.; Tita, V.; Spickenheuer, A. Buckling optimization of composite cylinders for axial compression: A design methodology considering a variable-axial fiber layout. *Compos. Struct.* **2019,** *222*, 110928.
23. Wang, Z.; Almeida, J.H.S., Jr.; St-Pierre, L.; Wang, Z.; Castro, S.G.P. Reliability-based buckling optimization with an accelerated Kriging meta model for filament-wound variable angle tow composite cylinders. *Compos. Struct*. **2020**, *254*, 112821.
24. Almeida, J.H.S., Jr.; Bittrich, L.; Spickenheuer, A. Improving the open-hole tension characteristics with variable-axial composite laminates: Optimization, progressive damage modeling and experimental observations. *Compos. Sci. Technol.* **2020**, *185*, 107889.
25. Bono, R.; Arnau, J.; Alarcon, R.; Blanca, M.J. Bias, precision, and accuracy of skewness and kurtosis estimators for frequently used continuous distributions. *Symmetry* **2020**, *12*, 1–17.
26. Kollo, T. Multivariate skewness and kurtosis measures with an application in ICA. *J. Multivar. Anal.* **2008**, *99*, 2328–2338.
27. Singh, A.K.; Gewali, L.P.; Khatiwada, J. New measures of skewness of a probability distribution. *Open J. Stat.* **2019**, *9*, 601–621.