LARGE DEPLOYABLE MEMBRANE STRUCTURES

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ABSTRACT

In the past years, miscellaneous techniques to stow and deploy large structures have been developed. Reasons for this trend are on the one hand the increasing interests on such large structures in space and on the other hand economical reasons (e.g. launching and supporting costs). The field of functions of such a deployable structure is extremely wide. So the most solar arrays and some antennas (Mars Express, Spartan 207) are constructed deployable. This paper shall prove the possibilities of deploying planar, large membrane surfaces for different applications. Therefore, the base line concept of a thin membrane, supported by a deployable frame, was chosen. Due to this concept, various options for the deployment will be compared and assessed. Furthermore, a short outlook on membrane design and manufacturing is given.

1. INTRODUCTION

This paper gives a short survey of the ongoing activities, regarding deployable membrane structures, of the DLR's Institute of Composite Structures and Adaptive Systems in Brunswick, Germany.

The current research is focused on a potential use of membrane structures as L- or P-band SAR antenna. Typical tasks for such antennas are remote sensing applications. The monitoring of ice-shields, continental drift, volcanism, glacier flow or biomasses, could be exemplary mission goals. Therefore, membrane structures with a size up to 30m seem to be possible. Since the exact dimensions depend on the specified task, a concrete definition at this time is not meaningful.

Secondary, other applications that rely on the availability of large membrane surface are possible, too. Hence, a use as sunshield, solar sail or as solar array should be feasible. In contrast to the other both applications, for the solar array additional structures have to be installed on the foil. Considering the additional structures that are necessary for a potential use as SAR antenna, a redesign from antenna to solar array should be realistic.

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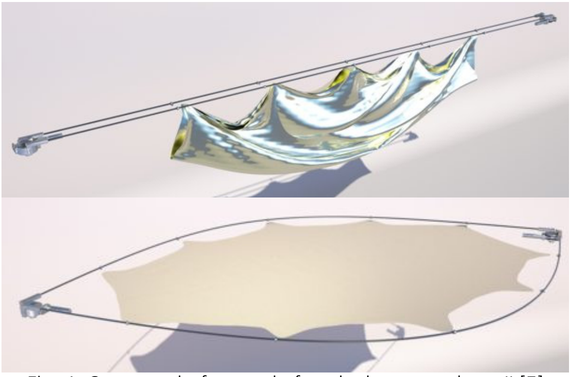

Fig. 1: Structure before and after deployment phase II [5]

2. BASE LINE DESIGN

To tauten a large area flat membrane a supporting frame is needed. According to the membranes function, the frame has to realize different tasks:

- Deployable design with a preferably high packing efficiency
- Act as interface between membrane and satellite
- Provide static forces for membrane tightening
- Take dynamic forces, excited by rotatory or translatory accelerations that are induced by thermal shocks or solar wind
- Provide a possibility to retighten the membrane (could be possible to compensate thermal strain or a partial membrane failure provoked by micro meteoroids)
- For an utilization like antennas or solar arrays, a wiring system for the membrane is needed
- Despite of all these claims, the systems should be as simple as possible to minimize the failure probability

As intersection of these requirements a relatively simple concept with a two step deployment mechanism has been developed. This mechanism is introduced during the following paragraphs.

During the first phase (phase I) of such a deployment, two masts have to be deployed, with a so far undefined deployment method. After the longitudinal deployment sequence, both masts are located parallel to each other and are connected with two spreader mechanisms at each end.

While the second, lateral deployment sequence (phase II) the two spreaders apply bending moments to the masts. Thereby, an elastic bending of both masts occurs. The resulting approximately elliptical shape can be used as frame for a membrane. Therefore, a membrane that was mounted to the frame before phase II, becomes deployed and tightened during the masts bending (see Fig. 1).

As the mechanism for the phase I deployment isn't clarified so far, a first demonstrator for the phase II deployment has been designed and manufactured. For this subscale demonstrator, pultruded CFRP members are used. They have a length of 2m and a diameter of 4mm. For the inducing of the necessary bending moments to the members, two electrical driven spreaders were manufactured (see Fig. 2).

Fig. 2: Photograph of one spreader mechanism

Furthermore, a 12µm thick polyester foil was cut and connected to the members by use of adhesive tape and metallic rings. Concretely, one membrane interface consists of one piece of adhesive tape and two metallic key rings (a smaller and a larger one). The large ring is connected with the membrane by use of the adhesive tape. The smaller ring is directly connected to the larger one. The small ring is slid onto the member. Because of relatively low friction between the ring and the member, the rings move automatically to their optimal positions during deployment. The first deployment tests deliver positive results. As shown in Fig. 3 the chosen principle works well.

Fig. 3: Deployed Sub-Scale-Model

In [6] a detailed surface measurement at this model is described. Therefore, a laser scanning system was used to determine the flatness of the membrane. Despite of a horizontal measurement setup and the associated gravitational sag, a RMS[1] value of 0.41mm for the average out-of-plane deflection was calculated.

Considering the fact that the maximum of the afore mentioned gravitational sag was approximately 2mm, a RMS value below 0.1mm for a 0-g environment seems to be realistic.

3. BOOM DESIGN

For the phase I deployment, a special mast structure is needed. On the one hand, it must be packable and deployable. On the other hand it has to be bendable to a radius of curvature of approximately 10m in minimum. Thereby, the bended masts have to keep enough structural reserves to bear static and dynamic forces that are induced by the membrane or the main module.

To make a choice out of the existing mast deployment mechanisms, a short overview is given in the next subsections.

3.1. Inflatable Booms

Meanwhile, inflatable boom techniques are described well in the relevant literature (see exemplary [1], [2], [3], [4]). The pack technologies for inflatable systems vary from simple folding to reeling or sophisticated folding methods (see exemplary Fig. 4). Unless these technologies use different possibilities to guarantee the final bearing capacity of the deployed structure. In principle, a permanently stabilization by the applied internal pressure is indeed possible. However, no inflatable structure is 100% airtight. The inflation gas diffuses slowly through tiny material pores or through seams. Hence, a continuous gas supply is needed to hold a constant internal pressure during the whole duration. Thus, a use of such inflatable structures is unprofitable, considering the additional weight and space for the gas generating or storing equipment.

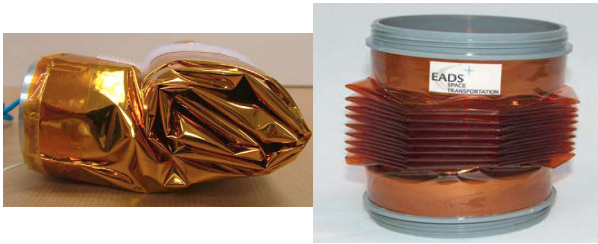

Fig. 4: Coiled[4] and folded[1] inflatable boom

To bypass this disadvantage, booms with resin impregnated fabrics was developed. These fabrics can be rigidized after the deployment sequence. So a further gas supply is not necessary to keep the structures mechanical properties. Depending on the types of resin and fabrics, the rigidization can be effected by different influences. The most established methods are rigidization through UV-light or heat.

Based on the assumption of fiber glass reinforcement and an UV-reactive resin, the following statements are possible:

- Positive aspects
  - + Very light Boom
  - + High packing efficiency
  - + UV-based rigidization by the use of sunlight is possible → no additional heating or radiation elements are necessary

[1] Root Mean Square: flatness indicator

- Negative aspects
  - The load bearing capacity during deployment and rigidization is lower then the rigidized structures capacity
  - Due to inhomogeneous radiation conditions, stress and, therefore, distortion in the rigidized structure could arise
  - Additional weight by gas containers or chemical gas generators and control technique

Fig. 5: Collapsible DLR Boom

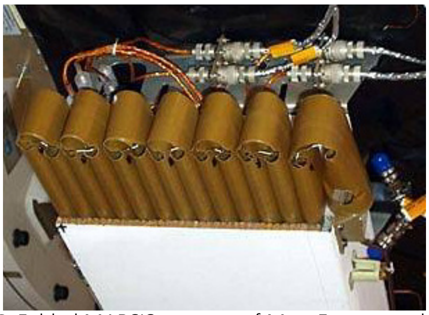

Fig. 6: Folded MARSIS antenna of Mars Express probe [9]

3.2. Collapsible Tubular Booms

Other representatives of deployable masts are rollable and foldable booms as pictured in Fig. 5 and Fig. 6. They are mainly made of thin walled composite materials. Per elastic deformation, a space-saving stowage of the booms is possible. In case of deployment, the stored deformation energy is sufficient to deploy the structure without any external energy supply.

Depending on the detailed geometry, this automatically deployment can be more or less chaotically and, therefore, poorly to control. This disadvantage can be regulated by use of a deployment guidance mechanism. Regrettably, every mechanism complicates this simple method and adds extra weight to the structure.

Statements to this deployment technique:

- Positive aspects
  + Relative light Boom
  + High packing efficiency
  + The CTE of CFRP booms can be adjusted to nearly 0 by an adequate laminate setup
  + Limited load bearing capacities during deployment (for a rolled boom with guidance mechanism)
- Negative aspects
  - Additional weight because of the guidance mechanism

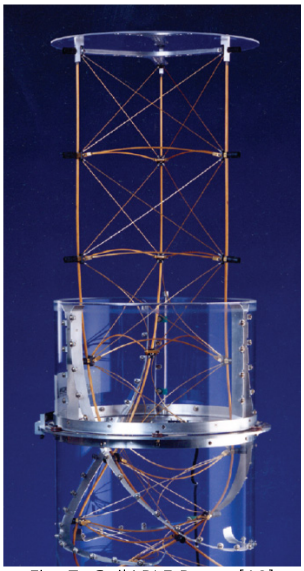

Fig. 7: CoilABLE Boom [10]

3.3. ABLE - Masts

The so called CoilABLE Booms from ATK (see Fig. 7) consists of many hinges, beams and ropes.

By torsion around the longitudinal axis, the mast can be shorten remarkably and stored space saving.

Statements to this deployment technique:

- Positive aspects
  + Middle packing efficiency
  + Relatively stiff
  + Limited load bearing capacities during deployment
  + Space proven
- Negative aspects
  - Many mechanical basic elements (high complexity)

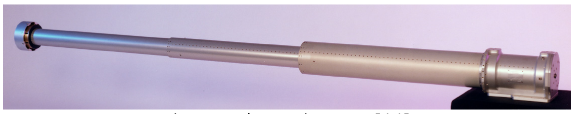

Fig. 8: Telescopic Mast [11]

3.4. Telescopic Masts

Finally, the telescopic systems (see Fig. 8) should be mentioned. They operate with the well-known telescopic arrangement of several cylinders, spindle drives and others force guiding elements.

Statements to this deployment technique:

- Positive aspects
  + Very stiff and according to this very resilient design
  + Load bearing capacity nearly independent from deployment completion
- Negative aspects
  - High weight
  - Relatively complex

3.5. Mast Systems Evaluation

At last, some of the shown systems have the potential to be modified for the given requirements. Mainly the collapsible, foldable and inflatable booms are good candidates for further studies.

As a first study the boom concept as shown in Fig. 5 is virtually modified and a simulation of a 6mx25m antenna is done [6]. For the first approach an adjustment of the cross section is performed to decrease the geometrical moment of inertia to consequently decrease the moments induced by bending.

The investigation shows that the booms are able to bear the given bending curvatures. But the margins until the critical buckling moments are quite small. Due to the modified cross section of the booms, the system stiffness decreases markedly. Here a further optimization of the booms cross section geometry and laminate setup shall generate a system with satisfying properties.

4. MEMBRANE DESIGN

The proposed deployment design provides the possibility to use approximately elliptical membranes. Through variation of the spreader angles a nearly circular shape can be modeled, too.

Therefore, it must be considered that not only the spreader angles are relevant for the resulting shape. Moreover, the factors like the material properties of booms and membrane or the dimensions of the membranes attachment forces are in very complex interaction with the final shape of the membrane.

4.1. Shape Prediction

To control this complex interaction, a program package was developed that contains Matlab and ANSYS routines. The program is as far as possible parameterized. So the user has to define the following values:

- Boom material properties and geometry
- Membrane material properties
- Length of the clamping at the end of each boom (depends on spreader geometry)
- Final spreader angle
- Positions of the 10 membrane-boom interfaces (membrane attachment points)
- Values of the 10 membrane attachment forces
- Geometrical membrane design rule parameter (membrane edge curvature radii, distances between membrane and boom, width of membrane attachment, etc.)

Because of the double symmetry of the given system, a simulation of only a quarter of the real model is possible and should be used to minimize the computing time. The computation consists of three steps that should be shortly explained in the following paragraphs.

During the first step a Matlab initialized ANSYS script calculates the deformation of a half boom. As base for this computation some of the above listed values where transferred from Matlab to ANSYS by use of a data file. The result of such a nonlinear solution of a half boom is pictured in Fig. 9.

Beside this plot, the exact coordinates of all points from the bended boom are stored to the hard disc drive to make them available for the following step.

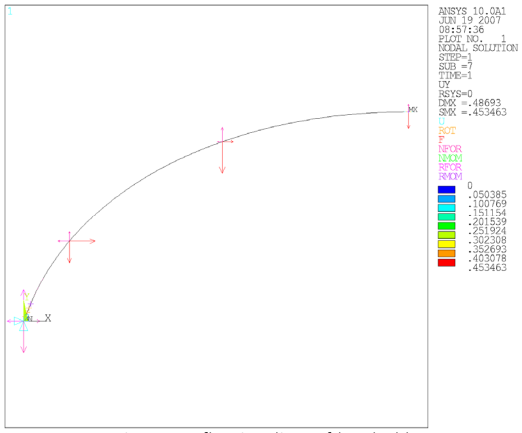

Fig. 9: Deflection line of loaded boom

Within the second step Matlab loads this data in its own workspace and calculates the resulting membrane shape. Therefore, the mentioned membrane design rules are respected.

As pictured in Fig. 10 the geometry of the membrane is designed in a format that is easy to transfer to ANSYS. So the final membrane shape results from a subtraction of simple areas like circles and polygons. The polygons vertices and the center points and radii of the circles were saved to hard disc again.

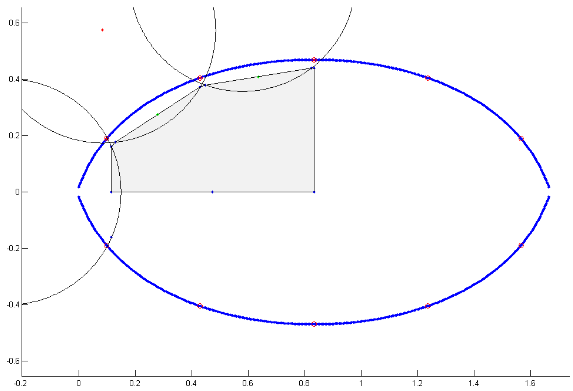

Fig. 10: Calculated membrane geometry

The third step is performed by ANSYS. Therefore, the before saved data was loaded to build the membranes model. Moreover, properties like Young's Modulus and thickness of the membrane have been transferred. For the given calculation, the data bases on 7.5µm thick Kapton (polyimide) foil. The attachment forces are set to 2N per attachment point. The attachment force directions depend on the angles of the boom at the particular interface position. After meshing and the definition of boundary conditions the FE-solution occurs. Fig. 11 shows the result of such a calculation. More precisely, the resulting displacement vectors of all FE-nodes are plotted.

For the given model the calculated displacement and stress characteristic looks realistic. But, a further comparison between these simulated values and measured values is necessary to finally validate this simulation method. As described in 4.3.1. first endeavors to build the needed test rig are still done.

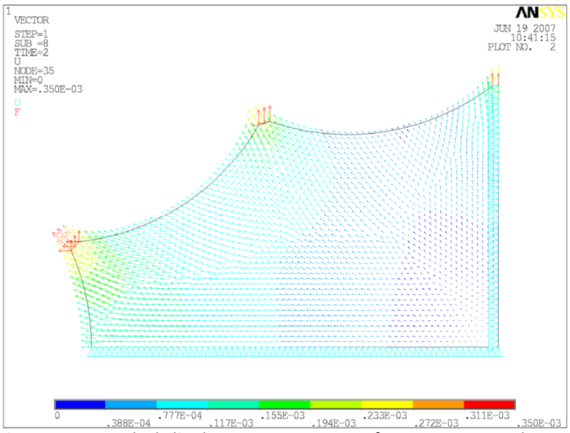

Fig. 11: Up-scaled displacement vectors of a quarter membrane (color bar units in meter)

4.2. Wrinkling Behavior

Limited by the local concentrated force attachment points, the stress characteristics in a membrane can't be optimal for such a force application. So wrinkling patterns mainly in direct environment to force attachment points can occur. The reason for wrinkling formation is the fact that membranes can't stand in-plane compression. As consequence on such an in-plane compression an out-of-plane buckling arises. This effect has been detailed investigated in various publications (see exemplary [7], [8]). Both numerical and analytical design models are available to predict regions where wrinkles could appear.

During former activities, concerning solar sails, the Institute of Composite Structures and Adaptive Systems had elaborated some know-how for such numerical wrinkling simulations. The existent routines work with an iterative-implicit algorithm and can identify areas with a high wrinkling probability.

These routines shall be adequate for a design of solar sails, solar arrays and sunshields. Reasonable is the fact that for example a partly wrinkled solar sail is still working. The propelling force of the sail is just decrease by a small percentage that results from the size and intensity of the wrinkled areas, but it still works. However, a membrane antenna with wrinkles does not only decrease its efficiency by the percentage of the wrinkled areas in relation to the unwrinkled one. Depending on the wrinkle amplitudes, the applied antenna modules are not in-plane. Hence, the antenna modules that are located in a wrinkled area can disturb the other modules by interfered amplification and erasement.

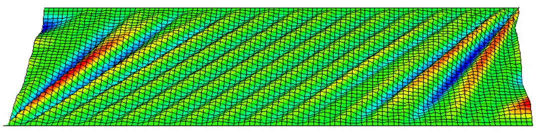
Fig. 12: Exemplary solution of an sheared membrane (source [7])

Because of this sensitivity an adaptation of the existing routine should be done in the future. Therefore, explicit algorithms as presented in [7] and [8] should be used to get further information like wavelength and amplitude on the calculated wrinkles. A result of such an explicit solution is displayed in Fig. 12. The plot bases on a FE calculation, done by David W. Sleight et al. in [7]. They simulate a thin Kapton membrane with dimensions of 128mm x 380mm x 25µm. The membrane is virtually clamped at the two longer edges. For inducing of a shear load the clamps where displaced relatively to each other by a few millimeters.

Obviously, the potential of these algorithms are quite good. Hence, an integration into our routines will be done in the next months.

4.3. Measurements

To validate the simulation results, a testing construction was designed and equipped. The construction should give the possibility to tighten a test membrane as realistic as possible. Therefore, adjustable attachment forces under predefined angles have to be applied. For this purpose the following test rig was constructed.

4.3.1. Test Rig

The rig consists of aluminum profile and has an active measurement area of 2.0mx1.8m (see Fig. 13). An applied test membrane is only held by the membrane attachment forces. The forces are provided by variable weights. These weight forces are guided by a simple system of pulleys to the membrane.

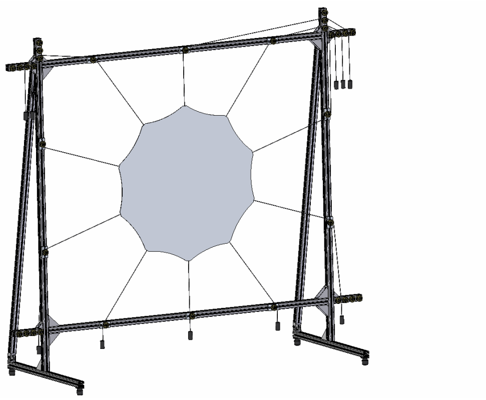
Fig. 13: Membrane test rig

The correct force angle for every membrane attachment point can be adjusted by disarranging movable pulley sliders. Resulting from the fact, that the membrane is just held by the applied forces, every displacement of such slider effects a displacement of the whole membrane and thereby a changing of all force angles. So an application of a test membrane with exact specifications of force attachment points and angles, with a kind of trial and error method, is very time consuming and not very precisely.

To optimize this application process, a Matlab script was written that calculates the position of each slider for a given test rig dimension and a set of force attachment points and angles. Fig. 14 shows the standard output of such calculation. This plot contains a small sketch of the sliders and the membrane. For a simple slider positioning the exact positions are explicitly written aside every slider. So the diagram can be printed and taken to the test rig easily.

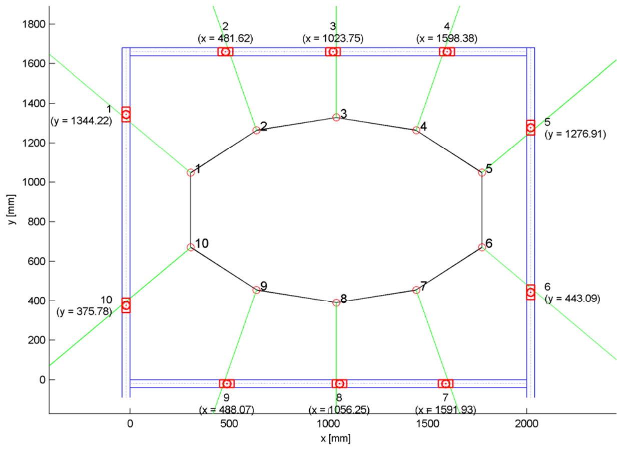

Fig. 14: Output of MATLAB calculation for slider positioning

4.3.2. Membrane Manufacturing

Different ways to manufacture a membrane are possible. Regarding the prototype status of past and future membranes and the experience that Kapton is quite poorly to cut, a handmade cutting and further processing is favored.

For this purpose the use of a vacuum cutting table has been found advisable. Furthermore, a large sheet of paper was put on the membrane. This procedure has two main advantages: At first, the paper is pressed to the table by the vacuum, too. So the membrane gets fixed during the cutting process. As former cuts had shown, this fact is very important. Without such stabilization, the cutting is very risky. Sometimes the cutter stucks at the membrane. If the cutting person doesn't stop the blade momentarily, the membrane becomes damaged at this point and could become unusable. Secondly, the paper provides the possibility to print a template of the desired membrane on it. After arrangement of the membrane blank and the paper, the cutting person can cut paper and membrane simultaneously by following the printed lines.

To create such a full scale template two alternatives, the use of a CAD software or the further usage of Matlab, were considered. For the development of a single template, here a CAD program would be the correct choice. But, for the ongoing research, we plan to manufacture some different membranes with different shapes and design parameters. Therefore, a program that creates a template automatically out of predefined parameters is a good solution. So a further Matlab routine was programmed that uses the same database as the above illustrated shape prediction package. Out of this shape prediction the set of force attachment points, containing coordinates, force angles and values, and the geometrical membrane design rule parameter, can be exported and used by the template routine. The program generates a bitmap-like graphic file that can be printed by every printer or plotter.

Fig. 15 shows the down scaled output of this routine. The accordant full scale template has a diameter of 1.2m and was used for the cut of the test membrane displayed in Fig. 17.

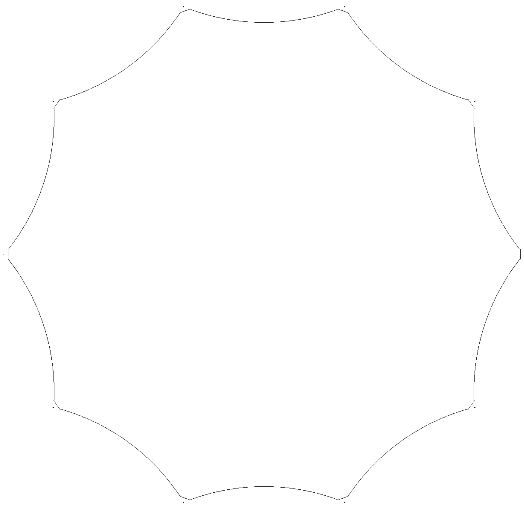

Fig. 15: Membrane cutting template

4.3.3. Measurement Technology

To measure the flatness of a membrane that was applied to the test rig, a scan arm (see Fig. 16) is used. This arm provides the possibility to perform a contact less measurement of a 3D object and transfer the received point cloud to a computer. The given system has a precision of approximately 50µm and can cover a plane of 2.5mx2.5m. For objects that are larger than 2.5m, it can be repositioned. By use of reference points, the several point clouds can be merged to one model later.

Fig. 16: INFINITE laser scan arm with Perceptron laser scanner

The laser scanner bases on a modified laser triangulation system and is able to record up to 458400 points per second.

During a measurement, the scan arm must be guided by a person. It doesn't contain any drive sections but only numerous sensors in its hinges. Combining the data of the arm sensors and the data of the laser scanner, a relative position of the measurement object towards the arms base point can be calculated.

4.3.4. First Measurements

For the first measurement a test membrane with a diameter of approximately 1.2m was manufactured and applied to the test rig. The membrane has an exact surface of 1m² (respecting the circular edges). This value was chosen to give a possibility to compare the values of this circular membrane with the values of future membranes with differing shapes. Holding forces of 2N are set to each of the 10 attachment points. Regarding this number of points, the force attachment angles vary from 0 to 324 degree by an interval of 36 degree.

After manufacturing and applying a measurement with the scan arm was performed. The result of it is displayed in Fig. 17.

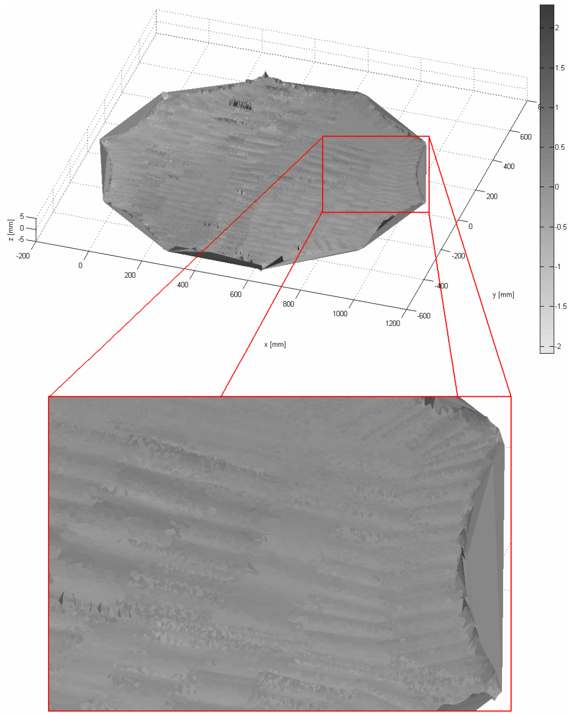

Fig. 17: Results of first surface scan

The measurement result shows wave patterns on the surface. But these patterns are not visible at the real membrane. So an explanation had to be found. During the causal research, an out-of-plane oscillation of the membrane was pointed out as reason. Caused by the in-plane attachment forces, the membrane isn't stabilized in out-of-plane direction. Hence, any force that affects perpendicular to the membrane causes a displacement of the membrane and the holding ropes.

Since the scan arm is guided by a person, lightly air turbulences arise from the closely moved scanner (medium scan distance 10cm) and the breathing person. Observations had shown that these influences are sufficient to excite membrane oscillations. An analysis of the given measurement data shows an oscillation amplitude of less then 0.5mm. Despite of these relatively light vibrations, the intended displaying of wrinkles is not possible and the acquired data is unusable for our purposes.

The best solution for this problem will be definitely the total elimination of the disturbing medium air. Limited by the given measurement technique and cost reasons such realization is not possible. Therefore, a modification of the test rig is currently in progress.

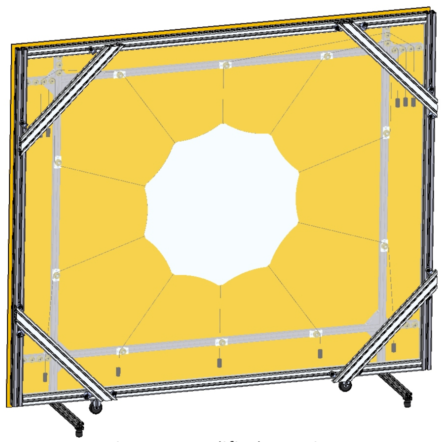
Fig. 18: Modified test rig

At the end of the activities, the membrane shall be encapsulated in the rig by the use of a back plane and front mounted glass panel (see Fig. 18). The interior of the test rig will be further filled with ambient air, but the encapsulation should minimize the feedback between inside and outside.

Tests have shown that surveys through glass panels are possible. But due to refraction, the values have to be corrected afterwards. For such a correction a detailed knowledge of the relative positions between glass plane and scan head are necessary. Fortunately, the scan arm provides a set of x, y and z coordinates and the pitch, roll and yaw angle of the scan head for every recorded point. With this data and the correct position of the glass plane, a mathematical correction of the measured points should be possible. Currently the development of such a correcting routine is ongoing.

5. SUMMARY & PERSPECTIVES

The here presented results could be a perspective for our future activities. Both, the simulation routines and the measurement equipment are under development. Therefore, at the moment they are not sure enough to deliver trustable results.

A prior task for the near future is the identification of a boom type that is suitable for the deployment phase I of the presented deploying mechanism. Parallel to this verification further designs of the membrane test rig and the numerical analysis will occur.

To examine a potential SAR antenna application, a cooperation with the DLR's Microwave and Radar Institute is aspired. As a result of this cooperation, an assessment of the usefulness of such a deployable membrane antenna should be delivered. Furthermore, very basic dimensioning should be done to concretize the FE models.

From our perspective, the shown deployment mechanism has a high potential. Applications as antenna, solar sail, sunshield and solar array are imaginable. First of all the simplicity of the mechanism and the possibility to use on-ground rigidized masts, are factors that clarify the robustness and the positive cost efficiency of this construction.

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