UNIVERSITI SAINS MALAYSIA

Laporan Akhir Projek Penyelidikan Jangka Pendek

Investigation on Mechanics of Folded Shell Like Surface Found in Nature

by

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ATTACHMENT 1

A research work has been carried out on the leaf of **Johannesteijsmannia altifrons**. This work falls within a comprehensive study with the ultimate aim of arriving at structural systems inspired from the leaf of **Johannesteijsmannia altifrons**. Surface data of the leaf is first captured using structured lighting method. A total of two leaves have been chosen for measurement. The captured data has been used to generate a model of the leaf. Two CAD based approaches, namely Pure/Rigid Geometry Approach and Natural Geometry Approach, for the purpose of generating doubly curved surfaces with folds have been proposed. These two approaches can be used to generate a variety of novel structural forms of shell surface with folds. Output from the generation procedures using the CAD based approach serves as input data for computational analysis in order to investigate the structural behaviour of shell surface with folds - a structural form inspired by nature.

Satu kajian telah dijalankan keatas daun ***Johannesteijsmannia altifrons.*** *Kajian ini tergolong dalam satu kajian lebih terperinci dengan objektif utama untuk menghasilkan sistem struktur yang diilhhamkan oleh daun* ***Johannesteijsmannia altifrons.*** *Data permukaan daun terlebih dahulu diukur dengan menggunakan kaedah pencahayaan berstruktur. Sejumlah dua daun telah dipilih untuk tujuan ukuran. Data yang diperolehi telah digunakan untuk menghasilkan satu model permukaan dalam bentuk daun yang dikaji. Dua pendekatan berdasarkan CAD, yang diberi nama sebagai Pendekatan Geometri Tulin/Tegar dan Pendekatan Geometri Semulajadi, untuk tujuan menjana data untuk permukaan lengkung dengan lipatan telah dibangunkan. Kedua-dua pendekatan ini boleh digunakan untuk menjana pelbagai permukaan kelompang dengan lipatan yang baru. Hasil penjanaan dari pendekatan berkenaan digunakan dalam proses analisis berkomputer untuk tujuan menyelidik kelakuan struktur permukaan kelompang dengan lipatan – satu sistem struktur yang diilhamkan oleh alam semulajadi.*

ATTACHMENT 2

Folded Shell Structures Inspired from the Leaves of *Johannesteijsmannia altifrons*

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Abstract

Research work carried out on the leaf of ***Johannesteijsmannia altifrons*** *is presented in this report. This work falls within a comprehensive study with the ultimate goal of arriving at structural systems inspired from the leaf of* ***Johannesteijsmannia altifrons****. Surface data of the leaf is first captured using structured lighting method. The captured data is then used to generate a model of the leaf. Two approaches, namely Pure/Rigid Geometry Approach and Natural Geometry Approach, for generating doubly curved surfaces with folds which have been proposed are highlighted upon.*

1. Introduction

Nature is very smart in optimizing shape and material. Comprehensive understanding of how nature handles such tasks under tight environmental constraints that can be limited as well unfavourable is a key issue to many researchers today. Surfaces found in nature offer a rich source of ideas for possible applications in engineering structures. Animal shells and plant leaves are among the natural surfaces that serve as a potential source of mimicry for new structural systems. Examples of studies inspired from nature are carried out by (Jirapong & Krawczyk [1], Balz & Güring [2], De Focatiis & Guest [3] and Kobayashi, Kresling & Vincent [4]).

Fig.1: Picture showing heights reached by Ja

In this research, the leaves of a majestic plant called ***Johannesteijsmannia altifrons (Ja)*** which belongs to the palm family have been investigated (Fig. 1). The leaves of *Ja* resemble a cantilevered shell structure with folds extending from the central spine. Such a combination of shell surface and folds might have contributed to the ability of the leaves to extend to a span of about 6 m. Apart from such positive structural merit, the existence of folds has also added element of aesthetic to the natural surface due to the interplay of shadows caused by the folds. In a pioneering work, (Ng [5]) has modeled the surface of ***Ja*** and investigated the leaf behavoiur under load through finite element analysis.

Apart from the data capturing part using structured lighting method, this briefing also highlights on methods of generating doubly curved surfaces with folds that resemble the surface of ***Ja*** – a natural object – which could possibly be adapted for engineering structures such as roofs. Comments on current stage of research and future tasks are also given.

2. Surface Data Acquisition

Due to the very flexible/deformable nature of the leaf of ***Ja***, a non-contact method called structured lighting method is used to measure the surface. The experimental setup used in capturing the leaf images is shown in Fig. 2. It is to be noted that the leaf pictures with shifted fringes on its surface are captured without cutting the leaf from its containing pot. This is an important aspect in order to compute a model that closely represents the leaf in its natural condition.

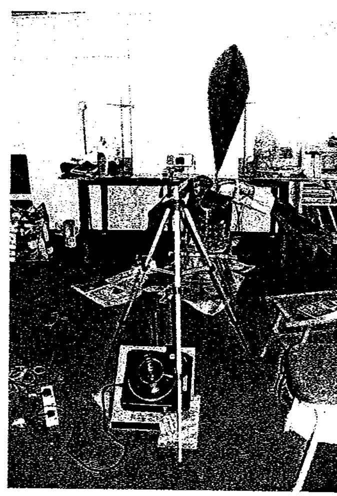

Fig. 2: Experimental setup for Ja measurement

The principle used in getting the 3D surface data of the leaf is illustrated in Fig. 3. 'S' is the measured shift in fringe which is used to obtain 'Z' through the equation ($Z = S/\tan\theta$). Fig. 4, shows the image used to calculate the 3D coordinates with the help of the shifted fringes over the surface of the leaf. The final result in the form of mesh and rendered shapes is shown in Fig. 5. The results obtained are quite representative to reflect the actual shape of the leaf.

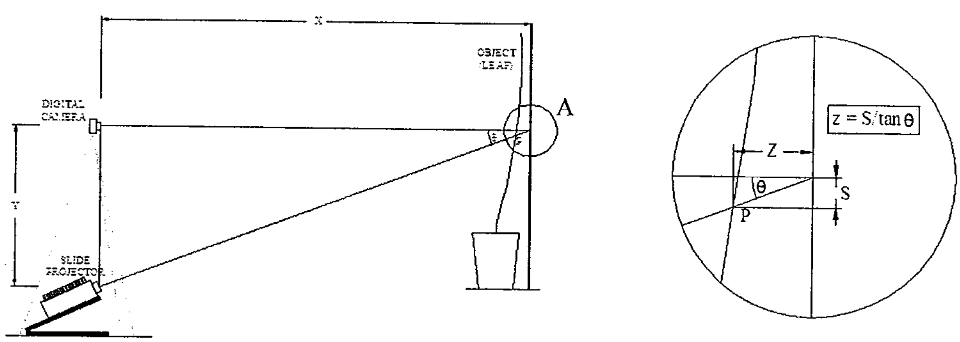

Fig. 3: Line diagram of the setup for measurement of leaf of *Ja* and the detail at A

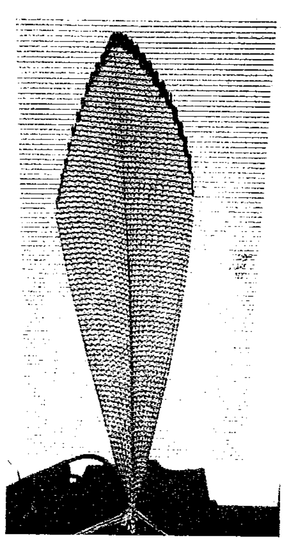

Fig. 4: Image of *Ja* leaf with fringe projections

Fig. 5: Meshed and rendered shapes of the modeled *Ja* leaf

3. Generation of Doubly Curved Folded Surfaces

Two, CAD based, approaches are proposed for generating doubly curved folded surfaces namely: "Pure/Rigid Geometry Approach" and "Natural Geometry Approach" (A-Razzack & Choong [6], A-Razzack et. al. [7] and A-Razzack, Choong & A-Majid [8]).

3.1 Pure/Rigid Geometry Approach

This approach is based on pure/rigid geometrical shapes (quadrilaterals). Under this category two types of models are generated. One by rotating the adjacent sides about only one diagonal of the quadrilateral (Figs. 6a & 6b) and the other through rotating the adjacent sides about both diagonals (Figs. 7a & 7b).

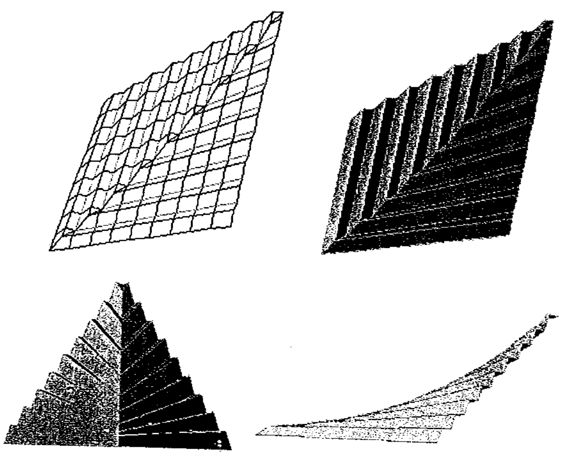

Fig. 6a: Meshed and rendered shapes of model generated using pure/rigid geometry with rotation about one axis

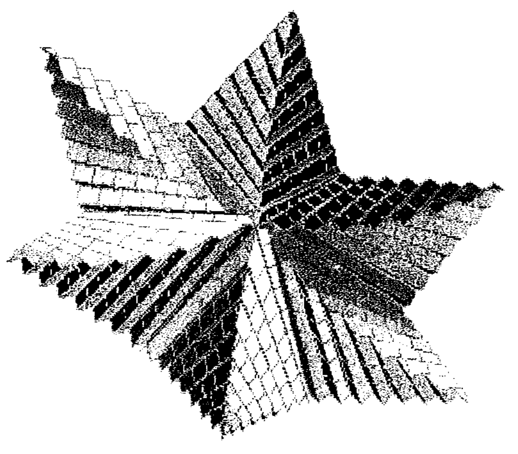

Fig. 6b: Possible shape of roofing systems (Rigid geometry & rotation about one axis)

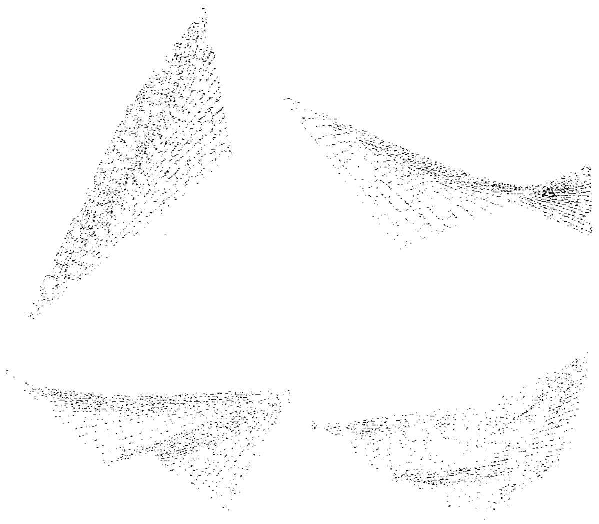

Fig. 7a: Meshed models generated using pure/rigid with rotation about both axes

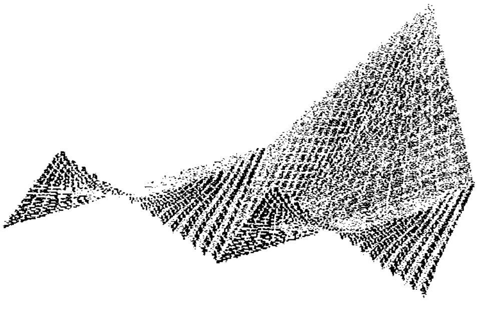

Fig. 7b: Rendered model of possible roofing system (Rigid geometry & rotation about both axes)

3.2 Natural Geometry Approach

Here, the 3D natural leaf boundary obtained from structures lighting melthod (Section 2) is used as the base upon which the entire leaf surface modeling is carried out. This approach differs from the rigid geometry approach (Section 3.1) in the first step of modeling where the rigid boundary frame is replaced by the natural boundary. Fig. 8, shows meshed and rendered shapes of the generated model.

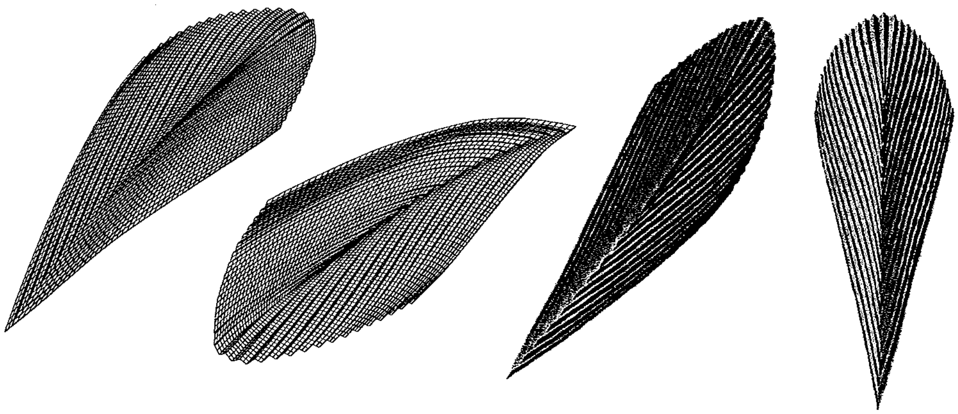

Fig. 8: Meshed and rendered shapes of the generated model (Natural geometry approach)

4. Conclusion

Structured lighting method has been successfully applied to model the ***Ja*** leaf thereby making the neccessary mesh data available for finite element analysis. Methods for generating double curved folded surfaces have been developed. These mothods provided the ground work on the basis of which realistic CAD based models of roofing systems can be generated for structural analsysis. The forseen advantage of the research is the evolution of a new categroy of doubly curved folded roofing systems made of thin concrete shell with inspiration coming from the world of nature.

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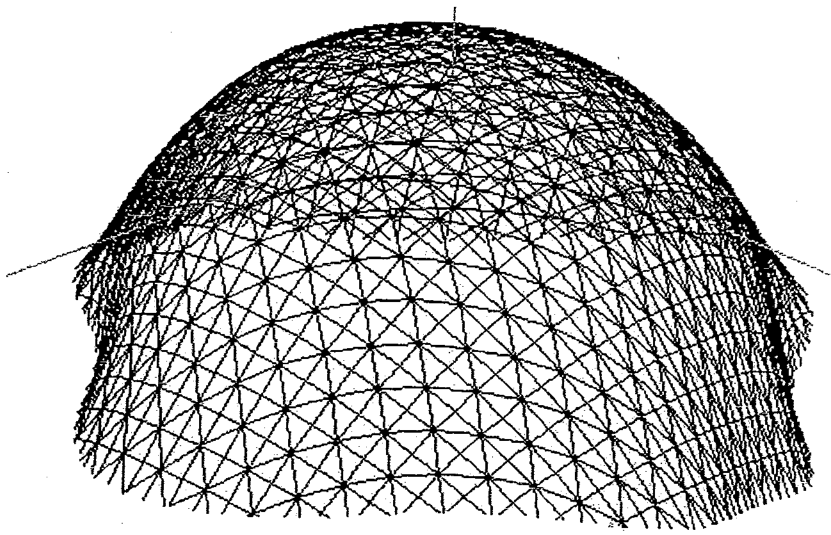

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A STUDY ON SHELL SURFACE WITH FOLDS – A NATURE INSPIRED IDEA FROM LEAVES OF JOHANNESTEIJSMANNIA ALTIFRON

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SUMMARY

In this research the surface data of the leaf is first captured using structured lighting method. The captured data is then used as input to generate a unit folded shell surface and variations that closely follow the natural geometry of the actual leaf. Two approaches, namely Pure/Rigid Geometry Approach and Natural Geometry Approach, for generating doubly curved surfaces with folds are also presented. The aim of this paper is to introduce an alternative structural concept for roof structures that combines both structural efficiency and architectural beauty inspired by nature.

Keywords: *Shells in nature, folds, Johannesteijsmannia altifrons, and nature inspired roof system.*

1. INTRODUCTION

Nature is very smart in optimizing shape and material. Using ideas from nature is justifiable based on the fact that existing natural systems could survive over thousands of years through adapting to the prevailing environmental conditions using nature's limited resources in an amazingly efficient manner. In case of engineering structures and materials the concern is cash cost whereas in case of natural systems, the cost is energy and the competition is not commercial but the more severe one of nature where the fittest survives and failures remain as fossils. Comprehensive understanding of how nature handles such tasks is a key issue to many researchers today. Learning from nature is called "Biomimetics or Biomimicry".

The term biomimetics was introduced in 1972 in the context of artificial enzymes as "the abstraction of good design from nature", George [1]. Biomimetics has also been defined as "the study of nature for the purpose of applications in technology, sometimes these studies lead to further discoveries about the natural systems they originate from", De Focatiis [2].

Biomimicry, with a broad perspective, as a systematic classified approach based on the function to be achieved has been presented by Benyus [3] who looks at nature as Model, Mentor and Measure. She discussed the term through exploring seven questions as examples of imitating the strategies followed by natural systems.

The European Space Agency [4], gives another systematic classification of biomimicry in the form of Biomimicry Technology Tree which, covers five areas of applications or functions to be achieved.

Vincent and Mann [5], introduced the idea to incorporate the biological knowledge into the current established non-biological knowledge database of inventive problem solution techniques known as TRIZ[1], a Russian abbreviation for (Teoryia Recheniya Izobretatelskikh Zadatch).

[1] TRIZ is invented by Genrich Altshuller (1988) meaning the Theory of Inventive Problem Solving based on current knowledge in mathematics, physics and chemistry. It is the biggest study ever carried out in human history which involves over 1500 person years of effort, with the target of building a functionally classified system that covers the known solutions to different science and engineering problems based on only 40 principles. Further information on TRIZ can be found on (http://www.triz.org).

Bogatyreva et el [6], reported on a project under execution at University of Bath to construct a database for incorporating the biologically inspired work achieved so far into TRIZ.

Surfaces found in nature offer a rich source of ideas for possible application as engineering structures. Animal shells, sea shells and plant leaves are among the natural surfaces that serve as a potential source of mimicry for new structural systems.

Jirapong & Krawczyk [7], studied seashells of spiral shapes. A mathematical model is proposed to describe the shell geometry with the objective of generating new architectural forms that can be used as input for structural analysis of the system. Balz & Güring [8], modeled the petal shapes of orchid blossom to study the shape-stability behaviour. They proposed this kind of structure for deployable or temporary buildings made of membranes and erected by air or water pressure. De Focatiis & Guest [9], looked into the deployment of tree leaves to find patterns for folding membranes aiming to arrive at structures which can be reduced in size for transportation or storage, and then automatically deployed. Kobayashi, Kresling & Vincent [10], modeled the leaves of hornbeam and beach as plane surfaces, with straight parallel folds, using numerical methods and studied their folding patterns for applications to areas such as solar panels, light weight antennae of satellites, deployable membranes such as tents, clothes or other coverings. Choong and Voon [11], carried out a study on the chicken egg shell to investigate its structural merits (strength and rigidity) versus shells of elliptical and spherical shapes.

This study investigates a majestic plant called Johannesteijsmannia altifrons (Ja) that belongs to the palm group; also known as the "Joey Palm". The habitat of Ja is the rainforest slopes and ridge-tops that are at least 500 m high. This type of palm grows in the rainforests of southern Thailand, Malaysia, Sumatra and Borneo. The Ja leaf is a diamond shaped doubly curved surface with folds extending from the main spine. Combination of the shape and the folded elements might have enabled these leaves to sometimes extend and self-support to a height of about 6 m, Figure 1. This plant presents a good example of how nature combines shape and material to enhance the load carrying capacity. Moreover, existence of folds has added an aesthetic element to the natural surface due to interplay of shadows caused by the folds. In a pioneering work, Ng [12] has modeled the surface of Ja and investigated the leaf behaviour under load through finite element analysis. A.Razzack & Choong [13], have proposed CAD based procedures with which doubly curved folded surfaces can be generated for application to roof structures using pure/rigid geometrical shape approach. Another method for generating doubly curved folded surfaces that resembles closer the natural folded surface of Ja has also been presented by A.Razzack, Choong, A.Majid & Kim [14], using leaf natural geometry approach.

Figure 1: *Picture showing heights reached by Ja*

Following the above two preliminary studies, further work has been carried out with the aim of improving the two approaches, namely Pure or Rigid Geometry Approach and Natural Geometry Approach, for generating doubly curved surfaces with folds. A modified procedure which gives better approximation to the leaf surface is introduced in this paper under the rigid geometry approach. On the other hand, the natural geometry approach necessitates the use of the natural leaf boundary as input to the model generation process; as such, surface data of the leaf is first captured using structured lighting method. Issues related to this method and the relevant captured images such as advantages, problems, limitations, and quantitative geometrical description based on the resulting model and the analyzed leaf are addressed in this paper. Having a model that closely represents the actual leaf will help to understand the structural behaviour of the doubly curved surface in the presence of folds through further computational study.

Unlike natural systems, engineering applications have different conditions and requirements. It is not our intention to fully copy the object under study like it occurs in nature; we are rather concerned about understanding the structural behaviour of this natural folded surface for possible application as structural roofing systems but certainly under different engineering conditions. This study is aimed as the first step towards the above ultimate goal.

2. SURFACE DATA ACQUISITION OF Ja

Coordinate measuring machines are the standard tools for capturing 3D data of solid objects. However, the very sensitive characteristic of the leaf to displacement under external effects necessitates implementation of a non-contact method for capturing the 3D data of the leaf surface. Among the non-contact measurement methods are Moiré contouring [15], holographic contouring [16], ESPI contouring [17] and fringe projection method (structured lighting) [18].

In this research "Structured Lighting Method" or "Fringe Projection Method" is applied. Advantages of this method are listed below:

- Experimental design and technique of analysis are simple.
- No costly optical instrument is required
- Information can be extracted from a single fringe pattern.
- Better contrast fringes for automatic analysis can be obtained compared to Moiré or ESPI method.

Figure 2, shows the experimental setup for capturing the leaf images. The camera and projector lenses centre lines are adjusted such that both lie in a common vertical plane. The reference screen is adjusted in a vertical position to form a 90° angle with the camera line. The projector is positioned on a plane whose inclination angle can be adjusted to get the best imaging setup as far as clarity and contrast of the fringes and object are concerned. It is to be noted that the leaf pictures with the shifted fringes on its surface are taken with the leaf being held in the containing pot. This is an important aspect in order to compute a model that closely represents the leaf in its natural, fully hydrated, and erect condition.

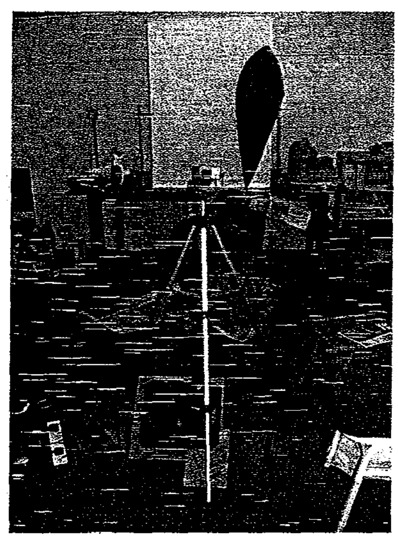


Figure 2: *Experimental setup for Ja measurement*

Figures 3a & 3b, show a line diagram that illustrates the principle used in calculating the 3D surface data of the leaf. Distance 'S' is the measured shift of the fringe on the leaf surface with respect to its horizontal positions on the vertical background reference screen. The shift values are used to calculate the z co-ordinate values using the equation ($z = S/\tan\theta$) with reference to the vertical background screen. Figure 4, shows the image used in calculating the 3D co-ordinates with the help of the shifted fringes over the surface of the leaf.

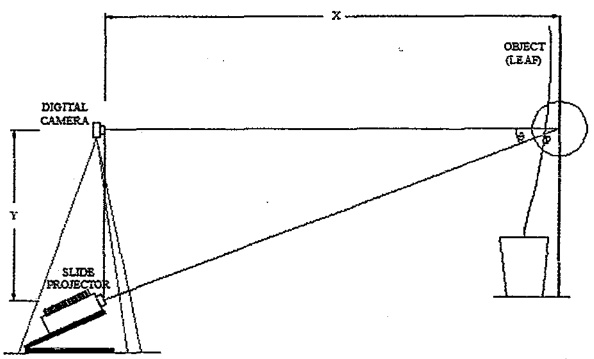


Figure (3a): Line diagram of the experimental setup

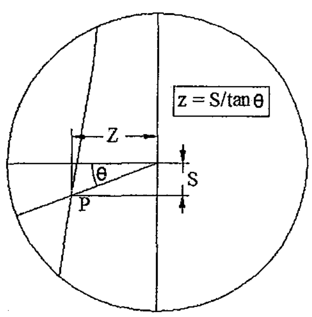


Figure (3b): Detail A of Fig. (3a)

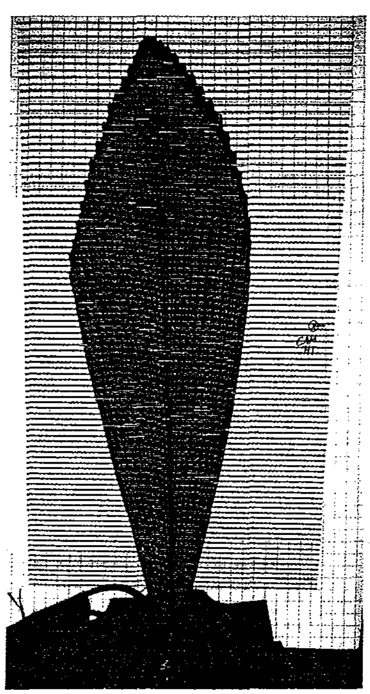


Figure 4: Image of Ja leaf with fringe projections

Limitations and problems associated with the fringe projection method and the captured images are addressed hereunder:

- Fringe projection method has so far been implemented to model small objects. Modeling large objects using this method is somewhat difficult and requires accurate experimental setup to ensure acceptable results.
- Imaging a single leaf among a group of leaves in the same pot requires careful handling of the plant in order to avoid any damage to other leaves as the specie under investigation is rare and costly. Moreover, capturing a leaf being cut from its pot is not a good idea as it quickly looses its shape due to dehydration.
- Fringe spacing depends on the type of slide projected and can not be changed during the experiment. For better results closely spaced fringes are preferable but are associated with large amount of data and longer processing time.
- Folds on the leaf surface are the main source of shadow which leads to loss of vital surface data especially towards the bottom of the leaf where they very closely merge into the stem.
- Proper lighting arrangement is necessary to ensure good illumination and contrast between the shifted fringes and the object under consideration. This issue is of particular importance in the case of Ja leaf due to its green colour which makes achieving a good contrast with black fringes a difficult task.
- Inclination or tilt of the projected fringes means extra calculation effort and time. This can be avoided if straight horizontal fringes are projected before capturing the images.
- Imaging large object is associated with high distortion in the picture. This problem is tackled by applying suitable scale factors in the horizontal and the vertical directions.

Issues related to the amount of error involved are not the subject of this paper. However, measurement calibration results of fringe projection method, applied to large objects such as the leaf of Ja, with reference to objects of known dimensions show error values of $\leq$ 5%. Moreover, final outcome in the form of meshed and rendered shapes of the leaf in different positions show that the results obtained are quite representative to reflect the actual shape of the leaf, Figure 5.

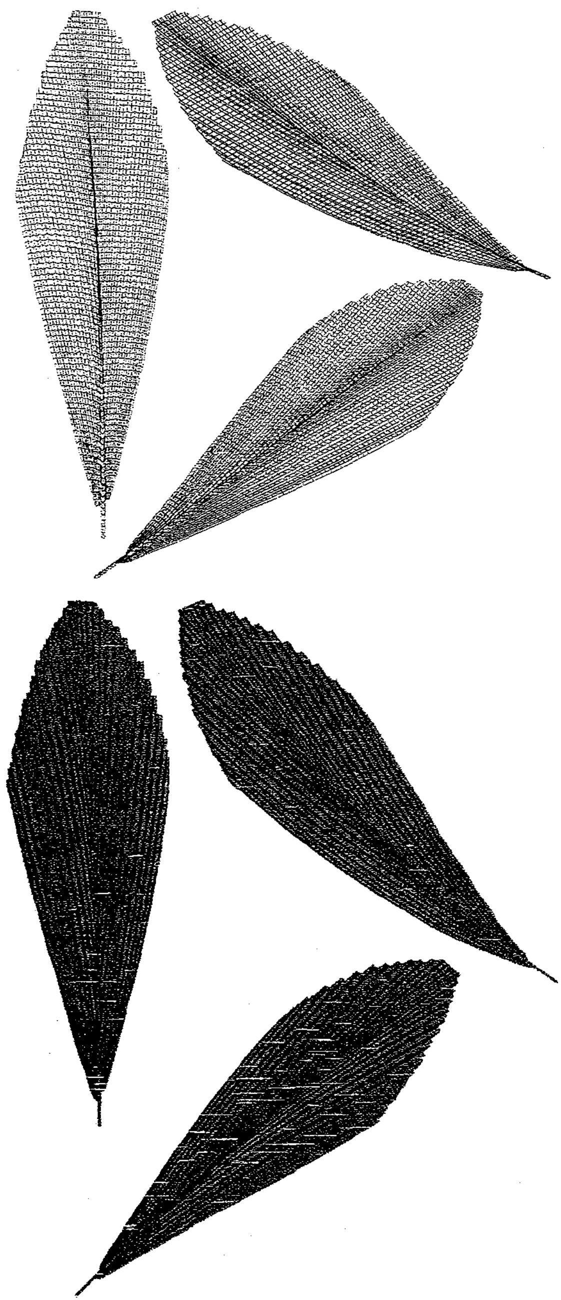


Figure 5: Meshed and rendered shapes of the modeled Ja leaf

Further observations on the leaf of Ja based on the measurement results are summarized below:

- Size of the rectangle containing the overall leaf in plan is about (31 x 102) cm.
- Number of folds on each side of the main stem is 15.
- If the leaf is inscribed inside a quadrilateral, then it can be seen that the folds run between the sides of the quadrilateral meeting at the top end of the leaf and the main stem.
- The angle between the folds' edges (ridge/valley lines) and the main stem measured at the location where the folds meet the main stem varies from about 8° for the edge fold to about 1° for the fold neighbouring the main stem. This observation is valid for folds on either side of the stem.
- Cross section area of the main stem reduces in the upward direction vanishing or merging with the folds near the widest dimension of the leaf i.e. nearly at 1/3rd the distance from the top of the leaf. Figure 6, shows variation of the cross section area of the main stem of the modeled leaf calculated at sections that are equally spaced over the length of the leaf.

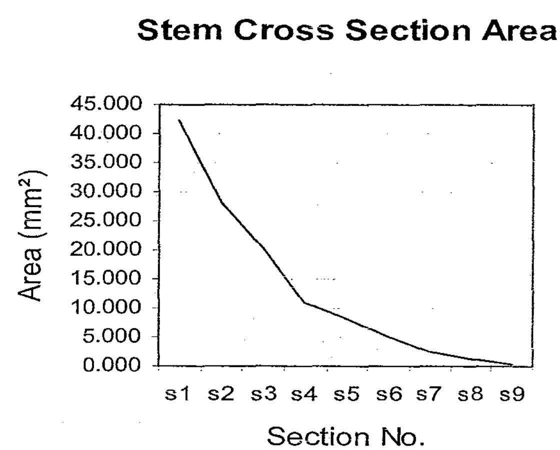


Figure 6: Variation of stem cross-section area

3. GENERATION OF DOUBLY CURVED FOLDED SURFACES

Doubly curved surfaces can be generated with the help of quadrilaterals (four sided shapes) by simply rotating any two adjacent sides through a certain angle about the diagonal joining the ends of the rotated sides. The same is true if the adjacent sides are rotated about both diagonals.

This paper presents two approaches for generating doubly curved folded surfaces. The first approach is based on pure/rigid geometrical shapes (quadrilaterals), hence called the "Rigid Geometry Approach"; under this category two models are generated – one by rotating the adjacent sides about only one diagonal and the other through rotating the adjacent sides about both diagonals. The other approach is based on the natural boundary of a real leaf, hence called the "Natural Geometry Approach"; under this category the boundary of the leaf model generated through structured lighting method, explained in section 2, is used.

The models shown hereafter are generated using CAD software utilizing the 3D modeling options.

3.1.1 Generation of Doubly Curved Folded Surfaces Using Rigid Geometry Approach And Rotation About One Diagonal/Axis

The model is generated based on an equal sided quadrilateral (rhombus) whose sides are rotated about the minor axis. Stepwise detailed description with illustrative figures is given below:

Step 1: A plane equal sided quadrilateral (rhombus) ABCD with side length (d) and interior angles (α) and (β) is drawn. The opposite angles are equal. The straight line joining the opposite corners AC and BD are called the Major Axis and the Minor Axis respectively, Figure 7.

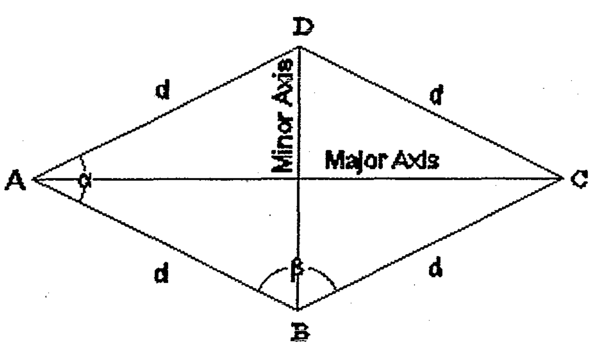


Figure 7: *Step 1 – The starting figure*

Step 2: The adjacent sides BC and CD are rotated through an angle θ about the minor axis (BD). Now point C takes a new position C'. The rest of the method depends on shape AB C'D based on which a double curved folded surface can be generated. Figure 8.

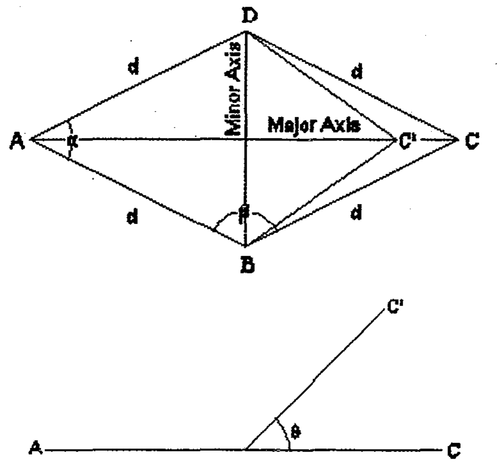


Figure 8: *Step 2 – C is tilted to C'*

Step 3: Using the quadrilateral ABC'D as the boundary a meshed surface is created. Number of folds on the surface depends on the number of mesh division, on the sides of the quadrilateral. Fig. (9), shows the mesh generated on ABC'D.

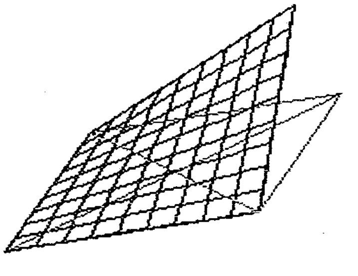


Figure 9: *Step 3 – ABC'D is meshed*

Step 4: Two curves are constructed joining the opposite corner points of the quadrilateral ABC'D. Both curves join the corner points passing through the nodes of the mesh elements as shown in Fig. (10). Curve AC' is an important component of the whole procedure as it defines the support locations from which the cantilevered folds emanate.

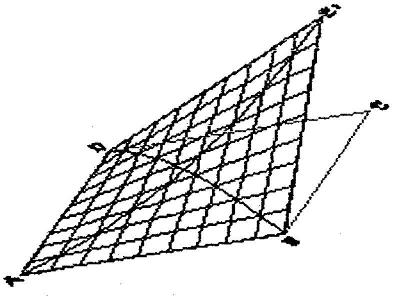


Figure 10: *Step 4 – Curves AC' and BD are drawn*

Step 5: This step defines the depth of the folded elements. A new surface identical to the one generated in Step 3 is created and positioned by shifting through a certain distance as per the desired depth of the folds, Figure 11.

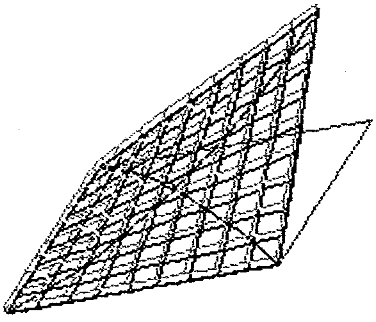


Figure 11: *Step 5 – Identical surface is created through shifting*

Step 6: The top and bottom surfaces work as the boundary within which the folds are created. Zigzag lines defining ends of the folds are formed along the edges and the curve AC', Figure 12.

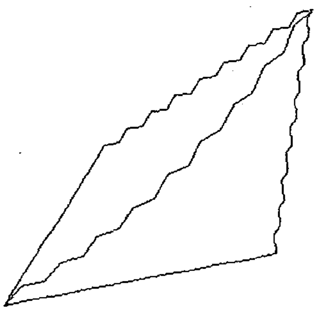


Figure 12: *Step 6 – Zigzag boundary is formed between the two surfaces*

Step 7: The wire frame created in Step 6 is the reference on which the folds are generated. It can be seen that the surface generated is a doubly curved folded surface, Fig. (13).

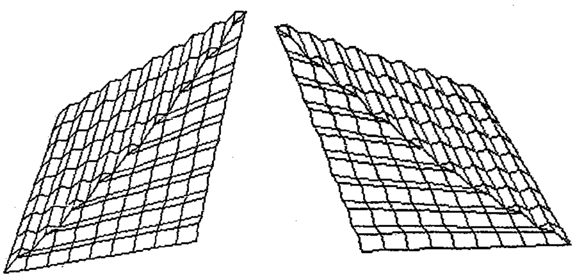


Figure 13: *Step 7 - Folds are generated and doubly curved folded surface is formed*

Rendered versions of the generated model are shown in Figure 14.

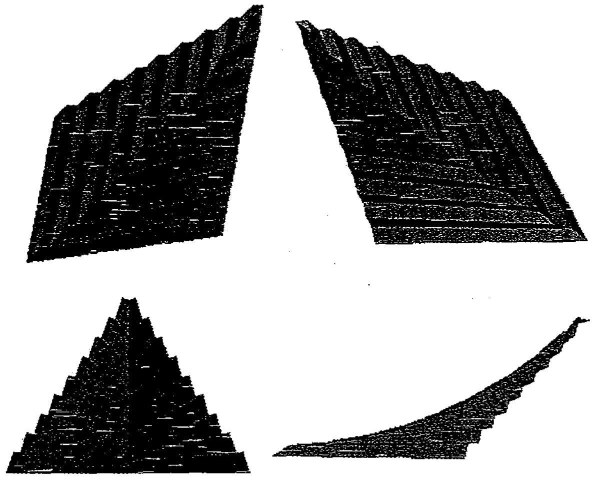


Figure 14: *Rendered shapes of the generated model*

A few possible shapes of roof structures obtained by assembling different numbers of unit folded surfaces are shown in Figure 15.

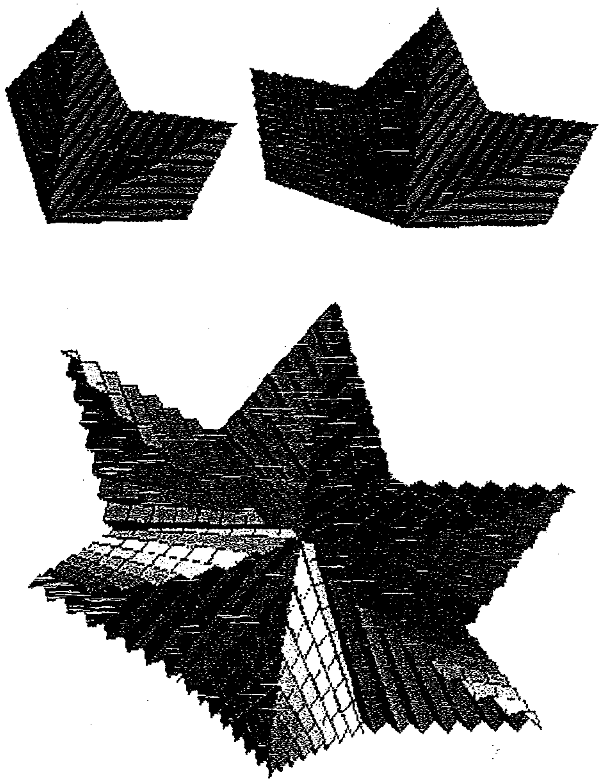


Figure 15: *Possible shapes of roofing systems (Rigid geometry & rotation about one axis)*

3.1.2 Generation of Doubly Curved Folded Surfaces Using Rigid Geometry Approach And Rotation About Both Diagonals/Axes - Getting Closer to the Leaf Shape

The model described in the previous section is generated by rotating two adjacent sides of the quadrilateral about the minor axis. Another option is to rotate the adjacent sides about both the minor as well the major axes. This step brings us closer to the real shape of the Ja leaf, a case which is applied to generate the surfaces shown in Figure 16.

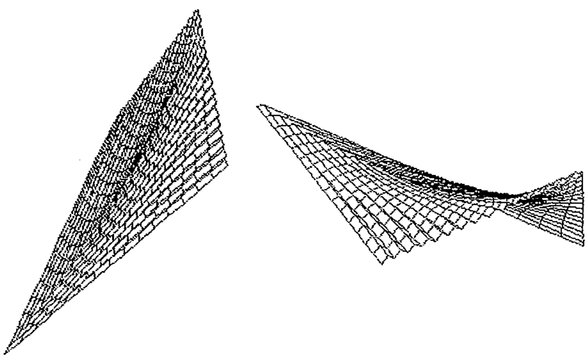


Figure 16: *Double curved leaf like folded surface generated using rigid geometry approach and rotation about both axes*

Other characteristics of the leaf such as proportional lengths of the edges and the number of folds on each side of the main stem are also considered. The model surface constructed is a 3D polygon mesh approximating a Coons surface patch mesh from four adjoining edges. This, in fact, gives a better approximation to the curved path formed by the folds over the original leaf surface. Meshed versions of assembled models with 2 and 3 units of the generated model are illustrated in Figure 17. Rendered shape of a possible roof structure is shown in Figure 18.

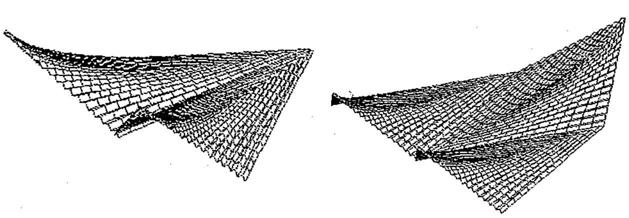


Figure 17: *2 and 3 units assembly of meshed models generated using rigid geometry approach and rotation about both axes*

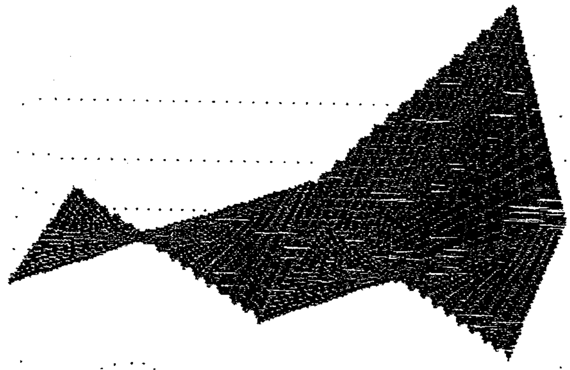


Figure 18: *Possible shapes of a roofing system, rigid geometry & rotation about both axes*

3.2. Generation of Doubly Curved Folded Surfaces Using Natural Geometry Approach - Further Enhancement

A simple modification over the procedures described in the previous section brings us very close to the real leaf shape. In fact, the starting step of the modeling processing is only altered through replacing the straight edges by the 3D boundary of the actual leaf as obtained from structured lighting method. A replica of the edges and the main spine of the actual model are defined in a 3D space which provides the frame on the basis of which coons surfaces are generated and curved folds are created. Stepwise description of the method is described with the help of Figures 19 to 23.

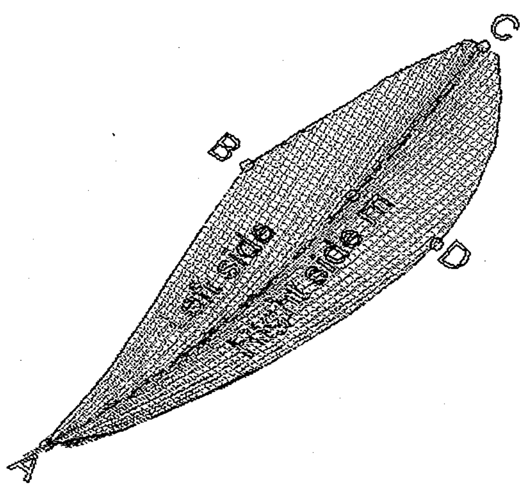


Figure 19: *Step 1- Forming curved edges based on model obtained from structured lighting method*

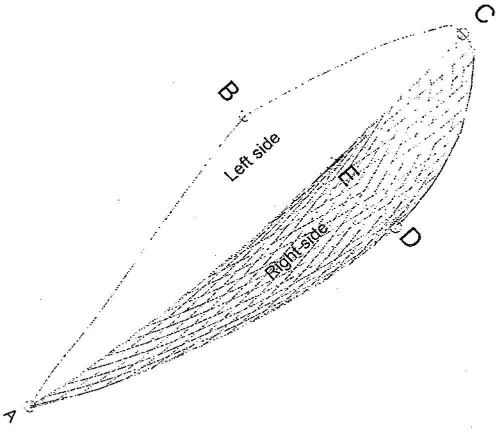


Figure 20: *Step 2- Right side of leaf is meshed*

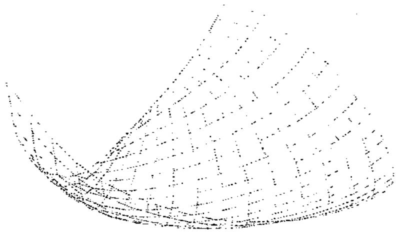


Figure 21: *Step 3- An identical surface is created through shifting*

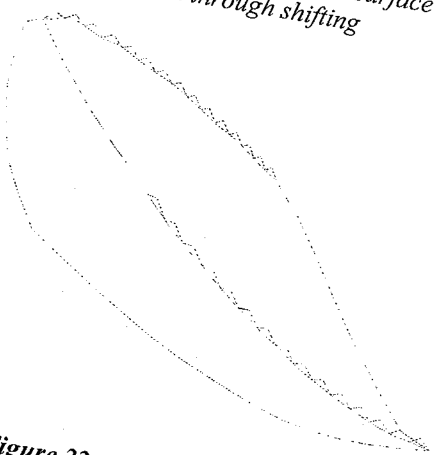
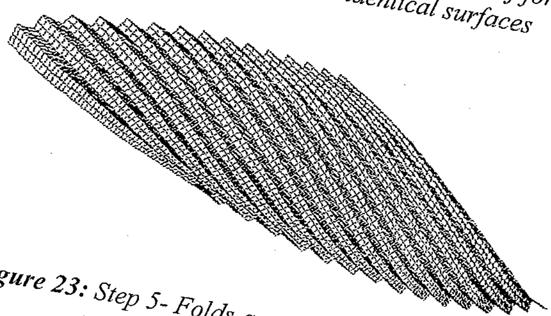


Figure 22: *Step 4- Zigzag boundary if formed between the two identical surfaces*



gure 23: *Step 5- Folds are generated and doubley curved folded surface is formed*

The actual leaf is not symmetrical. Moreover, the curve defining the main spine does not fall in a single plane; as such each half of the leaf has to be modeled separately using the same modeling steps as described above. 3D mirroring for the construction of full model under unsymmetrical situations leads to undesirable results due to formation of gaps at certain location and overlaps at others along the main spine, a case which will result in mesh connectivity problems if further analysis using finite element method, is to be carried out. If the main spine is contained in a single plane then it is sufficient to model half of the leaf and arrive at a perfectly symmetrical model. Final model of the left part of the leaf in the form of 3D mesh is shown in Figure 24. Rendered versions of both sides of the leaf are shown in Figure 25.

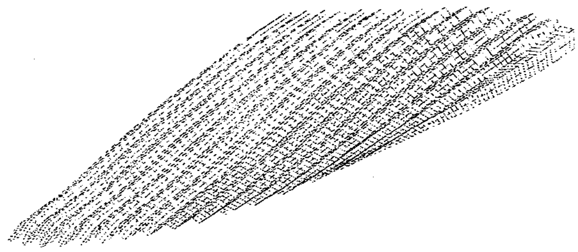


Figure 24: *3D mesh of the left half of the leaf, modeled separately*

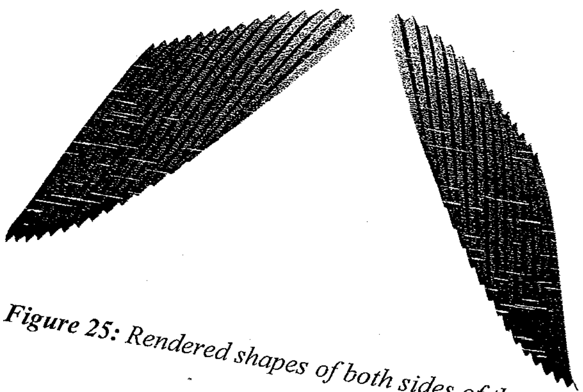


Figure 25: *Rendered shapes of both sides of the leaf*

Full rendered models can now be simply obtained through assembly of the left and right sides of the meshed models. Mesh connectivity is an important aspect to be looked into at this stage especially if the model has to be further analyzed using finite element method. Full model of the leaf in the form of meshed and rendered formats are shown in Figure 26.

Figure 26: *Meshed and rendered shapes of the generated leaf after assembling the two sides*

4. CONCLUSION

Application of structured lighting method in measuring the 3D doubly curved folded surface of the of leaf of Johannesteijsmannia altiforn (Ja) has been presented. Advantages, limitations and problems associated with the application of the method have also been addressed. Further it has been illustrated that fringe projection method when applied to large objects can yield representative results under properly controlled experimental setup and imaging environment. The result obtained is found to be quite representative and the surface data for further finite element analysis is made available.

Two approaches, namely Rigid Geometry Approach and Natural Geometry Approach, for generating doubly curved folded surfaces inspired from nature are presented. Both procedures are flexible enough to yield surfaces with different geometric parameters.

The *rigid geometry approach* can be based on four sided shapes with straight lines or well defined curved edges. A variety of doubly curved folded surfaces can be generated by simply changing the geometrical parameters such as side length, interior angles of the quadrilateral, rotation angle of the sides and the mesh type. The folds, generated can either take straight paths or curved paths. Models generated by rotating the sides of the quadrilateral about both axes of the quadrilateral give better approximation to the leaf surface.

The *natural geometry approach* differs from the rigid geometry approach in the boundary frame work that encompasses the whole model. In this approach the edges are generated following the natural boundary and the main spine of a real leaf model as obtained from fringe projection method. The rest of the procedure is the same as that of the other approach. The unsymmetrical nature of the leaf leads to mesh connectivity problems between corresponding folds along the main spine. Tackling this problem is an important step at the modeling stage especially if the model is to be used as an input for further finite element analysis.

The rigid geometry approach is a simple and fast procedure to generate doubly curved folded surfaces for possible application as *roof structures*. On the other hand the natural geometry approach is a relatively fast procedure compared to structure lighting method to generate very representative surfaces that very much resemble the actual leaf of Ja, with the advantage of generating meshed data according to design requirements that can be used as input to the finite element analysis to understand the structural behaviour of the leaf of Ja under different loading conditions.

The value of the research is the relatively simple and fast process of generating new forms inspired from nature using CAD software for possible application as roofing structural systems.

5. ACKNOWLEDGEMENT

The support provided by Universiti Sains Malaysia in the form of a short term research grant for this study is very much appreciated.

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Motivation and Objectives

At the IASS Executive Council, which was held in September 2003 previous to the annual conference of IASS at Montpellier, France,
formally approved a new Subgroup on Computational Morphogenesis as part of Working Group 13 (Numerical Methods for Shell and Spatial Structures).

The aims of this Subgroup is
(1) Diffuse thoughts on how computational morphogenesis can contribute to the art of structural design.
(2) Exchange ideas on utilization of structural optimization for structural design.

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In accordance with the objectives, the themes of the workshop will include structural optimization, form-finding, nonlinear programming, numerical methods and those application to the structural design of all kinds of structures,
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In order to minimize participants' loads of preparation for this activity and help the participants bring fresh fruits of their achievement, full papers are not required to prepare and the book of abstracts will be issued as the proceedings of workshop.
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A STUDY ON THE STRUCTURAL MERITS OF SHELL SURFACE WITH FOLDS INSPIRED BY THE LEAVES OF *Johannesteijsmannia altifrons*

Suhail A.Razzack and K.K.Choong

School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia

ABSTRACT

The leaves of the majestic plant called *Johannesteijsmannia altifrons*(Ja) belonging to the palm group are studied for possible application to engineering structures. The leaf is a diamond shaped doubly curved surface with folds extending from the main central spine. Combination of the shape and the folded elements might have enabled these leaves to sometimes extend and self-supported to a free standing height of about 6 m. In order that we can take one step further by applying the idea of the above mentioned folded surfaces inspired by nature to engineering structures, it is important that we understand the load carrying characteristics of this natural folded surface under practical engineering requirement. In this study, generated computer models of folded surfaces inspired by Ja have been analysed under self-weight loading condition. Comparisons have been made with similar surfaces where the folds have been flattened. Preliminary results show that surface with folds have performed better in terms of strength and stiffness. Extension of the idea to engineering structures taking into consideration factors such as thickness of surface, number of folds on the surface , type of materials to be used for the surface and support condition have also been investigated. Configurations suitable for practical application have been identified and proposed in this study. Results of analysis carried out in terms of stress distribution, maximum stress level and deflection of folded surface have been used to investigate the structural advantage of folded surface modeled after the leaves of Ja.

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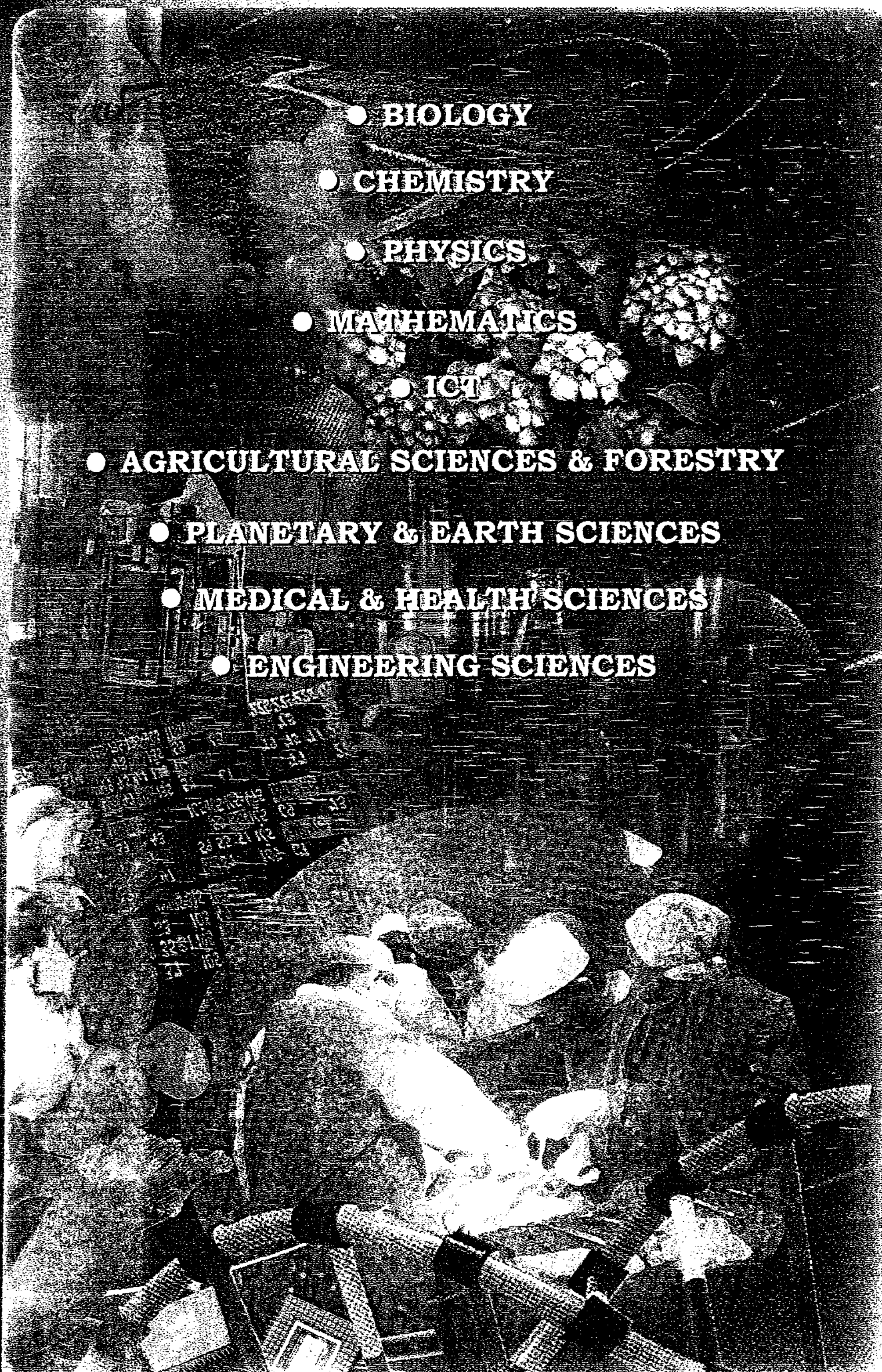

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A Study On The Measurement Of Irregular Surface Profile Using Structured Lighting Method

by
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Abstract

Efficiency of structural members is highly dependent on shape. Surface with folds is an example of surfaces with high structural efficiency in terms of the ratio of self weight to load carrying capacity. Moreover, shadows caused by the folds impart an aesthetic element to such surfaces. Comprehensive understanding of the structural behaviour of folded surfaces of different shapes requires clear definition of the geometry of the structural system under consideration. Existence of folds makes the task of measuring such surfaces difficult especially in the case of doubly curved folded surfaces. This paper presents the procedure for measuring large objects with folds using structured lighting method following the conventional approach. This is then followed by a modified approach that remarkably reduces the errors resulting from the conventional structured lighting approach. The objective of this paper is to illustrate the workability of a low cost non-contact technique for measuring objects with high variation in surface profile. Results of measurement on two objects with irregular surface profile using the proposed modified approach are shown. The proposed approach is found to have yielded results with satisfactory accuracy and has the potential to be applied to engineering problems where data of irregular surface profile are needed.

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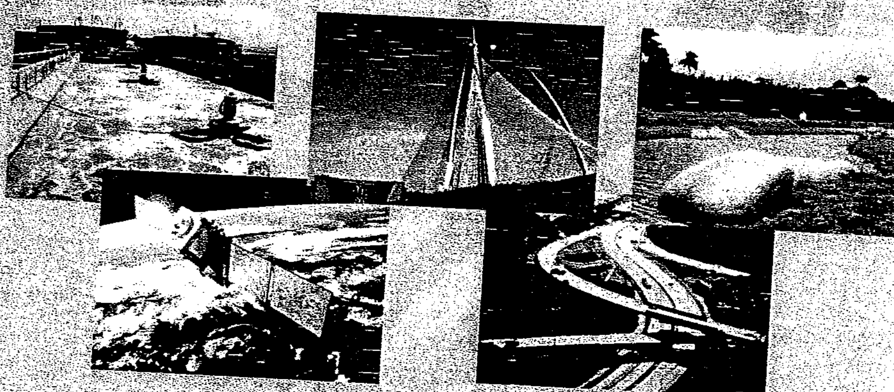

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S7

Folded Shells Inspired from the Leaf of Johannesteijsmannia altifrons

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Abstract

Examples of shell structures in nature are many. Among such natural examples, plant leaves occur in nature in different forms. Of special interest to this study is the shell-like surface with folds which can be observed in leaves of many plants such as the Johannesteijsmannia altifrons (Ja) which belongs to the palm family. The leaf of Ja is a double curved folded surface resembling cantilevered shell structures with folds extending from the central spine. Combination of the shape and the folded elements might have enabled these leaves to sometimes extend to a height of about 6m. Apart from such positive characteristics of load carrying capacity; the existence of folds has also added an aesthetic element to the natural surface due to the interplay of shadows caused by the folds. In this study, three units of Ja leaves have been measured applying structured lighting method. CAD based generation procedures of leaf-like shell surfaces with folds are presented. The aim of this paper is to illustrate the reliability of structured lighting method in generating actual leaf models and to present a fast method for generating doubly curved folded surfaces that can be beneficially adopted as alternative "nature-inspired" new roof structural system.

Keywords: *Johannesteijsmannia altifrons*, folds, nature inspired roof system, shells in nature.

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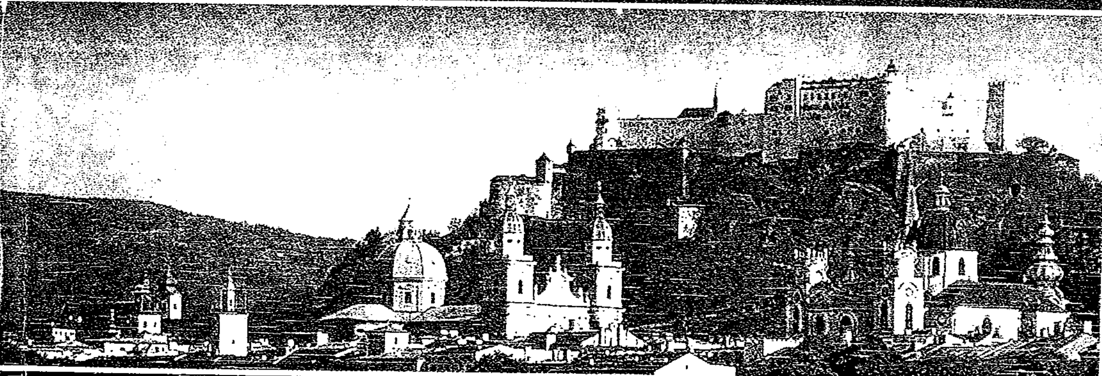

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Formfinding and Optimization I

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Shell surface with folds – Mimicking idea from leaves of Johannesteijsmannia altifrons

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Abstract

Surfaces found in nature can serve as sources of idea which can be adopted for possible application in engineering structures. Of special interest are shell-like surfaces with folds which can be observed in leaves of many plants. In this research, the leaves of a majestic plant called Johannesteijsmannia altifrons which belong to the palm family will be investigated. The leaves of Johannesteijsmannia altifrons resembles a cantilevered shell structure with folds extending from the central spine. Such combination of shell surface and folds might have contributed to the ability of the leaves of Johannesteijsmannia altifrons to extend to a span of about 6m. Apart from such positive characteristic from the point of view of load carrying capacity, the existence of folds has also added element of aesthetic to the natural surface due to the interplay of shadows caused by the folds. In this paper, leaves of Johannesteijsmannia altifrons has been first measured using structural lighting method. Using the information obtained about the surface data as reference, procedures to generate shell surface with folds are then presented. The generated surface could be beneficially adopted as alternative "nature-like" new roof structural system.

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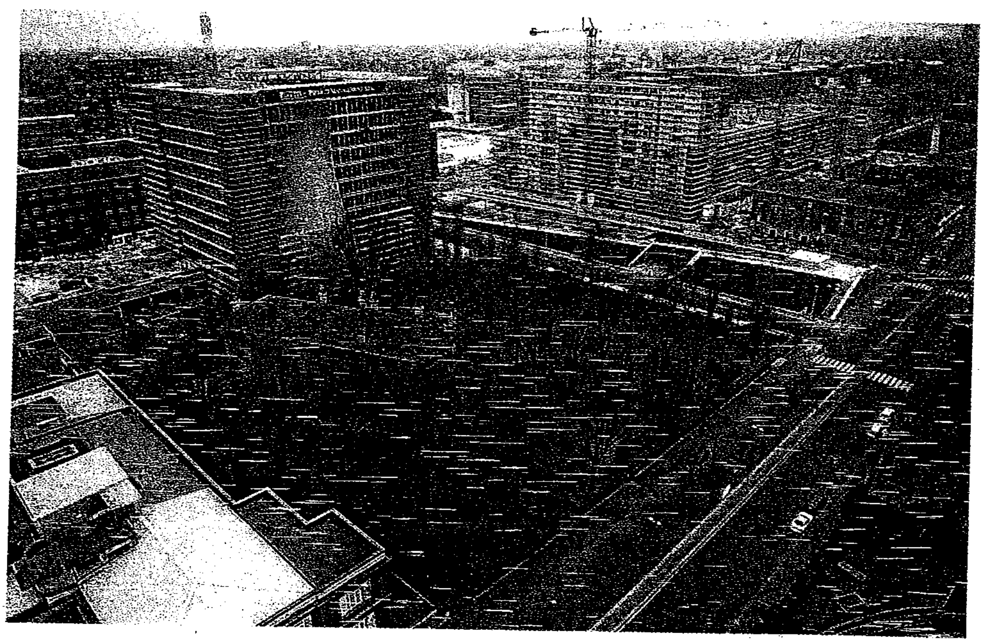

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STRUCTURAL CONCEPTS OF SHELL WITH FOLDS - IDEA FROM THE WORLD OF PLANTS

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Abstract

Nature presents the best optimization examples in the use of shape and material. Plants and animals adapt to their environment through control over the assembly and shaping of the limited resources. Shell surfaces found in nature, such as sea shells and plant leaves, can serve as a source of inspiration for possible application to engineering structures. The magnificent leaves "Johannesteijsmannia altifrons" – that belongs to the palm family – also known as the "Joey Palm" - are the subject of this research. The leaves of Johannesteijsmannia altifrons are diamond shaped, double curved surfaces with folds extending from the main spine. The overall leaf can be looked at as a main cantilever (main stem) from which secondary cantilevers folded components, joined along their edges to form a single leaf unit, emanate to extend on either side of the main stem. Combination of the shape and the folded elements might have enabled these leaves to sometimes extend and self-support to a span of 6 m. Apart from such positive characteristics of load carrying capacity, the existence of folds has also added an aesthetic element to the natural surface due to the interplay of shadows caused by the folds. In this research the surface data of the leaf is first captured using structured lighting method. The captured data is then used as input to generate a unit folded shell surface and variations that closely follow the natural geometry of the actual leaf. The aim of this paper is to present an alternative structural concept for roof structures that combines both structural efficiency and architectural beauty inspired by nature.

Keywords: shells in nature, folds, Johannesteijsmannia altifrons, nature inspired roof system

1. Introduction

Nature is very smart in optimizing shape and material. Comprehensive understanding of how nature handles such tasks under tight environmental constraints that can be limited as well as unfavorable is a key issue to many researchers today. Surfaces found in nature offer a rich source of ideas for possible application as engineering structures. Animal shells, seashells and plant leaves are among the natural surfaces that serve as a potential source of mimicry for new structural systems.

Jirapong & Krawczyk [1], studied seashells of spiral shapes. A mathematical model is proposed to describe the shell geometry with the objective of generating new architectural forms that can be used as input to the structural analysis of the system. Balz & Gűring [2], modeled the petal shapes of orchid blossom to study the shape-stability behaviour. They proposed this kind of structure for deployable or temporary buildings made of membranes and erected by air or water pressure. De Focatiis & Guest [3], looked into the deployment of tree leaves to find patterns for folding membranes aiming to arrive at structures which can be reduced in size for transportation or storage, and then automatically deployed. Kobayashi, Kresling & Vincent [4], modeled the leaves of hornbeam and beech as plane surfaces, with straight parallel folds, using numerical methods and studied their folding patterns for applications to areas such as solar panels, light weight antennae of satellites, deployable membranes such as tents, clothes or other coverings.

This study investigates a majestic plant called Johannesteijsmannia altifrons (JA) that belongs to the palm group; also known as the "Joey Palm". The leaf is a diamond shaped, double curved surface with folds extending from the main spine. Combination of shape and the folded elements might have enabled these leaves to sometimes extend and self-support to a height of about 6 m, Fig. (1). This presents a good example of how nature combines shape and material to enhance the load carrying capacity. Moreover, existence of folds has added an aesthetic element to the natural surface due to interplay of shadows caused by the folds. In a pioneering work, Ng [5] has modeled the surface of JA and investigated the leaf behaviour under load through finite element analysis. Razzack and Choong [6], have proposed AutoCAD based procedures with which doubly curved folded surfaces can be generated for application to roof structures using pure geometrical shape approach.

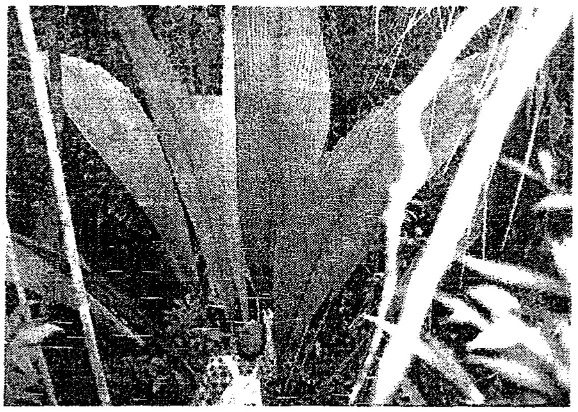

Fig. 1: Picture showing heights reached be JA

This paper presents another method for generating doubly curved folded surfaces that resembles closer the natural surface of JA. Surface data acquisition of the actual leaf is first described. This is then followed by the explanation of the proposed "Natural Approach" for the generation of doubly curved folded surfaces.

2. Surface Data Acquisition of JA Leaf

The very sensitive characteristic of the leaf to displacement under external effects necessitates implementation of a non-contact method for capturing the 3D data of the leaf surface. As such, a low cost method known as the "Structured Lighting Method" or "Fringe Projection Method" is applied where a set of parallel fringes are projected at an angle over the leaf surface and images are capture using commercial quality digital camera. Triangulation methods are then used to calculate the 3D coordinates of the leaf surface. Experimental setup for capturing the leaf images is illustrated in Fig. (2). The leaf images are captured with the leaf being held in the containing pot so as to compute a 3D model that closely represents the leaf in its natural condition.

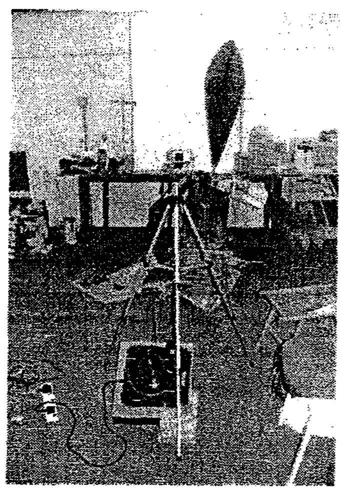

Fig. 2: Experimental setup for JA measurement

Fig. (3), shows a line diagram that illustrates the principle used in calculating the 3D surface data of the leaf. The distance 'S' is the measured shift of the fringe on the leaf surface with respect to its horizontal position on the vertical background screen. The shift values are used to calculate the z co-ordinate values using the equation: ($z = S/\tan\theta$) with reference to the vertical background screen. Fig. (4), shows the captured image used in calculating the 3D coordinates with the help of the shifted fringes over the surface of the leaf. The final 3D mesh of the calculated model is shown in Fig. (5). It can be observed that the results obtained are quite representative.

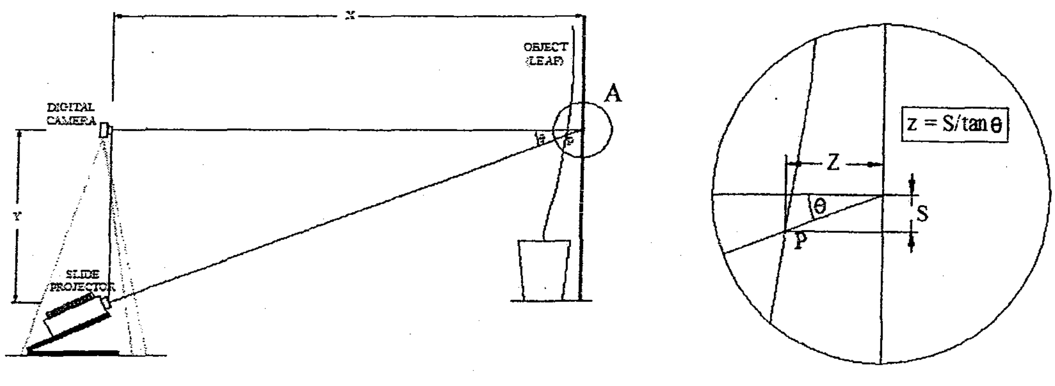

Fig. (3): Schematic diagram of the setup for the measurement of leaf of JA and the detail at A

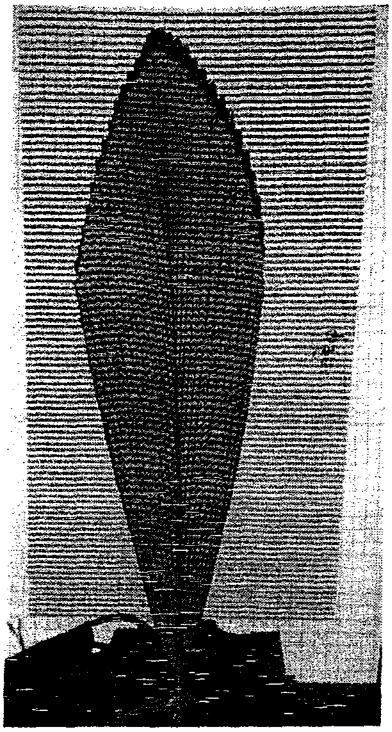

Fig. (4): Image of JA leaf with fringe projections

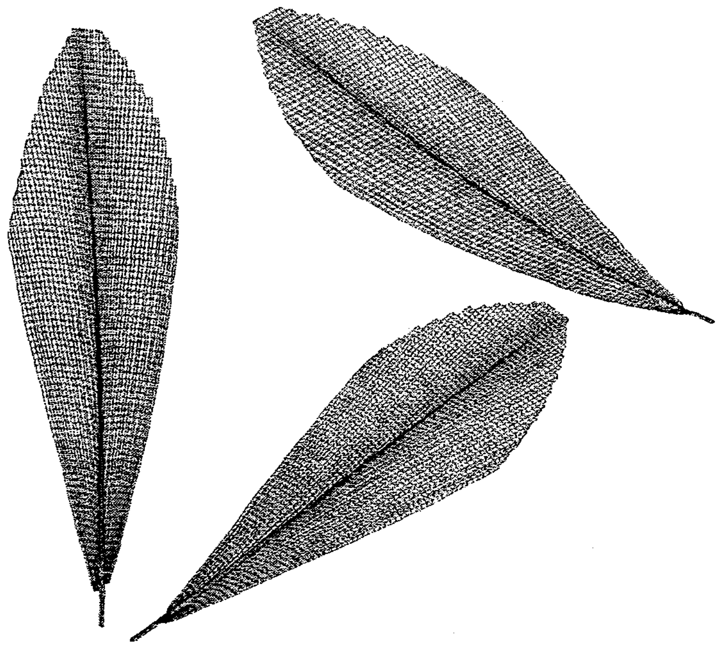

Fig. (5): Calculated leaf model in the form of 3D mesh

3. Generation of Doubly Curved Folded Surfaces Using Natural Geometry

The approach followed here in generating the double curved leaf model is termed as the "Natural Approach" due to the fact that the 3D natural leaf boundary obtained from structured lighting method is used as the base upon which the entire leaf surface modeling is carried out. Figs. (6) to (11) show the process of generation by utilizing 3D modeling options available in CAD software. The approach presented here differs from the rigid geometry approach [6] in the first step of modeling where the rigid boundary frame is replaced by the natural boundary obtained from structured lighting method. A mesh of size (15 x 15) is used to simulate the number of folds on the actual leaf surface. It can be observed that the end result very much resembles the actual leaf.

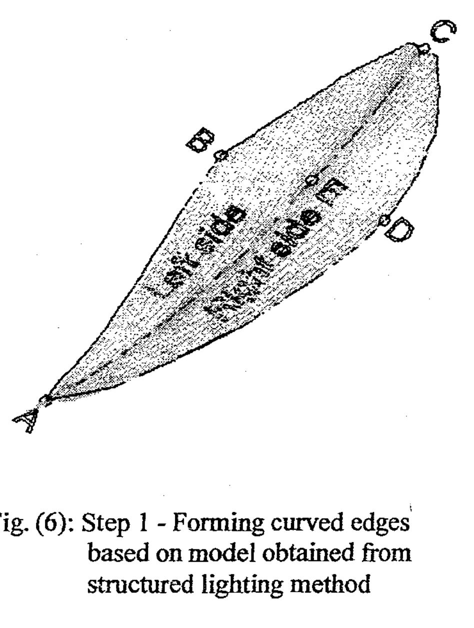

Fig. (6): Step 1 - Forming curved edges based on model obtained from structured lighting method

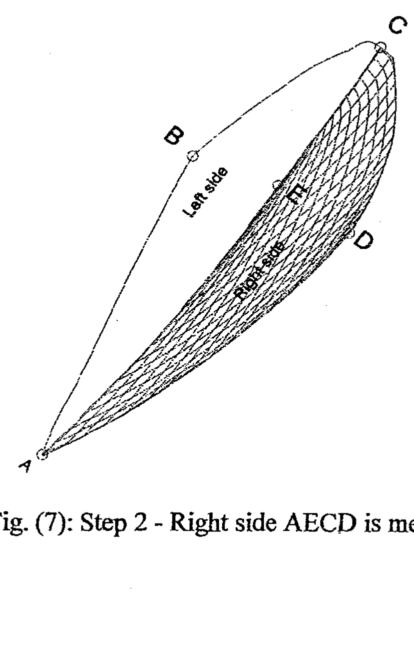

Fig. (7): Step 2 - Right side AECD is meshed

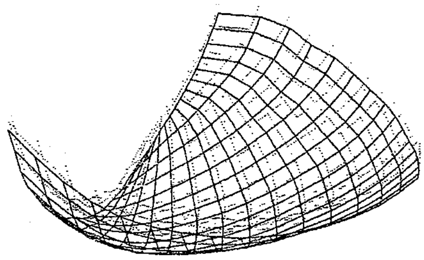

Fig. (8): Step 3 – Creating an identical surface through shifting

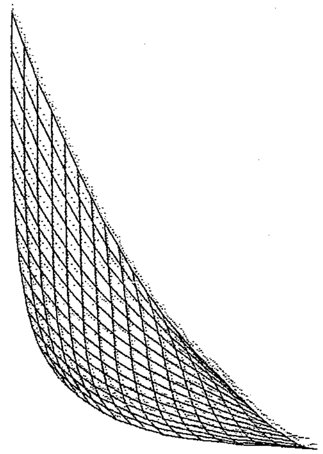

Fig. (9): Another view of result in Step 3

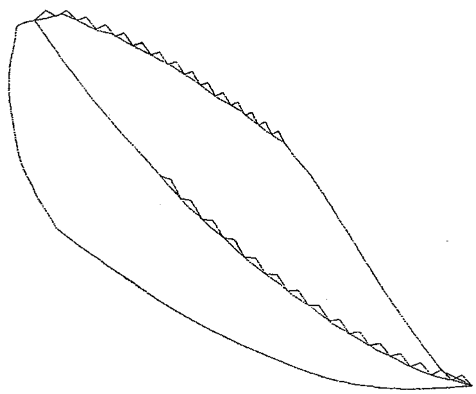

Fig. (10): Step 4 – Zigzag boundary is formed between the two surfaces

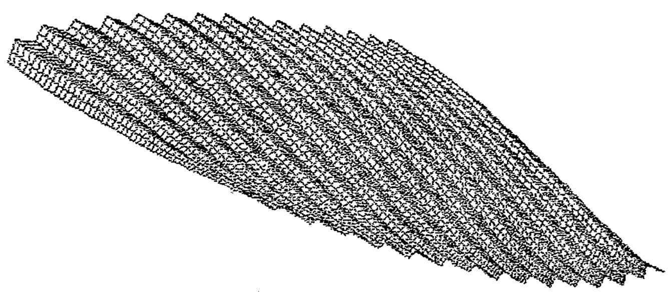

Fig. (11): Step 5 – Folds are generated and doubly curved folded surface is formed

The actual leaf is not symmetrical. Moreover, points along the centre line of the main spine are not in the same plane, as such the left and right sides of the leaf have to be modeled individually using the same modeling steps as described above. 3D mirroring for the construction of full model, under such unsymmetrical situations leads to undesirable results due to formation of gaps at certain locations and overlaps at others along the mid spine in the final model. If the points along the center line of the mid spine are all located in the same plane then it is sufficient to model half of the leaf and arrive at a perfectly full symmetrical model. Final result of the left part of the leaf in the form of 3D mesh is shown in Fig. (12).

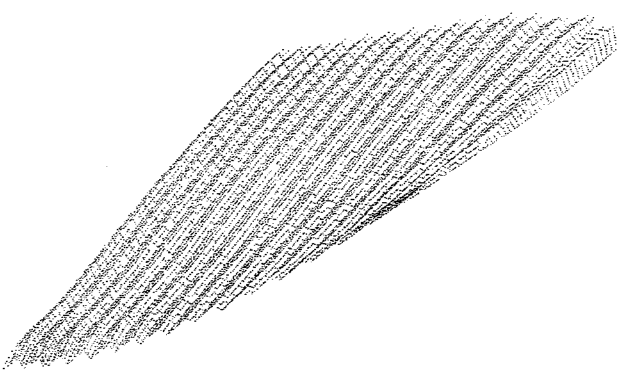

Fig. (12): 3D mesh of left half of the leaf, modeled separately

Full rendered model of both sides are shown in Fig. (13). Full leaf model can now be simply obtained through assembly of the left and right sides of the meshed models. Fig. (14), shows the full leaf 3D meshed model viewed from different angles.

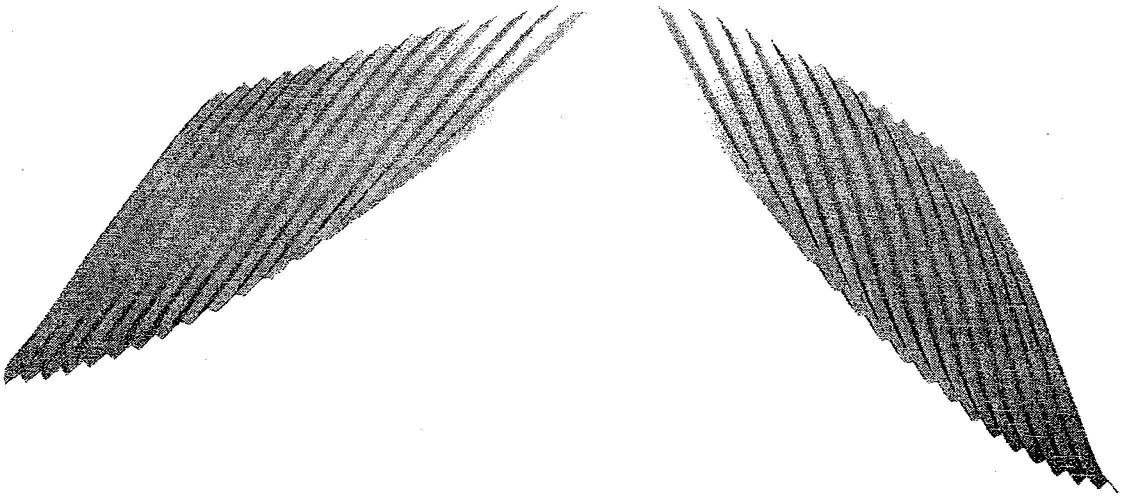

Fig. (13): Rendered models of the left and right sides of the analyzed leaf

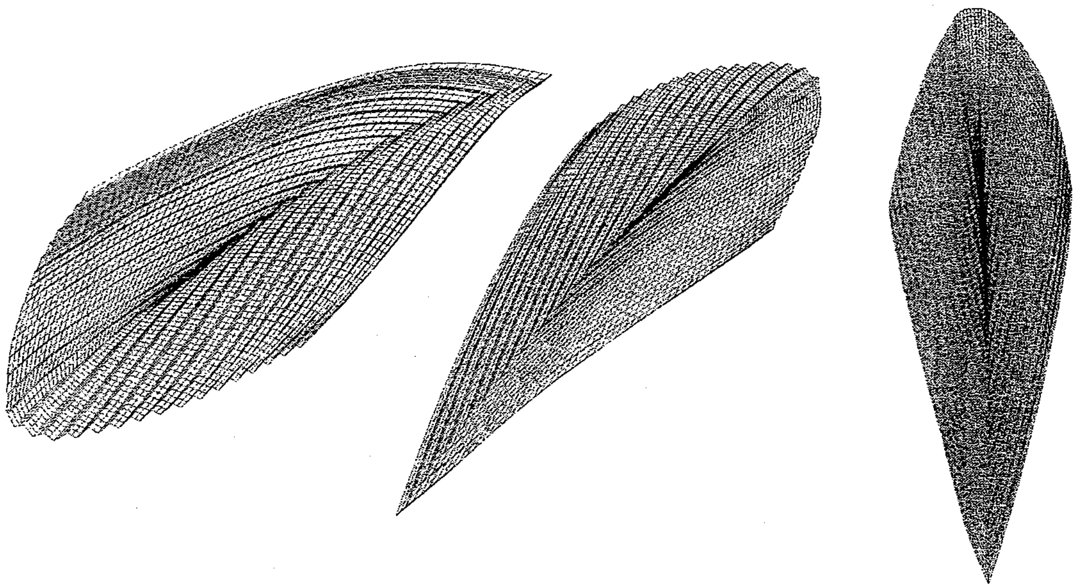

Fig. (14): 3D meshed model of the full leaf in different positions

4. Conclusion

Application of structured lighting method in measuring the 3D double curved surface of the leaf of JA to obtain representative results has been presented. The result obtained has been used as basic input to generate JA leaf models using CAD software by means of an approach called the "Natural Approach". This method has shown to be able to yield good quality models that are closer to the actual leaf surface in nature. Advantage of this "Natural Approach" lies in the relatively easy generation of 3D curved folded models that strikingly resemble the JA.

5. Acknowledgement

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