Modeling a New Concept of Tether Deployer with Retrievable Capability for Space Applications

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Overview

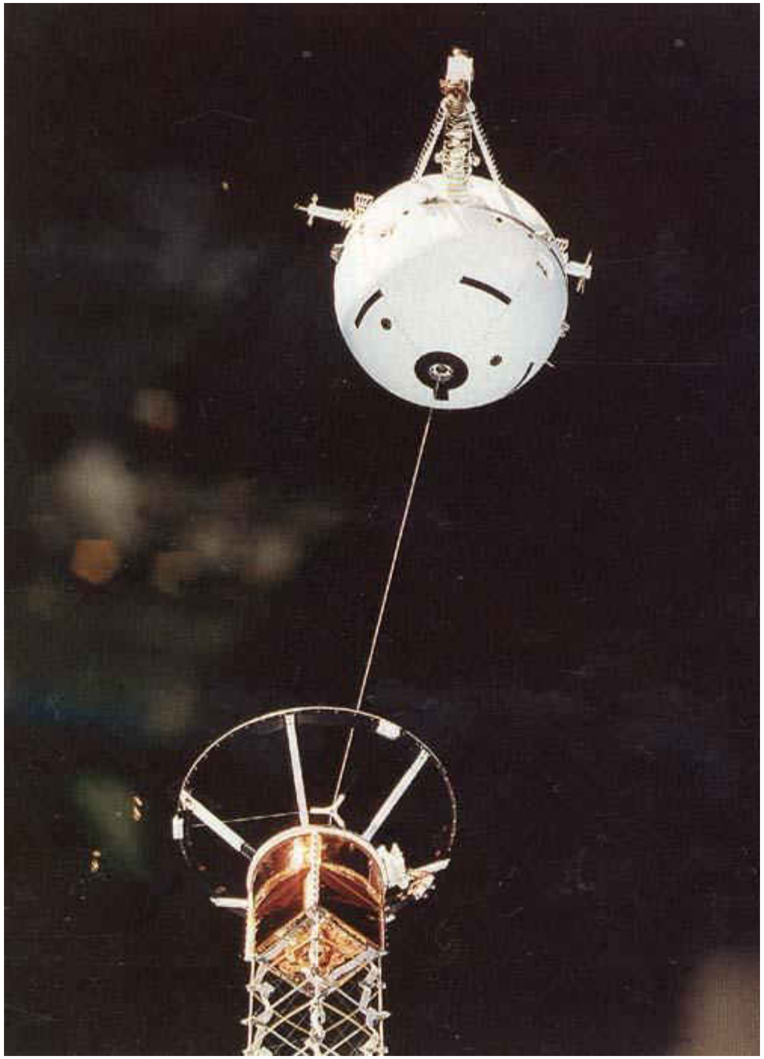
1. Introduction
2. Proposed concept
3. Models & control
4. Simulations
5. Conclusions

Introduction

What did we want to do?

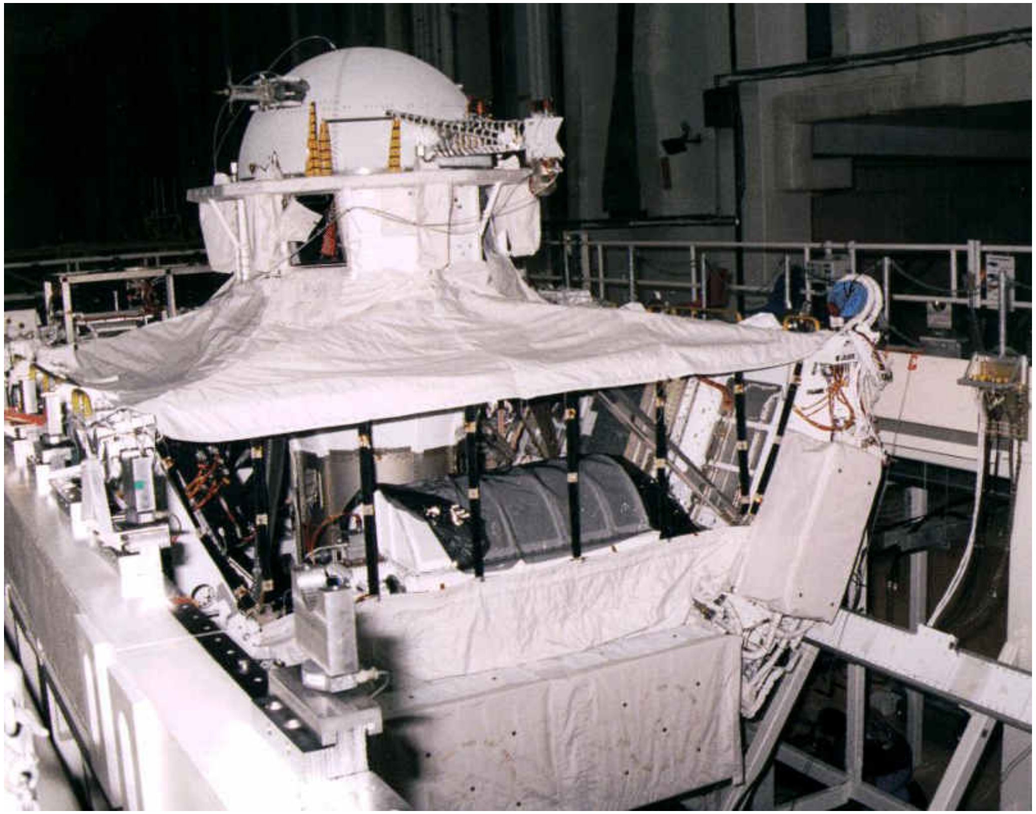
1. Model a tether deployer with retrievable capability
2. Simple & reliable
3. Compact & light

Tether heritage (1/2)



1992 – TSS-1 – 20 km tether

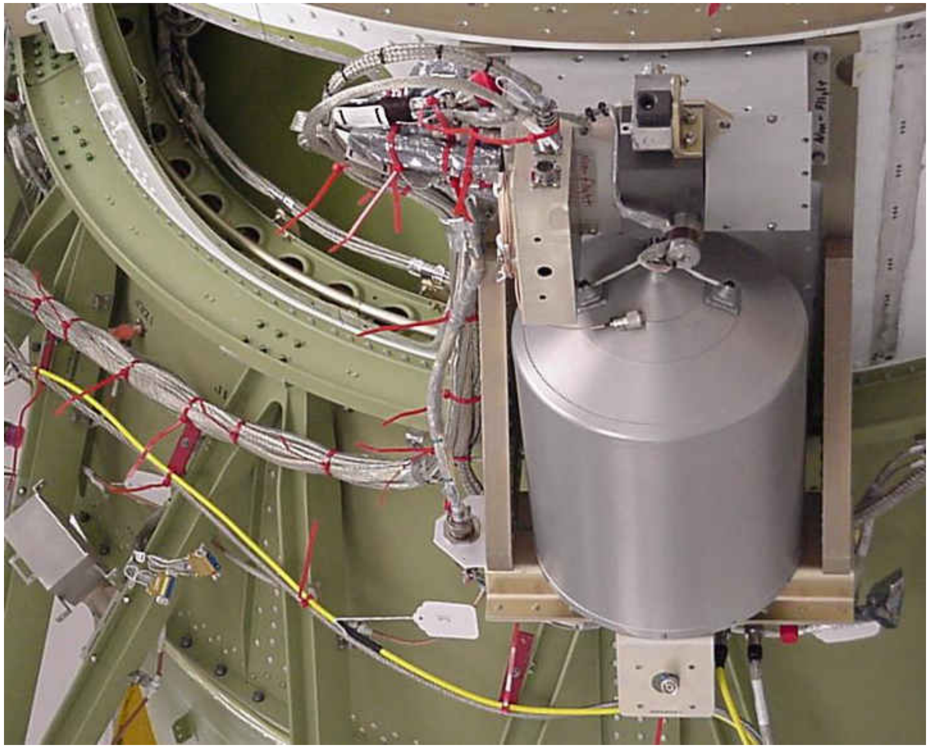
- 670 kg satellite + tether
- 4800 kg pallet & support



Tether heritage (2/2)

1994 – SEDS-II – 20 km tether

- 33 kg tip mass + tether
- 10 kg deployer hardware



Proposed concept

Proposed concept (1/2)

Proposed concept (1/2)

Deployment phase

Proposed concept (1/2)

How to control tether motion during deployment?

Low-Inertia (SEDS-like)... ... *Inductive Brake* (TSS-like)

PD control

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PD control

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How to control tether motion during deployment?

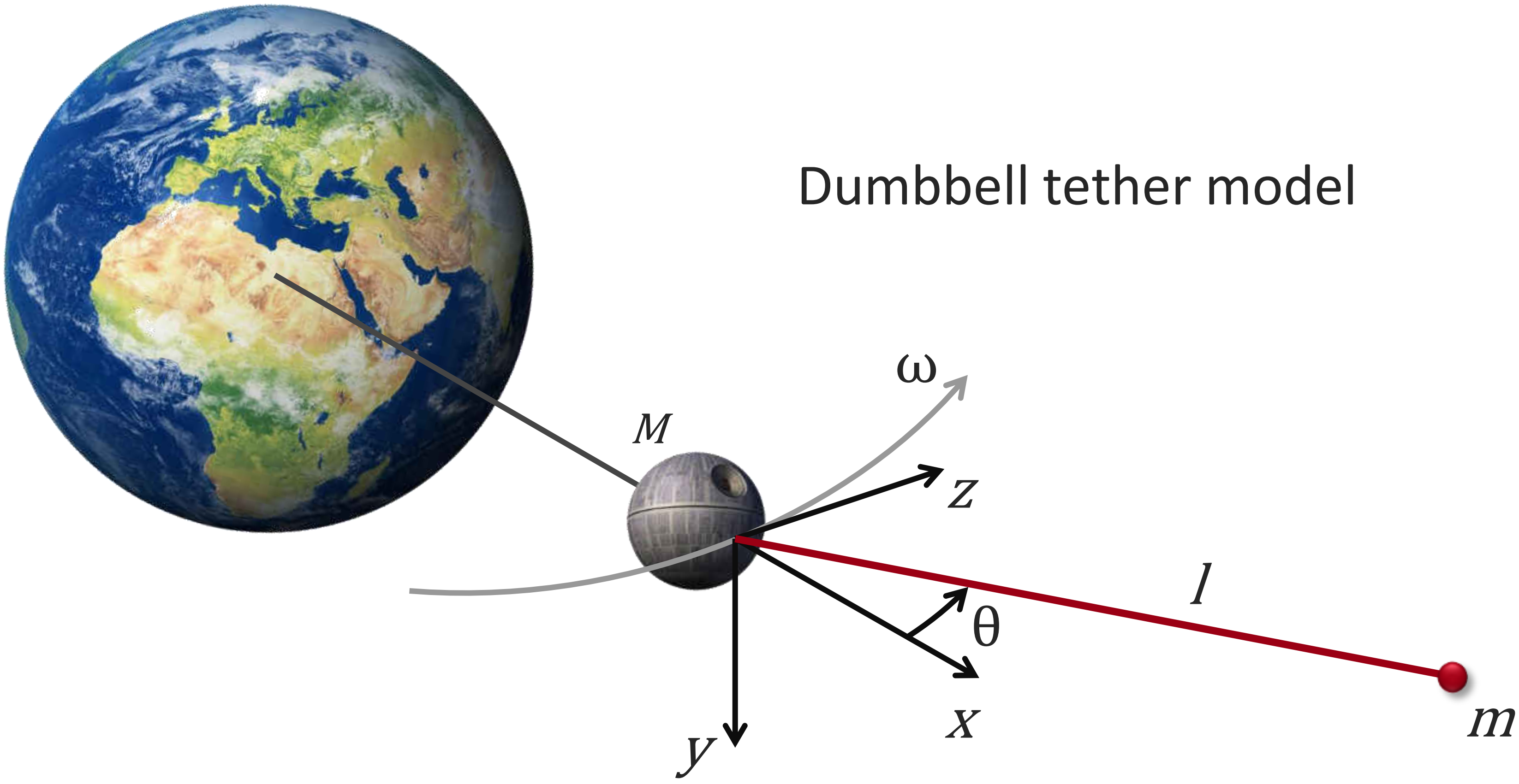
Low-Inertia (SEDS-like)… … *Inductive Brake* (TSS-like)

PD control

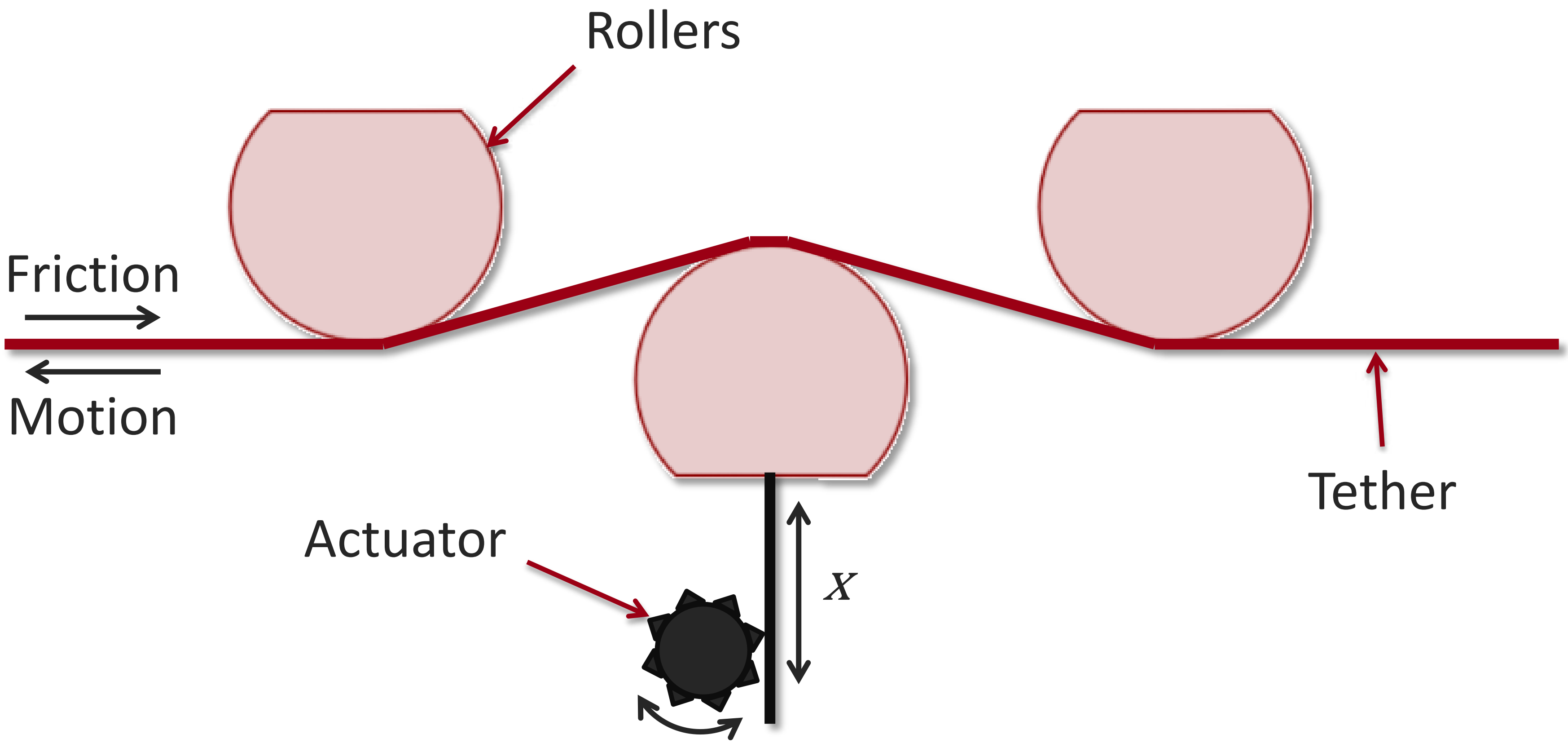
Models & control

Models (1/2)

Dumbbell tether model



Mechanical brake (low-inertia)



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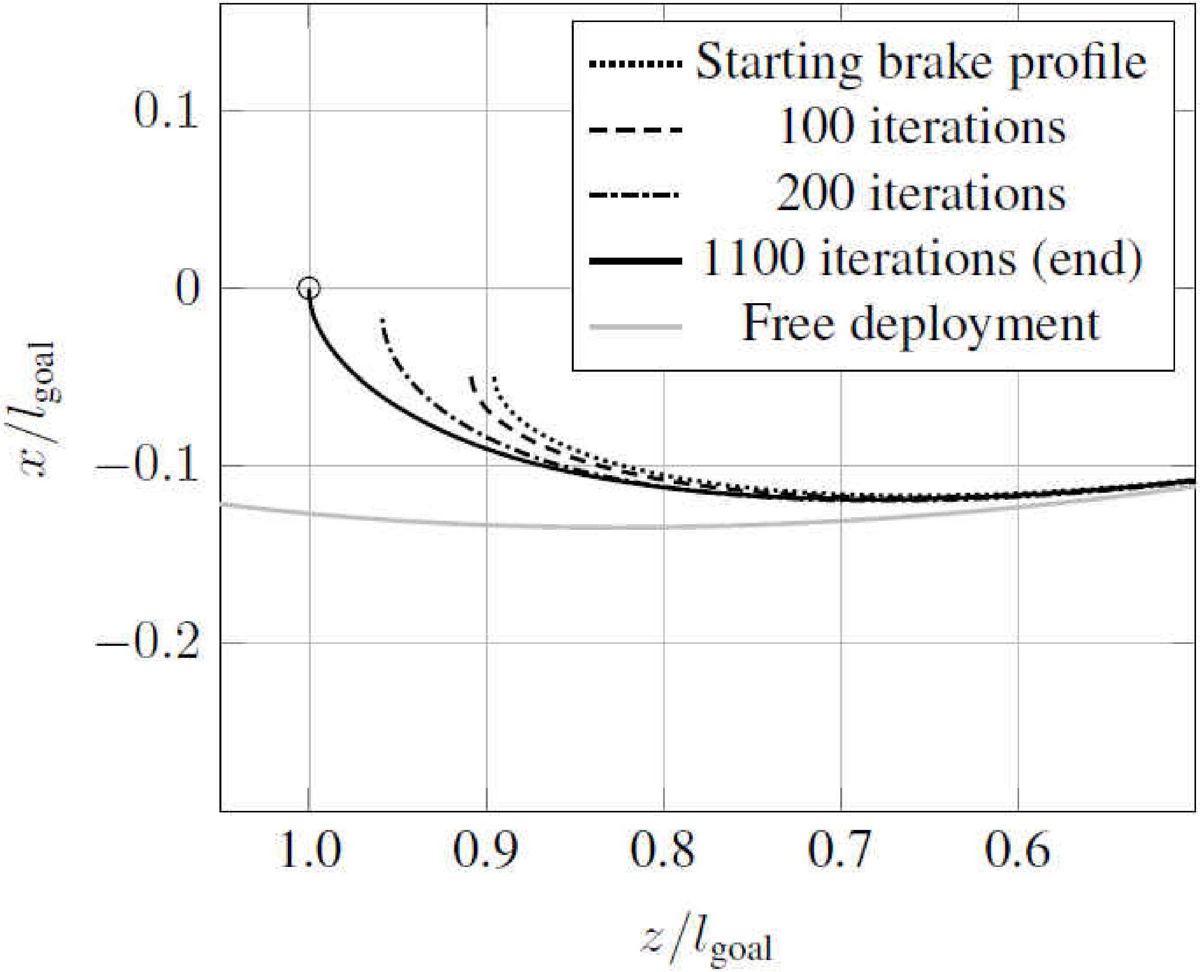
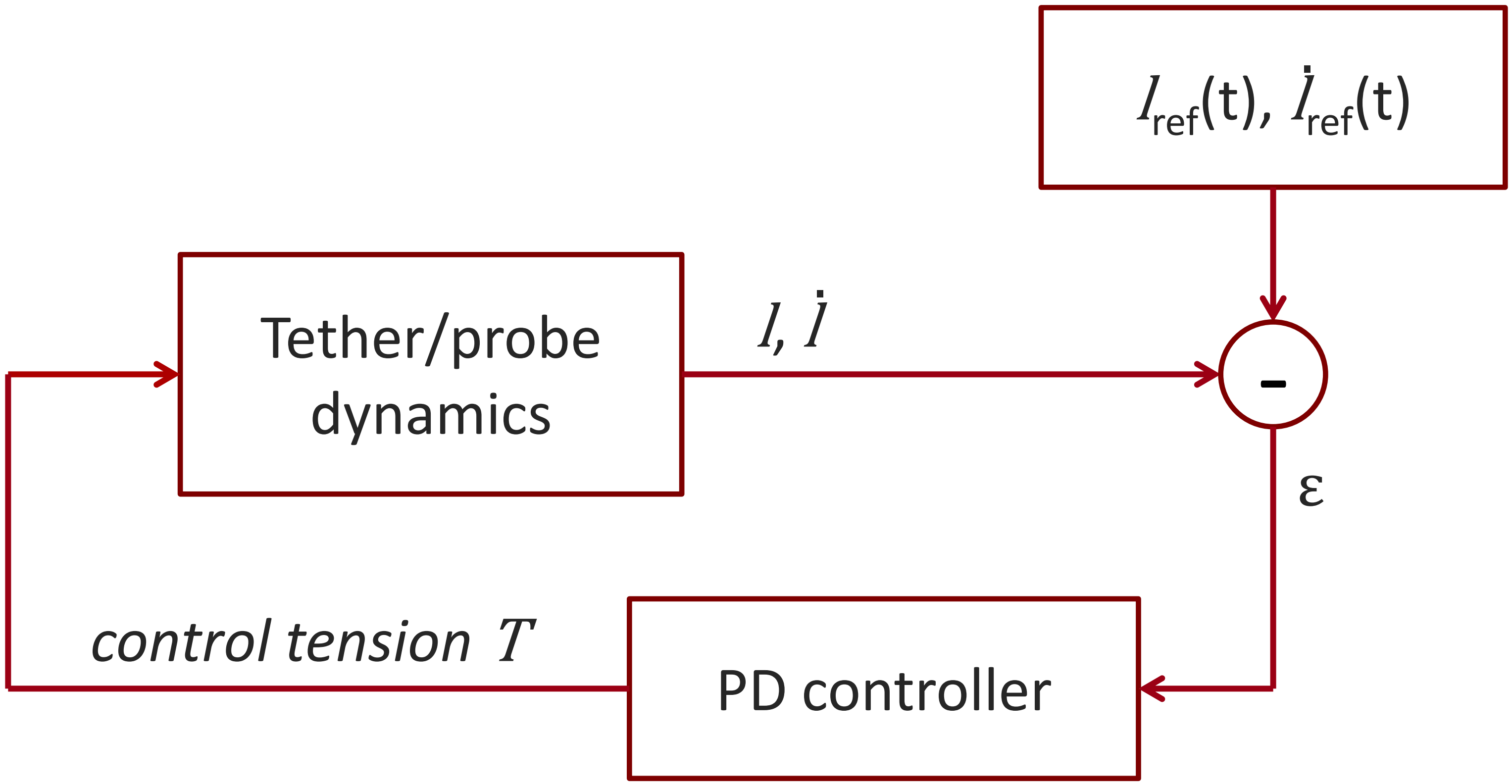
Reference trajectory optimization – Nelder-Mead algorithm



Control (2/2)

Reference trajectories feed-forward – $l_{ref}(t)$, $\dot{l}_{ref}(t)$



Equations (deployment)

LI

$$\begin{cases} \ddot{l}(m+\rho l) + \frac{\rho}{2}\dot{l}^2 + l\left(m + \frac{\rho}{2}l\right)\left[\left(\omega + \dot{\theta}\right)^2 + 3\omega\cos^2(\theta)\right] = -4\frac{\lambda p}{d}x - T_0 \\ \ddot{\theta} + 3\frac{2m+\rho l}{3m+\rho l}\left(\omega + \dot{\theta}\right)\frac{\dot{l}}{l} + 3\omega^2\sin(\theta)\cos(\theta) = 0 \end{cases}$$

IB

$$\begin{cases} J\frac{\partial i}{\partial t} + Ri = V - k_v\dot{\psi} \\ \ddot{\psi}\left[\frac{I}{r} + r(m+\rho r\psi)\right] + \dot{\psi}\left(\frac{b}{r} + \frac{\rho}{2}r^2\dot{\psi}\right) - \psi r\left(m + \frac{\rho}{2}r\psi\right)\left[\left(\omega + \dot{\theta}\right)^2 + \dots \right. \\ \left. \dots + 3\omega^2\cos^2(\theta)\right] = -\frac{k_t}{r}i - T_0 \\ \ddot{\theta} + 3\frac{2m+\rho\psi r}{3m+\rho\psi r}\left(\omega + \dot{\theta}\right)\frac{\dot{\psi}}{\psi} + 3\omega^2\sin(\theta)\cos(\theta) = 0 \end{cases}$$

Equations (deployment)

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$$\ddot{l}(m+\rho l) + \frac{\rho}{2}\dot{l}^2 + l\left(m+\frac{\rho}{2}l\right)\left[\left(\omega+\dot{\theta}\right)^2 + 3\omega\cos^2(\theta)\right] = -4\frac{\lambda p}{d}x - T_0$$

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$$\ddot{\theta} + 3\frac{2m+\rho\psi r}{3m+\rho\psi r}\left(\omega+\dot{\theta}\right)\frac{\dot{\psi}}{\psi} + 3\omega^2\sin(\theta)\cos(\theta) = 0$$

Control (x, V)

Inner friction (T_0)

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LI

$$\ddot{l}(m+\rho l) + \frac{\rho}{2}\dot{l}^2 + l\left(m+\frac{\rho}{2}l\right)\left[\left(\omega+\dot{\theta}\right)^2 + 3\omega\cos^2(\theta)\right] = -4\frac{\lambda p}{d}x - T_0$$

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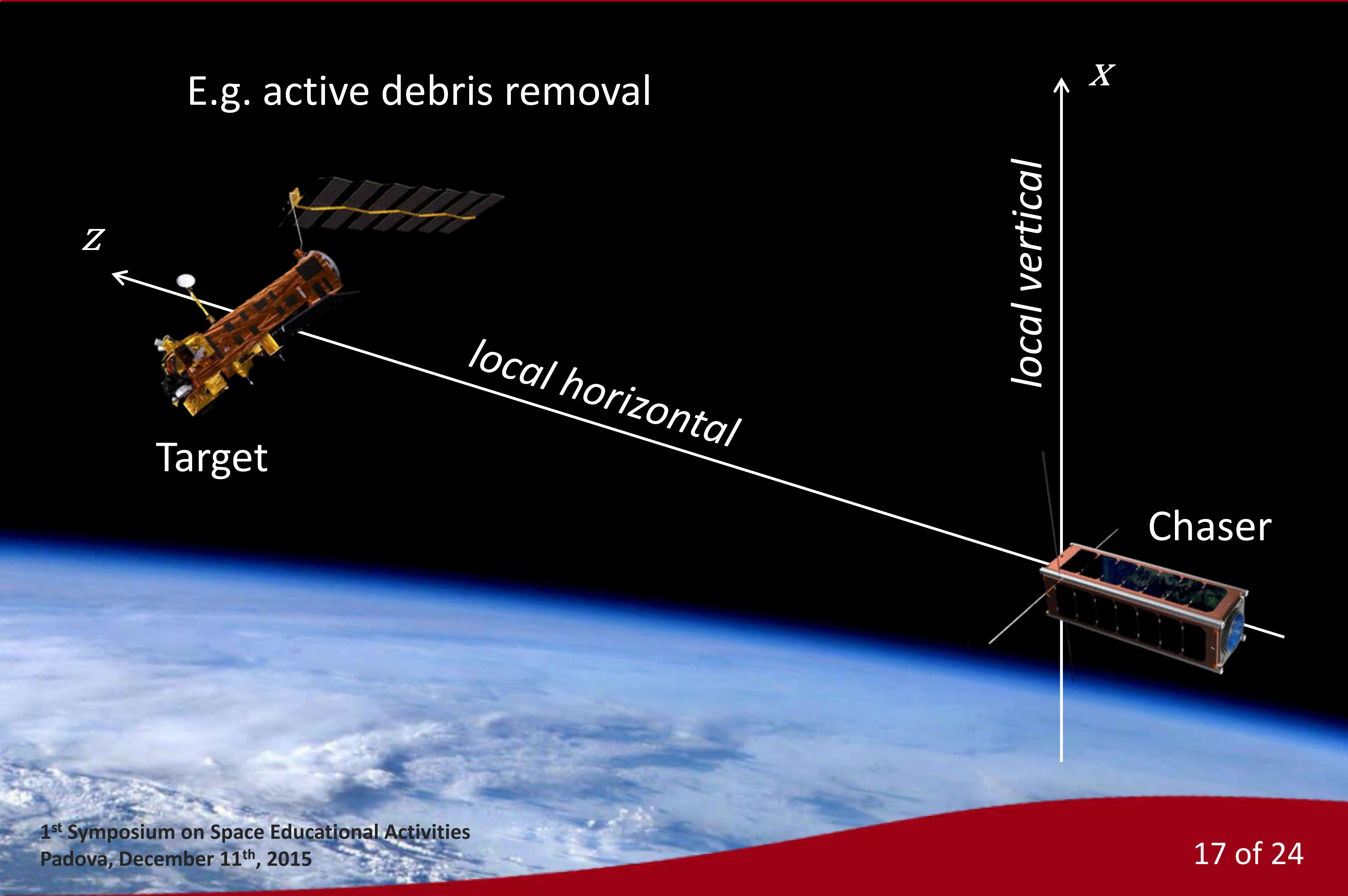
$$\ddot{\theta} + 3\frac{2m+\rho\psi r}{3m+\rho\psi r}\left(\omega+\dot{\theta}\right)\frac{\dot{\psi}}{\psi} + 3\omega^2\sin(\theta)\cos(\theta) = 0$$

Control (x, V)

Inner friction (T_0): 15 mN (LI), 150 mN (IB)

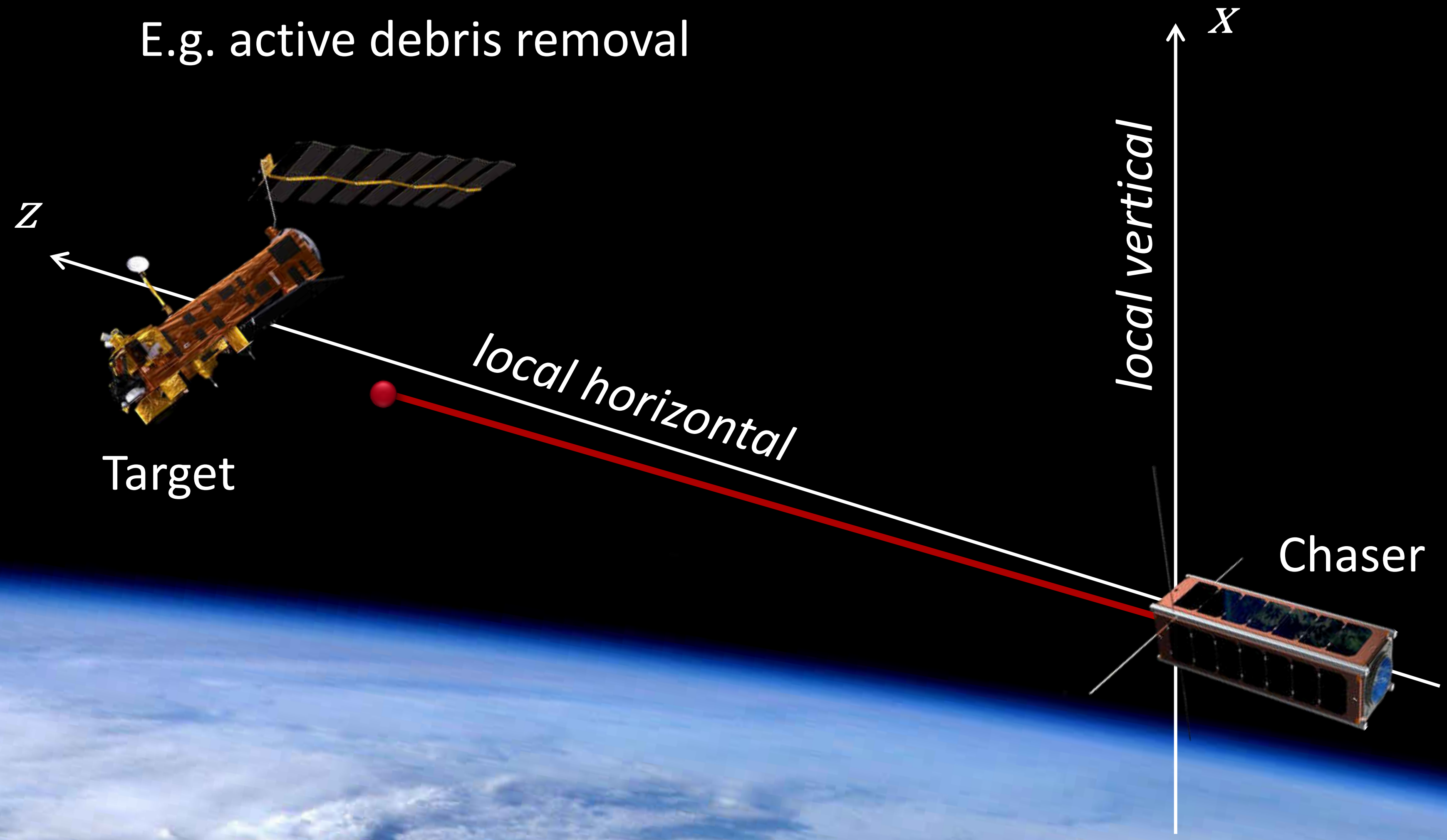
Simulations

Deployment scenario (1/2)



Deployment scenario (1/2)

E.g. active debris removal



Deployment scenario (1/2)

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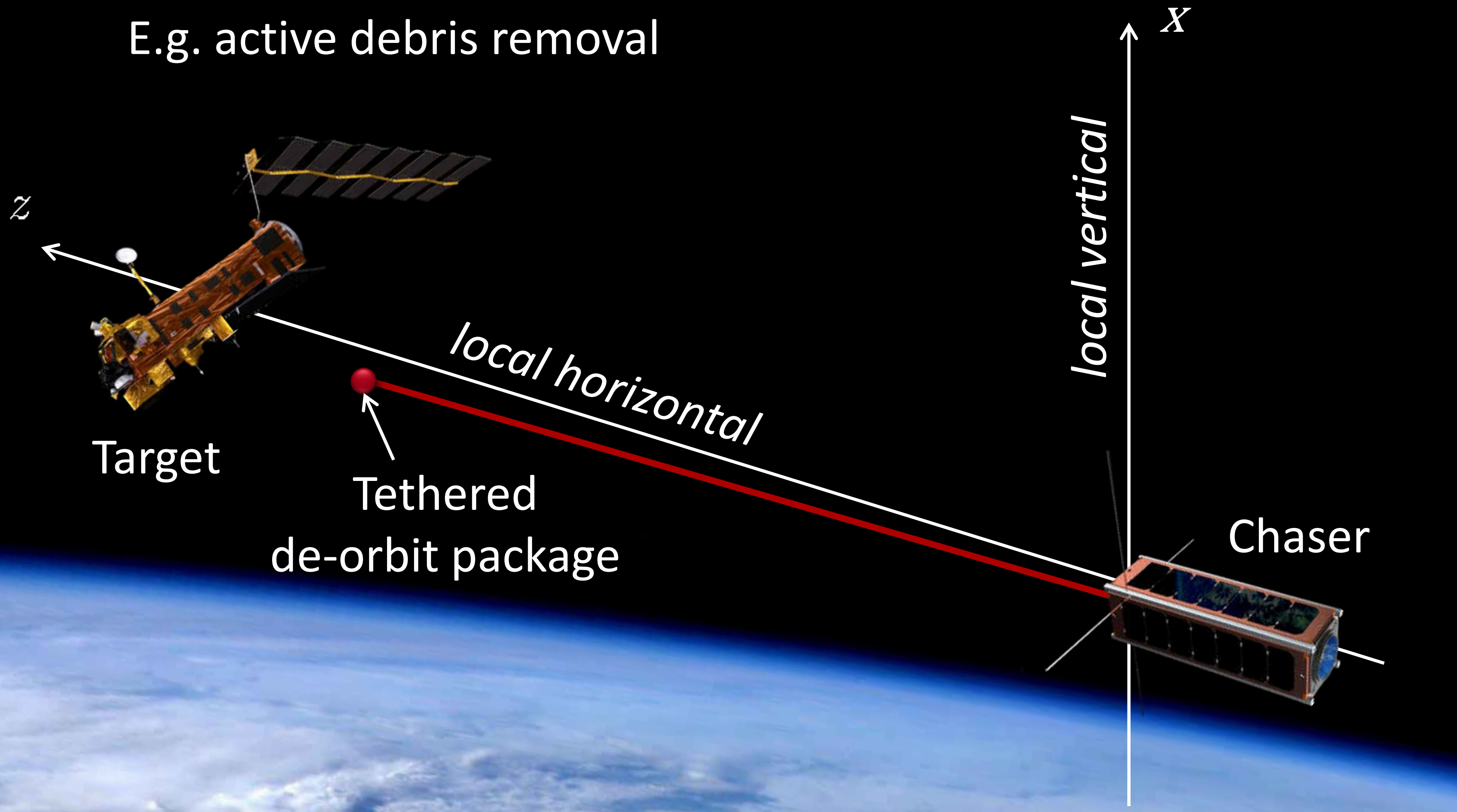
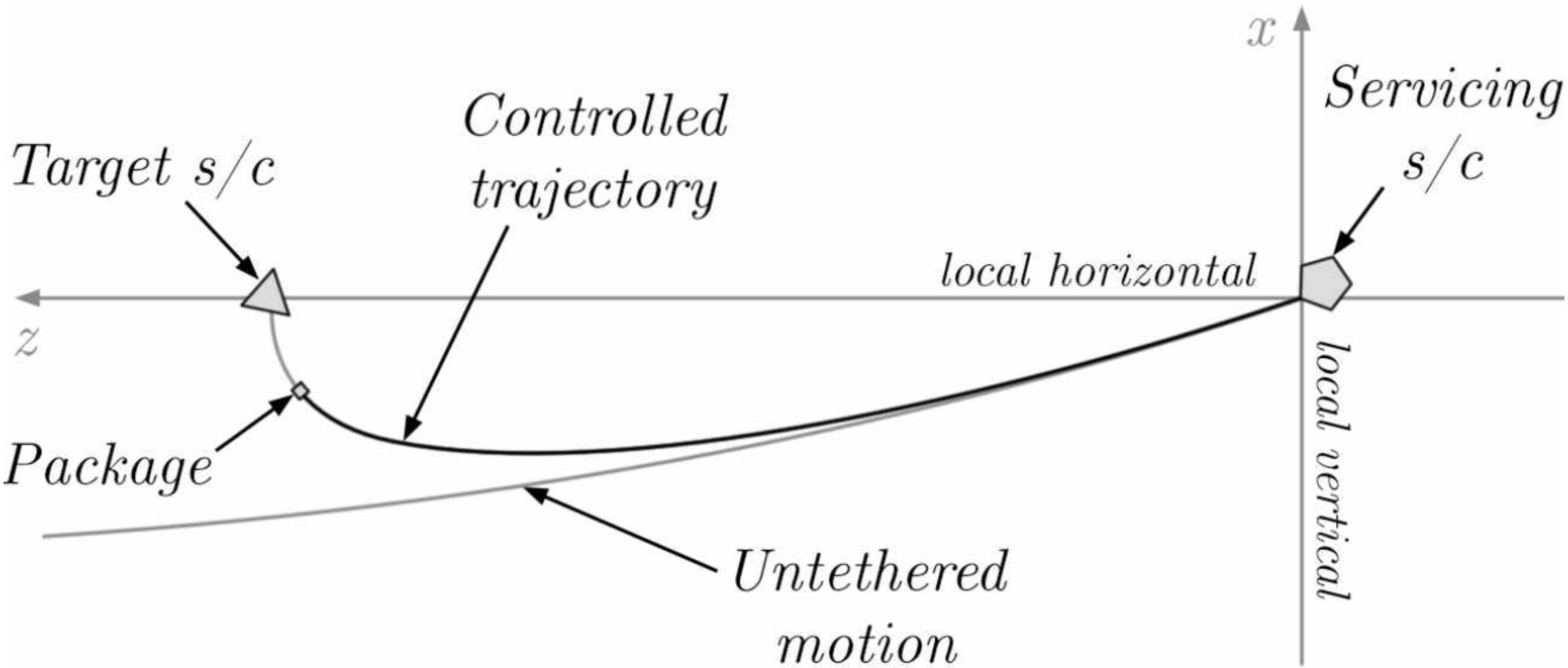
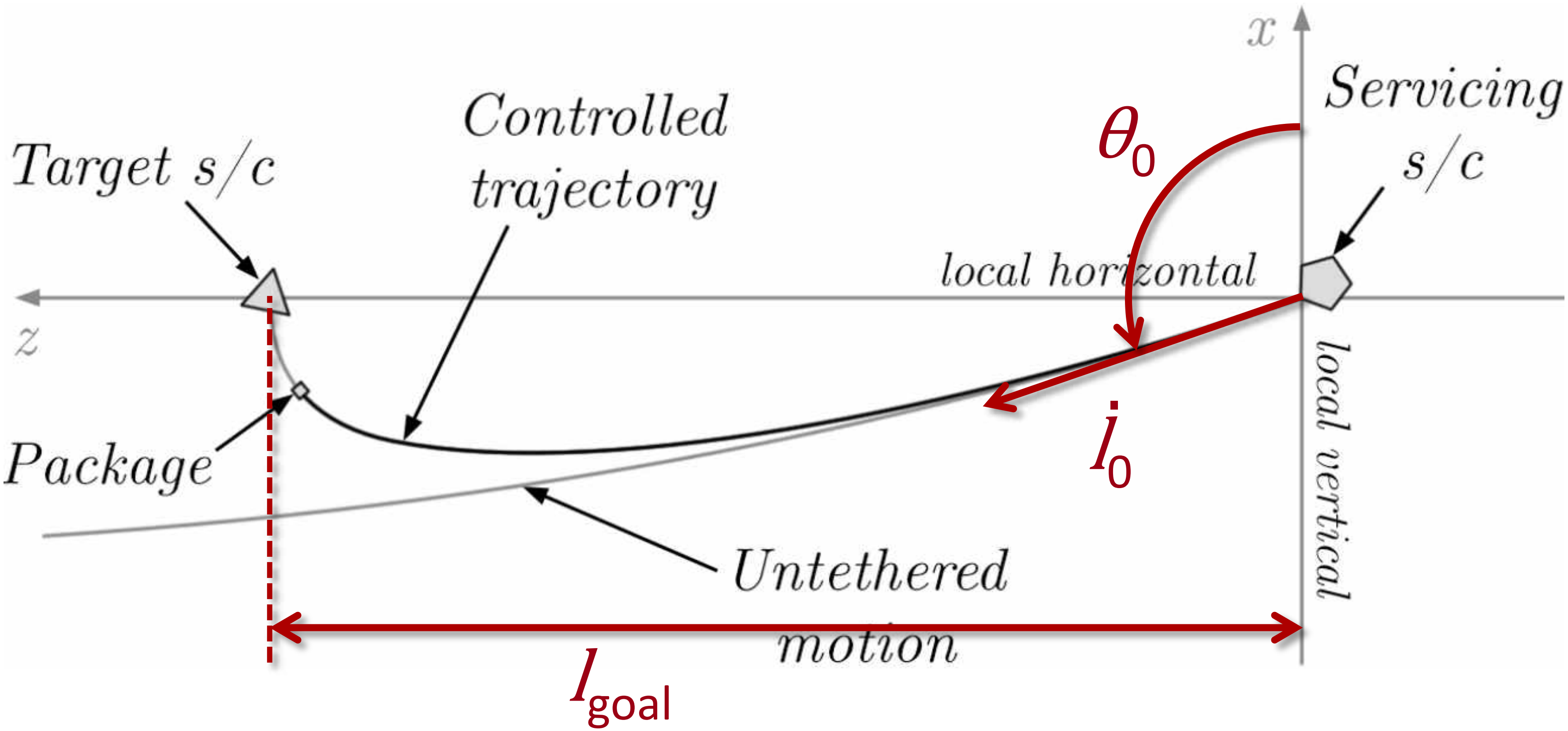


Deployment scenario (2/2)



Deployment scenario (2/2)



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Simulations results

l_{goal} (m) → / $\dot{l}_0$ (m/s) ↓	50		100		200	
	LI	IB	LI	IB	LI	IB
0.50	●	⊖	●	⊖	⊖	⊖
0.75	⊕	⊖	●	⊖	●	⊖
1.00	⊕	●	⊕	⊖	●	⊖
1.50	⊕	●	⊕	●	⊕	⊖
1.75	⊕	●	⊕	●	⊕	⊖
2.00	⊕	●	⊕	●	⊕	●

(●): successful deployments

(⊕): insufficient brake authority control

(⊖): insufficient initial velocity

Simulations results

l_{goal} (m) → / $\dot{l}_0$ (m/s) ↓	50 LI	50 IB	100 LI	100 IB	200 LI	200 IB
0.50	●	⊖	●	⊖	⊖	⊖
0.75	⊕	⊖	●	⊖	●	⊖
1.00	⊕	●	⊕	⊖	●	⊖
1.50	⊕	●	⊕	●	⊕	⊖
1.75	⊕	●	⊕	●	⊕	⊖
2.00	⊕	●	⊕	●	⊕	●

Required higher launch velocity

(●): successful deployments

(⊕): insufficient brake authority control

(⊖): insufficient initial velocity

Results

Simulations results

l_{goal} (m) → $\dot{l}_0$ (m/s) ↓	50 LI	50 IB	100 LI	100 IB	200 LI	200 IB
0.50	●	⊖	●	⊖	⊖	⊖
0.75	⊕	⊖	●	⊖	●	⊖
1.00	⊕	●	⊕	⊖	●	⊖
1.50	⊕	●	⊕	●	⊕	⊖
1.75	⊕	●	⊕	●	⊕	⊖
2.00	⊕	●	⊕	●	⊕	●

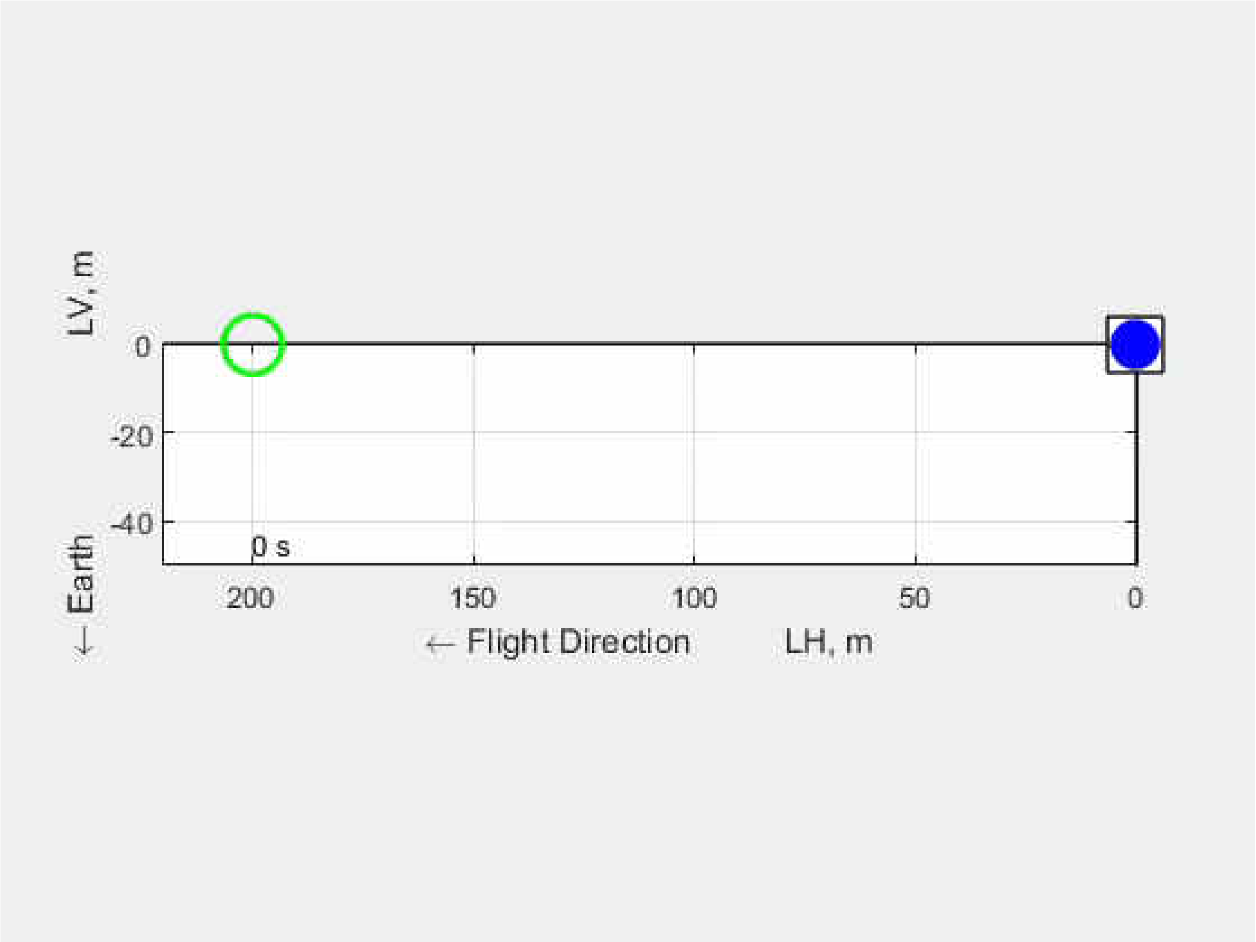
Less control authority w.r.t. IB

(●): successful deployments

(⊕): insufficient brake authority control

(⊖): insufficient initial velocity

Successful deployment



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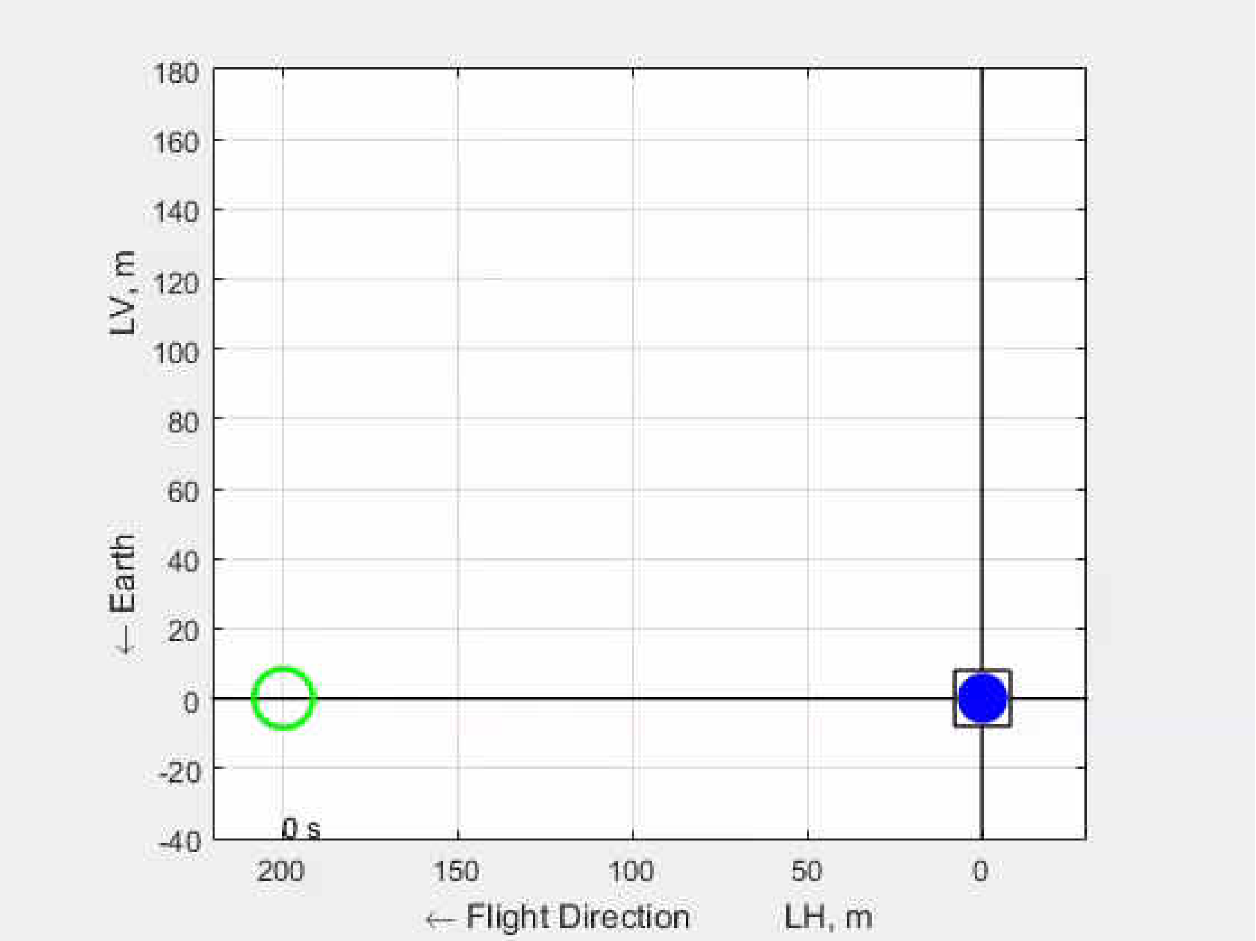
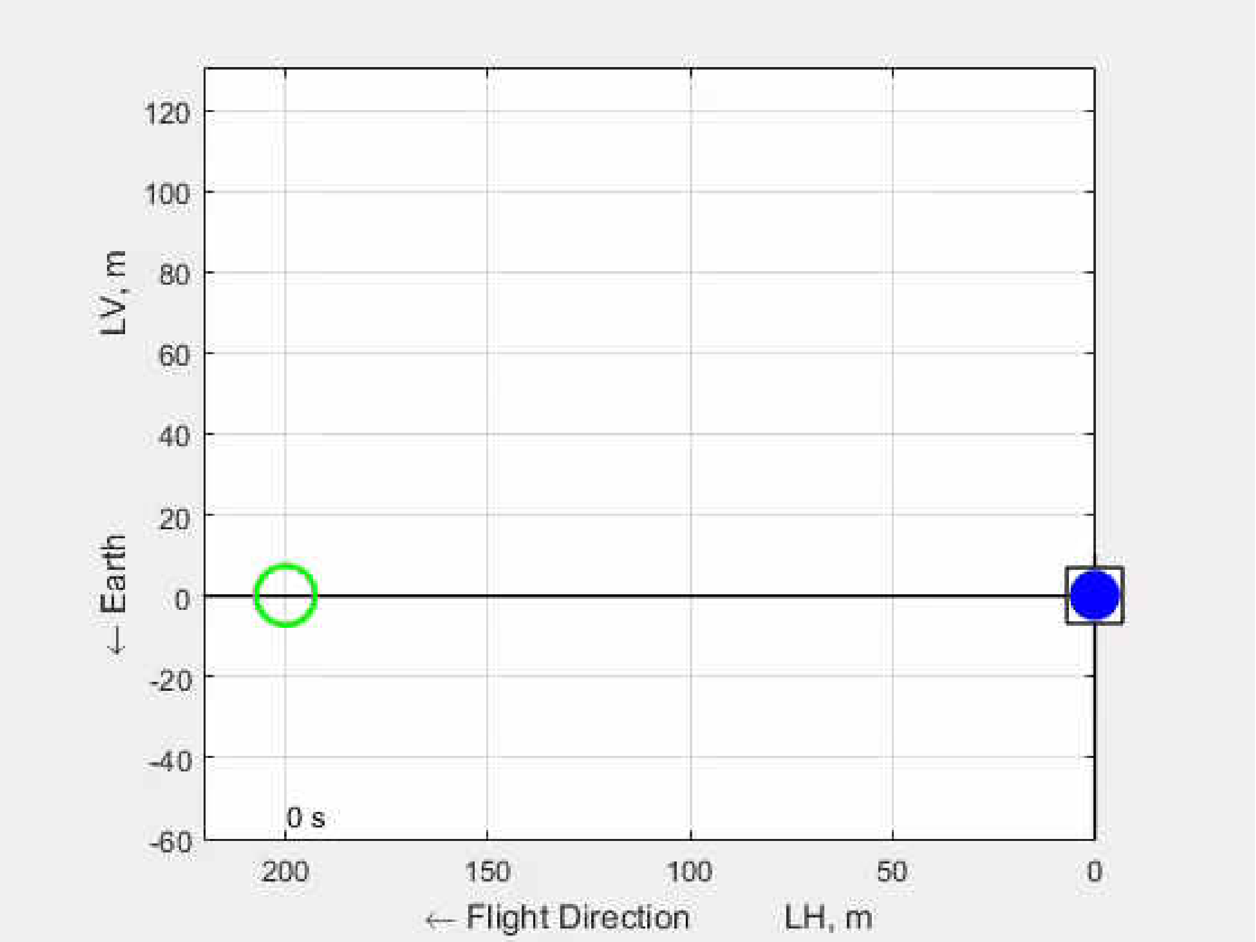
Deployment failure – insufficient launch velocity



Deployment example (3/3)

Deployment failure – insufficient deployer control authority



Conclusions

Conclusions

Inductive brake

1. More control authority
2. Less actuators
3. Some critical issues during deployment are addressed

Low-inertia

1. Easier ground test phase
2. Requires less energy (T_0)
3. Higher tolerance of design inaccuracies (less parts in synch. motion)

Conclusions

Inductive brake

1. More control authority
2. Less actuators
3. Some critical issues during deployment are addressed

Low-inertia

1. Easier ground test phase
2. Requires less energy (T_0)
3. Higher tolerance of design inaccuracies (less parts in synch. motion)

- Questions? -

Extras – YES2

2007 – YES2

- 12 kg endmass + tether
- 24 kg deployment hardware

Extras – motion equations

$$\ddot{l} = -\frac{\rho \dot{l}^2}{2(m+\rho l)} + l\,\frac{2m+\rho l}{2(m+\rho l)}\left[\left(\omega+\dot{\theta}\right)^2 + 3\omega^2\cos^2(\theta)\right] - \frac{T}{m+\rho l}$$

$$\ddot{\theta} = -3\,\frac{2m+\rho l}{3m+\rho l}\left(\omega+\dot{\theta}\right)\frac{\dot{l}}{l} - 3\omega^2\sin(\theta)\cos(\theta)$$

Extras – motion equations

Convective

Centrifugal

Gravity gradient

Tether tension (control)

$$\ddot{l} = -\frac{\rho \dot{l}^2}{2(m+\rho l)} + l\frac{2m+\rho l}{2(m+\rho l)}\left[\left(\omega+\dot{\theta}\right)^2 + 3\omega^2\cos^2(\theta)\right] - \frac{T}{m+\rho l}$$

$$\ddot{\theta} = -3\frac{2m+\rho l}{3m+\rho l}\left(\omega+\dot{\theta}\right)\frac{\dot{l}}{l} - 3\omega^2\sin(\theta)\cos(\theta)$$

Stabilizing if $\dot{l} > 0$

Extras – system parameters

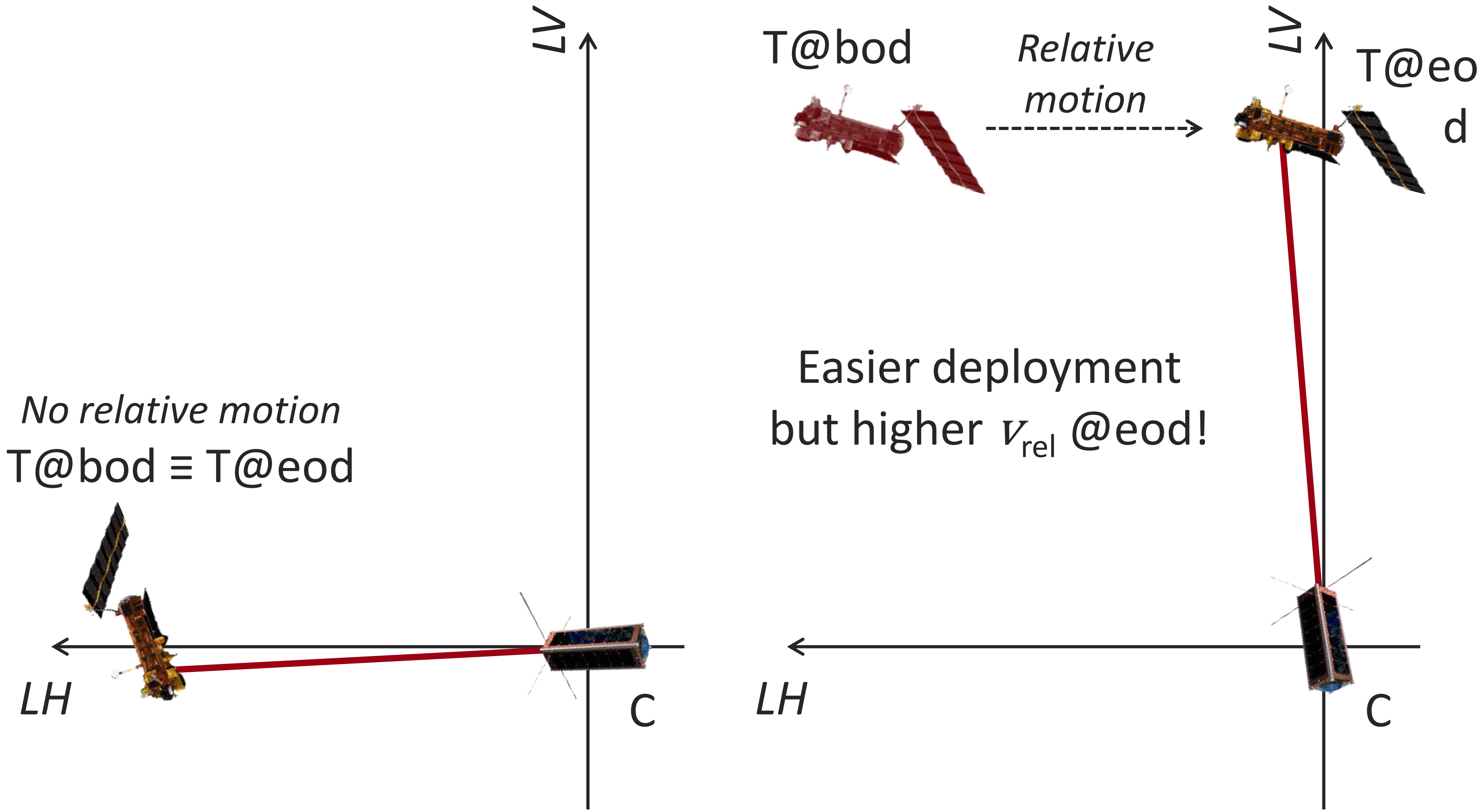
Parameter	Value	Unit
b	$3 \cdot 10^{-6}$	Ns/rad
d	$9 \cdot 10^{-2}$	m
e	0	1
I	$17 \cdot 10^{-7}$	kg m^2
J	$3.65 \cdot 10^{-4}$	H
k_v	$4.05 \cdot 10^{-3}$	Vs/rad
k_t	$3.8675 \cdot 10^{-2}$	Nm/A
p	$3 \cdot 10^{-2}$	m
r	$15 \cdot 10^{-2}$	m
R	2.98	Ω
$T_{0,\text{li}}$	$15 \cdot 10^{-3}$	N
$T_{0,\text{ib}}$	$150 \cdot 10^{-3}$	N
m	20	kg
λ	0.5	N/m
ρ	$1.35 \cdot 10^{-3}$	kg/m
ω	$1.0382 \cdot 10^{-3}$	rad/s

Low-inertia → $T_{0,\text{li}}$

Inductive brake → $T_{0,\text{ib}}$

Higher inner friction in IB due to more sliding parts

Extras – deployment scenario



θ_0 values chosen in the simulations

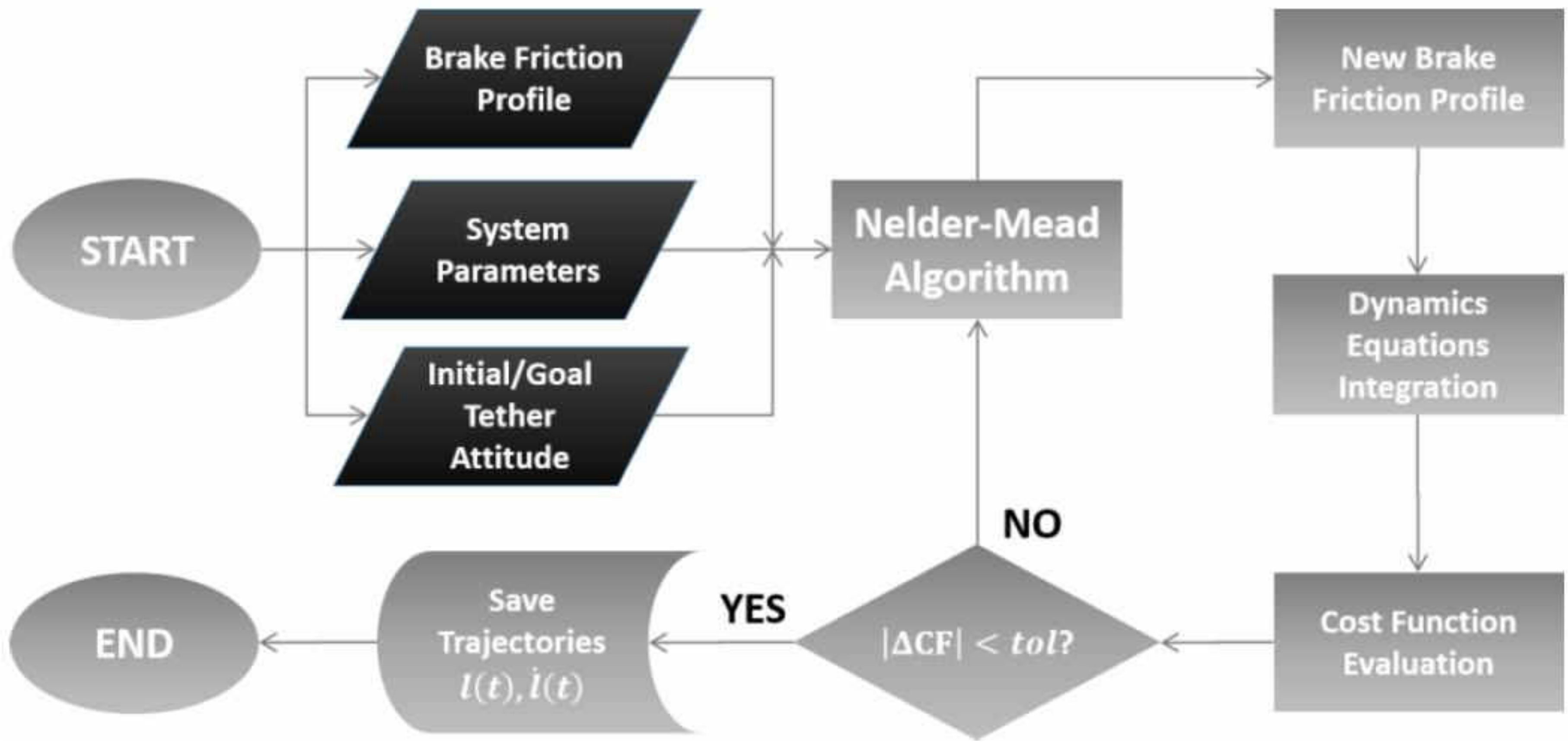
l_{goal} (m) → $\dot{l}_0$ (m/s) ↓	50	100	200
0.50	103°	115°	134°
0.75	99°	107°	123°
1.00	96°	101°	114°
1.50	95°	98°	108°
1.75	94.5°	97°	105°
2.00	94°	96°	102°

$$\theta_0 = \theta_{\text{goal}} - \bar{\dot{\theta}} t_{\text{end}}$$

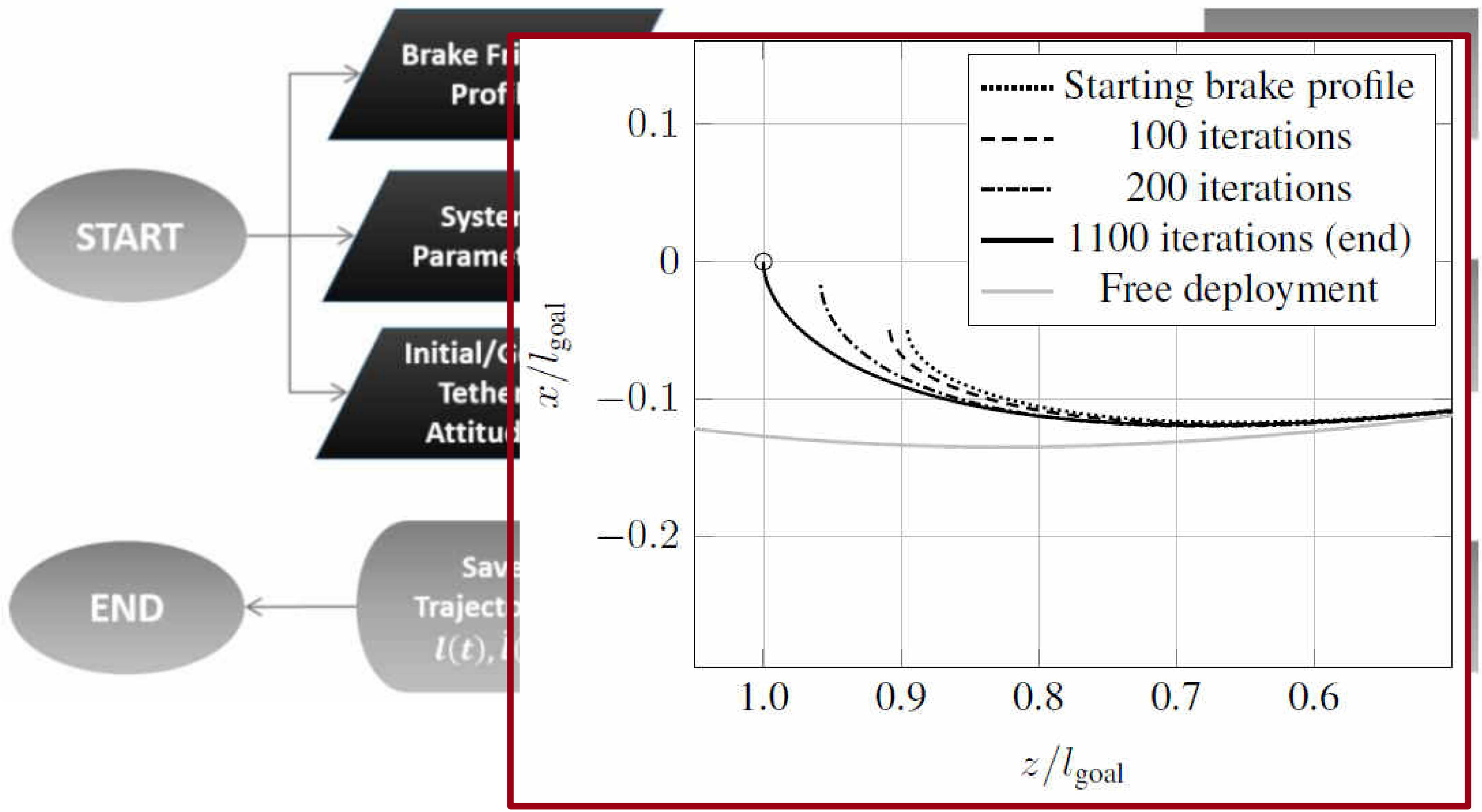
$$\bar{\dot{\theta}} = \bar{\dot{\theta}}\left(\omega, \theta_{\text{goal}}, l_{\text{goal}}, \dot{l}_0\right)$$

$$t_{\text{end}} = t_{\text{end}}\left(\dot{l}_0, T_0, \bar{F}_{\text{friction}}\right)$$

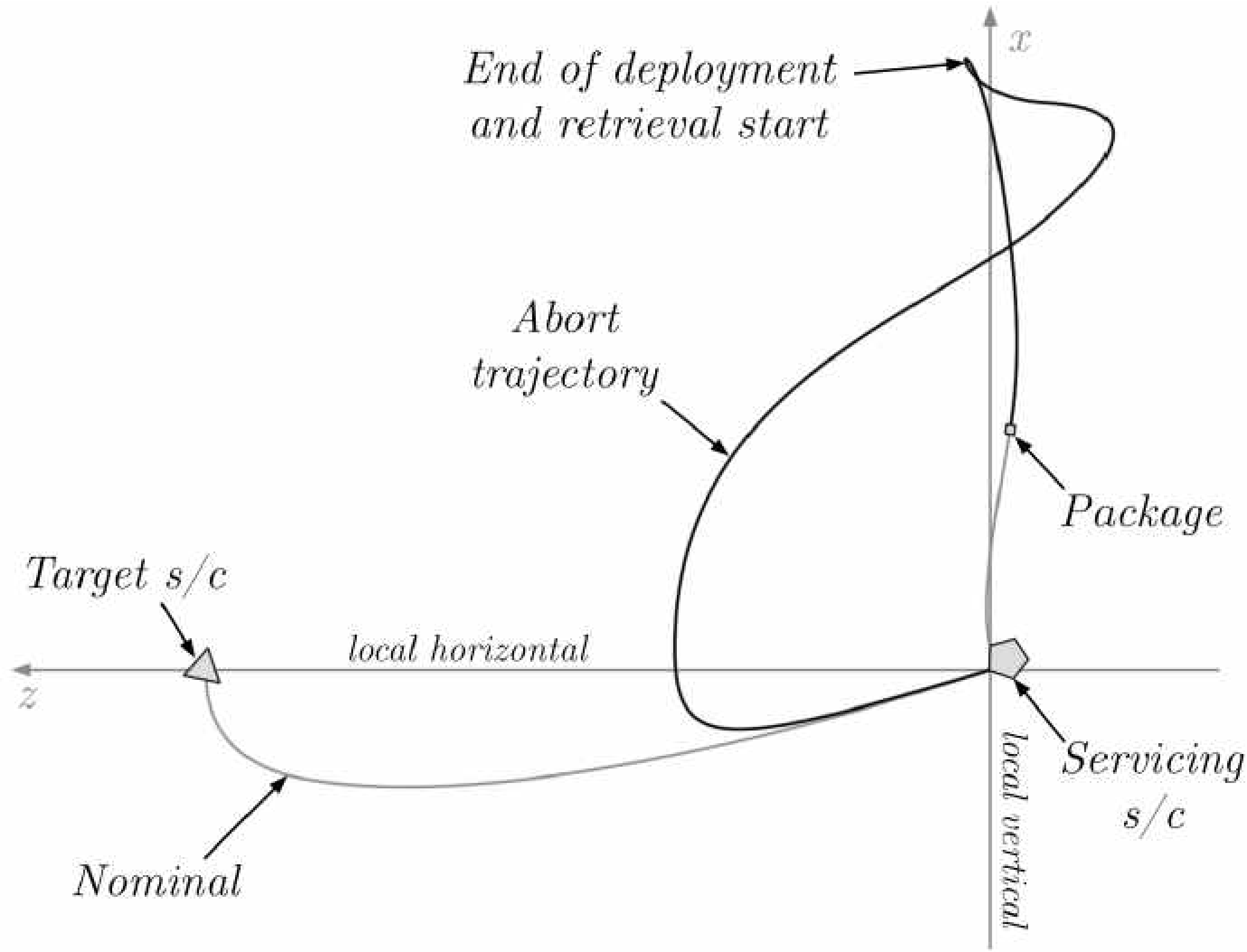
Extras – Nelder-Mead algorithm



Extras – Nelder-Mead algorithm



Extras – abort capability



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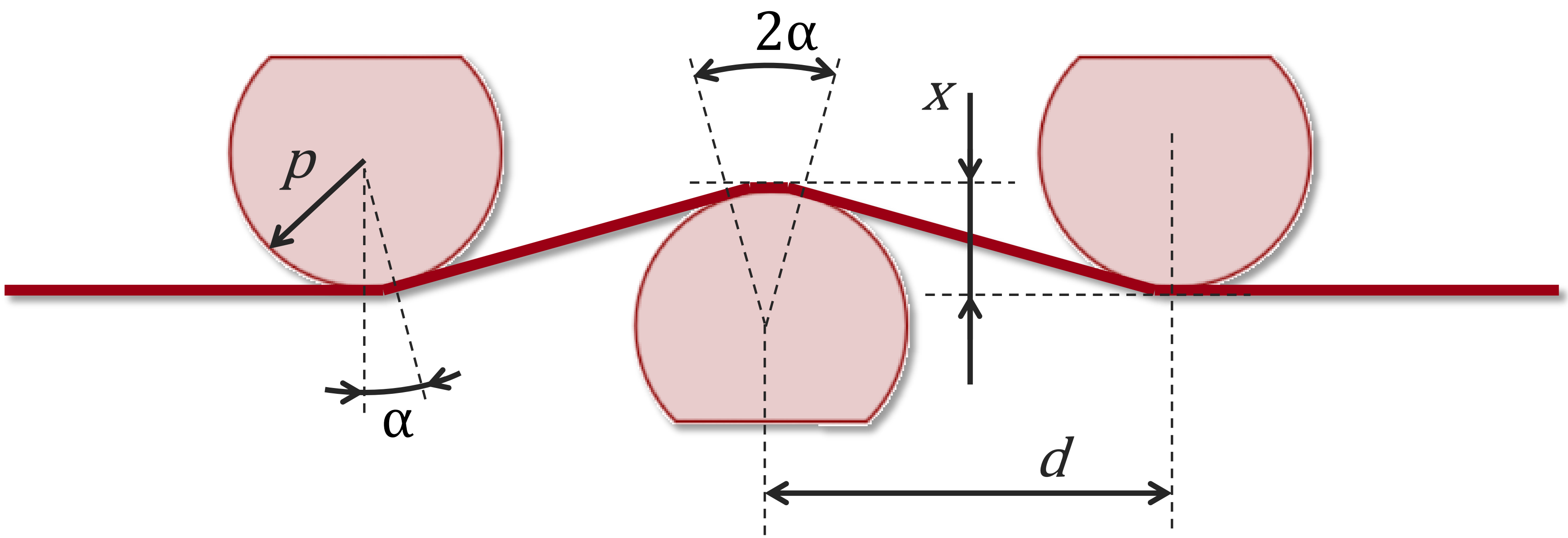
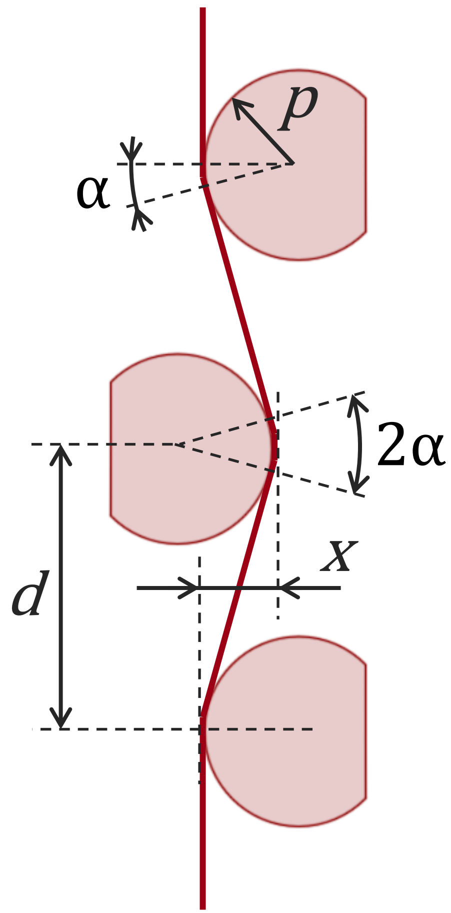
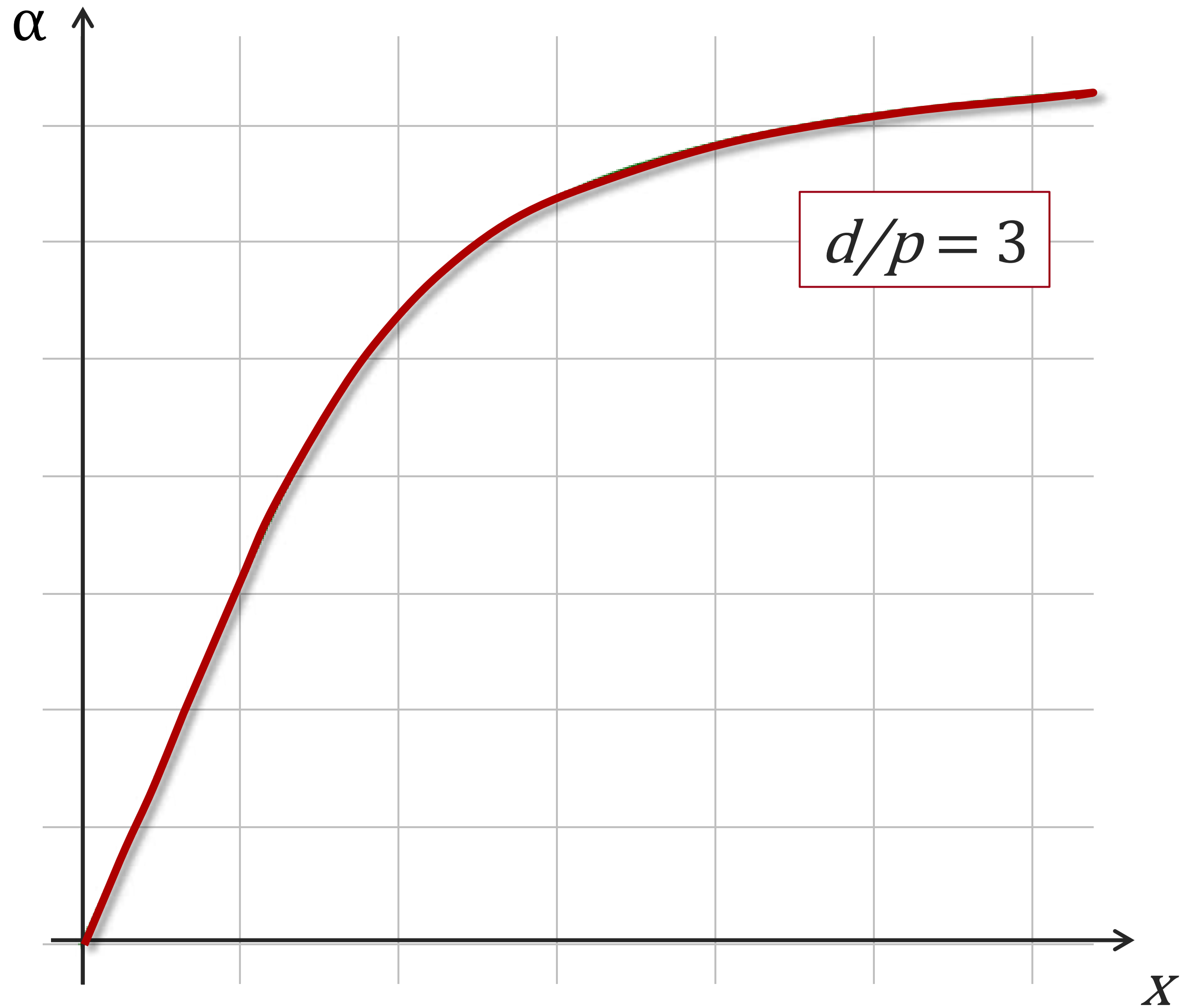
Mechanical brake

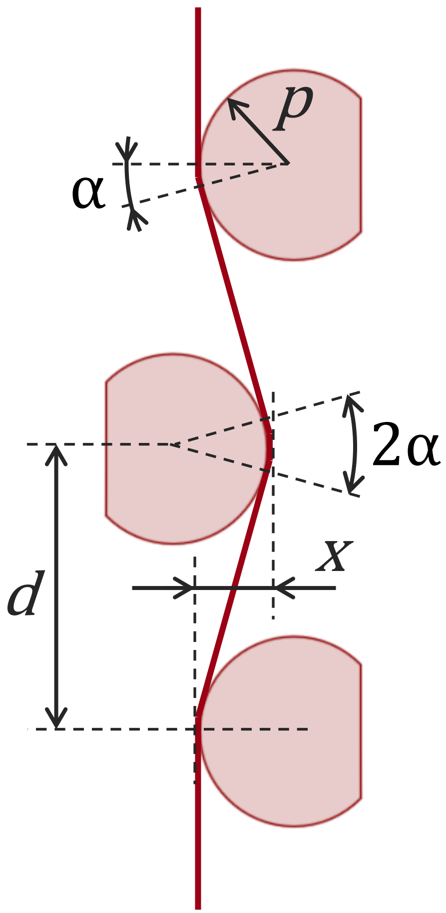


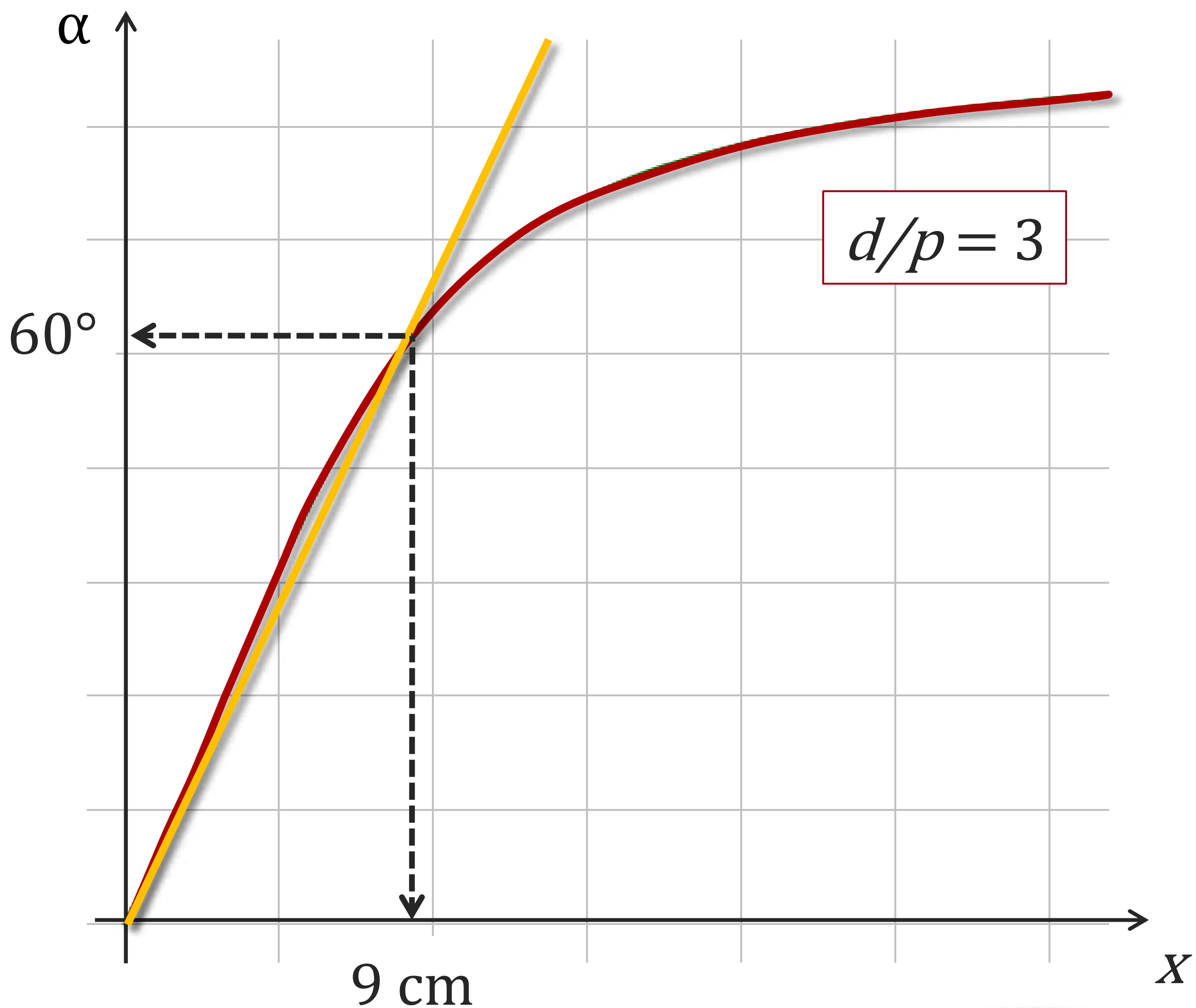
Extras – models





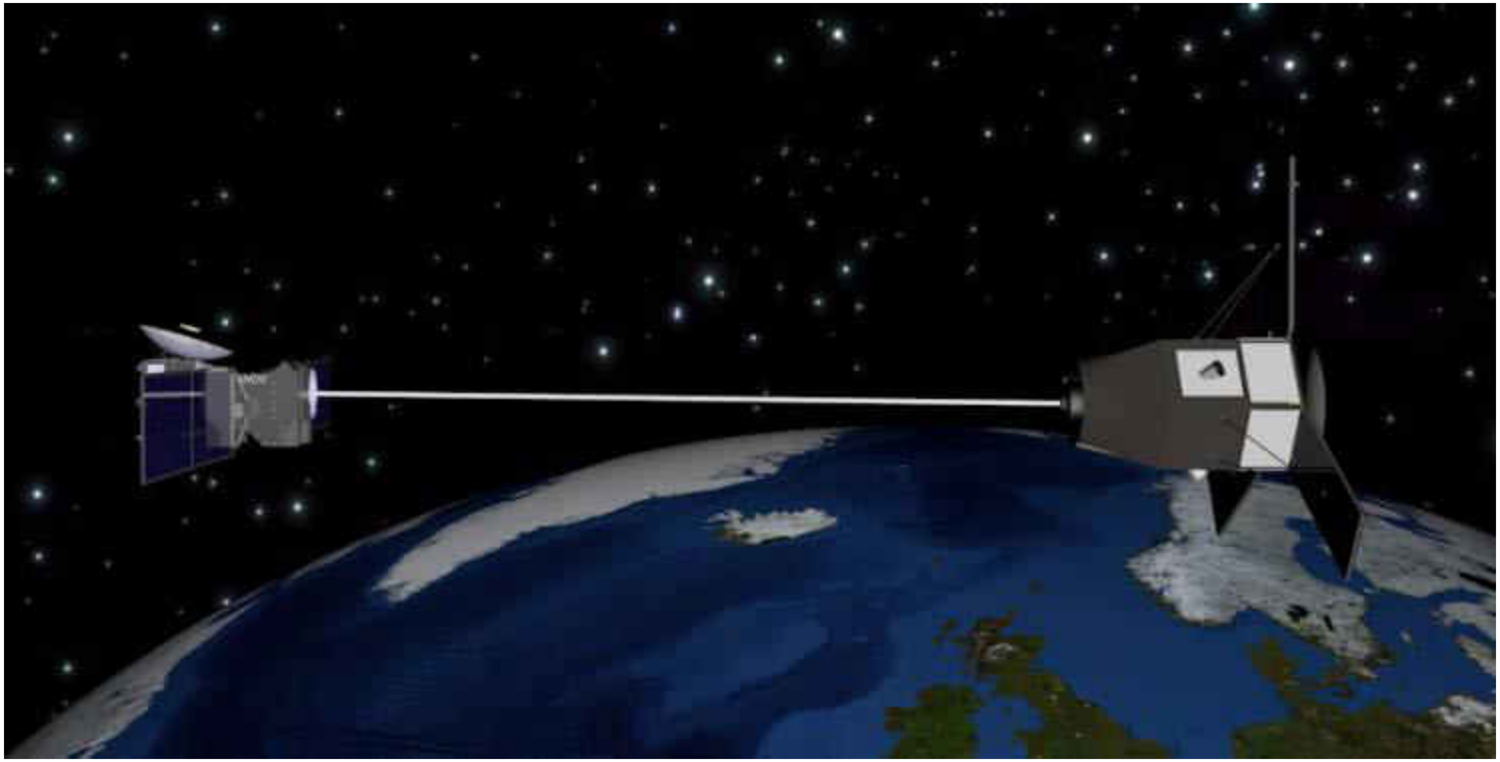
Extras – models





What could we do?

New docking techniques



Extras – DC motor