NONLINEAR MODELING AND ACTIVE FLATNESS CONTROL OF MEMBRANE STRUCTURES

X. Wang, Y. -R. Hu, W. Zheng, C.Sulik, Y. Shen
Directorate of Spacecraft Engineering,
Canadian Space Agency
Saint-Hubert, Quebec, J3Y 8Y9
Canada

OVERVIEW

Membrane structures are attracting attention from space industry as excellent candidates for lightweight large structures in the weightless and airless environment, which can be utilized to improve the performance and reduce the cost of space exploration and earth observation missions. Wrinkles of membrane structures caused by in-orbit thermal disturbance and other factors would comprise the performance of membrane structures. In this paper, a nonlinear dynamic model for a square membrane structures is developed using the finite element method based on the thin shell theory (TST) and an active flatness control system is developed with multiple shape memory alloy (SMA) actuators installed around the boundary of a rectangular membrane. The experiment results also demonstrate the GA algorithm is able to find the tension forces combination. Active flatness control system can substantially improve the flatness of the membrane structure. Possible ways to incorporate dynamic model results to active control system are discussed.

1. INTRODUCTION

In weightless and airless space environment, membranes have been considered as excellent candidates to implement lightweight extreme large structures, such as antenna reflectors and solar sails [1]. Membrane structures can be folded or stowed to a small volume during launch and function as a large structure after their deployment. This kind of structures has advantages in achieving very low mass and very high packaging efficiency. Their ultra-lightweight and small-volume properties can potentially reduce the overall space program cost by reducing launch vehicle size requirement by an order of 10 [2].

However, this fondest dream was hampered by a number of technological difficulties such as lack of suitable membrane materials, reliable deployment mechanisms, and techniques to maintain surface accuracy of membrane structure in-orbit. Recent strides in these technical areas increase feasibility and interest in the application of membrane structures in various types of space programs. Examples of on-going effort include membrane Synthetic Aperture Antenna [2], membrane sun shields for James Webb Space Telescope (JSWT) [3], solar sail structure for In-Space Propulsion (ISP) program [4], and a parabolic cylindrical reflector antenna for a precipitation satellite [5]. Other proposed applications include human habitats in space, planetary surface exploration vehicles, and adaptive optics [1].

At the Canadian Space Agency, an in-house research project is going on to enable the development of a C-band membrane Synthetic Aperture Radar (SAR) antenna. The team for this project is aiming to tackle a number of technical challenges of large membrane structure: dynamic modelling and structure design of membrane structures, active flatness and vibration control, Transmitter/Receiver module design, deployment mechanism design and control. Among these challenges, active flatness and vibration control is considered the most challenging and vital mechanical problem. In the space environment, the membrane structure is expected to have surface distortion mainly due to the thermal effects in space, in addition to distortion caused by initial configuration, such as imperfect deployment, and long-term change in material properties. Surface accuracy of membrane structures is extremely important for membrane to achieve higher accuracy, which would enable some higher accuracy observation missions, such as soil moisture missions, hazards missions, and freeze/thaw missions.

Un-tensioned membranes have little bending and compressive stiffness. Very small uneven mechanical load or thermal variation would induce local buckling, i.e. wrinkles. Properly tensioned membranes have finite bending and compressive stiffness to prevent generation of wrinkles. However, constant tension scheme, i.e. passive flatness control, do not adapt to time-varying environment, especially thermal environment. Hence, a pure passive control method is insufficient to maintain the membrane flatness. An active control system is required to compensate for wrinkle effects.

Compared with selective heating, "patch-on", and embedded sensing and actuating, boundary manipulation is more intuitive and effective [2]. Patching sensors and actuators onto the membrane surface may adversely affect functionalities of membrane structure. Selective heating requires heating devices behind membrane structures, which will complicate membrane structures and deployment mechanism. It has been analytically and experimentally proven that boundary manipulation solution can significantly improve surface accuracy. This paper addresses active flatness control problem of tensioned membrane using shape memory alloy (SMA) actuators installed around the boundary of a rectangular membrane.

In order to properly design an active flatness control system, dynamic modelling of the membrane structure is very important. The development of dynamic model of wrinkled membrane structures has been quite challenging. In this paper, a thin shell theory (TST)[6]-based finite element model is developed using the ABAQUS software package. A corner-loaded square membrane is modelled. Wrinkle patterns under different load ratios are studied. The relationship surface of tension load and wrinkle amplitude is obtained, which agrees with results from a simplified analytical model. Using the relationship of tension loads and wrinkle amplitude as the fitness function, a genetic algorithm search was performed. It is demonstrated that the GA is able to obtain the optimal tension. The GA algorithm is also implemented in the experimental system, which includes a rectangular membrane with twenty SMA tension actuators around the membrane. Utilizing the assistance of flatness measurement from vision system, it is demonstrated the GA algorithm is able to find tension combinations that can substantially improve the surface flatness. However, the control design is not based on dynamic modelling, which is the current state in the membrane structure research. Further discussion on possible incorporation of dynamic model into active control system is given at the end of the paper.

The remainder of the paper is organized as follows. Section 2 reviews current membrane methods and describes the model we developed. Section 3 introduces simulation performed based on such a model. Section 4 depicts the experimental system for active flatness control and experimental results are given. Section 5 concludes the paper and discusses future work.

2. MEMBRANE WRINKLING MODELING

Tremendous amount of efforts have been undetaken in analytical and numerical modeling of membrane structures. Generally speaking, there are two kinds of methods: 2-D theory methods and 3-D theory methods. While the assumption of 2-D theories is "membrane is two-dimensional continuum unable to carry compression and with negligible bending stiffness" [7] , the 3-D theories models membranes using the thin shell theory where a finite bending stiffness is taken into account.

2.1. Membrane Theory Based Modeling

The theory basis for 2-D methods is the Tension Field Theory (TFT) [7], which is a modifiction of plane stress theory by incorporating buckling theory. In this theory, principal stress is positive along wrinkle directions and the principal stress perpendical to the wrinkle direction is close to zero. Since 2-D membrane-based theory assumes small compression, the compression stress has be eliminated either by changing material properties or penalty functions. Methods differ from each other in the way the compression stress is eliminated and the way wrinkles are interpreted. Essentially, 2-D theories share the essentially same constitutive relationship. The TFT is implemented by the iterative material properties(IMP) method in finite element procedures. Although 2-D theories can predict wrinkle region and stress and strain level quite accurately and computationally efficiently, wrinkle-amplitude cannot be predicted, which is generally required by active flatness control.

2.2. Thin Shell Theory (TST) Based Modeling

In order to predict out-of-plane deformations of membrane structures, bending stiffness must be taken into account. Hence, thin shell theories have to be used. In order to initiate the wrinkling process, i.e. out-of-plane displacement, when only in-plane forces are applied, artifical imperfection are added to the structural model. Artificial imperfection, be either combintion of buckling modes [8] or random imperfection [6], creates membrane to bending. By using locking-free shell element, like ABAQUS S4R5, and hour glass control [9], quasi-static analysis of a corner-loaded square membrane is performed with a refined model. When this kind of method is used, cautions need to be taken in order to obtain good convergence.

In order to improve the convergence of FE analysis, explicit time analysis is used, which does not require inversing near-singular stiffness matrix and requires long computation time [10]. In order to speed up compuation, mass scaling technique is employed. In summary, shell-element based method can obtain out-of-plane displacement at the cost of FE model with a large number of elements and longer compuational time. This poses a challenge for simulation of active flatness control. Furthermore, dynamic wrinkling simulation is even more time-consuming, which necessiates updating stiffness matrix and even adpative remeshing.

2.3. Finite Element Model of a Corner-Loaded Model

In order to design an active flatness control system, which requires out-of-plane displacement, a TST-based FE model is developed using ABAQUS.

The details of the model are plotted in Figure 1. The dimension of the membrane has roughly same geometry as membrane in [6]. The membrane has a side-length of 500mm, with a truncated edge size of 7mm. T_1 and T_2 are evenly distributed to nodes along these edges to reduce the singularity that might be caused by concentrated loads. The membrane is modelled as shell element S4R5,

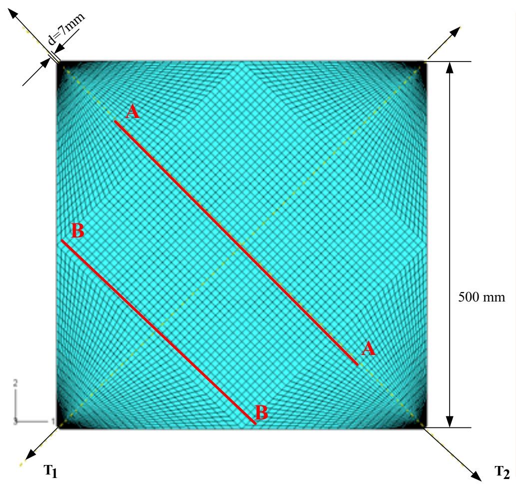


Figure 1. A corner-loaded membrane meshed in Abaqus

with four nodes and five degrees of freedom for each node. The element type incorporates large-displacement and small-strain assumptions. The element also features hourglass control, which uses an artificial stiffness to suppress zero-energy modes. For more information on the element, readers can refer to [9].

The material used in the membrane is Kapton, with Young's modulus $E = 2790 N/mm^2$, Possion ratio $\nu = 0.34$. The thickness of the membrane is 0.0254mm. The membrane is meshed to 5292 elements with 5461 nodes, each of which has five degrees of freedom.

Randomly generated out-of-plane artificial imperfection is generated in Matlab and added to nodes membrane to trigger the initiation of wrinkles, i.e. the coupling of in-plane force and out-of-plane displacement. The study was a static analysis with geometric nonlinearity considered. The Newton-Raphson method is used to try small steps to gradually apply the static load to the membrane as a ramp. A parametric study has been carried out to study the influence of the artificial imperfection level on the maximum wrinkle amplitude. The conclusion is that at certain region, the artificial imperfection does not affect the wrinkle amplitude much. However, it is found that sometimes there are sudden drops of wrinkle amplitudes. This is probably caused by distribution of artifical imperfection, which could counter-act the initiation of wrinkling.

Another parametric study was performed to study the effect on edge length over the wrinkling initiation. It is concluded that basically the edge length doesnot change the the wrinkle amplitude much.

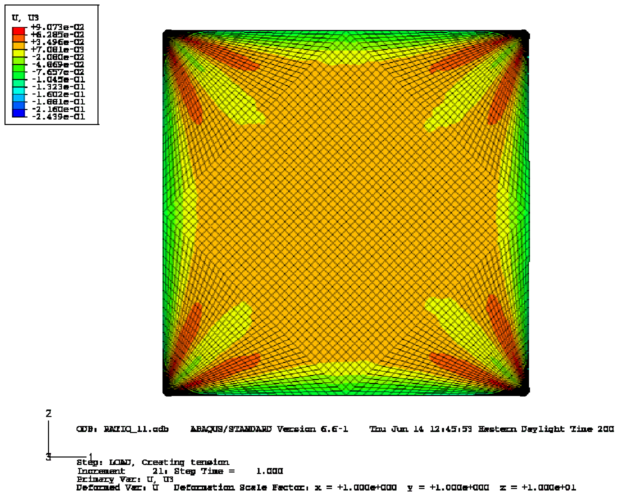
2.4. Load Ratio Study

Different loads were applied to the corners of the membrane to study the wrinkle amplitude. Figure 2 shows the out-of-plane dispacment of membrane contour when different loads were applied to the membrane. Figure 2 (a) shows wrinkling pattern. the load ratio 1:1 case where $T_1 = T_2 = 0.42N$. It is observed that two wrinkles at amplitude of $0.1mm$ are developed close to the corner of the membrane. The middle part of the membrane basically has a zero out-of-plane displacement, i.e at the level of 0.02mm, which is basically the level of artifical imperfection.

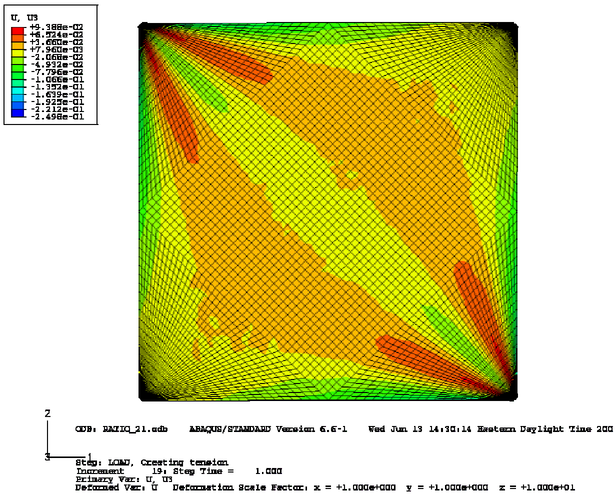
Figure 2 (b) shows the wrinkling pattern when $T_1 = 0.42N$, $T_2 = 0.84N$. It is observed that two wrinkles at amplitude are also developed close to the corner of the membrane, however at the level of 0.1mm. The wrinkles appearing at the diagnal direction are getting closer to each other, but at very low level.

Figure 2 (c) shows the wrinkling pattern when $T_1 = 0.42N$, $T_2 = 1.68N$. A large wrinkle appears along the diagonal direction, at the level of 0.6mm.

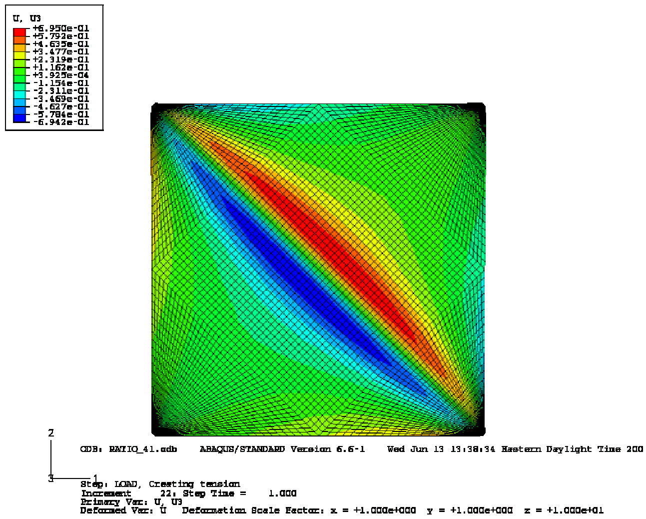
This kind of tensioning load ratio study was performed when T_1 and T_2 vary from 0.105N to 1.42 N. The results are used to perform interpolation and surfaces are plotted. Figure 3. (a) shows the maximum wrinkle amplitude along



(a)



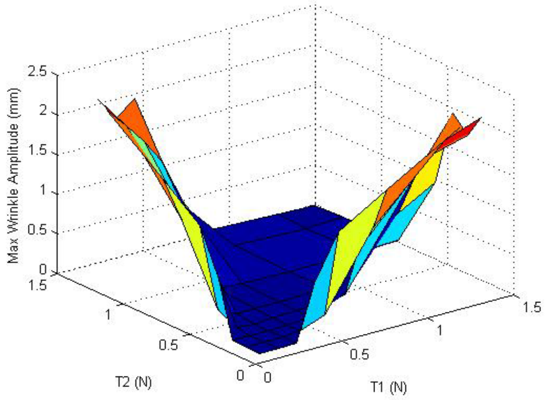
(b)



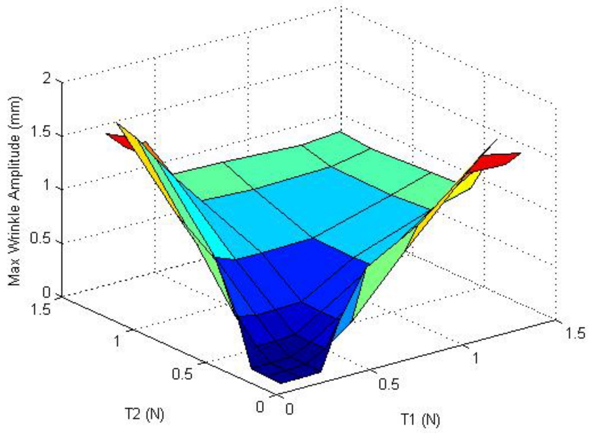
(c)

Figure 2. Wrinkle pattern with different load ratio: (a) $T_1/T_2 = 1:1$; (a) $T_1/T_2 = 1:2$; (a) $T_1/T_2 = 1:4$.

A-A cross-section (shown in Fig. 1) when these loads are applied. Figure 3. (b) shows the maximum wrinkle



(a)



(b)

Figure 3. Relationship of load ratio and maximum wrinkle amplitude along: (a) cross-section *A-A* (b) cross-section *B-B*.

amplitude along B-B (shown in Figure 1)cross section. It can be observed the wrinkle amplitude decreases when T_1 and T_2 are very close to each other. When the load ratio reaches 2, wrinkle amplitude increases very rapidly. Wrinkle amplitudes are very high when the load ratio is very high. In general in order to achieve convergence with high load ratios (>3 depending on the loads) a small stability factor was added (between 10^{-10} and 10^{-15}). This kind of surface shape and relationship is consistent with the relationship obtained from a simplified analytical model [23].

Current comptational efforts are undetaken to perform a coupled thermomechanical stress analysis of corner loaded membrane. The tension analysis and thermal-mechanical of load will be performed on an experimental membrane prototype, i.e. a membrane with twenty tension forces.

3. FLATNESS GA SIMULATION OF TENSION FORCE SEARCH

The numerical results from Finite Element modeling gives us guidance on design of mechanical structures and active control system. The surface we obtained in Figure 3 has a complex geometric shape and computationally expensive to obtain. Efforts need to take to attain convergence. Additionally, results are difficult to relate to experimental results, espeically for membranes with complex geometries. Due to complexity and computation amount of the finite element models for membrane structures, the finite element model cannot be used in the real-time flatness control system directly. Thus, an optimization-based flatness control method is developed to compensate for effects of wrinkle of membrane structures based on the adaptive genetic algorithm. In this optimization-based flatness control method, the adaptive genetic algorithm is used to search optimal tension force which are applied by the SMA actuators under flatness value performance index. Subsection 3.1. introduces the genetic algorithm. Subsection 3.2. describes our experimental system. Subsction 3.3. gives experimental results.

3.1. An Introduction of Genetic Algorithm

The basic process of a GA search is depicted in Figure. 4. For more detailed introduction on GA process, readers can refer to a tutorial [12].

In the GA searching process, each candidate tension force is coded to a chromosome, using the gray coding scheme [12]. In the gray coding scheme, the number of different digits in two adjacent values is constant. Hence the gray coding scheme can eliminate the hidden representational bias in conventional binary coding. Individuals are randomly generated as the initial population. The candidates are decoded to get the real value of tension forces. The fitness (performance) values, i.e. a function of the maximum wrinkle amplitudes, are obtained using a fitness evaluation function, which could be a mathematic model or a learning based model. In the experimental part of this paper, the real-tension forces are applied to the membrane directly. The fitness value is the maximum wrinkle amplitude using the finite element model developed in Section 2. In future studies, a learning-based model will be used to provide fitness information for candidate forces, which will provide a faster search. Two parental individuals from a population are selected according to their fitness. The better the fitness, the bigger

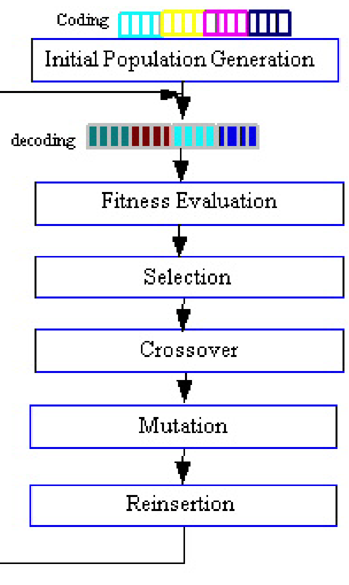


Figure 4. GA search process

chance to be selected. The stochastic universal sampling scheme is used to select parents. Using a crossover probability, the selected parents are crossed over to form a new offspring. If no crossover was performed, offspring is an exact copy of the parents. Using a mutation probability, mutate new offspring at arbitrarily selected locus. New offspring is inserted to the new population. After the best individuals are obtained, decode them to the required parameters, and choose one as the optimized solution.

3.2. Experimental System Decription

As mentioned in Section 1, an experimental system has been developed to study the dynamics and active flatness control of membrane structures. The system can accurately apply desired tension forces at selected locations and measure the surface profile in real-time. The tension forces are realized using SMA actuators and strain gauge sensors. The system is also equipped with an infrared camera, which measures temperature profile on the membrane, and a thermocouple, which measures the ambient temperature at a single point in real-time. A ceramic radiator is used to provide thermal disturbances, which would cause wrinkling of membrane. The system gives us the capability to investigate the influence of thermal disturbance and tension forces and to test various active flatness control algorithms.

The experiment system is showed in Figure 5. Figure 6 depicts the overall architecture of the experimental system. The system is a layered system based on real-time workshop (RTW) architecture of Matlab [13]. The host PC has three functions: (1) flatness measurement: which measures displacement of points on the membrane using the photogrammetry technique [14]; (2) dynamic model or learning model. The dynamic model based on analytical or numerical solution usually is not fast enough to be used in real-time. Hence, a learning model is proposed to map the applied tension forces to the resultant surface flatness, which is measured using the vision system. The learning model is not the topic of this paper; (3) Searching algorithm, the searching algorithm searches the best tension force combination based on a dynamic model or a learning mode. In this paper, the search algorithm is based the real-time measurement. The genetic algorithm is utilized to decide the desired tension force based on a dynamic model and/or the vision system measurement.

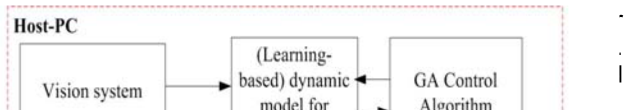
The RTW toolbox generates C code and compiles C program to executable program, which is then downloaded to the target xPC via the TCP/IP protocol. On the xPC, the tension control program downloaded runs continuously under a real-time operating system. During the control process, the searching program on the host computer sends desired tension forces to the target PC dynamically.

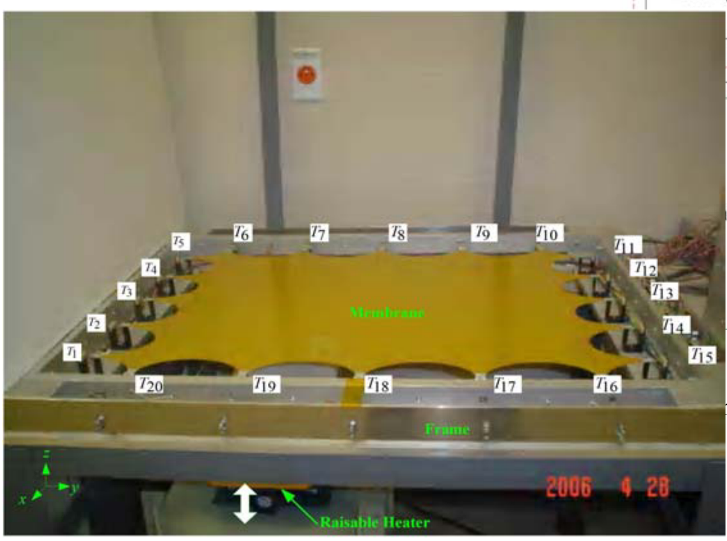
By using this system architecture, the system has a very good real-time performance benefiting from the real-time operating system, which guarantee that the desired tension forces are maintained. This kind of schemes enables hardware-in-the-loop system identification and artificial intelligence-based control algorithms without sacrificing real-time performance.

The tension control is implemented on the target PC. When electrical current is applied to SMA wires, SMA wires are heated up and start to contract. Tension forces are applied to the membrane. The tension forces are measured strain gauges installed as shown in Figure 8. The control algorithm is implemented under xPC real-time operating system, which updates 1000 times per second. The update rate is much faster than the response time of the SMA actuator. Hence, the tension can be maintained during the active flatness control process.

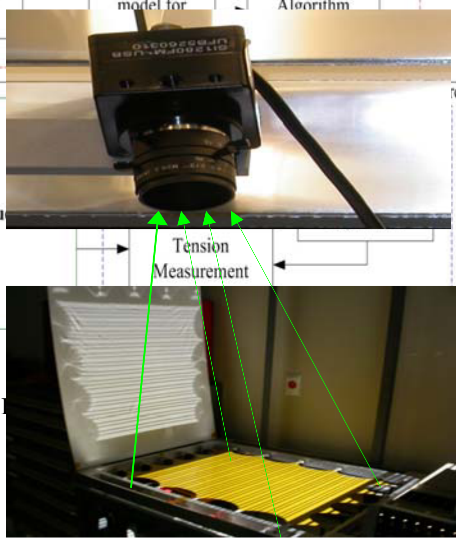
3.3. Experimental Results

Experiments are performed on the experimental setup shown in Figure 7. The searching algorithm was an improvement over simple GA: Fuzzy logic integrated genetic algorithm (FLIGA) [15].





(a)



(b)

Figure 5. Experiment system: (a) the membrane with SMA wire actuators; (b) the real-time vision system, with a camera shown in above and membrane with projected stripes on the bottom.

during the optimization process. In early stage, the mutation rate should be higher so mutation can happen more often so the search space could be explored. In the later search stage, as excellent candidates emerges, crossover should happen among good candidates so convergence can be achieved. Mutation and crossover parameters are adjusted dynamically based on the performance index of previous search steps. Fuzzy logic interface are designed to regulate these two parameters.

Among 20 actuators forces around the membrane, Eighteen SMA actuators are controlled. The upper limits of the tension forces are set to be 7.0 Newton. A lower limit of 0.5N is also set to maintain the flatness. Two SMA actuator, actuator12 and 17 are uncontrolled. They are used to balance other tension forces in the *x, y* directions.

After the heater under the membrane is turned on, wrinkles appear due to the heating disturbance. After the active flatness control is turned on, wrinkle amplitudes start to decrease. This process is demonstrated in Fig. 7. Each control process roughly takes less than 1 minute to converge. he results demonstrate that the FLIGA is able to reach convergence faster and reach a better control accuracy.

4. CONCLUSIONS

This paper reflects the current states on two aspects of membrane structure research: nonlinear modelling and active shape control. Research in nonlinear modelling is making progress in wrinkle amplitude prediction and thermo-mechanical analysis. However, the reliability, fidelity, and computationally efficiency are preventing them from being used in real-time control. Currently, active shape control has to depend on non-dynamics based approaches, such as learning-based model, evolutionary algorithms.

However, the correlation of learning-based approach /evolutionary algorithms with numerical model would provide important insight to the controller design. Some rules could be extracted from the dynamic model. The dynamic model could be utilized to optimize the control system. So controller can be designed with better robustness.

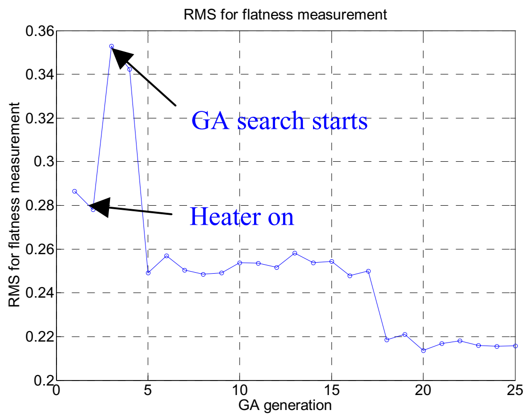


Figure.7. The variation of flatness measurement

REFERENCES

[1] H. Jenkins, (Editor), *Compliant Structures in Nature and Engineering*, WIT Press, (2005).

[2] C.H. Jenkins, (Editor), "Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications", *Progress in Astronautics and Aeronautics*, Vol.191, (2001).

[3] J. Johnston, J. Blandino, J. Black, R. Pappa, "Structural analysis and testing of a subscale sunshield membrane layer", *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*,Vol.4, p. 3151-3160, (2003).

[4] E. E. Montgomery, L. Johnson, "The development of solar sail propulsion for NASA science missions to the inner solar system", *Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference and Exhibit*, Vol. 1, p 60-65 , (2004).

[5] Y. Rahmat-Samii, J. Huang, B. Lopez, M. Lou,E. Im, S.L. Durden, K. Bahadori, "Advanced precipitation radar antenna: Array-fed offset membrane cylindrical reflector antenna", *IEEE Transactions on Antennas and Propagation*, Vol. 53, No.8, August, p. 2503-2515, (2005).

[6] A. Tessler, D.W.Sleight, J.T. Wang, "Non-Linear Shell Modeling of Thin Membranes with Emphasis on Structural Wrinkling," *AIAA Journal of Spacecraft and Rockets*, 42 (2), March–April (2005).

[7] D.J.Steigmann, "Tension field theory", *Proceedings of the Royal Society of London, Series A (Mathematical and Physical Sciences)*, Vol. 429, No. 1876, p 141-73, (1990).

[8] Y.W. Wong, S. Pellegrino, "Wrinkled membranes. Part II: analytical models", *Journal of Mechanics of Materials and Structures*, 1(1), 25-59, (2006).

[9] ABAQUS Theory menual, version 6.7, SIMULIA inc., 2007

[10] JT Wang, T Chen, DW Sleight, A Tessler, "Simulating Nonlinear Deformations of Solar Sail Membranes Using Explicit Time Integration"
- techreports.larc.nasa.gov

[11] X. Wang, W. Zheng, Y.-R. Hu, "Adaptive Genetic Algorithm for Active Flatness Control of Membrane Structures", *Proceedings of the 9th Cansmart Meeting - International Workshop on Smart Materials and Structures, Toronto*, Canada, p. 257-266, (2006).

[12] A. Chipperfield, P. Fleming, H. Pohlheim, H., C. Fonseca, Manual for Genetic Algorithm Toolbox, for use with Matlab, Version 1.2, University of Sheffield, U.K, (1994).

[13] *Real-Time Workshop® For Use with Simulink, version 6.0*, Mathworks, (2006)

[14] E. Trucco, A. Verri, *Introductory techniques for 3-D computer Vison*, Prentice Hall, (1998).

[15] X. Wang, W. Zheng, Y.R. Hu, "Active Flatness Control of Membrane Structures Using Fuzzy Logic Integrated Genetic Algorithm", *in the proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference(**AIAA-SDM**)*, Waikiki, Hawaii, USA, April 23-26, 2007