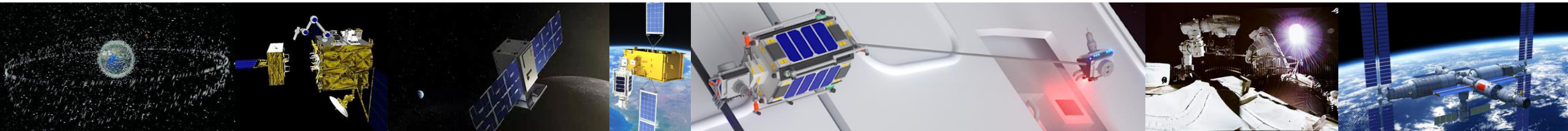
Design of Movement Scheme for Space Station Servicing CubeSat

Speaker: Senwei Lv(Fuzhen Yao)

Tutor: Rui Qi, Yao Zhang

Beijing Institute of Technology



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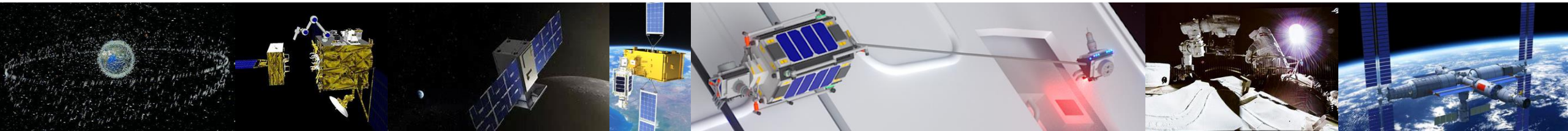
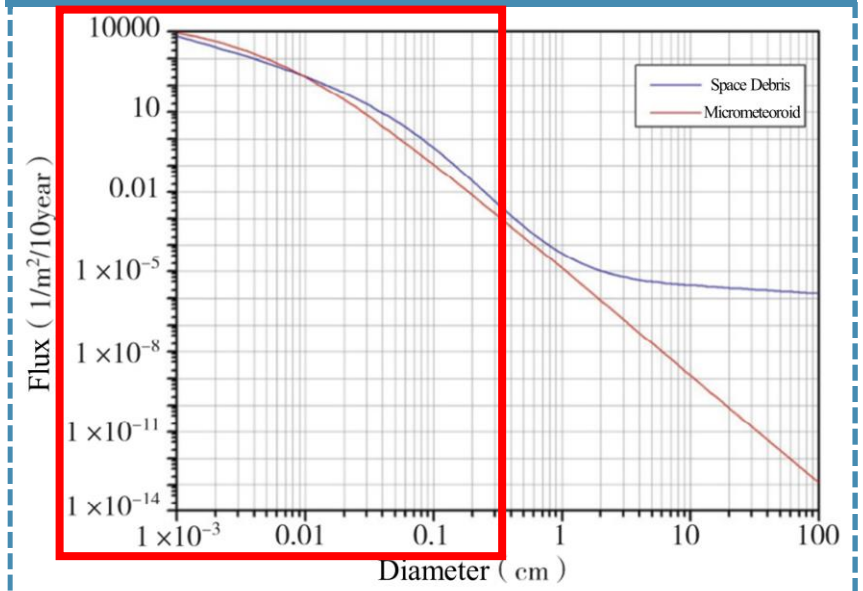


1 Backgrounds

Space Debris Threats



- **High Flux**

  10000/m²/10year[1]

- **High Relative Velocity**

  4~10km/s[1]

Current Solution

Need for Specialization And Automation

EVA for On-orbit Servicing

Astronauts with Robotic Arm

Defects:

- **High Time Cost**

  2.6h/person/day[2]

- **High Risk**
- **Low Efficiency**

  6.25h per time in average

[1]J Yan. “Space Debris Protection Design for the Space Station”, Space Debris Research.
[2]L Zeng. “Research on space system maintainability ＆maintenance technology in NASA and ESA”, Journal of Astronautics.

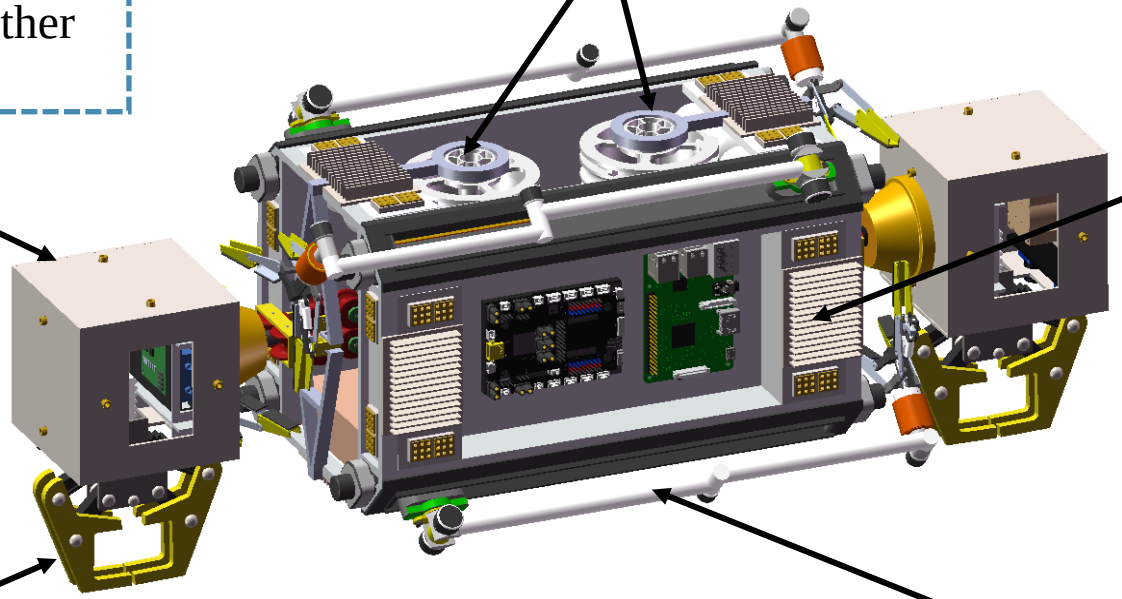
2.1 Structure Design

Winch

Stores and retracts the umbilical cord

Probe

Lightweight design, integrated camera, gripper, thruster and other functional components



Mother Satellite

Control, communication, and power core of the whole satellite

Gripper

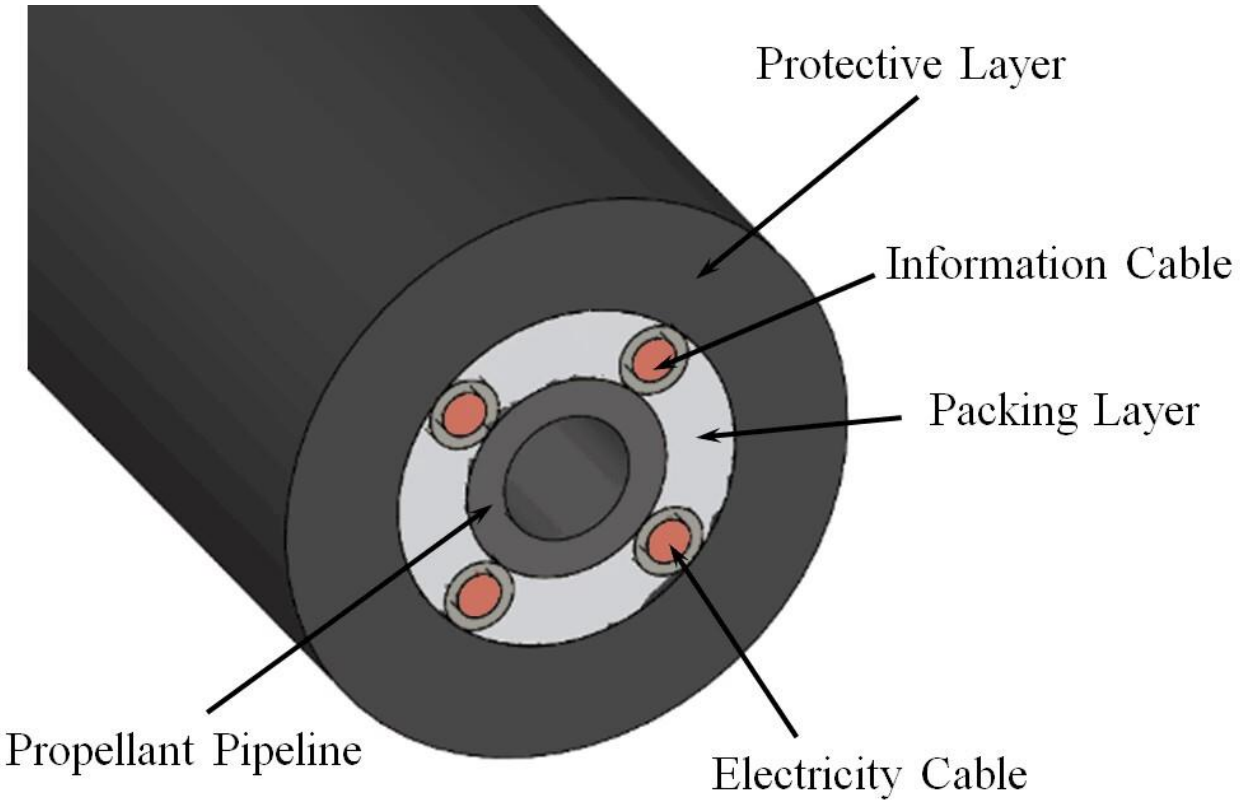
Able to grip handles and trusses

Robotic Arm

Close to the body and does not occupy space. There is a slide rail at the root, allows it can flexibly grasp objects in different directions and shapes

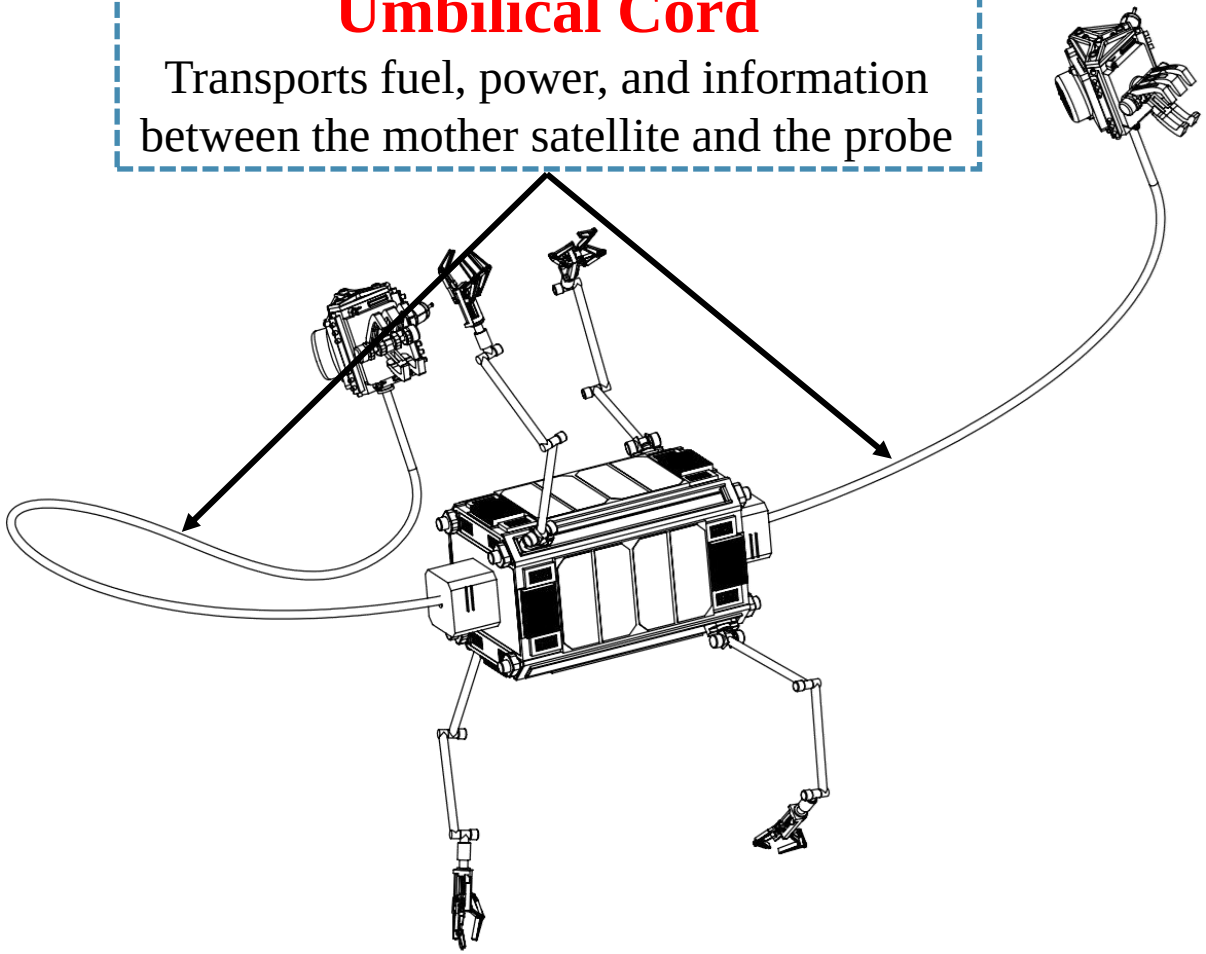
[3] V Hruby. “Tethered Robot for Spacecraft Self Inspection and Servicing”, 2018 AIAA SPACE and Astronautics Forum and Exposition Research.

2.1 Structure Design



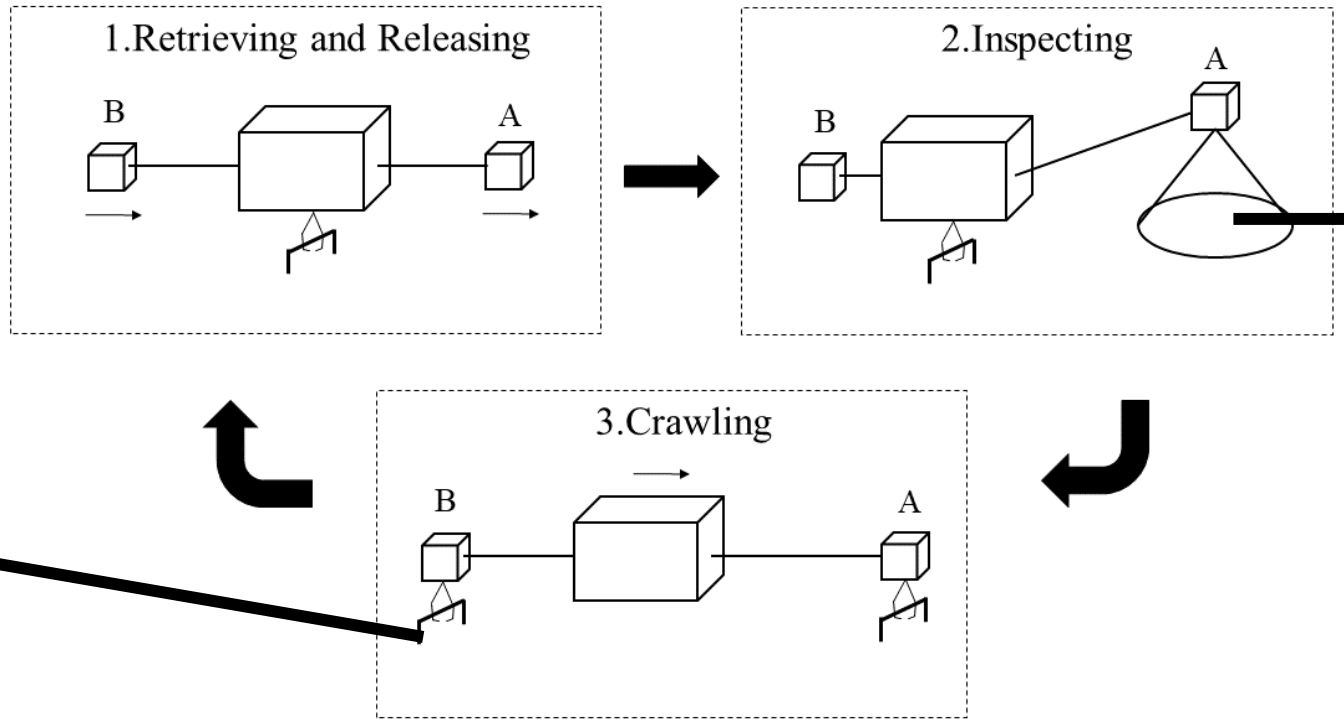
Umbilical Cord

Transports fuel, power, and information between the mother satellite and the probe

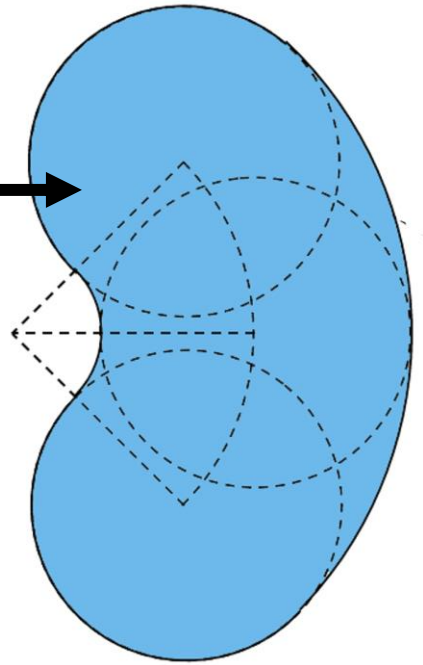


2.2 Movement and Inspection Scheme

Handles on Space Station



Movement and Inspection Scheme



Inspection Area

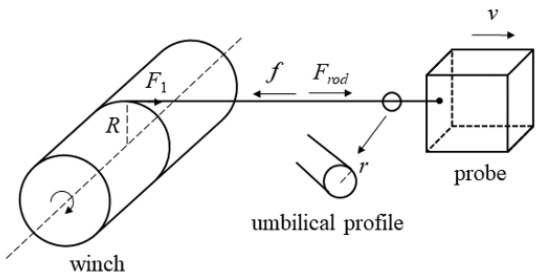
Electricity-Gas Hybrid Movement and Inspection Scheme, or EGH for short

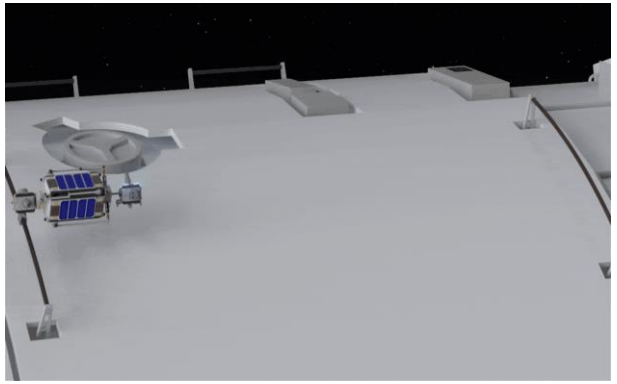
Repeat EGH Movement Scheme to Conduct Wide Range Movement on Space Station

3.1 Retrieval and Release Process

Consider the effect of umbilical and winch

Releasing Process





Dynamical Equation:

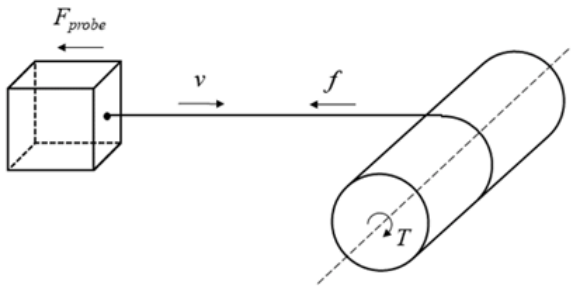
$$m(x)\ddot{x}(t) = F_{rod} - f - F_{tether}$$

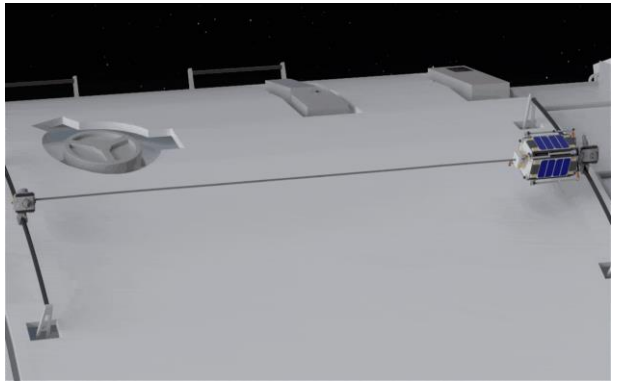
where

$$m(x) = \lambda x + m_{probe}$$

$$F_{tether} = J_{release}\ddot{x}(t)/R^2$$

Retrieval Process





Dynamical Equation:

$$J(x)\ddot{\alpha}(t) = T - \left(F_{probe} + f\right)R$$

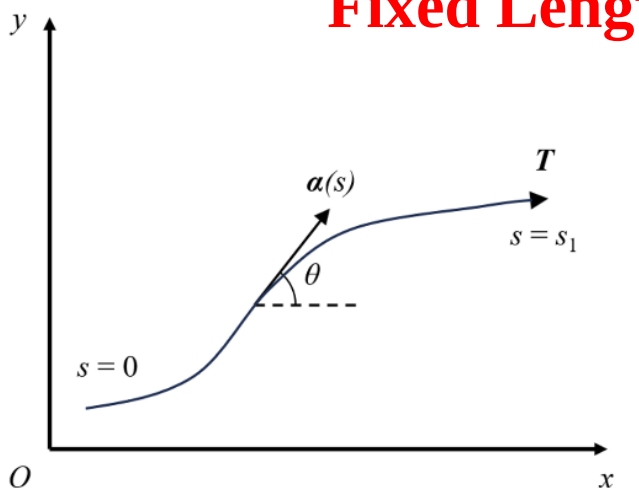
where

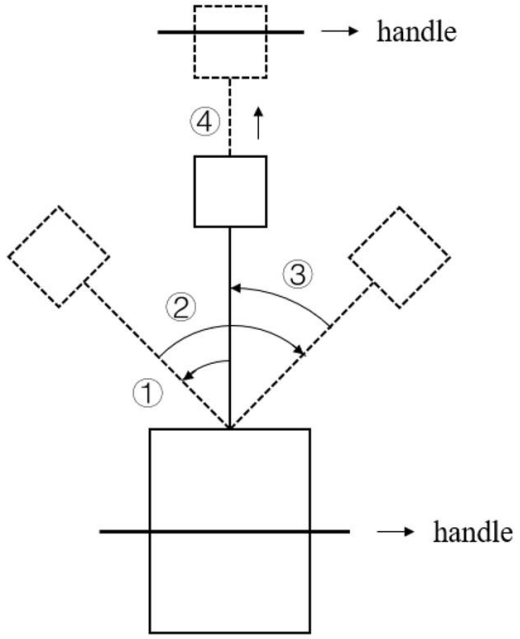
$$J(x) = \left[J_{recycle}/R + m(x)R\right]$$

$$J_{recycle} = J_{release} + \lambda(2x - L_{handle})(R^2 + 0.75r^2)$$

3.2 Inspection Process

Fixed Length of Umbilical





Dynamical Equation in Arc Coordinates:

$$\begin{cases} \rho\dfrac{\partial^2\boldsymbol{\theta}}{\partial t^2} - T_{tether}\dfrac{\partial^2\boldsymbol{\theta}}{\partial s^2} - 2\dfrac{\partial T_{tether}}{\partial s}\dfrac{\partial\boldsymbol{\theta}}{\partial s} - \boldsymbol{\alpha}\times\boldsymbol{F_{probe}} = 0 \\ \dfrac{\partial^2 T_{tether}}{\partial s^2} - \left(\dfrac{\partial\boldsymbol{\theta}}{\partial s}\right)^2 T_{tether} + \rho\left(\dfrac{\partial\boldsymbol{\theta}}{\partial t}\right)^2 + \boldsymbol{\alpha}\cdot\boldsymbol{F_{probe}} = 0 \end{cases}$$

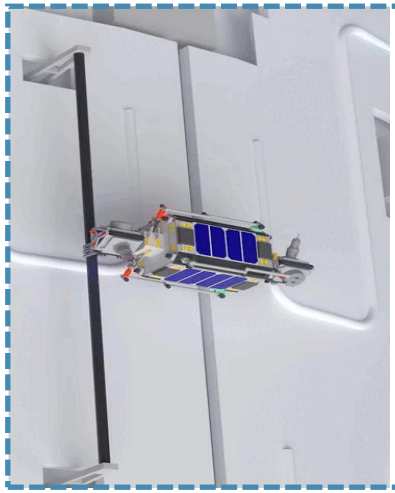
When Curvature Equals 0

$$\frac{\partial\boldsymbol{\theta}}{\partial s} = 0$$

$$\begin{cases} \boldsymbol{\theta}(t) = \boldsymbol{\theta}_0 + \dot{\boldsymbol{\theta}}(t)t \\ T_{tether} = T_{tether0} + C_1 s + \dfrac{1}{2}\lambda s^2\dot{\boldsymbol{\theta}}^2(t) \end{cases}$$

where

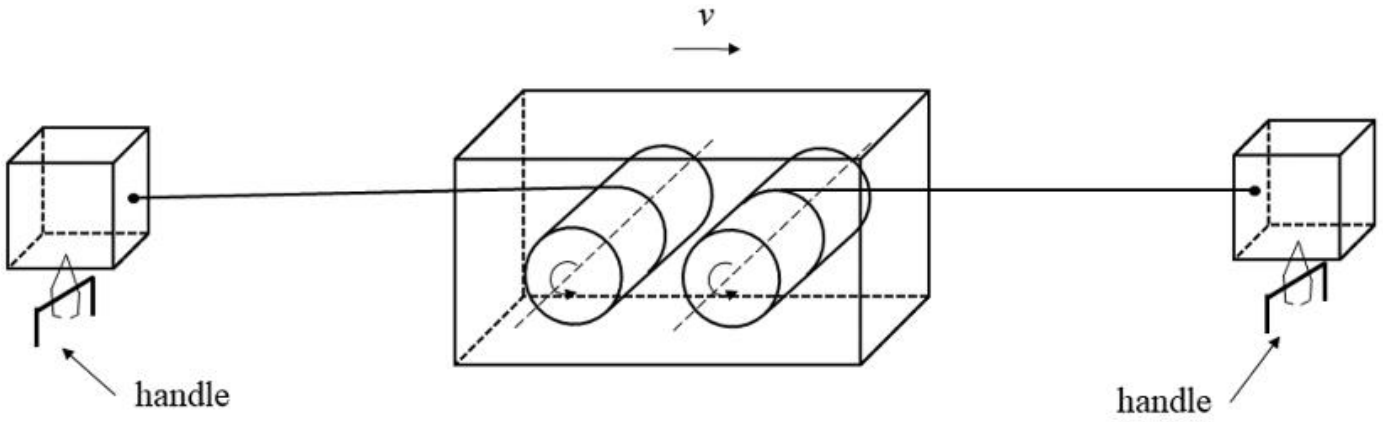
$$C_1 = \frac{F_{tether1} - F_{tether0} - \dfrac{1}{2}\lambda s^2\dot{\boldsymbol{\theta}}^2(t)}{s_1}$$

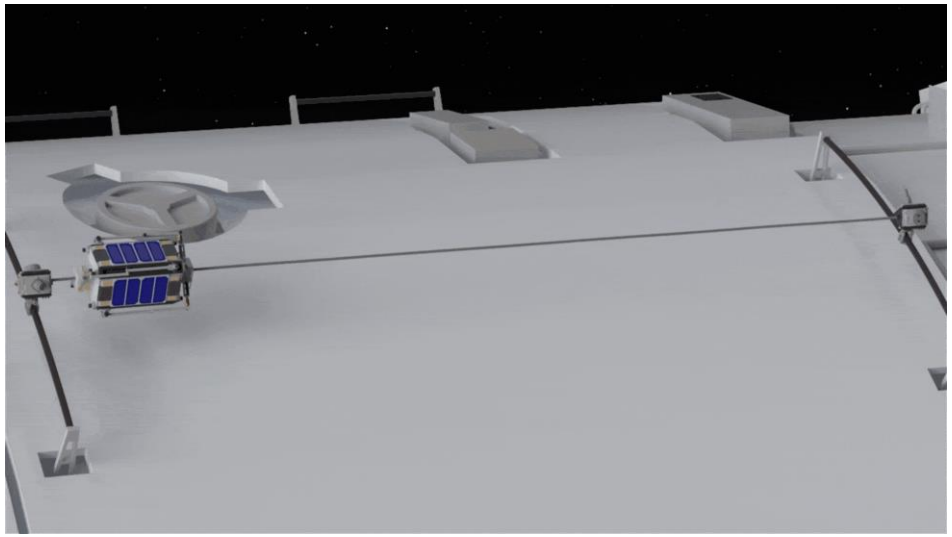


When probe conducts inspection, applying thrust at the end of umbilical can keep umbilical straight.

3.3 Crawling Process

Two winches respectively retract and release umbilical.

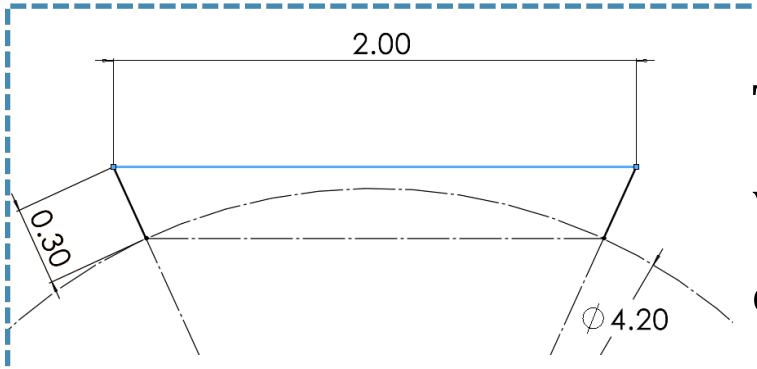




Dynamical Equation:

$$\left(\frac{J_{satellite}}{R} + m_{satellite}R\right)\ddot{x}(t) = 2(T - fR)$$

Here x represents the displacement of Mother Satellite.



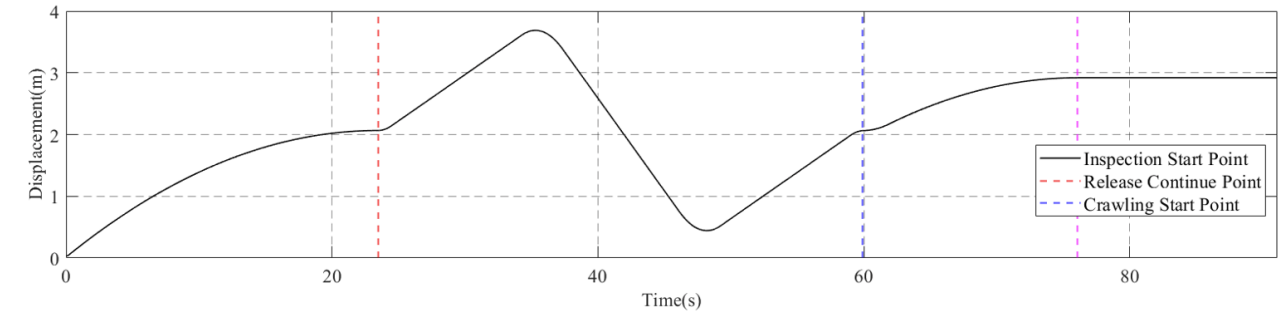
The movement path won't be interfered by cabin surface.

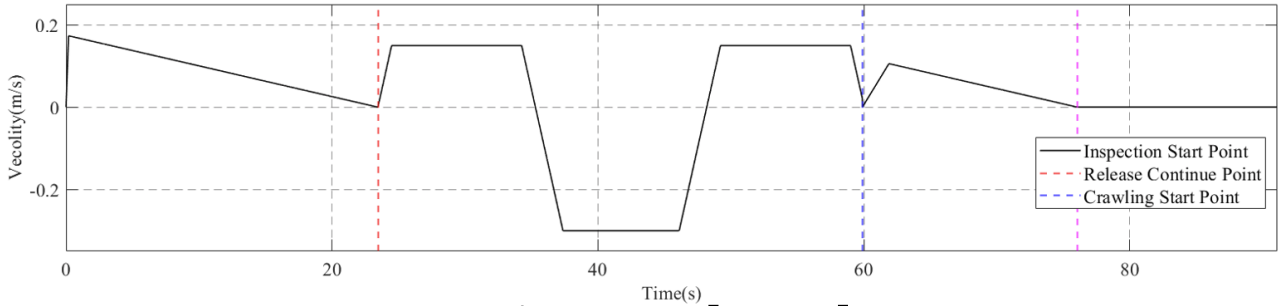
4.1 Single-Step Movement Analysis

Consider the whole CubeSat's single-step movement between two handles.

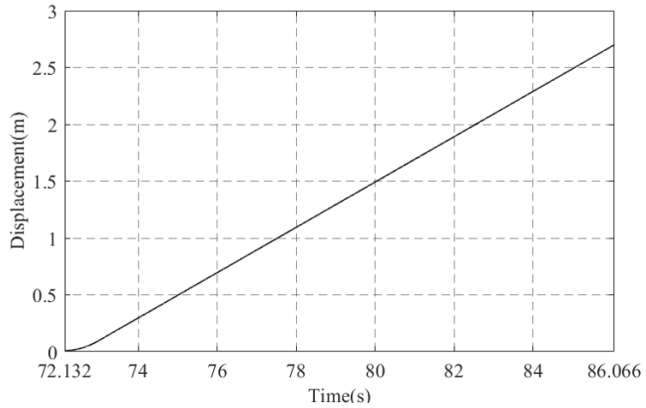
Parameters	Values	Units
Length of Umbilical Cord	3	m
Linear Density of Umbilical Cord	0.08	kg/m
Radius of Umbilical Cord	3.5	mm
Mass of Probe	1	kg
Mass of Mother Satellite	8	kg
Radius of Winch	0.05	m
Mass of Winch	0.1	kg

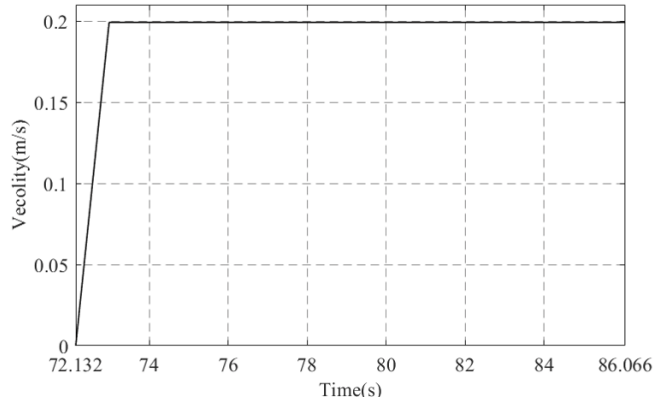
Key Parameters Used in Simulation





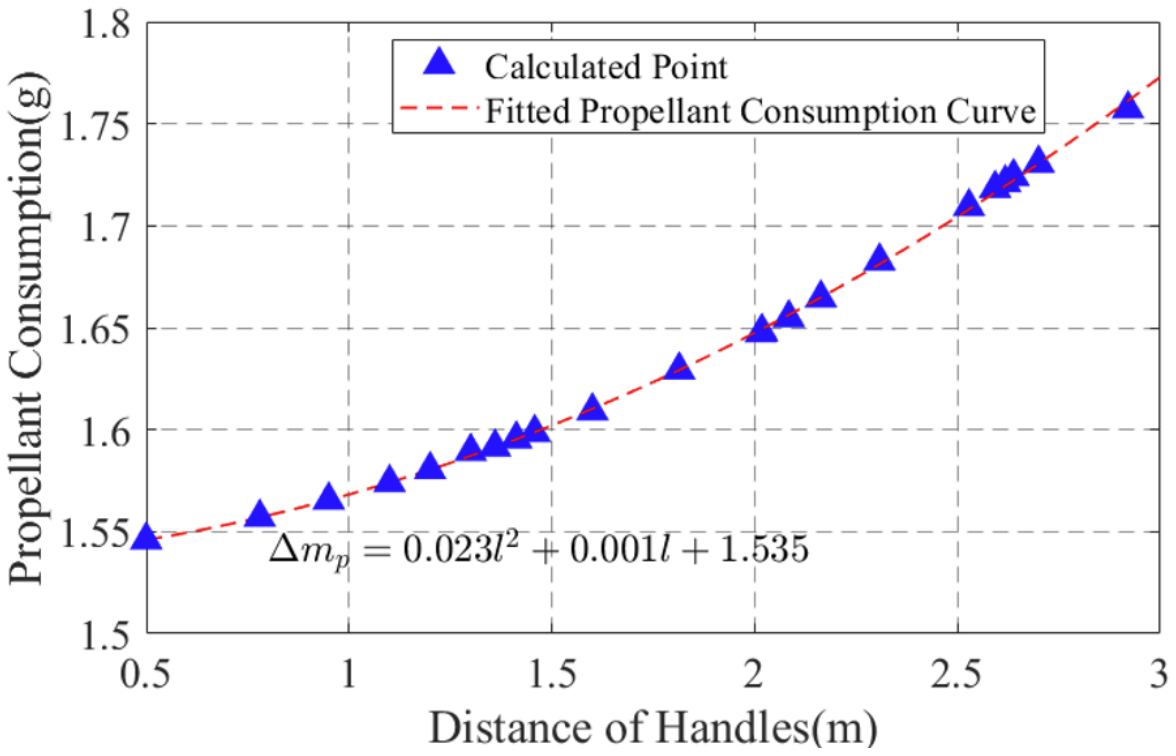
Probe's *x*-*t* and *v*-*t* Plot



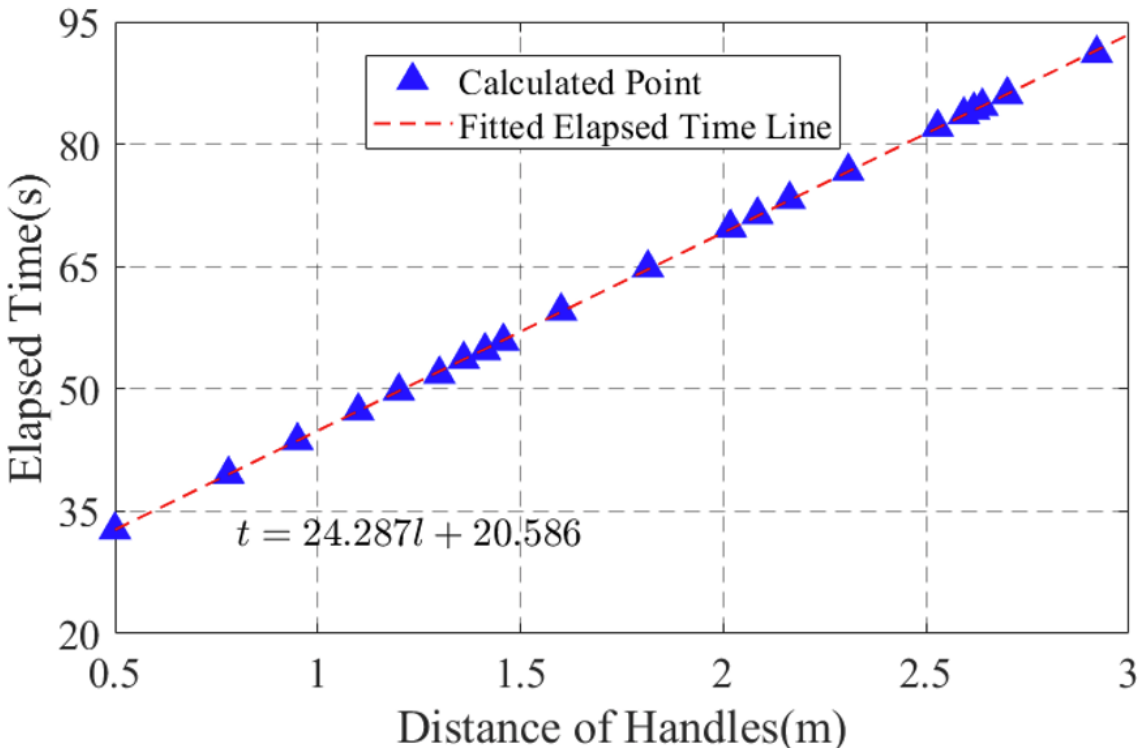


Mother Satellite's *x*-*t* and *v*-*t* Plot

4.1 Single-Step Movement Analysis

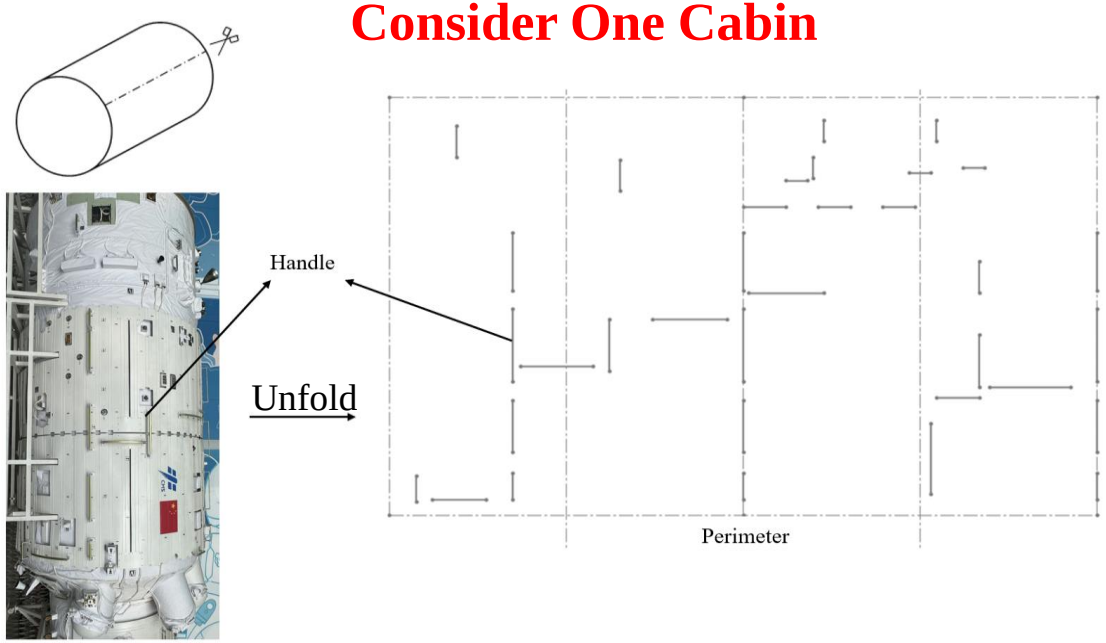


The relation between thruster consumption and distance of handles is of the second degree.



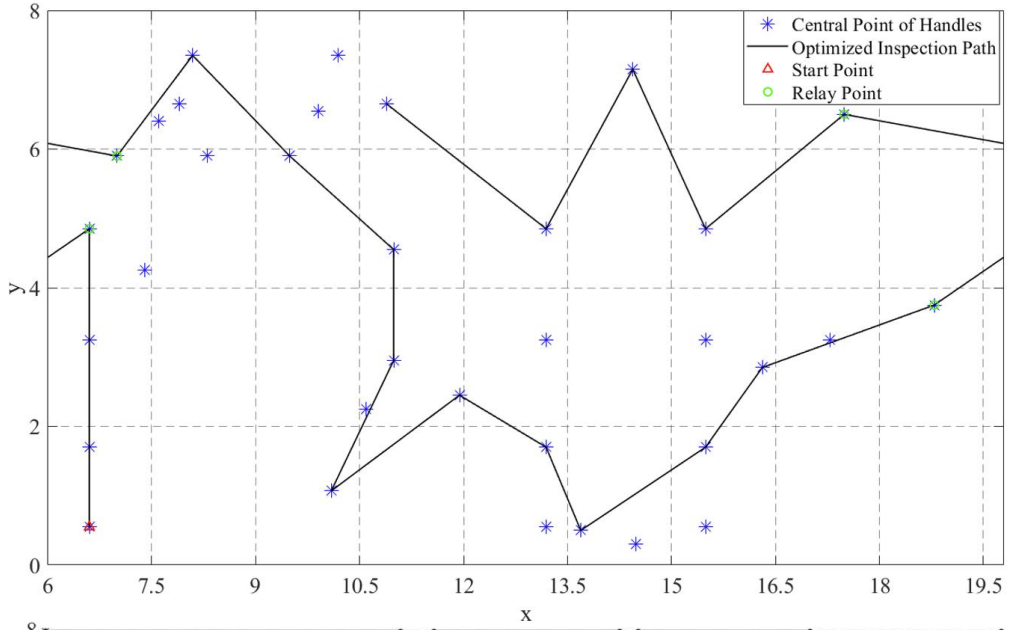
The relation between time consumption and distance of handles is linear.

4.2 Partly Inspection Analysis



Consider One Cabin

SQP Optimized Path

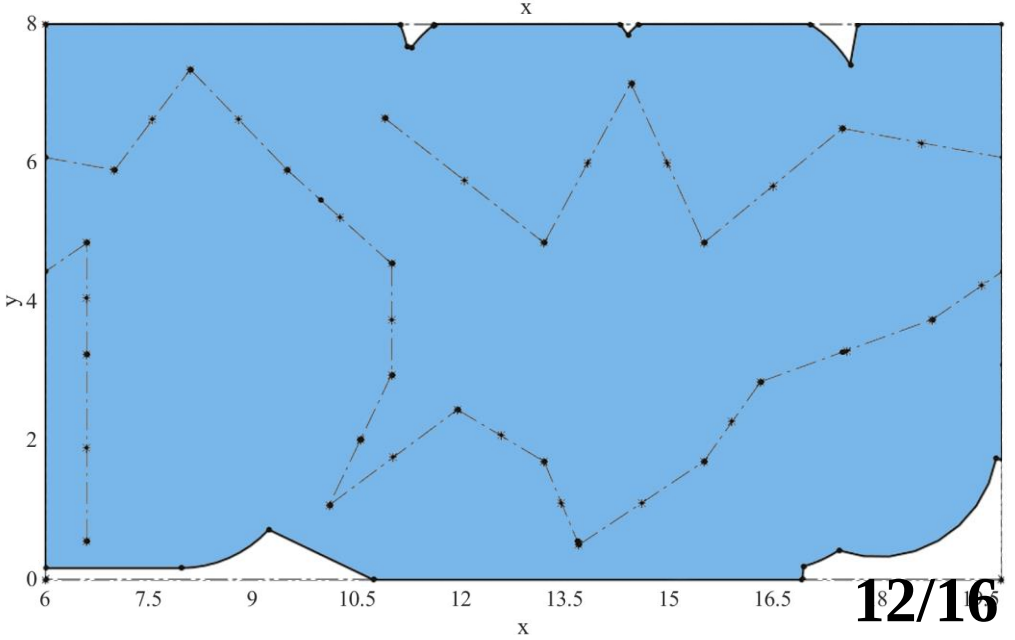


Optimization Objects:

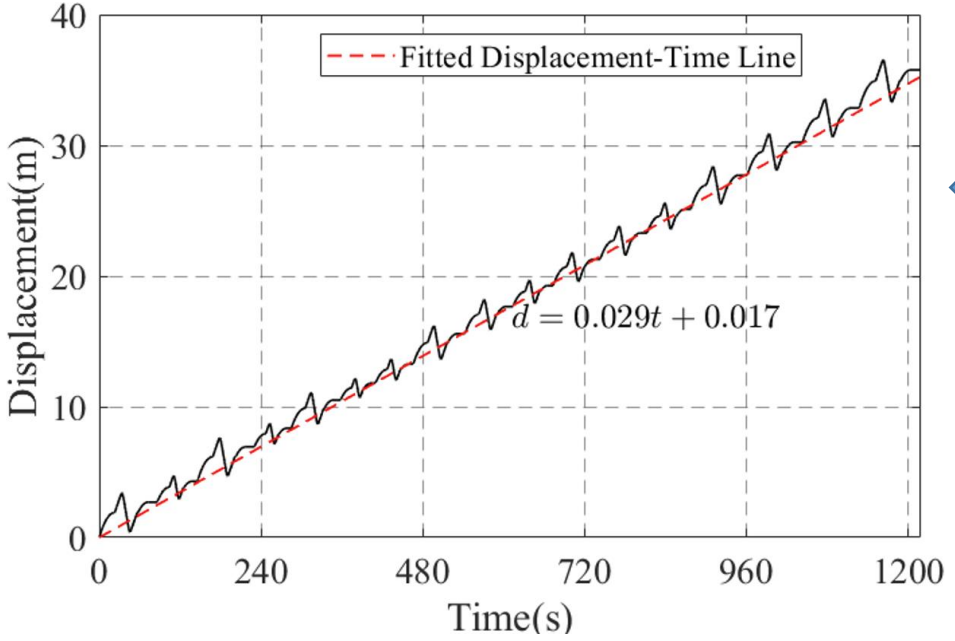
- **Whole Propellant Consumption** $\sum \Delta m_p$
- **Whole Time Consumption** $\sum \Delta t$

Optimization Results:

- $\sum \Delta t = 1218\text{s}$
- $\sum \Delta m_p = 48.08\text{g}$
- **Coverage Rate** = 97%



4.2 Partly Inspection Analysis

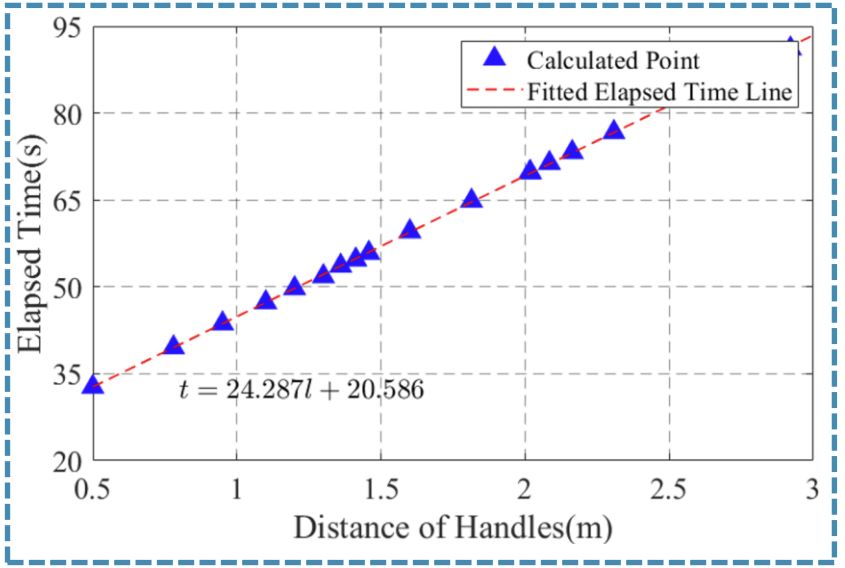


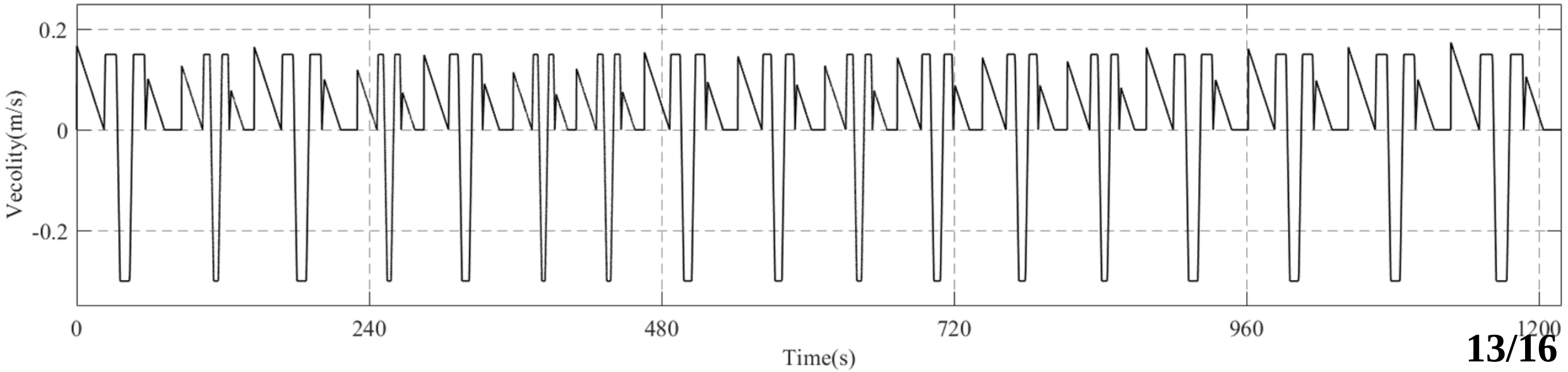
Result in Linear Relation

One Cabin Inspection

Probe's *x*-*t* Plot

Probe's *v*-*t* Plot





4.3 Overall Inspection Analysis

Consider Tiangong Space Station (7 Cabins)

Estimation of Overall Inspection Time Consumption:

142min (20min per cabin)

Estimation of Overall Inspection Propellant Consumption:

336.56g (48g per cabin)

Estimated Maximum Service Life:

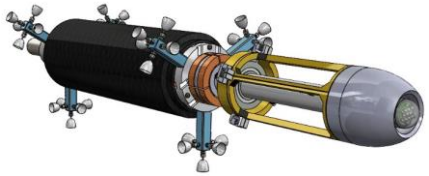
7month (Without Propellant Supply)

2year (With Propellant Supply)

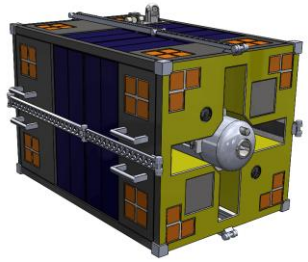
5 Current Progress

Design

Version 1



- For debris removal



Version 2

- For on-orbit service

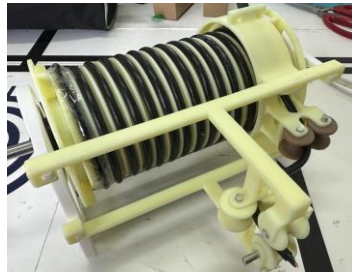
Version 3

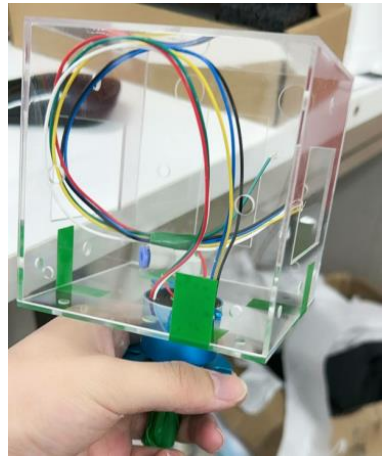
- Make prototype and ground test

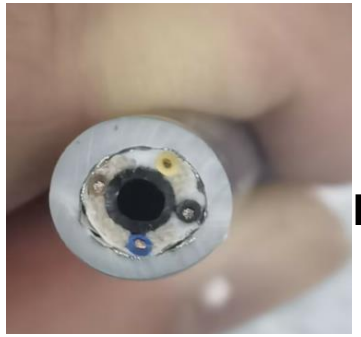
Multi-arm Umbilical CubeSat

Award

Progress







- Winch, Umbilical Cord and Probe's Prototype Making

Design Iteration

SUCC(2023) First Prize

Prototype Making

Thanks for Listening

Your comments and suggestions are appreciated!