Master's thesis review

Deployment Behavior of Membrane Structure Using Inflatable Tube as Support Member

インフレータブルチューブを支持部材とする膜構造物の展開挙動

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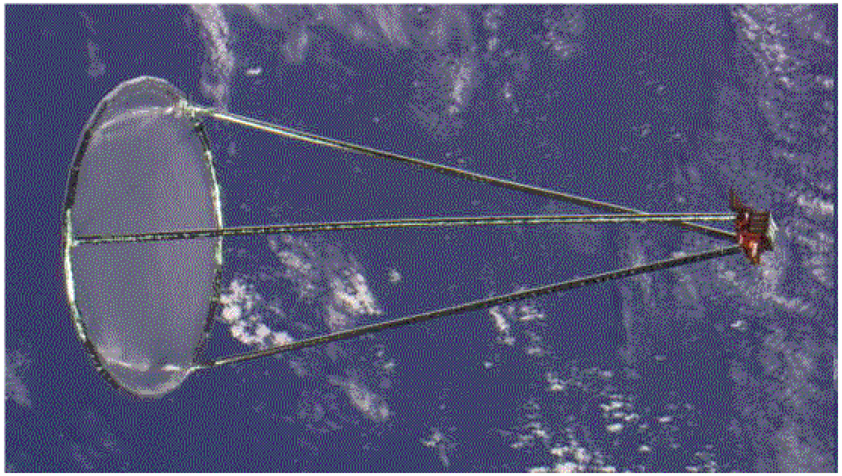
【Contents】

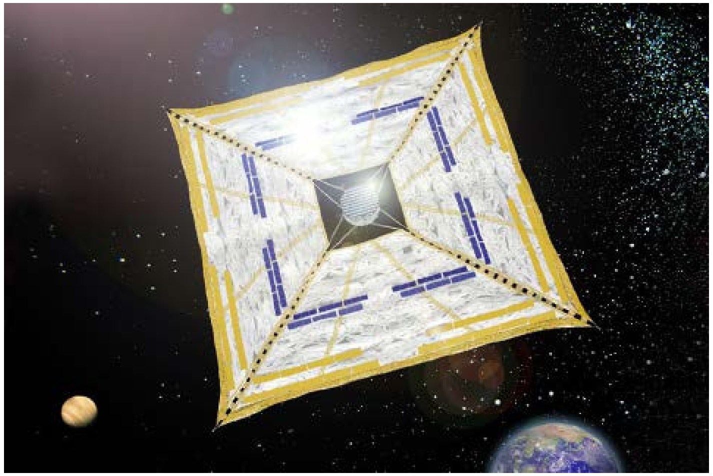
Research background

Combined membrane structure

- In recent years, combined membrane structure is attracted attention as a next generation space structure style.
- e.g.: inflatable antenna experiment "SPARTAN", small solar power sail demonstrator "IKAROS"
- The optimal storage method, deployment method and speculation of deployment behavior are studied.



SPARTAN ©NASA



IKAROS ©JAXA

Combined membrane structure

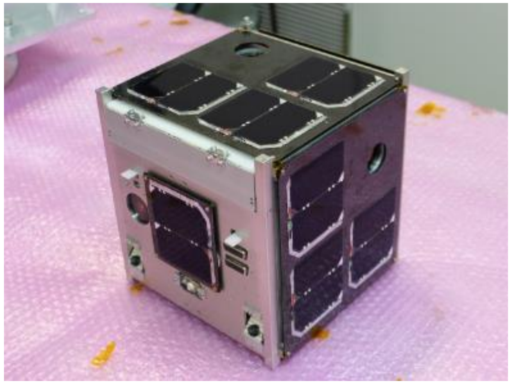
Advantages of combined membrane structure

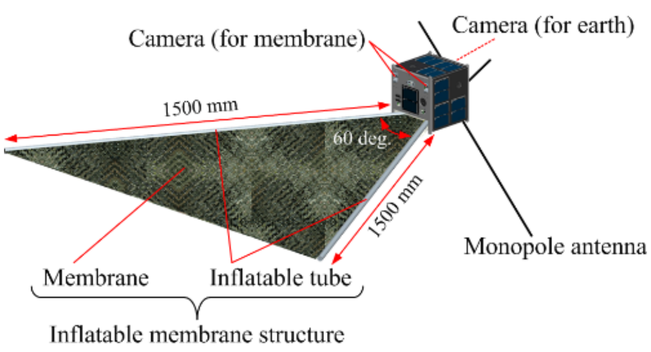
- One-action deployment is possible.
- Compared with the assembly formula, deployment time is short.
- It is possible to deploy a large area with a relatively lightweight and simple mechanism.
- Because the deployed structure is low volume and light weight, the ratio of capacity and weight in the satellite is small. Therefore, it can be expected to be used for small satellites.

Nano-satellite "SPROUT"

- Nihon University designed and developed a CubeSat named "SPROUT".
- In May 24 2014, SPROUT was launched by H-IIA and injected into a sun-synchronous orbit of 600 km altitude.

Mission: Demonstration of deployment of combined membrane structure

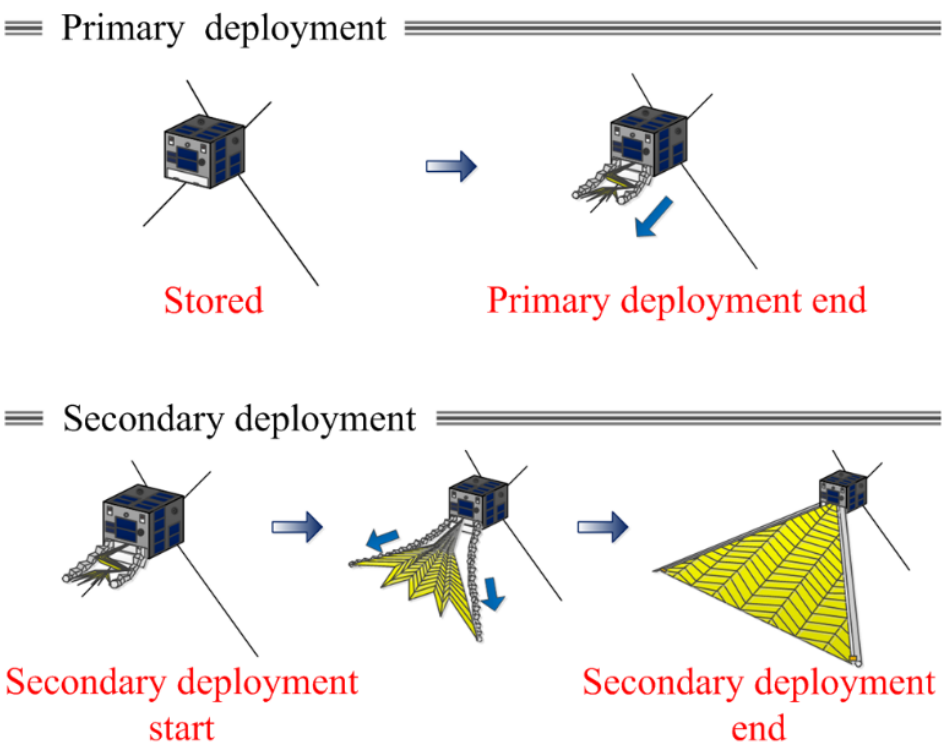


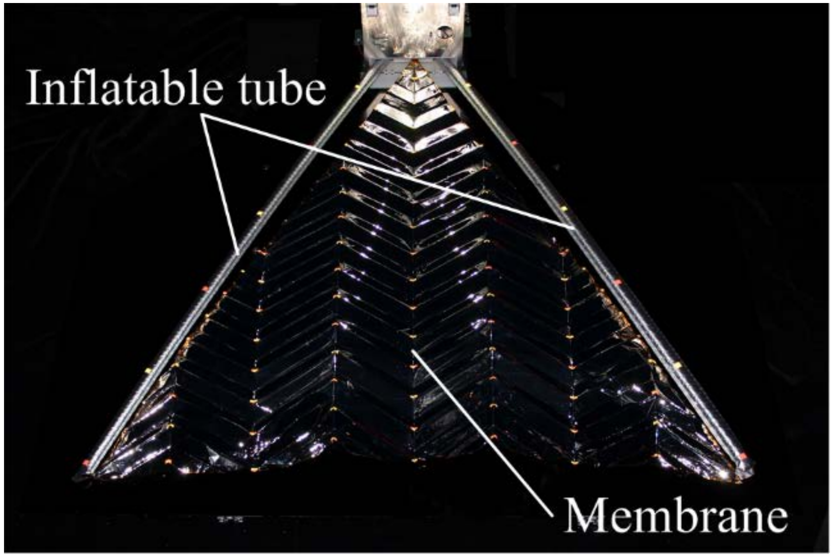


How to deploy SPROUT

・The membrane structure of SPROUT consists of two inflatable tubes and an equilateral triangular thin membrane.

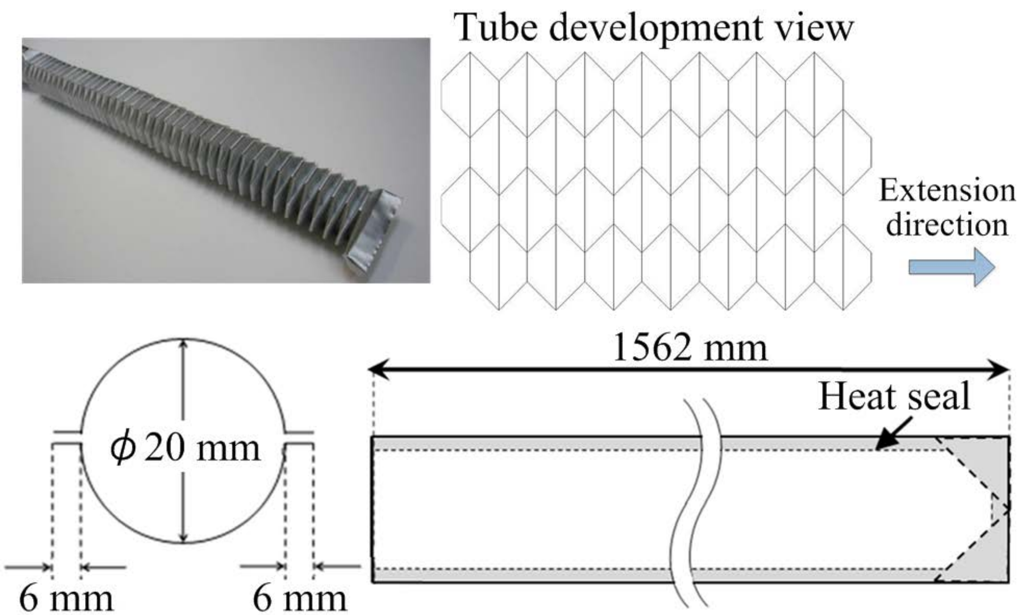
・Tubes extend by inserting gas inside. The membrane deploys by being pulled by the tubes.





Inflatable tube

- Specifications of aluminum laminate film

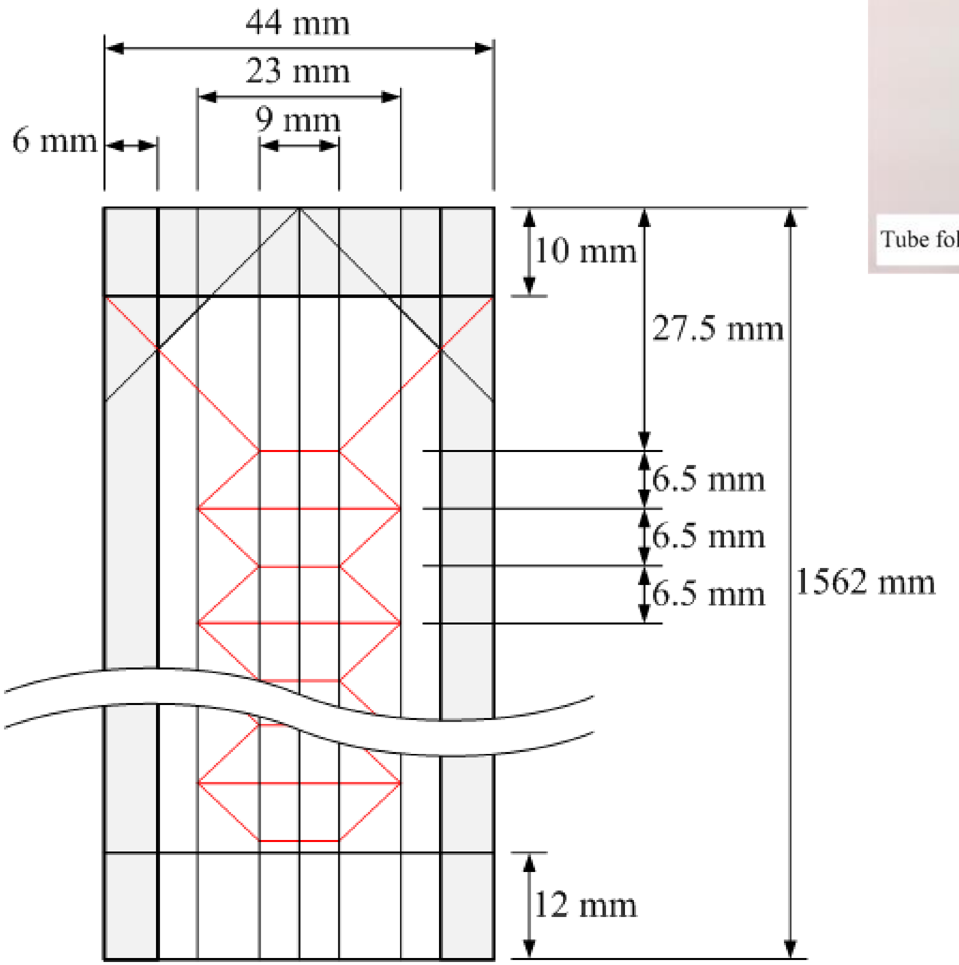


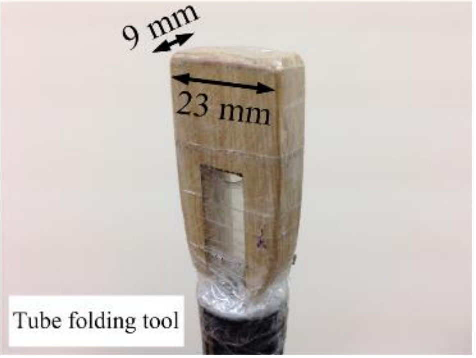
Item	Value
Thickness	75 µm
Density	1543 kg/m^3
Young's modulus	12.4 GPa
Second moment of area	2.38×10^{-10} m^4
Stiffness	2.95 N·m^2

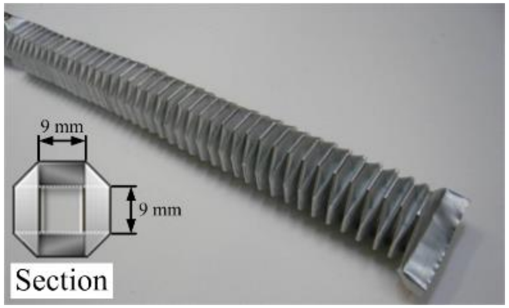
Material	Thickness
Silicon oxide vapor deposition nylon	15 µm
Aluminum	20 µm
L-LDPE (Linear polyethylene)	40 µm
Total thickness	75 µm

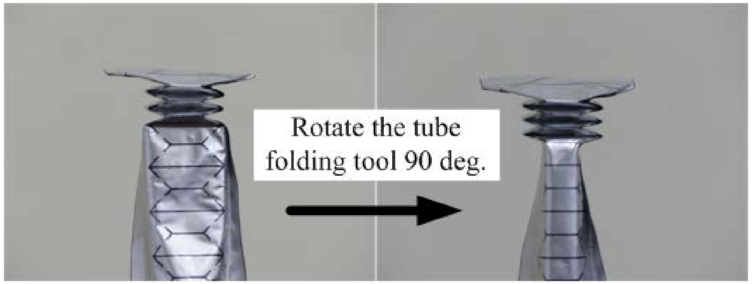
Inflatable tube

- How to fold a tube







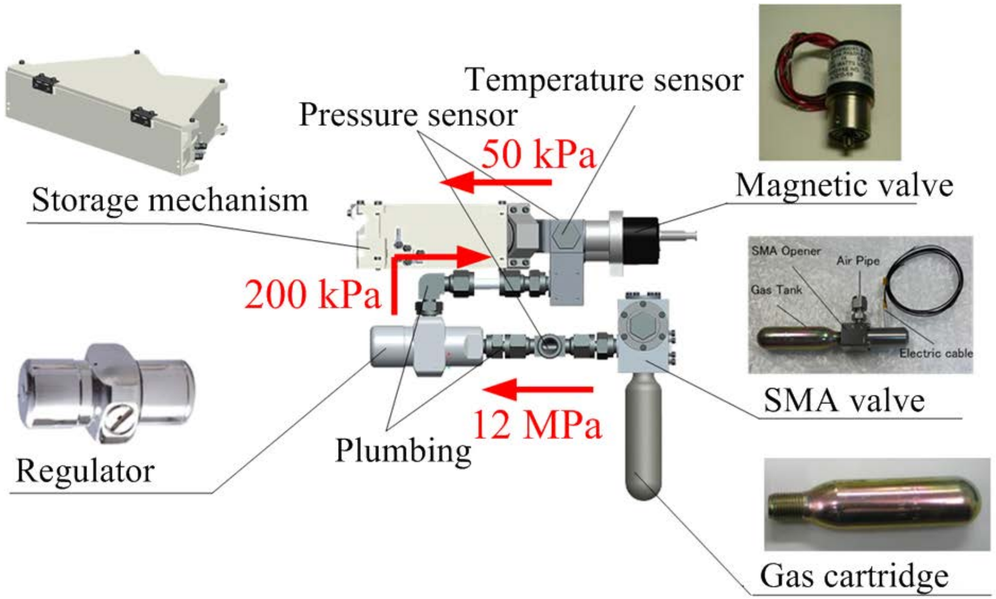


[mm]

Tube folding tool (Long side)	23
Tube folding tool (Short side)	9
Heat seal width	6
Tube length	1562
Distance between fold	6.5

Gas injection system

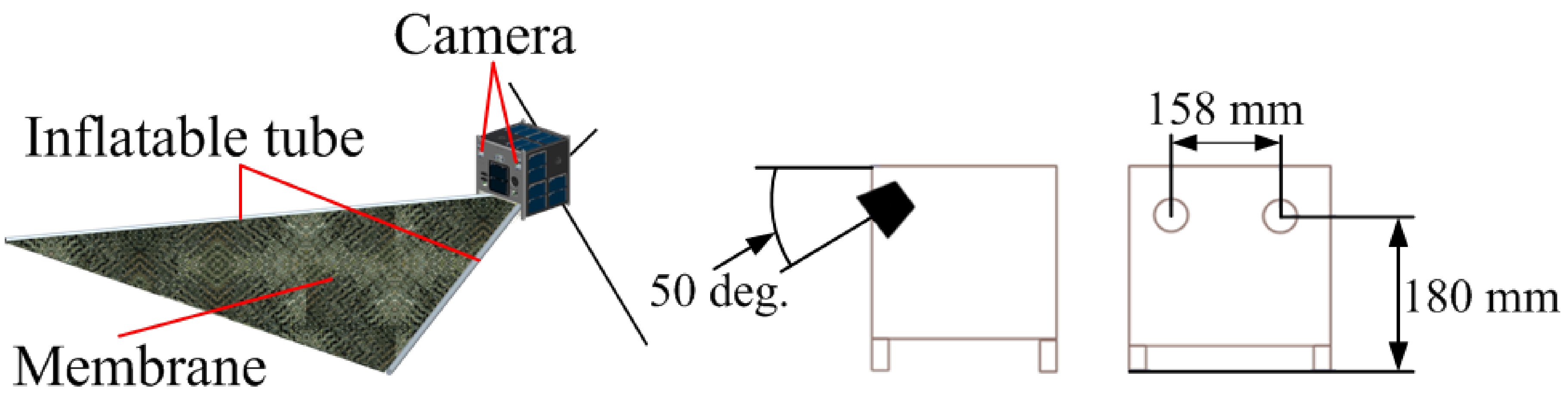
- The gas injection system consists of a gas cartridge, SMA valve, regulator, magnetic valve, and plumbing. The nichrome wire in the SMA valve is heated and the needle expands, whereby the hole opens in the gas tank.
- The released N_2 gas is depressurized to about 200 kPa by the regulator. Then, the magnetic valve controls the pressure inside the tube to be 50 kPa.



Deployment result on orbit

Deployment result on orbit

- About 1 year after launch, membrane deployment on orbit was carried out. In order to measure the three-dimensional position of the membrane structure after deployment, photographs were taken from the left and right of the structure with two cameras.



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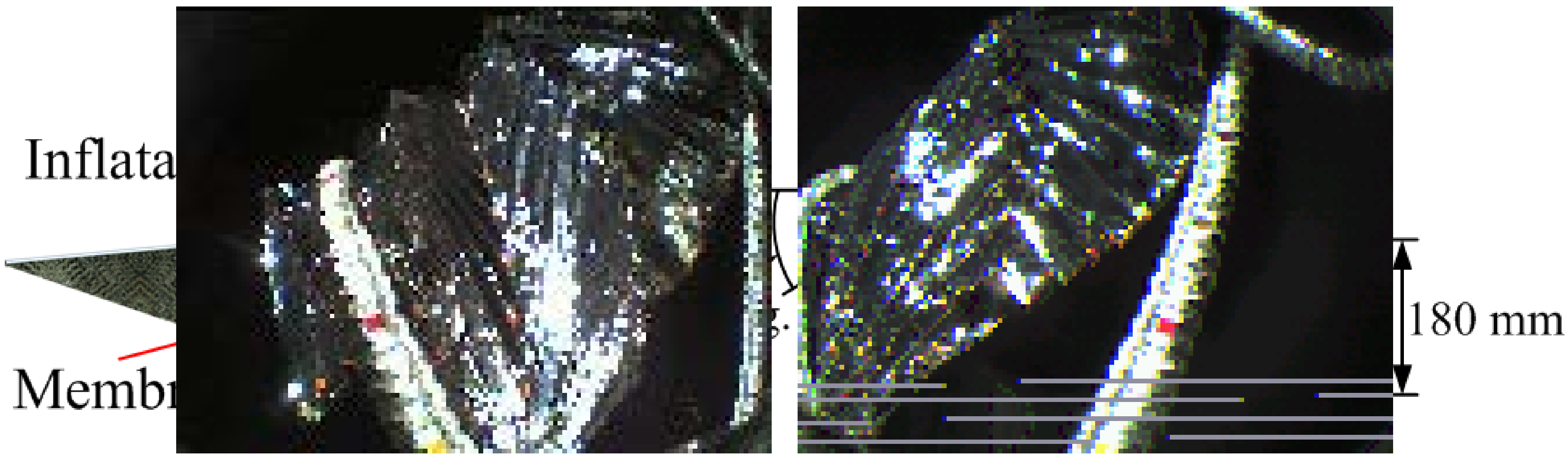
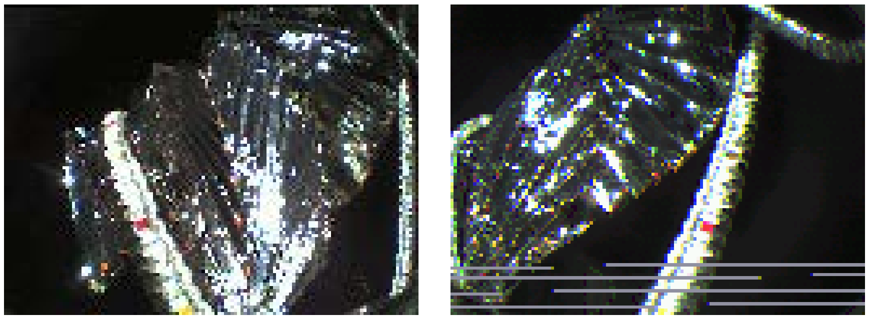


Deployment photos on orbit

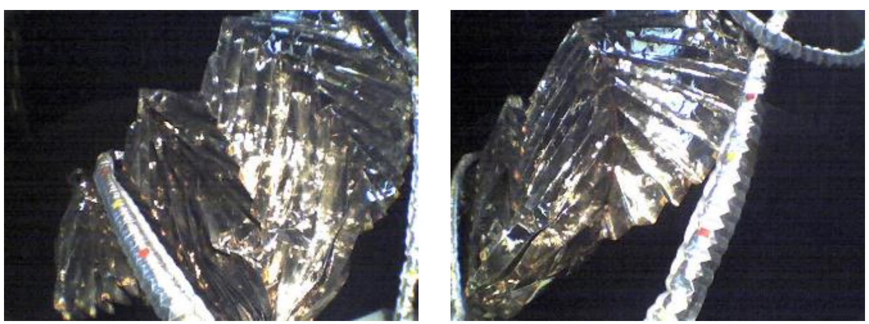
Miyazaki Yamazaki Lab.
Aerospace Structural Engineering

Deployment result on orbit

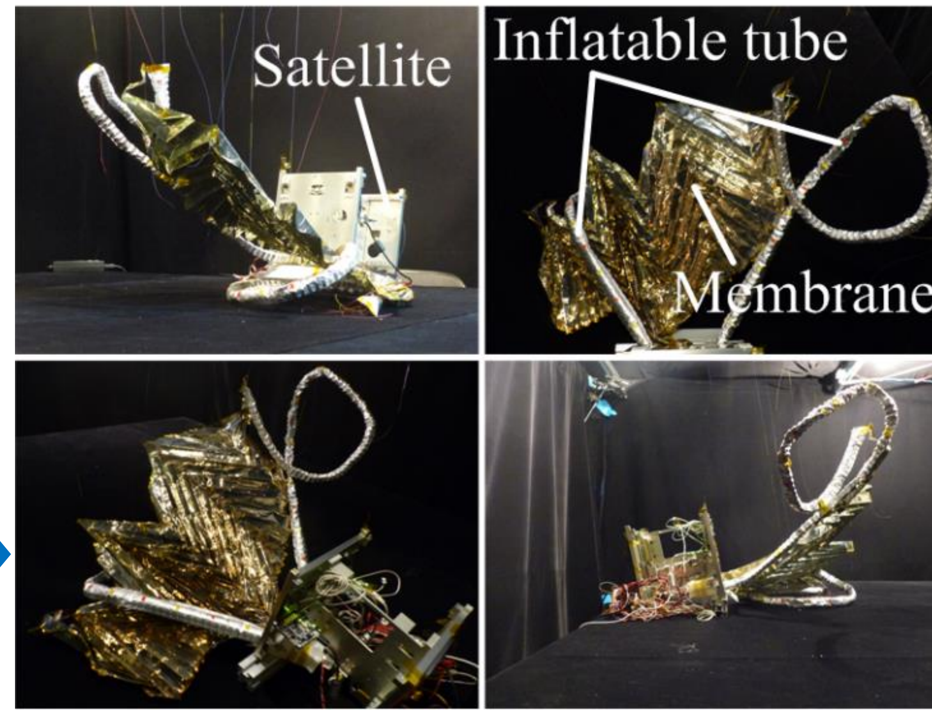
- Shape reproduction on the ground



Deployment photos on orbit

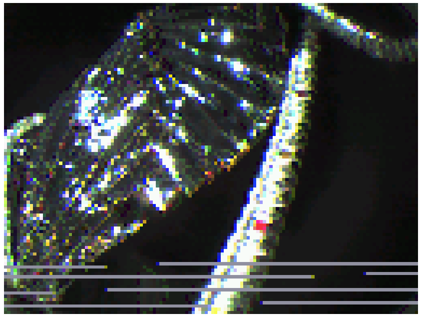


Shape reproduction photos

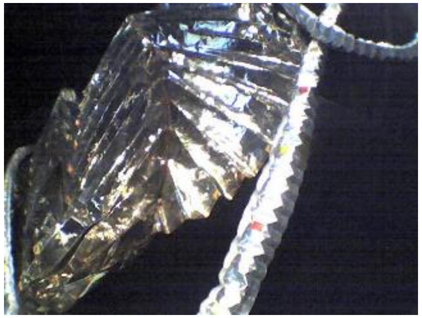


From different viewpoints

Deployment result on orbit

Deployment photos on orbit

Shape reproduction photos

- Membrane expansion ratio was 15.2% (More than 80% in the plan).
- According to the pressure sensor data, the pressure value at deployment was about 30 kPa (50 kPa in the plan).
- Tubes were spiral.

✓ Possible cause

- Membrane and tubes caught somewhere.
- They became hard by long-term storage.
- Gas pressure was insufficient (Gas leak occurred).

Purpose of research

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Purpose of research

To investigate the reason why SPROUT on orbit could not be fully deployed and to reproduce the deployment behavior when fully deployed.

【Approach method】

(1) Check the state of the membrane structure on orbit and estimate the cause.
(2) Determine the parameters of the experiment based on the estimated cause, and perform the experiment (micro-gravity environment and long-term storage experiment).

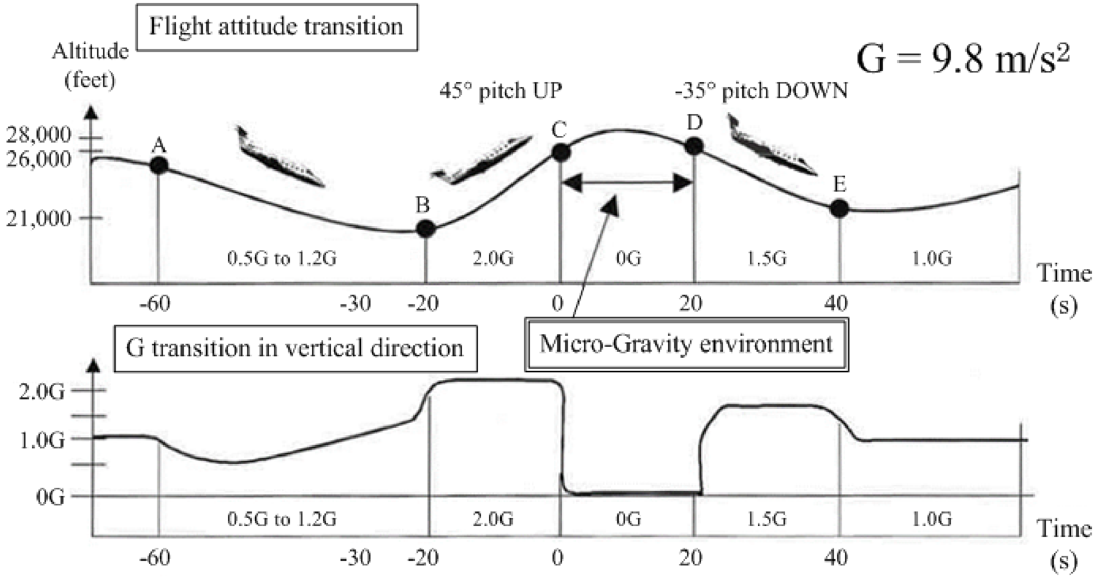
From these experiments, we verify the validity of the estimation and verify how the micro-gravity and long-term storage affected the membrane structure and consider it.

Micro-gravity experiment

Micro-gravity experiment

- As the aircraft flies parabolic, a microgravity of about 1×10^{-2}G is formed for about 20 seconds.
- Deployment membrane and tubes simulating SPROUT and take moving picture of its deployment behavior.

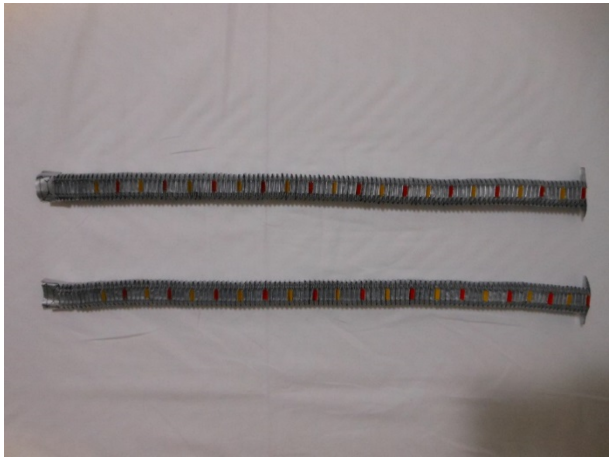
Aircraft MU-300



Gravity transition graph

Micro-gravity experiment

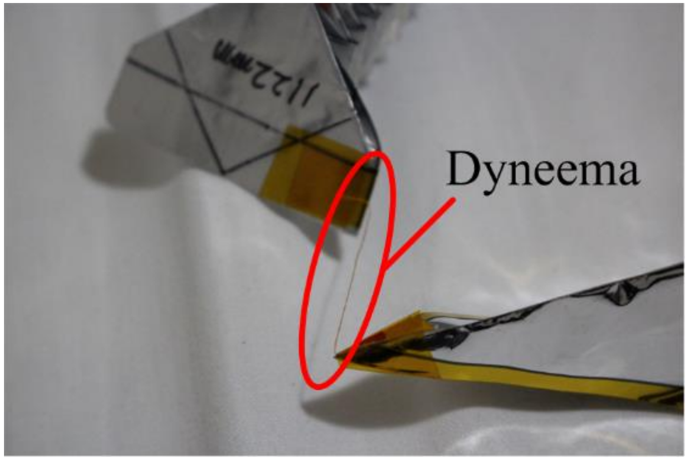
- Experiment specimen



Inflatable tube

Membrane

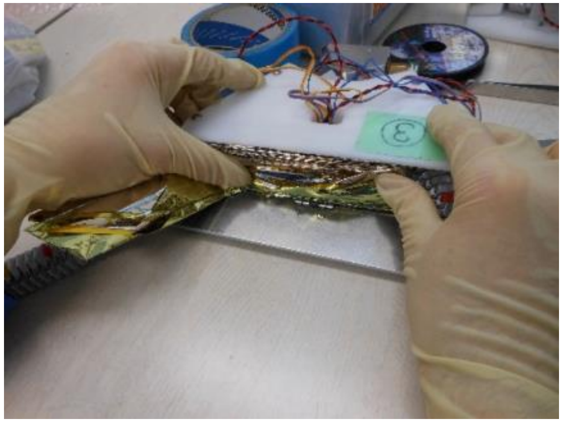
Connection between membrane and tube



In addition, it is equipped with piezo sensor, temperature sensor, pressure sensor.

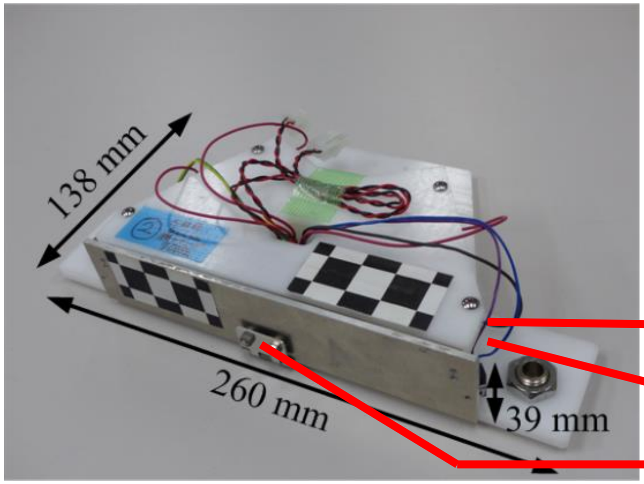
Micro-gravity experiment

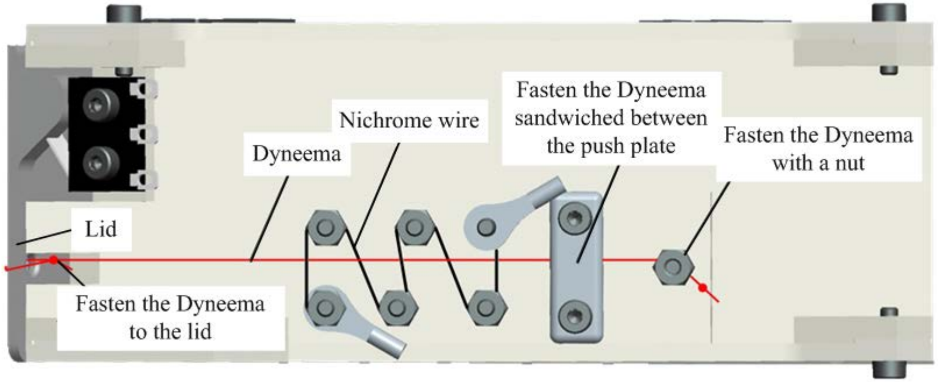
Before storage



Store tubes and membrane

Storage condition





①Retain lid by Dyneema

②Fusing Dyneema by applying voltage to nichrome wire

③Lid opens by spring hinge

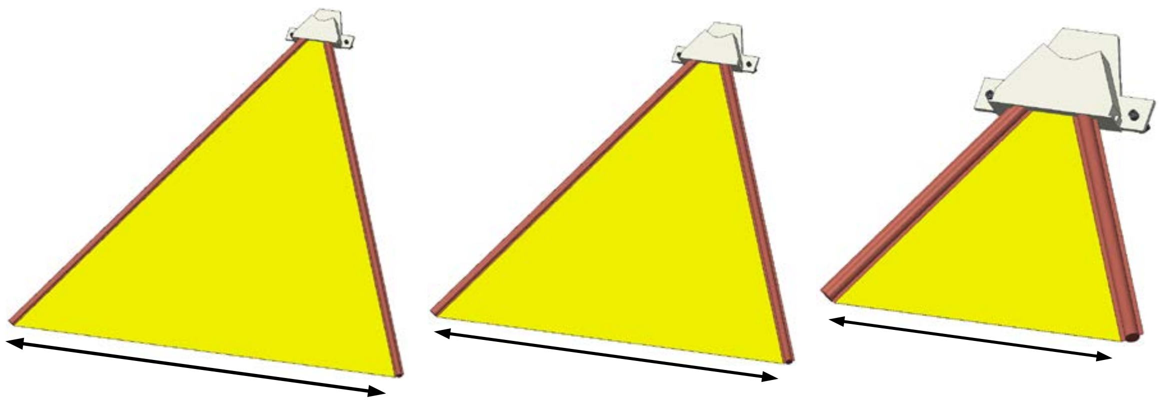
Micro-gravity experiment

- Experiment contents

Size	Tubes + membrane or Onry tubes	Pressure control value	Number of times
440 mm (Tube: 462 mm)	Tubes + membrane	30 kPa	1
		50 kPa	1
		70 kPa	1
	Only tubes	30 kPa	1
		50 kPa	1
		70 kPa	1
1100 mm (Tube: 1122mm)	Tubes + membrane	50 kPa	3
	Only tubes	50 kPa	2
1540 mm (Tube: 1562mm)	Tubes + membrane	50 kPa	3

Micro-gravity experiment

- Experiment contents



Inflatable tube

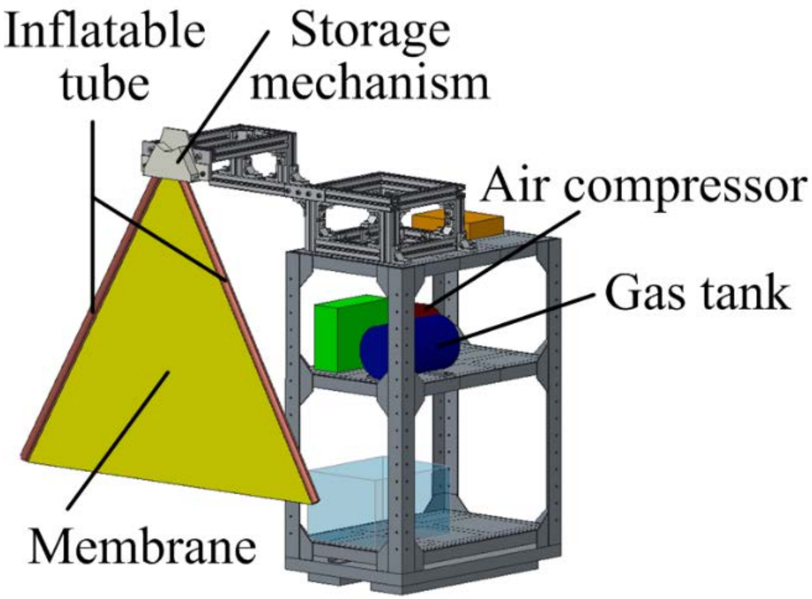
1540 mm size

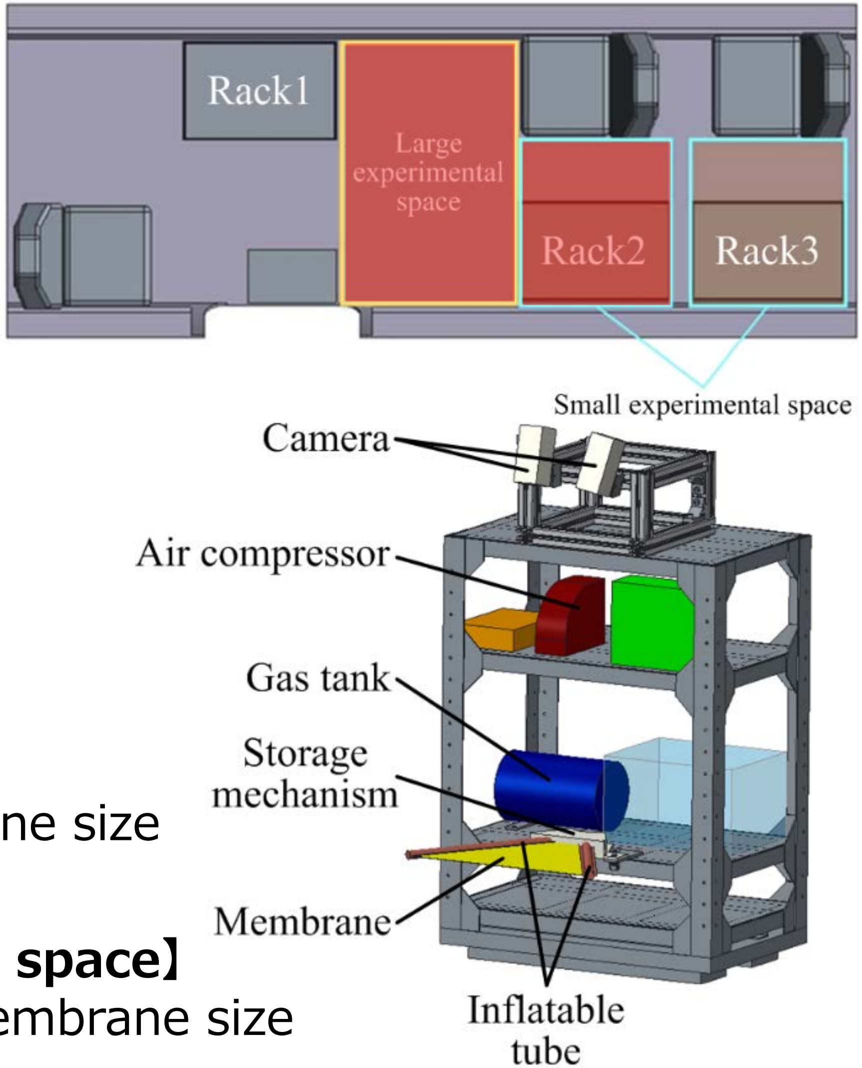
1100 mm size

440 mm size

Micro-gravity experiment

- Experimental layout





【Large experiment space】
RACK1: 1100 mm, 1540 mm membrane size

【Small experiment space】
RACK2: 440 mm membrane size

Micro-gravity experiment

- Experimental result (1540 mm size (tube + membrane 50kPa))

- The membrane caught inside the deployment mechanism, preventing deployment. The tube was spiral.
- Binding forth is not so strong.

Micro-gravity experiment

- Experimental result (1540 mm size (tube + membrane 50kPa))

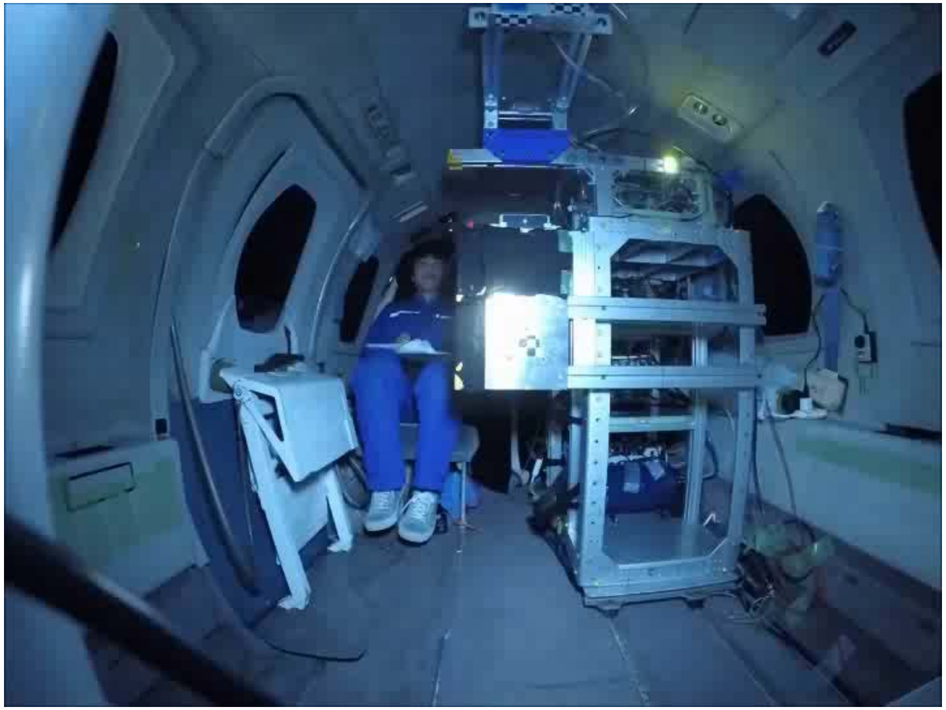
・Day6,First time

- The tube tries to extend, but it is pulled because the deployment of the membrane is not smooth.

Micro-gravity experiment

- Experimental result (1100 mm size (tube + membrane 50kPa))

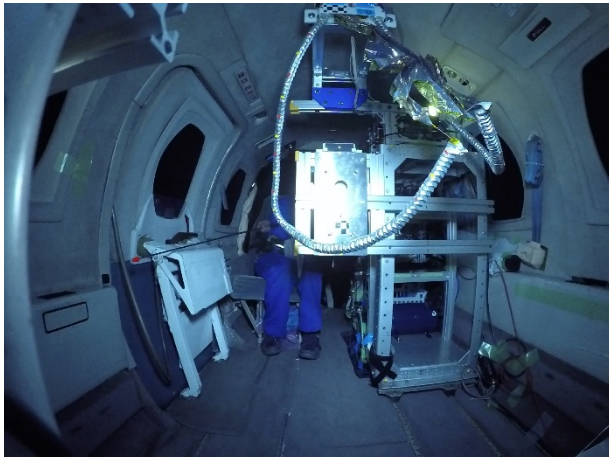
・Day6,Second time



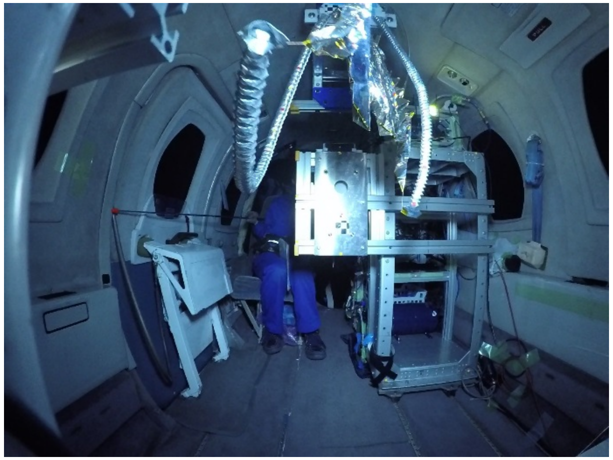
- The tube tries to extend, but it is pulled because the deployment of the membrane is not smooth.

Micro-gravity experiment

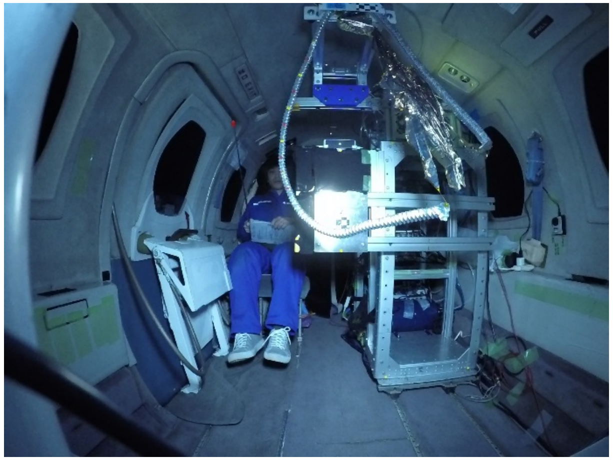
a. Day2, First time



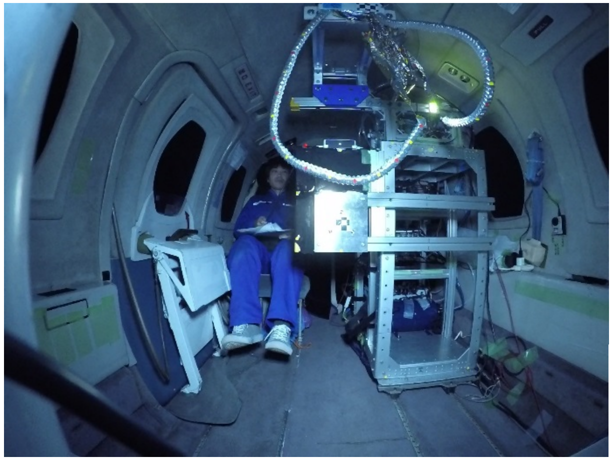
b. Day3, First time



c. Day3, Second time



d. Day6, First time



e. Day6, Second time

a,c,e: 1100 mm size, 50 kPa
b,d: 1540 mm size, 50 kPa

Micro-gravity experiment

- Experimental result (1100 mm size (tube only 50kPa))

① Day2,Third time

②Day6,Third time

- Even in the case of only the tube, it expanded while bending.

Long-term storage experiment

Long-term storage experiment

- Long-term storage experiment were conducted using deployment mechanism that had been stored for 3 years and 5 months.

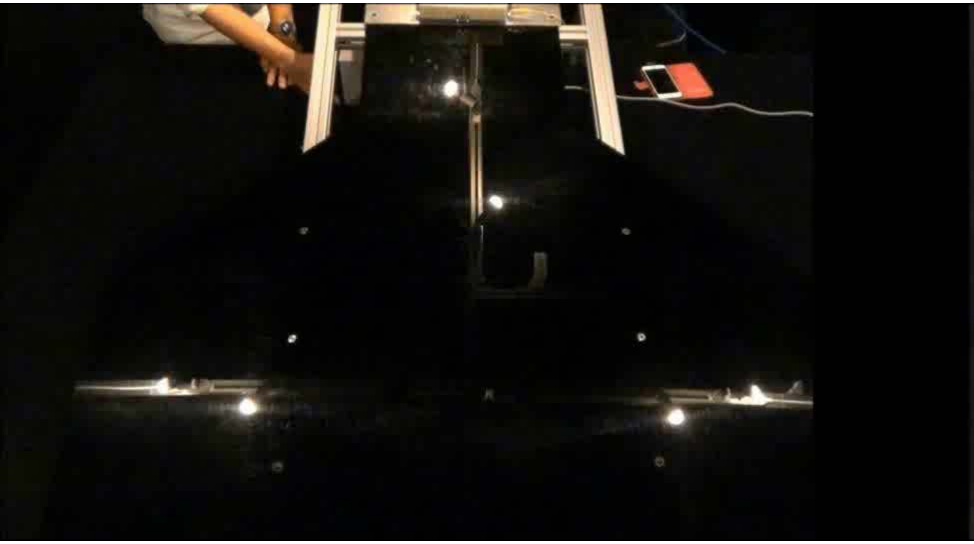
Storage period: about 3 years and 5 months
Storage location: Techno Place 15 (Clean room)

Long-term storage experiment

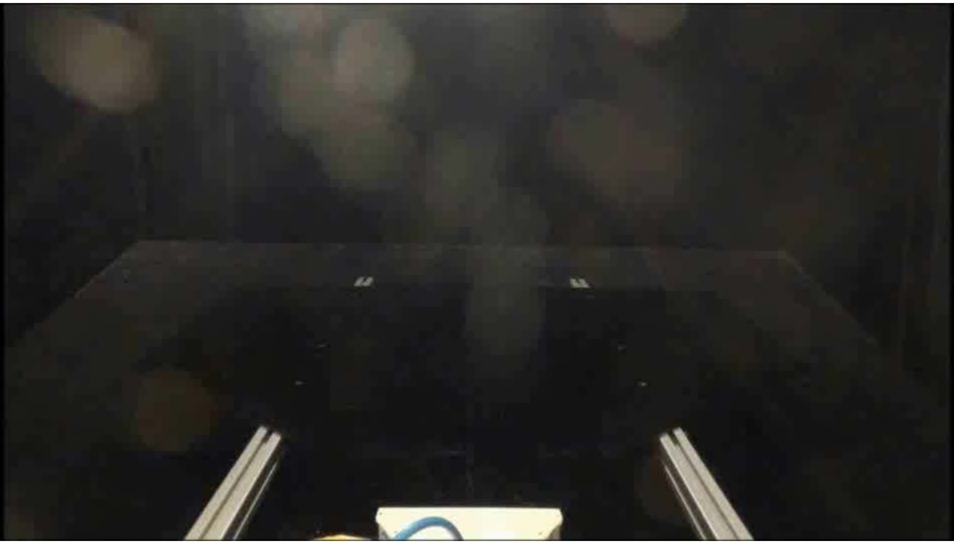
- ✓ Tube: length 1562 mm. 2 pieces
- ✓ Membrane: equilateral triangular film with a side length of 1540 mm. 1 sheet

Long-term storage experiment

- Deployment result



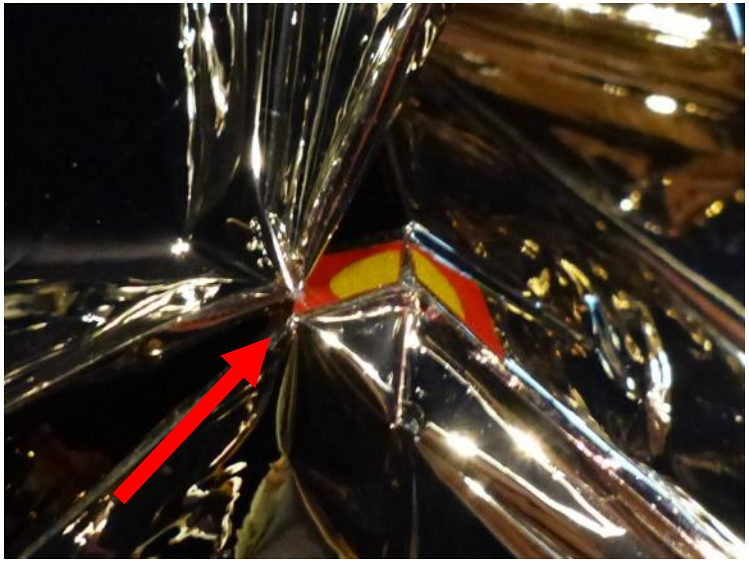
From top (left camera)



From specimen direction

Long-term storage experiment

- Deployment result
- ✓ The membrane stuck to the feature point.
- ✓ The tube was bent because the membrane did not deploy.
- ✓ The tube remained bent.



Stuck point

Bent point

Conclusion/Consideration

Conclusion/Consideration

- Membrane stuck
  - ✓ The position where the membrane was restrained during the micro-gravity experiment and long-term storage experiment are near the fold of the image shown below.

⇒This point coincides with the constrained point of the membrane on the orbit.

Long-term stored experiment→

↑Darkroom experiment

Micro-gravity experiment→

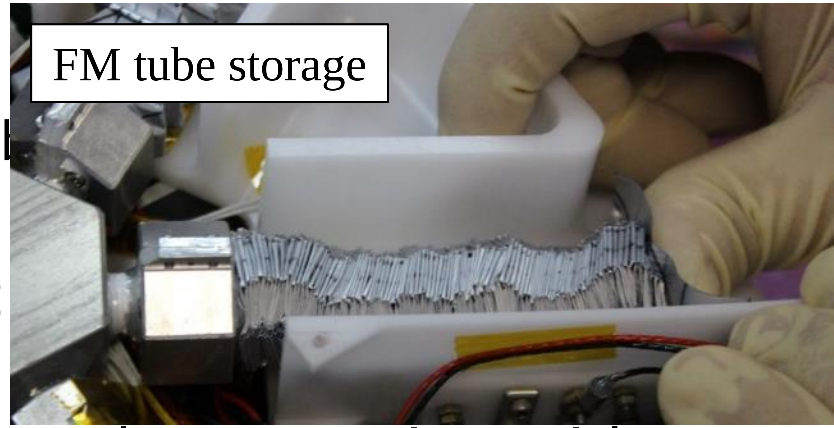
Conclusion/Consideration

- Bend of tube

  The cause of the habit of folding tu

  →The fold strength is not constant

  →Bend when stored in deployment



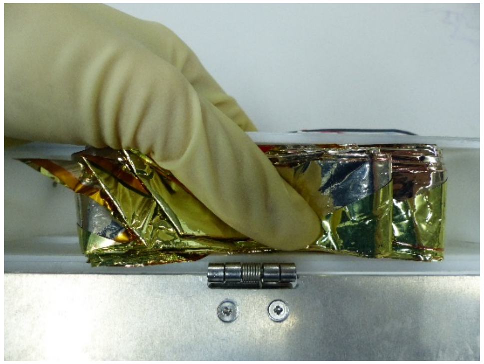
- ✓ In the primary deployment, the tube extension with curvature.
- ✓ In the secondary deployment, gas force concentrates on the outside of the tube curve.
- ✓ Tubes are pulled by the membrane and becomes more curved.

Conclusion/Consideration

Improvement example

Longitudinal and lateral direction (Fig. A) : The storage part of the tube is narrowed in accordance with the longitudinal direction and lateral direction of the tube to prevent deflection of the tube (blue frame). The storage part of the membrane is widened in the longitudinal direction. (orange frame)

Extension direction (Fig. B): The storage part of the tube and membrane extends in the extension direction of the membrane structure (blue and orange frame).



Fold width of membrane and longitudinal direction

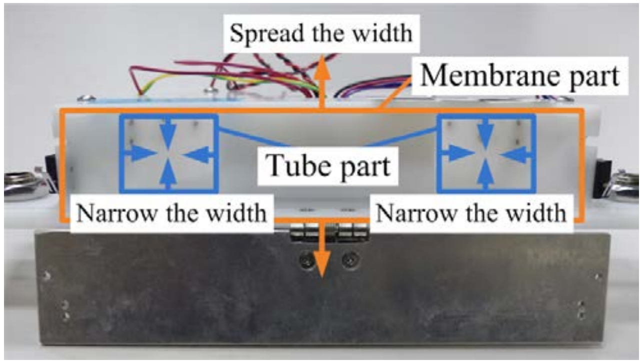


Fig. A: Longitudinal and lateral direction

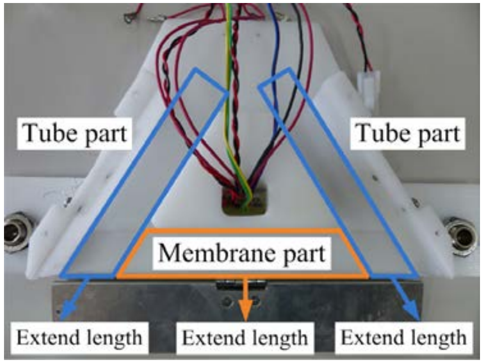


Fig. B: Extension direction

Conclusion/Consideration

- Improvement example

Besides this, it can be expected to narrow the folding width of the Miura fold on the membrane surface and increase the thickness of the tube.

By increasing the thickness of the tube, it is possible that the influence such as the difference in the width of the fold and the strength of the folding manually attached can be reduced by improving the flexural rigidity.

Thank you for your attention

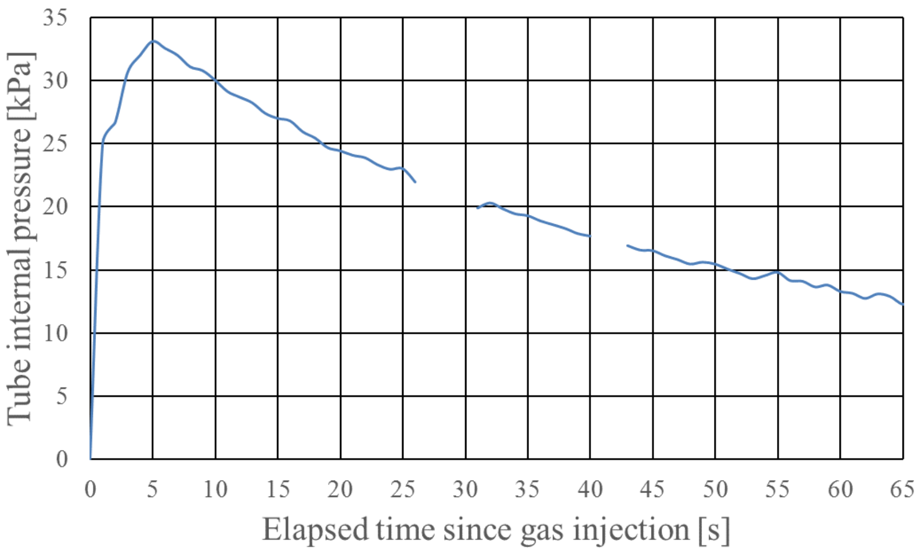
Appendix

Future tasks

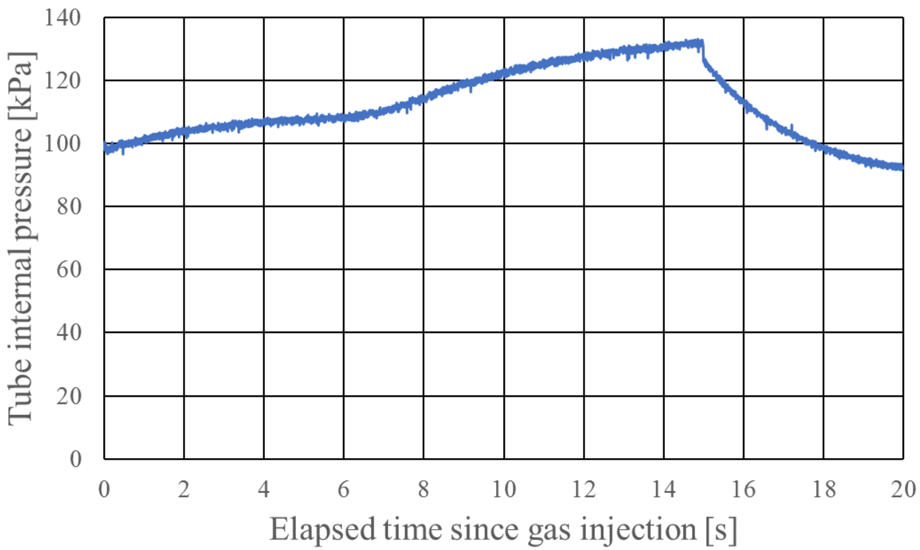
- Confirm the validity of the experimental results in numerical analysis and estimate the development behavior of various combined membrane structures beforehand.
- We aim to be able to design the deployed structure considering the condition of the storage condition.

Appendix(Gas pressure)

- Comparison of gas pressure inside the tube

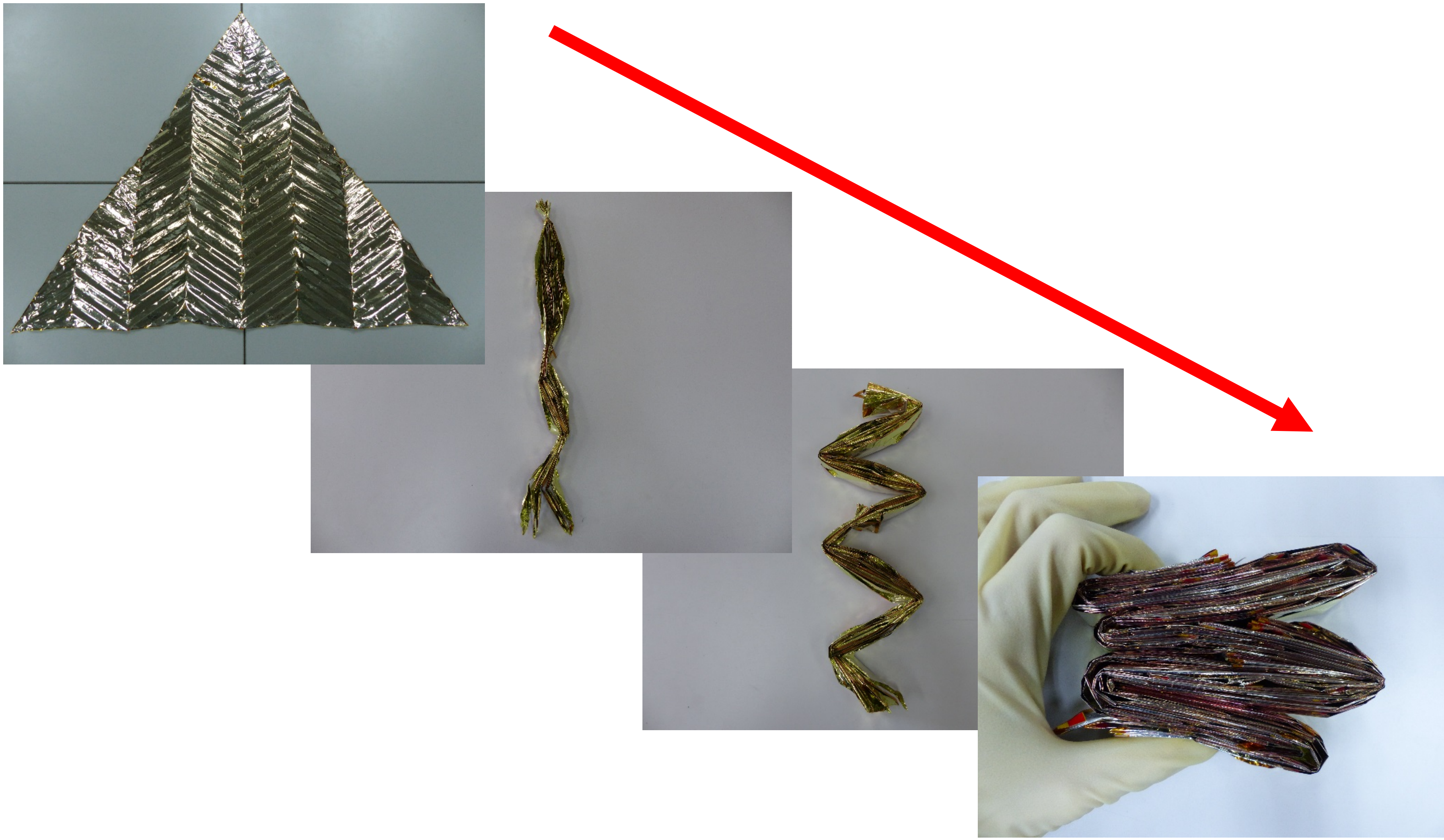


On orbit

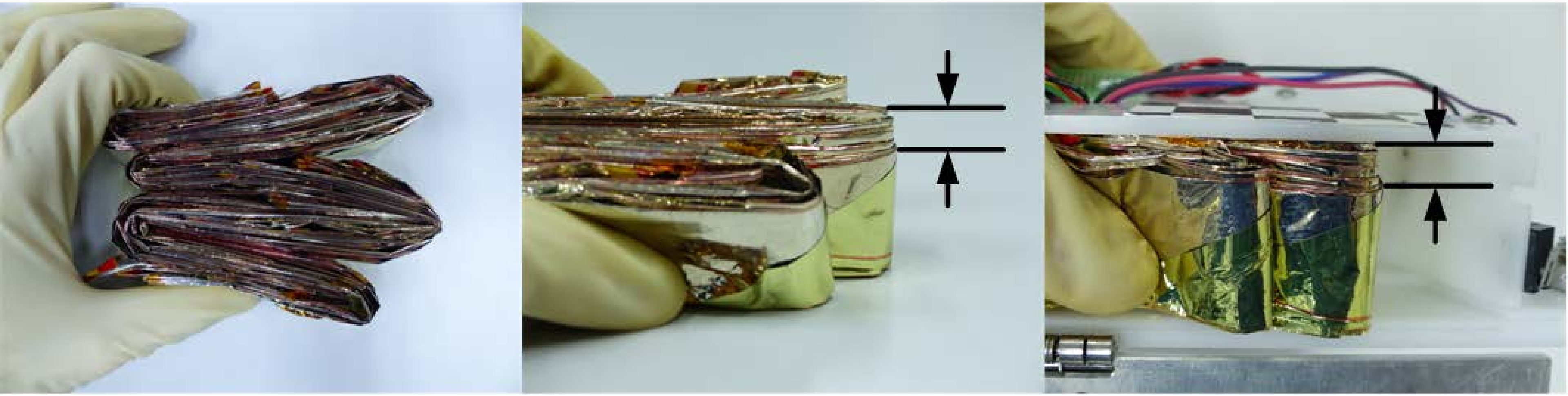


Micro-gravity experiment
(restrained)

Appendix(How to fold the membrane)



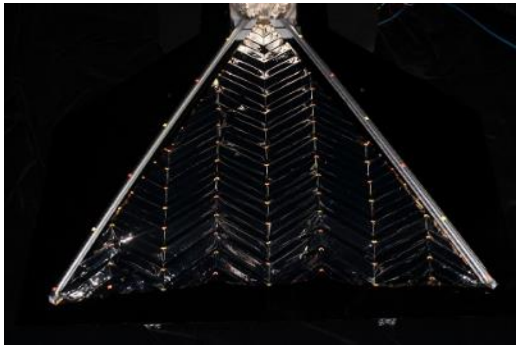
Appendix(Influence on storage mechanism)



Appendix(数値計算アプローチ方法)

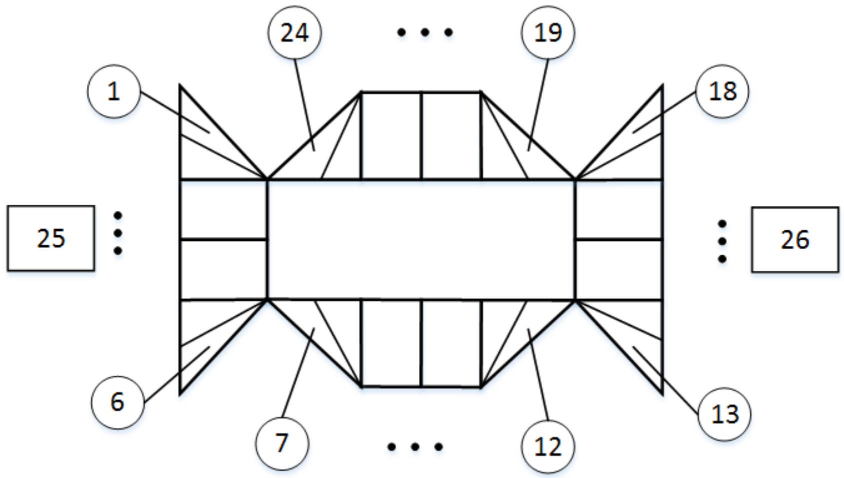
1. チューブをモデル化する
2. ガス要素の導入
3. 折り目要素の導入
4. チューブの先端を弾いて振動をみる
5. パラメータの合わせこみ(折り目剛性，圧縮剛性など)
6. 実験データとの比較により，さらに詳細なモデル化(収納機構から受ける力など)

まずはチューブ1本で展開できるようにする

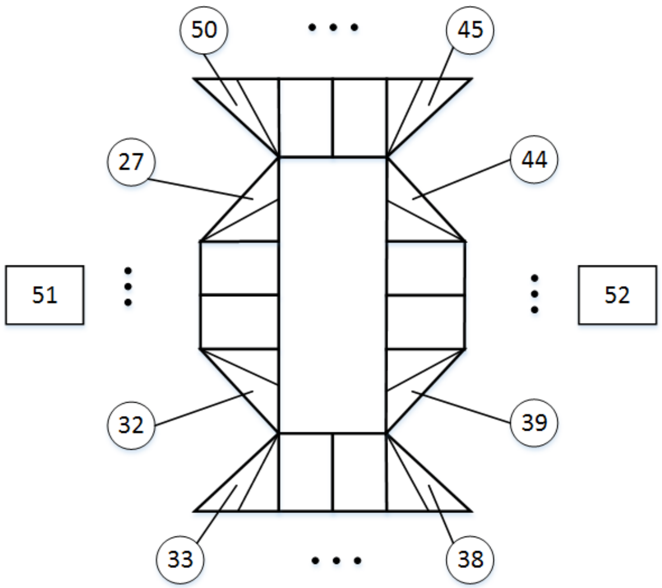


Appendix(チューブモデル化－要素分割－)

- NEDAに実装されている膜要素に合うように，断面間をつなぐ台形上の膜面を，三角形の要素と四角形の要素を作成していく.
- それに四角形のつばを加える.
- 要素には，断面の左側面，上から順に反時計回りに要素番号を振っていく.



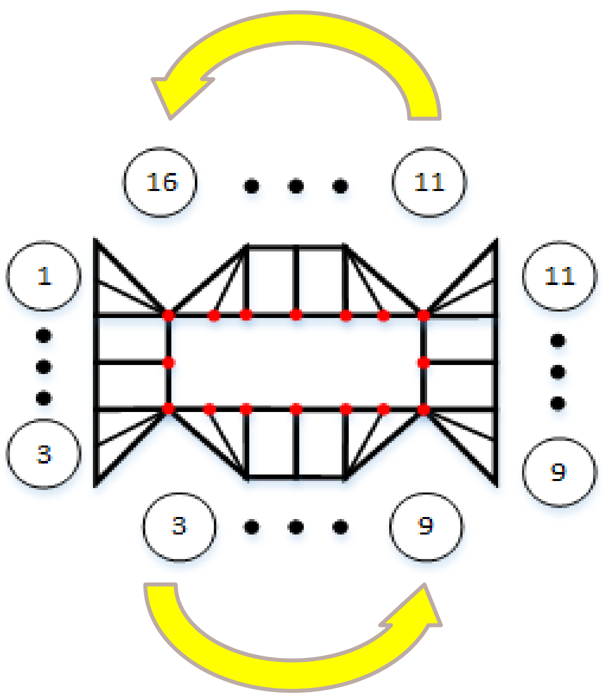
➢ 断面1



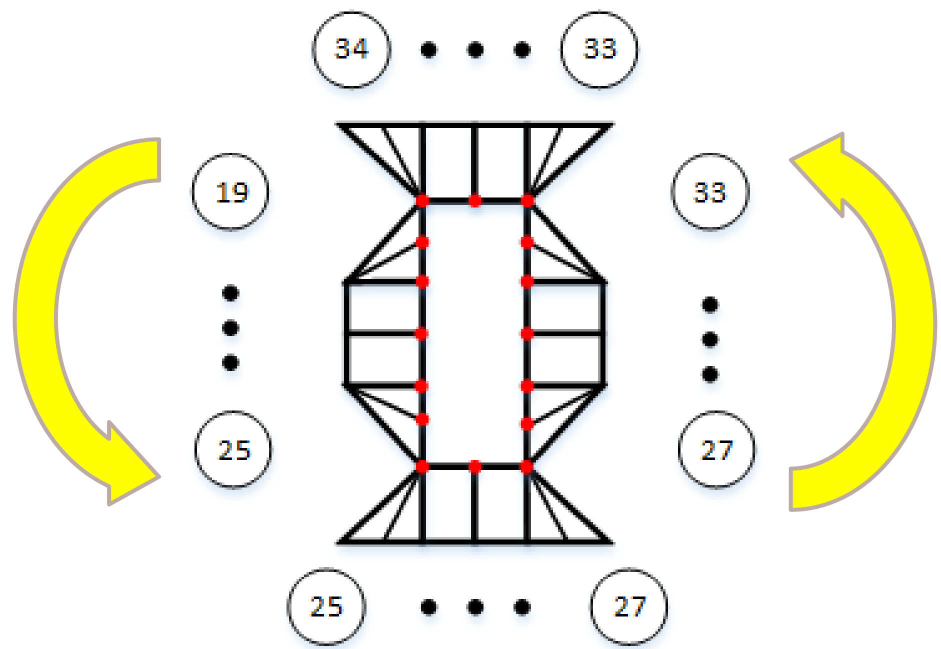
➢ 断面2

Appendix(チューブモデル化－節点番号付け－)

- 節点についても同様に左上から順に反時計回りで番号づけを行う.
- つばについては一つの断面につき，2つの節点を与える.



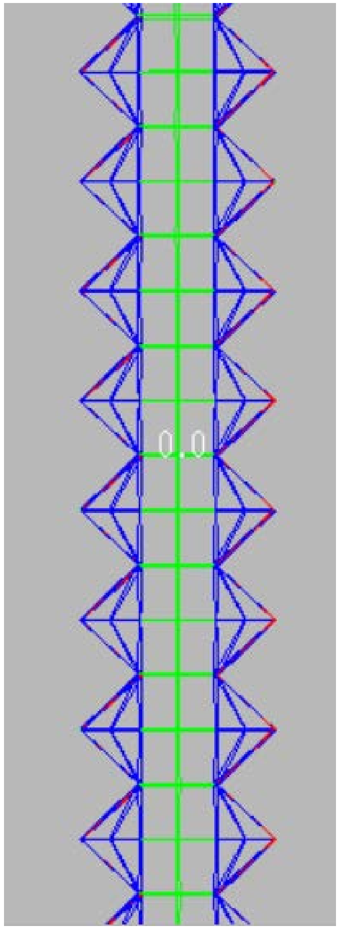
➢ 断面1

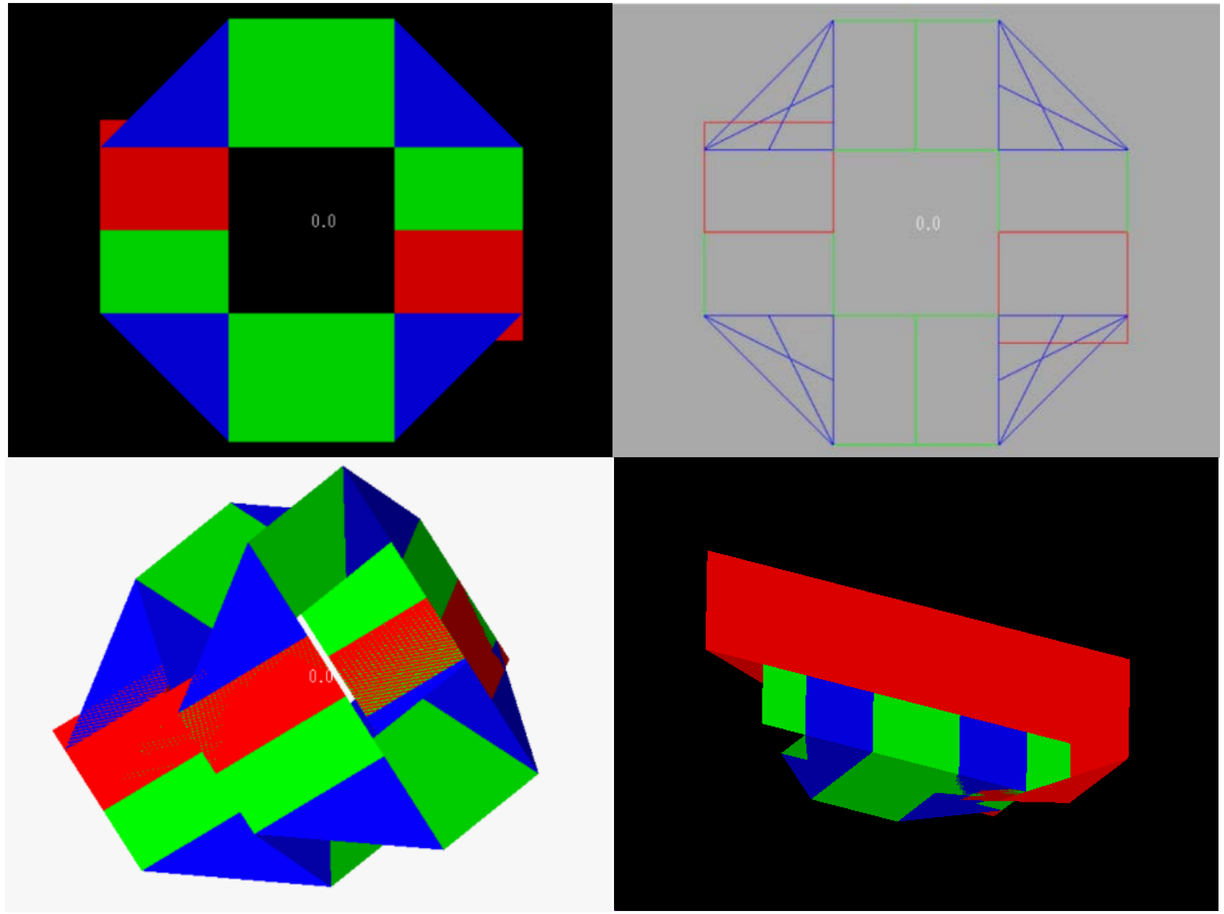


➢ 断面2

Appendix(チューブモデル)

- MicroAVSによるモデルの可視化





Appendix(研究背景)

- 事前実験

・SPROUT打ち上げ前には実際よりも小さい膜面・チューブで微小重力実験を実施.

・大型真空槽においても膜面展開することを確認.

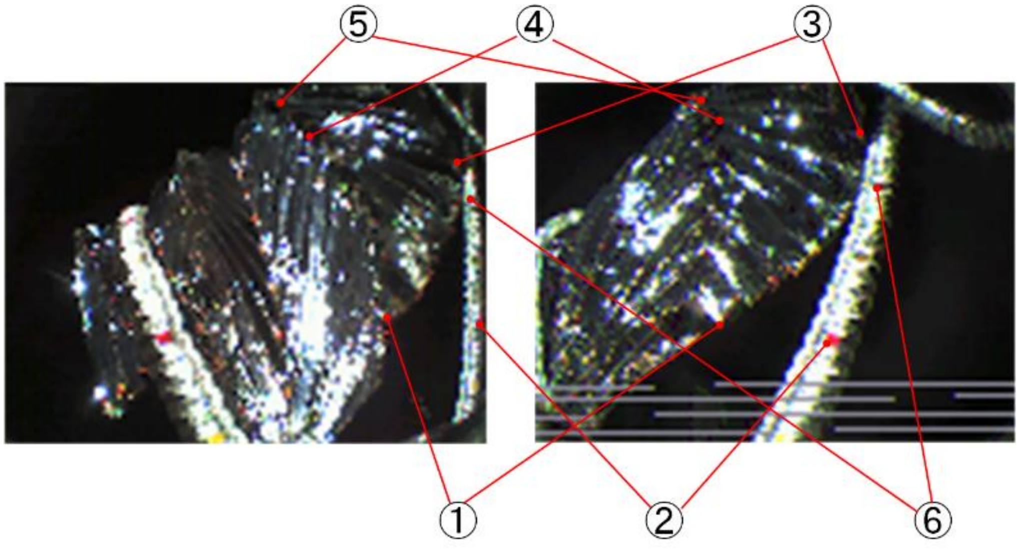
⇒軌道上実証へ

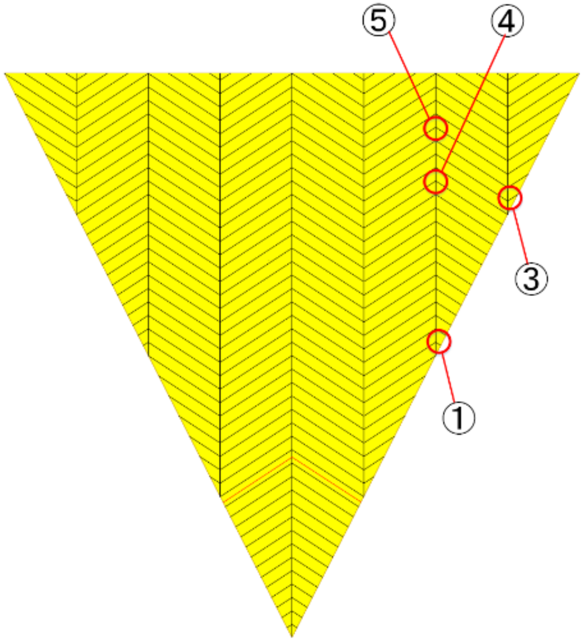
2013年航空機実験

大型真空槽試験

Appendix(軌道上展開結果)

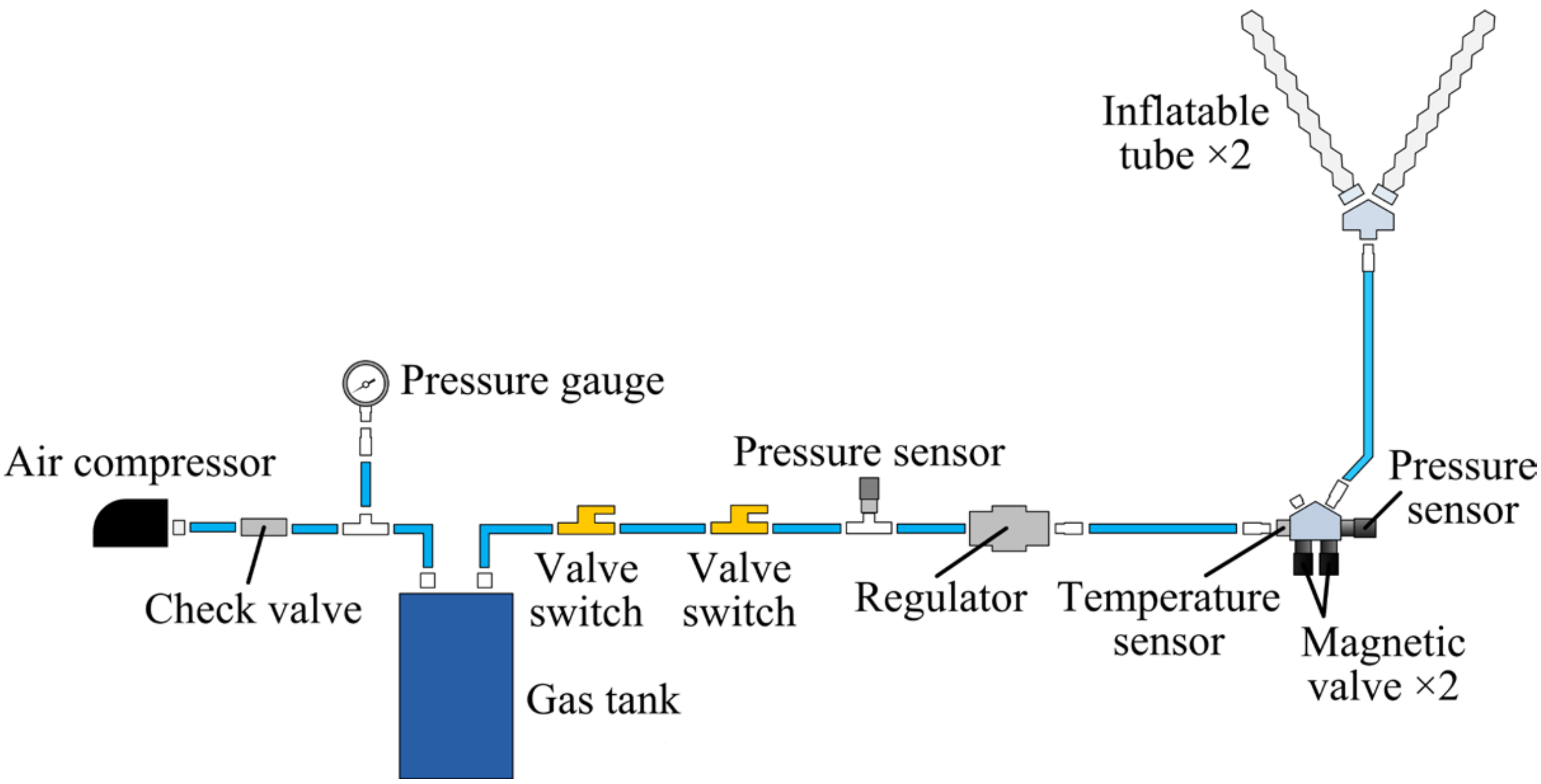
- 画像が粗く，読み取りが難しいため，読み取り易い6つの点(膜面:5,チューブ:1)について，ステレオ視によりマーカーの三次元位置座標を計測．





Appendix(航空機内でのガス注入システム)

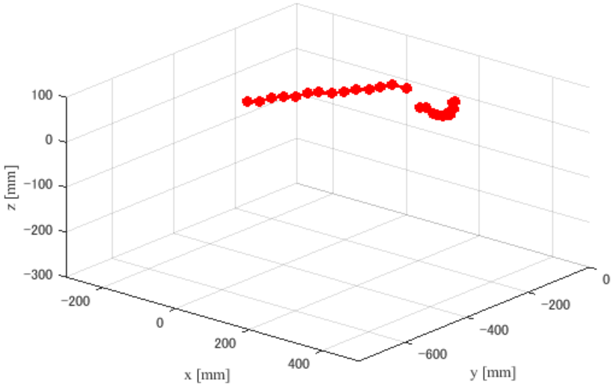
- 航空法の制限上高圧ガスの使用は禁止されているため，ガス注入システムについてはコンプレッサーとガスタンクを用いたものに変更し，SPROUTに準拠するシステムとした．

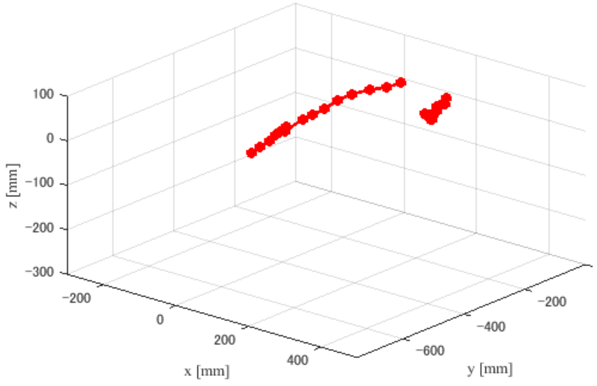


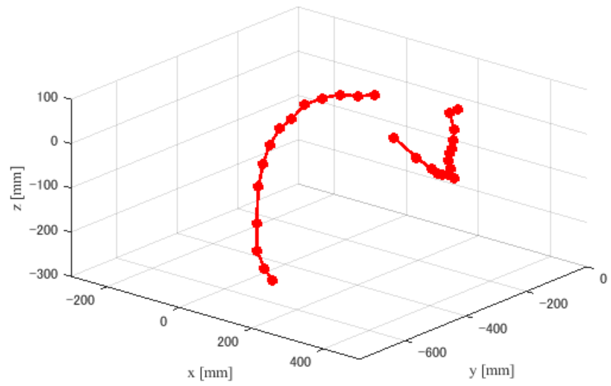
実験結果(1122mm膜付き)

- 展開形状の比較

①1122mm膜付き 50kPa(2日目1回目)



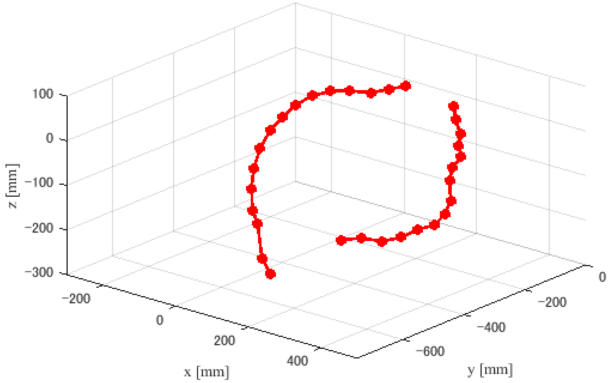


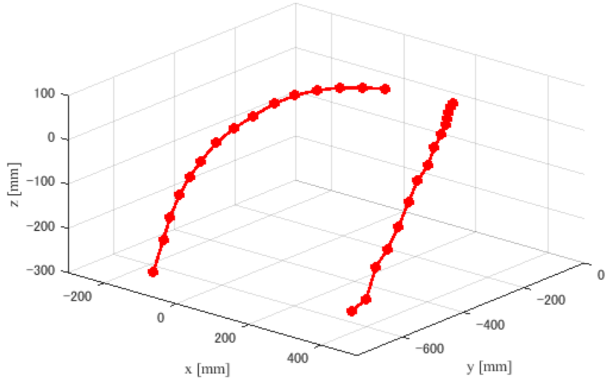


実験結果(1122mm膜付き)

展開形状の比較

①1122mm膜付き 50kPa(2日目1回目)

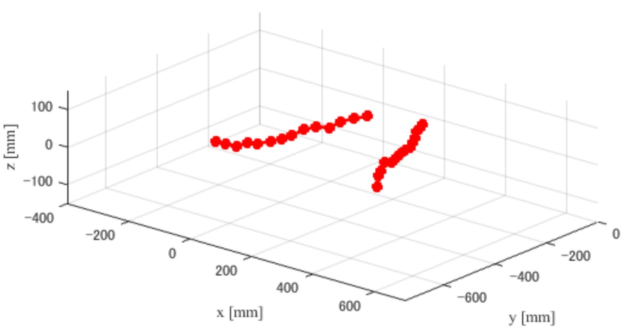


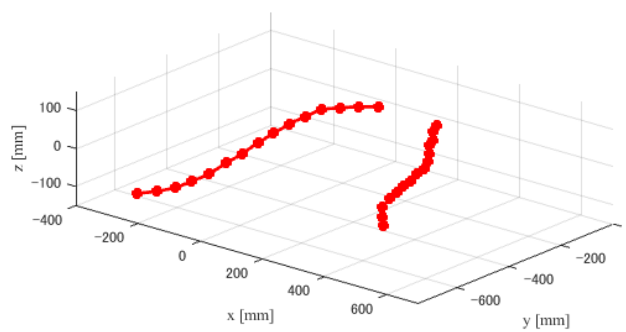


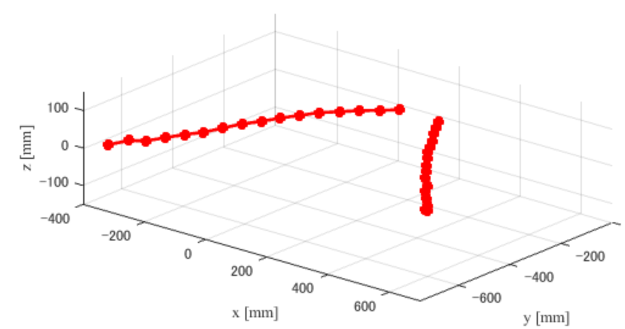
実験結果(1122mmチューブ)

- 展開形状の比較

②1122mmチューブのみ 50kPa(2日目3回目)



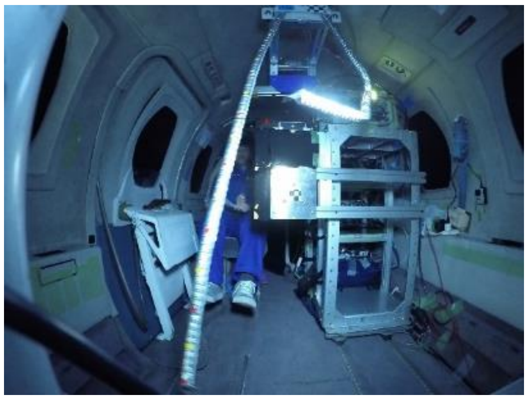


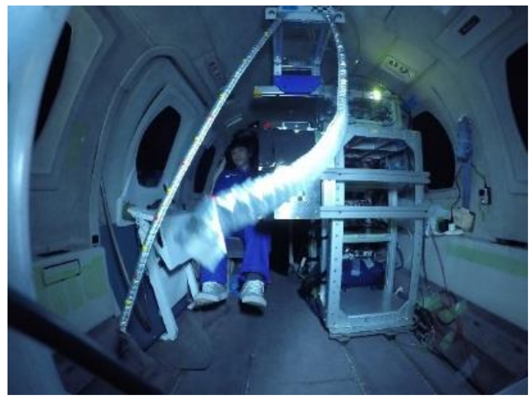


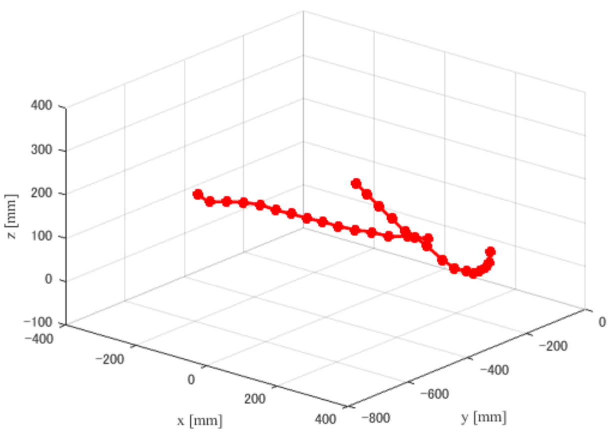
実験結果(1122mmチューブ)

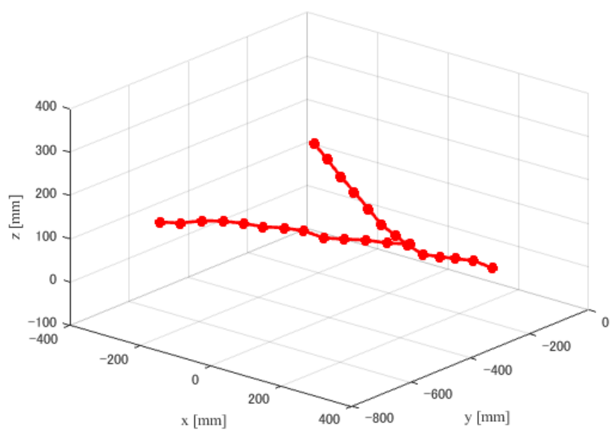
- 展開形状の比較

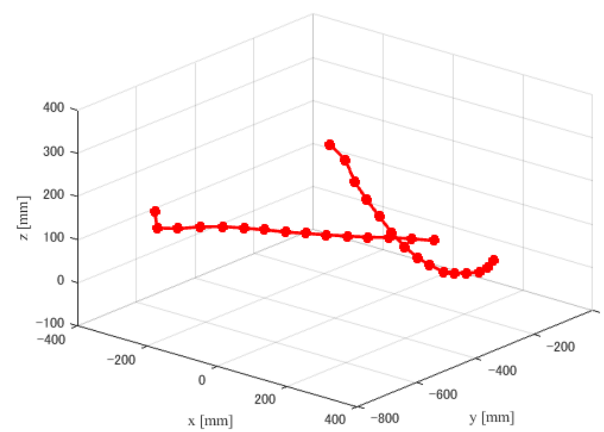
③1122mmチューブのみ 50kPa(6日目3回目)









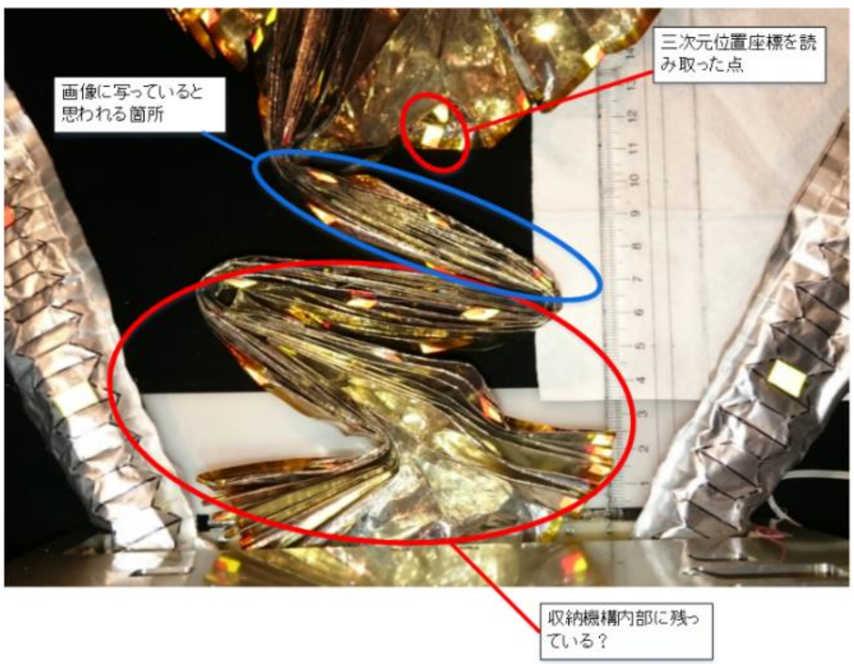


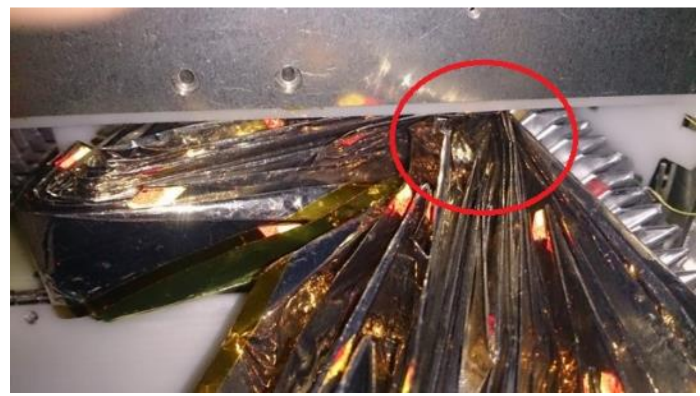
考察・結論

膜面の引っかかりについて

- ✓ 軌道上膜展開において膜面が拘束されたであろう位置は，最後に膜を供試体内に収納するときの「く」の字型の折り目付近であるとみられる．今回の航空機実験で膜が拘束された位置も，画像で見ると「く」の字型の折り目付近である．

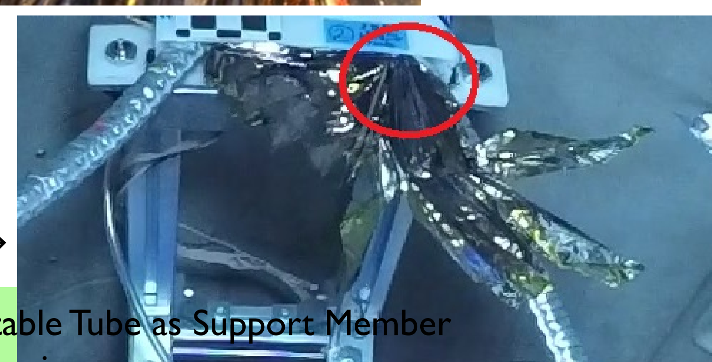
⇒この場所は膜の折り目が集中している場所であり，段差(高さ)が付きやすく，軌道上で引っかかっている位置とも一致する．





←地上模擬(軌道上再現)

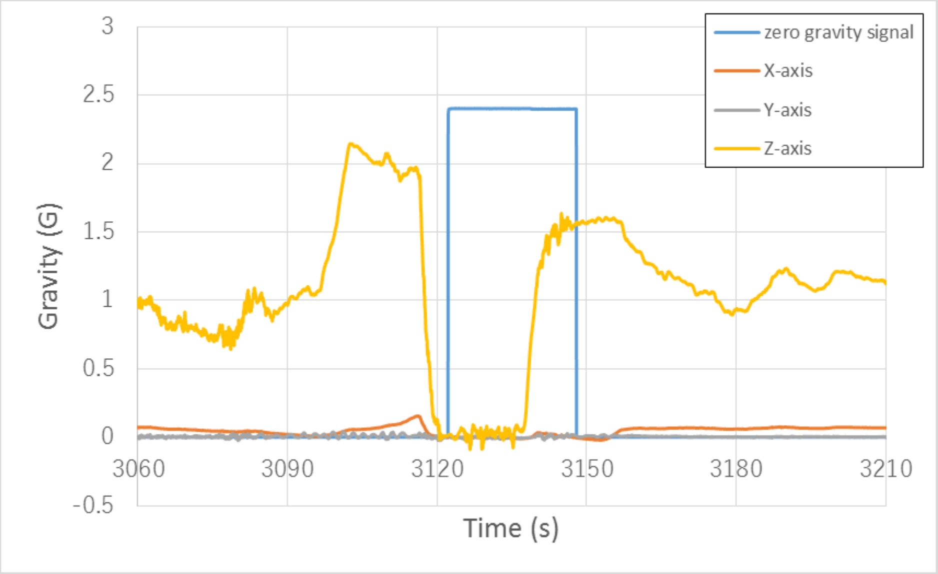
航空機実験→

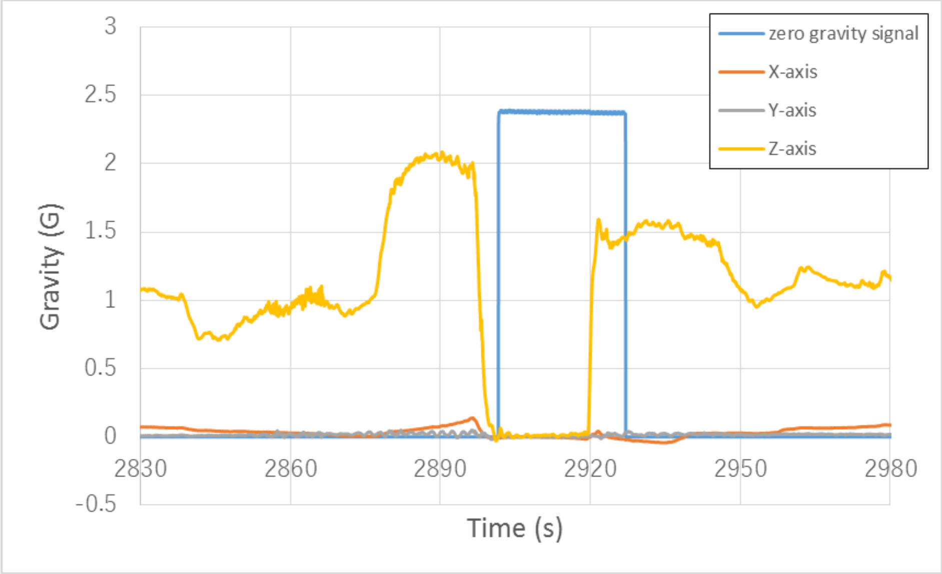


考察・結論

- チューブの湾曲について

①1122mmチューブのみ 50kPa(2日目3回目) ②1122mmチューブのみ 50kPa(6日目3回目)





- データロガーの重力値遷移より，展開中はXYZ方向いずれもほぼ0Gなので，湾曲はチューブに依存したものである.

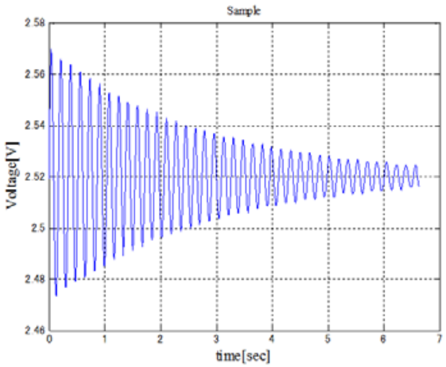
Appendix(ピエゾセンサ)

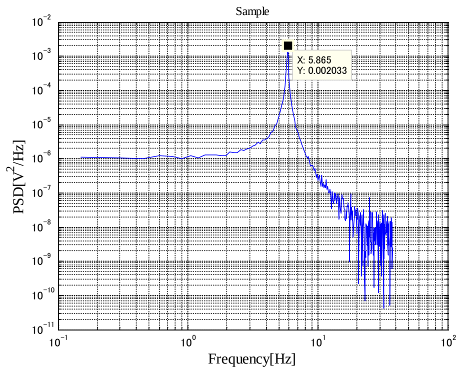
- 実験供試体（ピエゾセンサ）

型番	シート部寸法[mm]		電極部寸法[mm]		全体の厚さ[μm]	フィルムの厚さ[μm]	静電容量[nF]
	A	B	C	D			
DT1-028K/L	16	41	12	30	40	28	1.38

Appendix(振動データ(航空機実験))

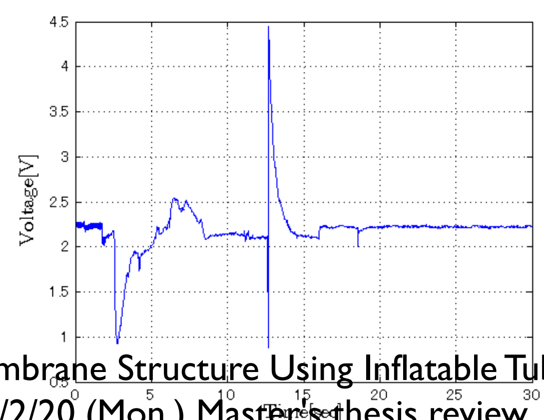
- ピエゾセンサによりチューブの振動データを取得.
- 電圧値と時間の関係で出力される生データをFFT解析し，PSD(パワースペクトル密度)と周波数の関係に変換.
- 変換後のピークが立っている点での周波数の値を知ることで固有振動数を知ることができる(＝柔軟構造物の剛性の評価ができる).

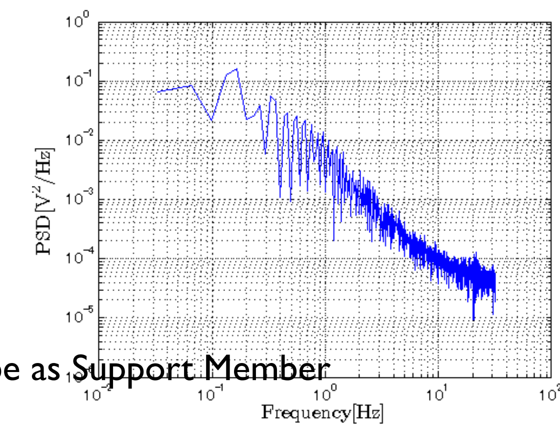




←例(理想)

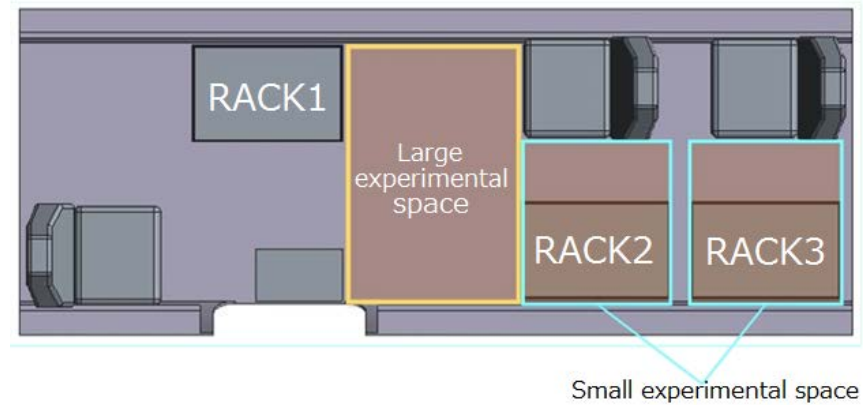
↓結果(2日目1回目)

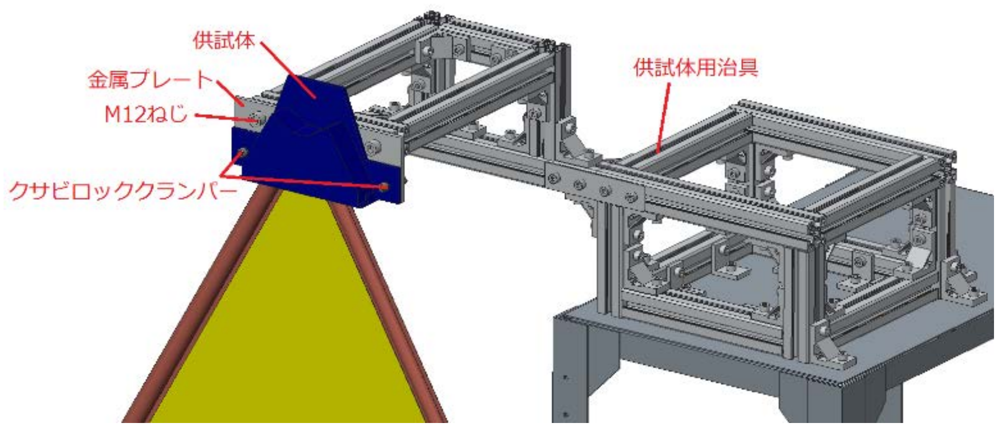




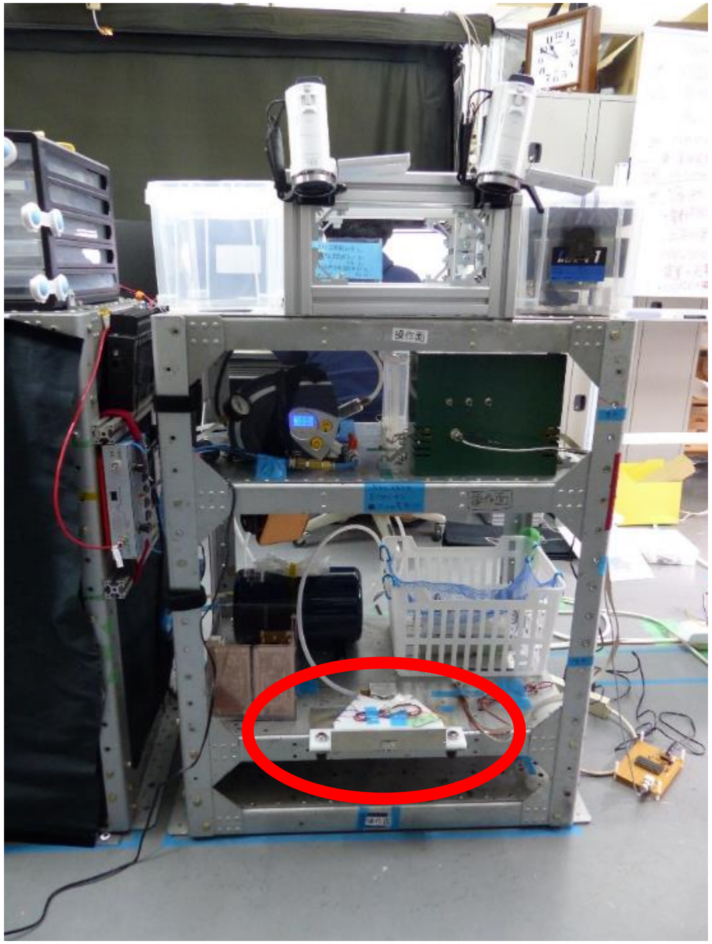
Appendix(ラック1への取り付け)

ラック1実験時

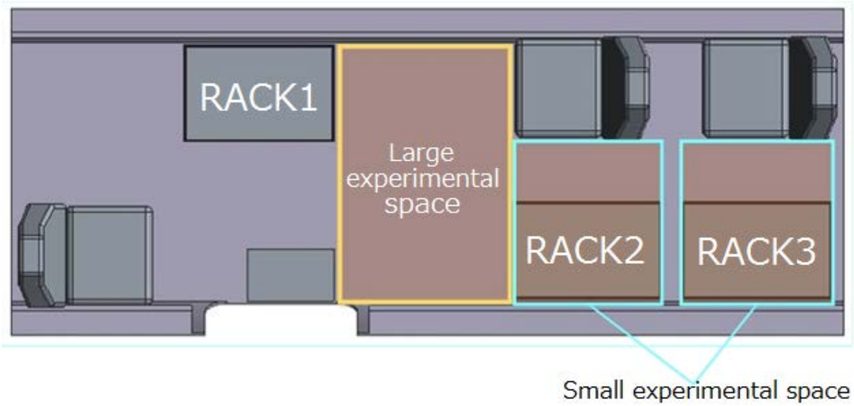


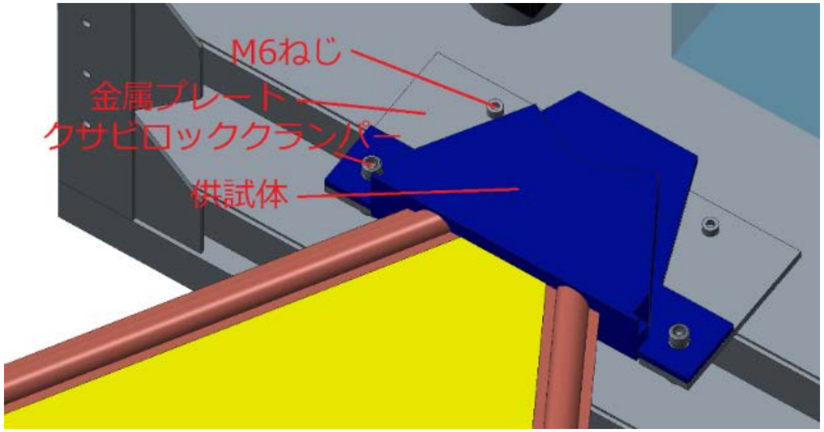


Appendix(ラック2への取り付け)



ラック2実験時

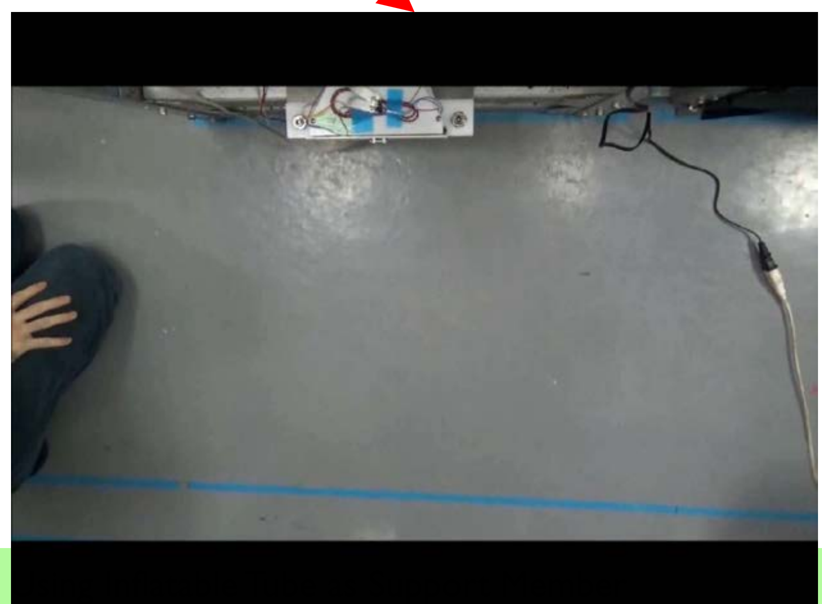




Appendix(ラック2展開確認)

Left Camera

Right Camera



Appendix(考察・結論)

- 軌道上及び今回膜面が引っかかった実験では，チューブ内圧がいずれも設定ガス圧の50kPaに達していない．また．膜の拘束力はそこまで大きくはないとみられる．

⇒ガスのリーク等がなく伸展力が十分であれば引っかかりを解消でき，チューブの湾曲やスパイラルが起こっても十分な展開を行うことができた可能性が考えられる．

引っかかりが生じた展開のガス注入開始からのチューブ内圧の履歴(絶対圧)