Suppression of Tether-net Shrinking Motion using Double-linked Bullet

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1.1 Research Background

- Tether-net is expected as a promising tool for space debris capture.

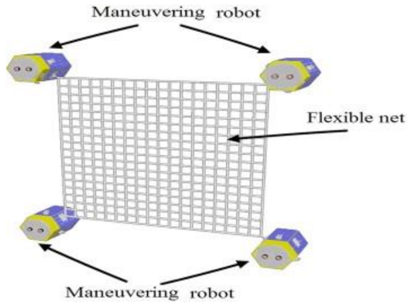
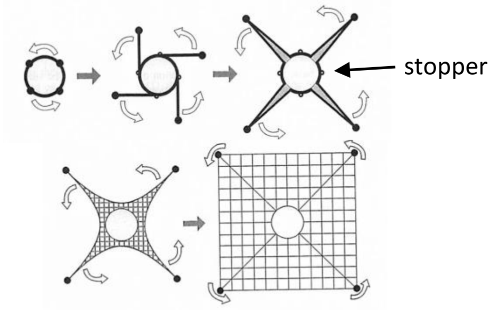
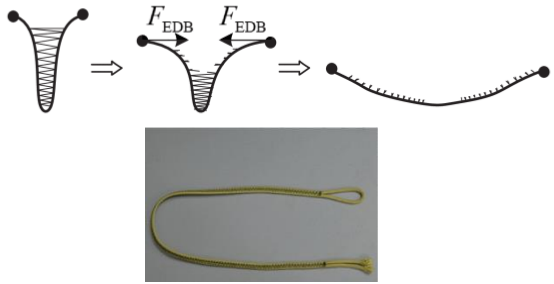
- However, tether-net starts reshrinking after full deployment owing to tension.

- Reshrinking motion may deteriorate the debris capture capability of the tether-net.

1.1 Research Background (cont.)

Previous existing methods for preventing tether-net's rebounding motion

Table 1. Drawback of previous methods for suppression of tether-net's rebounding motion

Maneuvering robot	Centrifugal force by rotational motion	Energy dissipation band
		
Robot attitude control is necessary, and (maneuvering robot) **bullet design becomes complicated**.	**Rotational ejection is necessary**. Tether-net must be locked until the arms are fully straightened. **Complicate deployment process**	**The max expanded area becomes smaller than the original net size** due to energy dissipation

1.2 Research Objective

- A double-linked bullet is newly proposed as an alternative solution to the problem of tether-net's reshrinking motion after full deployment, and
- its effectiveness is studied numerically and experimentally.

2.1 Proposed Tether-net

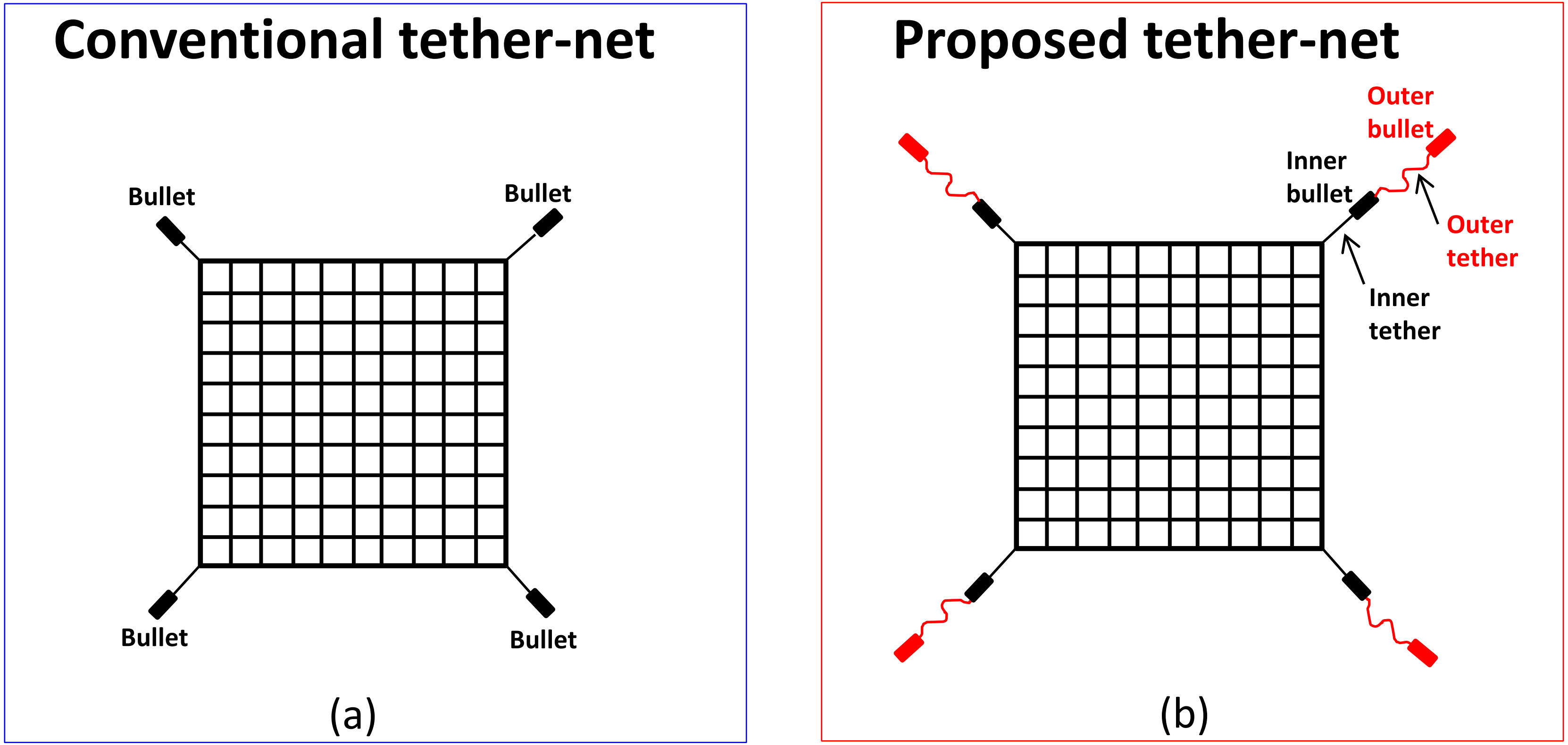


Fig. 1. Tether-net configurations: (a) conventional and (b) proposed

2.2 Rebounding Motion Prevention Mechanism

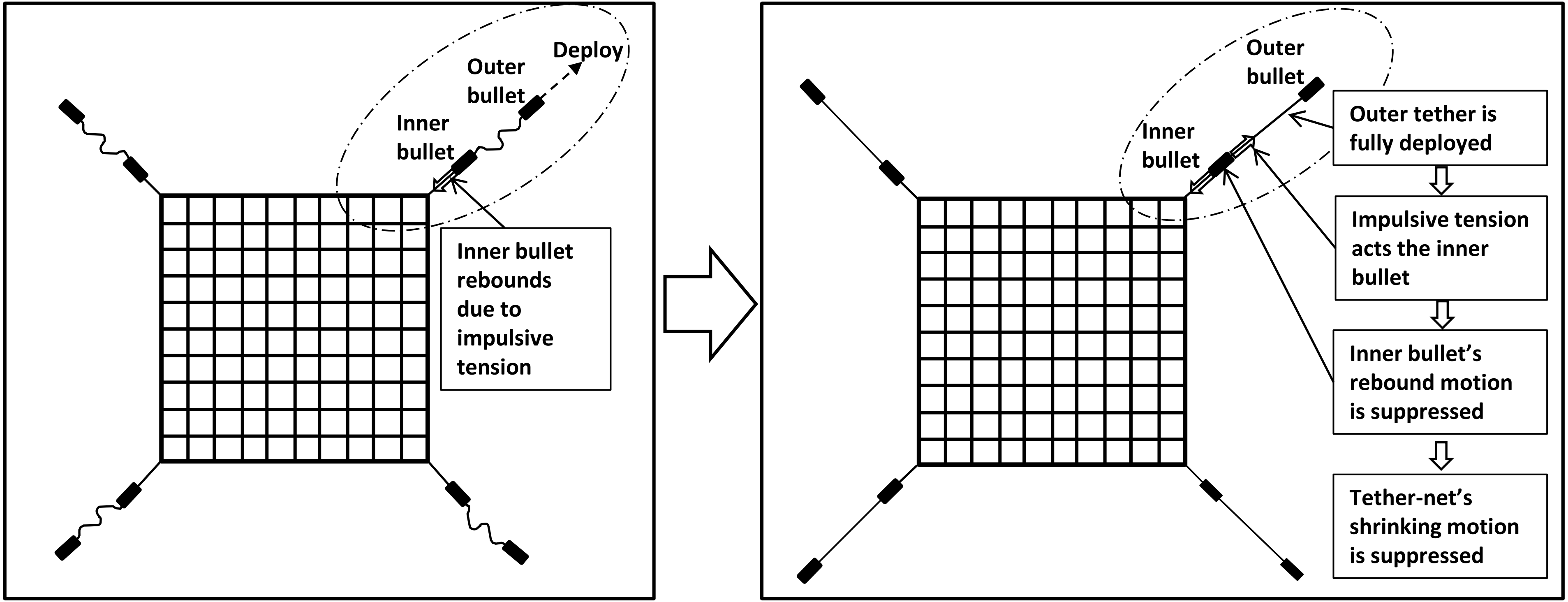


Fig. 2. Conceptual mechanism of preventing tether-net reshrinking motion by double-linked bullet

2.3 Modeling for Simulations

Lumped mass-model

Tension(i-th node)

$$\boldsymbol{T}_{i,j} = \begin{cases} -T_{i,j}\hat{\boldsymbol{e}}_{ij} & \text{if } (l_{i,j} > l_{i,j,0}) \\ 0 & \text{if } (l_{i,j} \leq l_{i,j,0}) \end{cases} \quad (1)$$

$$T_{i,j} = k_{i,j}(l_{i,j} - l_{i,j,0}) + c_{i,j}(\boldsymbol{v}_{i,j} \cdot \hat{\boldsymbol{e}}_{ij}) \quad (2)$$

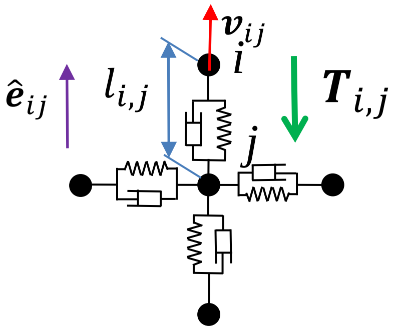


Fig. 3. Lumped mass model.

Aerodynamic force model

Drag $\boldsymbol{D}_i = \frac{1}{2}\rho v_i^2 C_{Di} dl \boldsymbol{e}_{Di}$ $\quad C_{Di} = 0.022 + 1.1\sin^3\alpha_i$ (3)

Lift $\boldsymbol{L}_i = \frac{1}{2}\rho v_i^2 C_{Li} dl \boldsymbol{e}_{Li}$ $\quad C_{Li} = 1.1\sin^2\alpha\cos\alpha$ (4)

α_i : Angle of attack

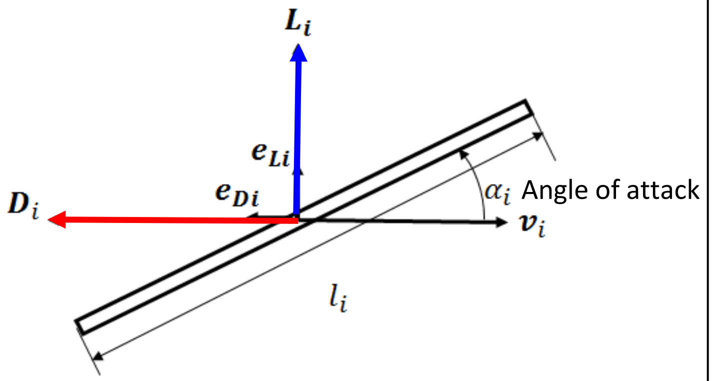


Fig. 4. Aerodynamic force on tether-net segment.

3. Tether-net Ejector

Ejection angle adjustable mechanism

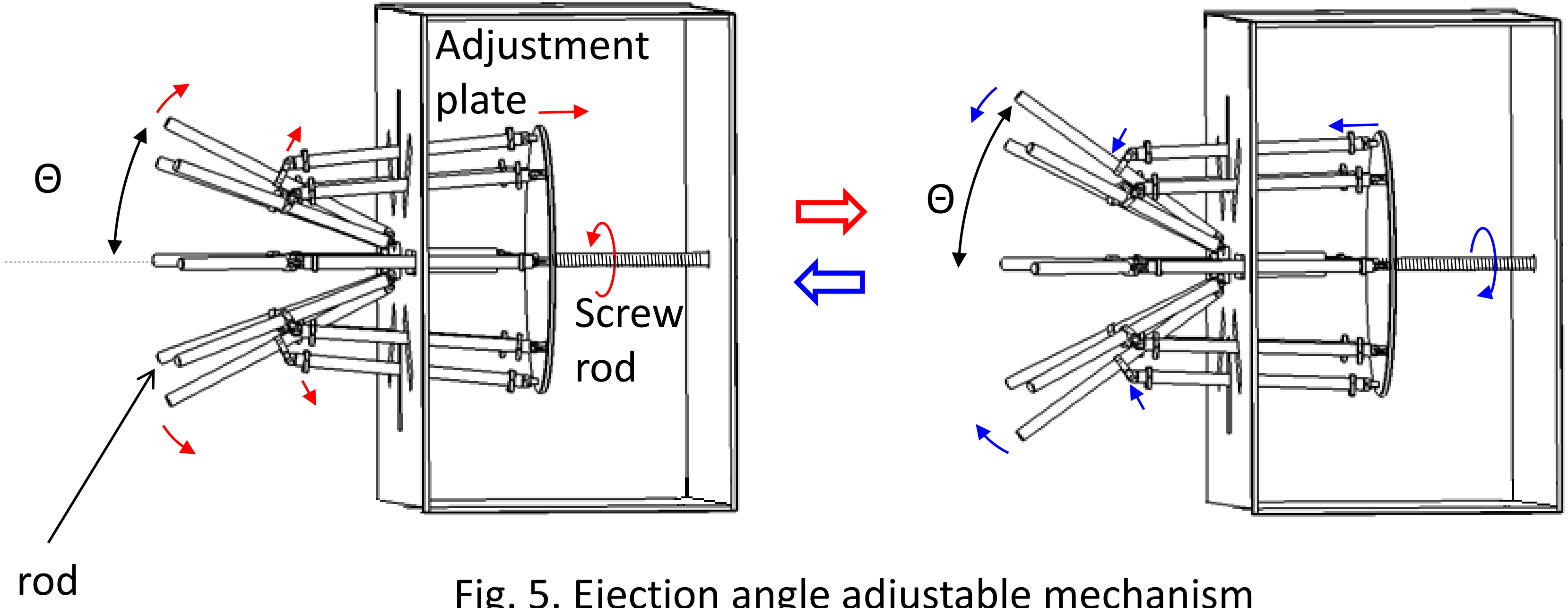


Fig. 5. Ejection angle adjustable mechanism

4.1 Simulation Conditions

Tether-net Model

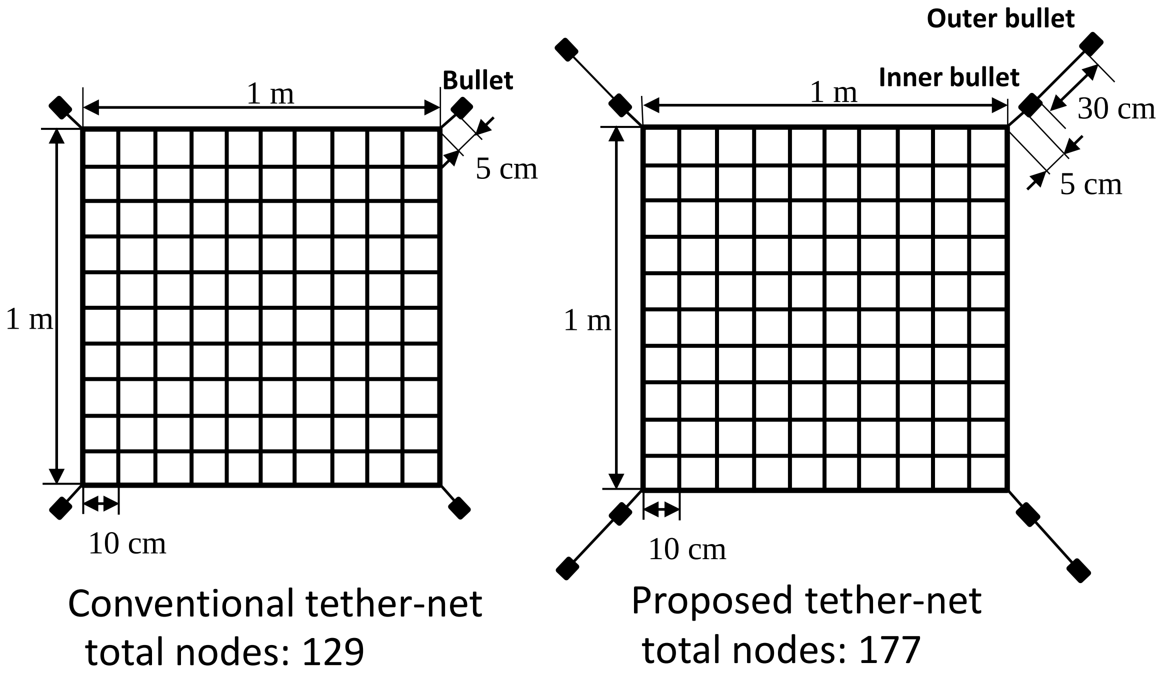
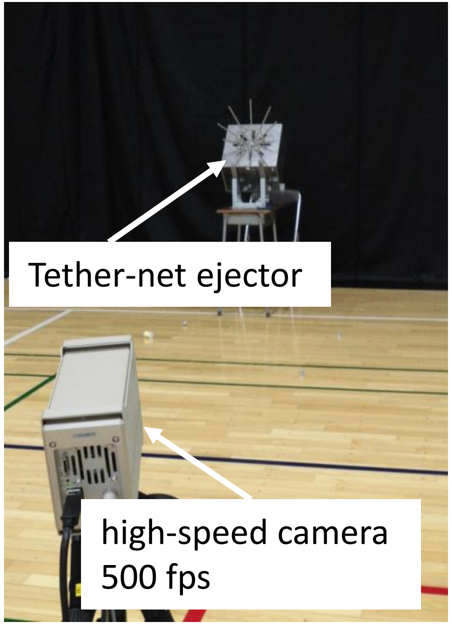


Fig. 6. Tether-net model: (a) conventional and (b) proposed

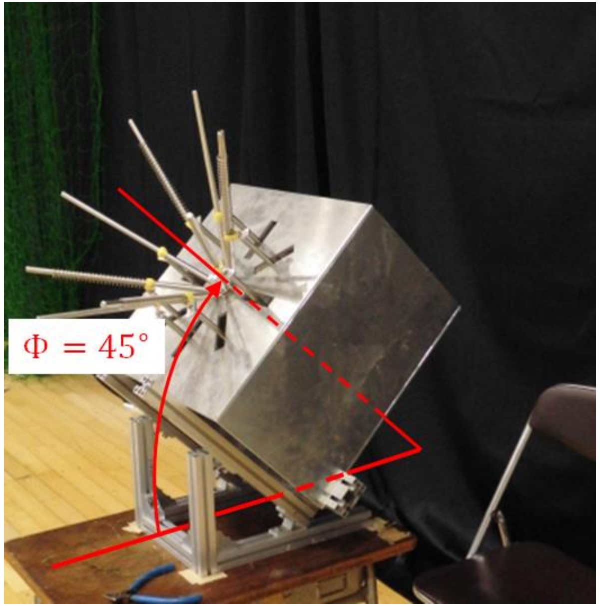
Table 2. Specifications of tether- net

Parameter	Value
Material	Kevlar
Diameter of string, d	1 mm
Net size	1 m × 1 m
Knot spacing (segment length), l	10 cm
Inner tether length	5 cm
Outer tether length	30 cm
Young's modulus	70.5 GPa
Mass of net excluding bullets	8.8 g
Damping ratio	3.2
Mass of inner bullet	33. 2 g
Mass of outer bullet	33. 2 g

4.2 Experimental Conditions



Experimental setup



Shooting angle

Fig. 7. Experimental environment

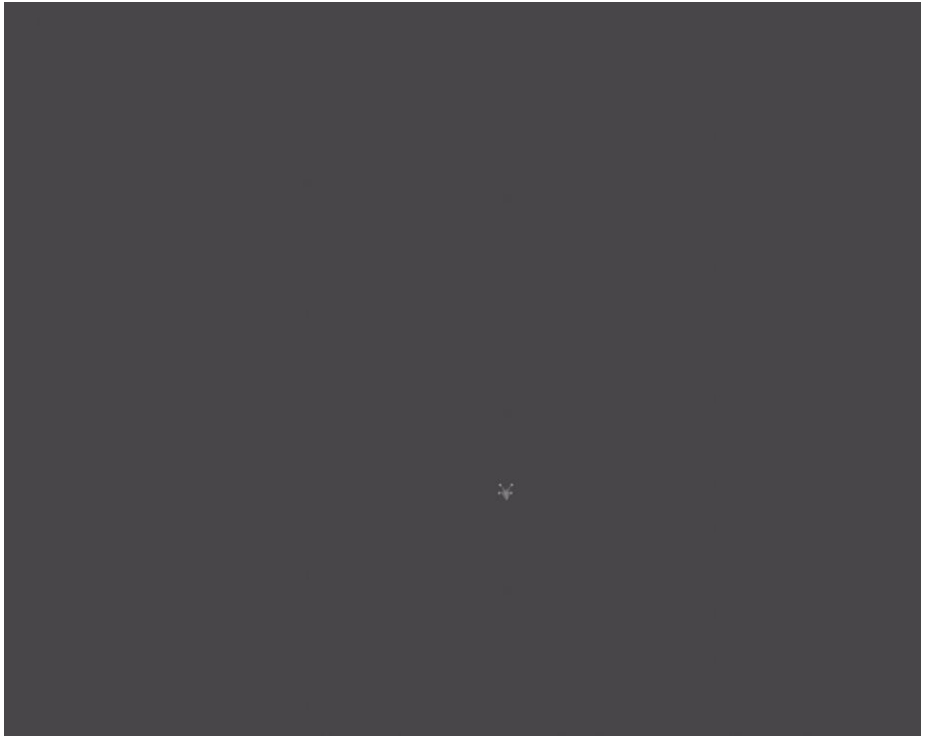
Table 3. Specifications of spring

Parameter	Value
Natural length	15 cm
Spring constant	0.231 N/mm
Compression distance	9 cm

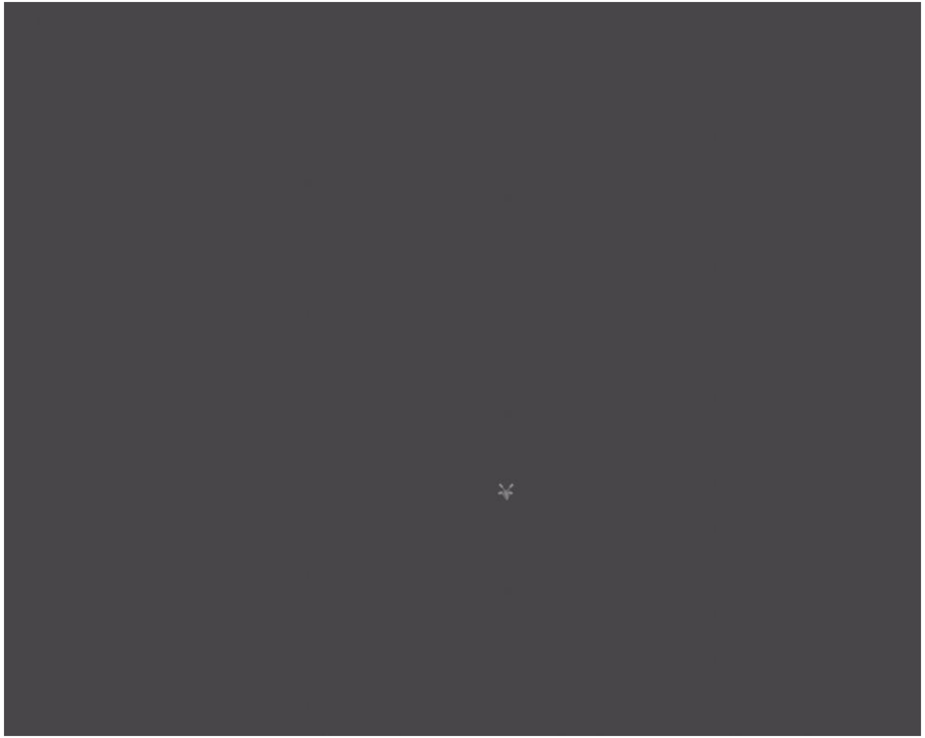
Table 4. Ejection conditions

Parameter	Value
Shooting angle	45 deg
Bullet ejection speed	5.31 m/s
Bullet ejection angle	15, 30, 45 deg

4.3.1 Simulation Results (15deg)

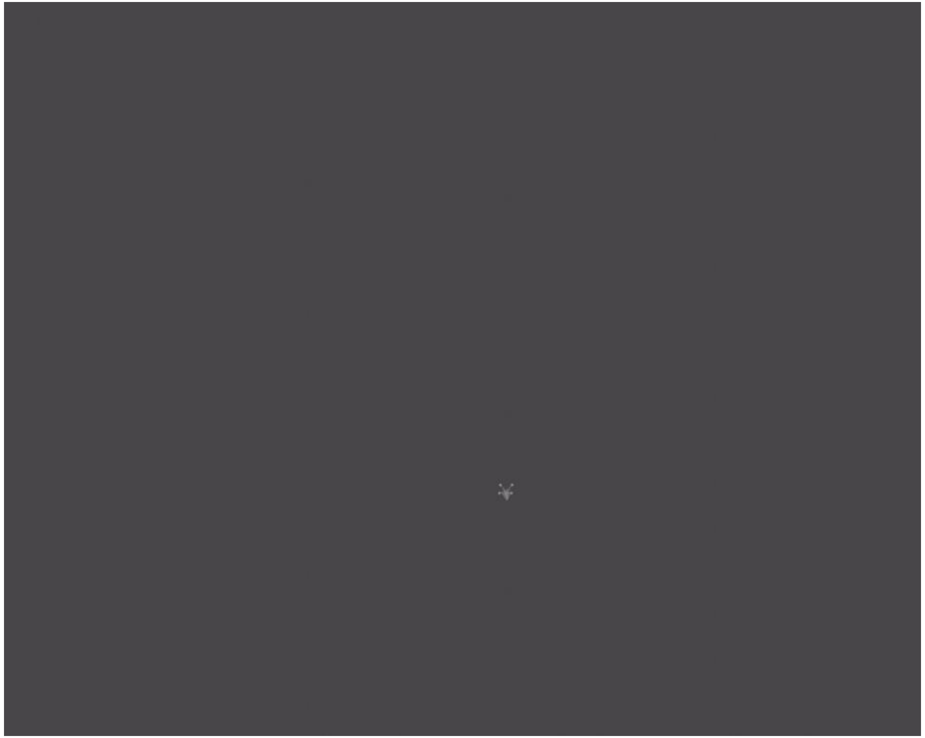


Conventional tether-net

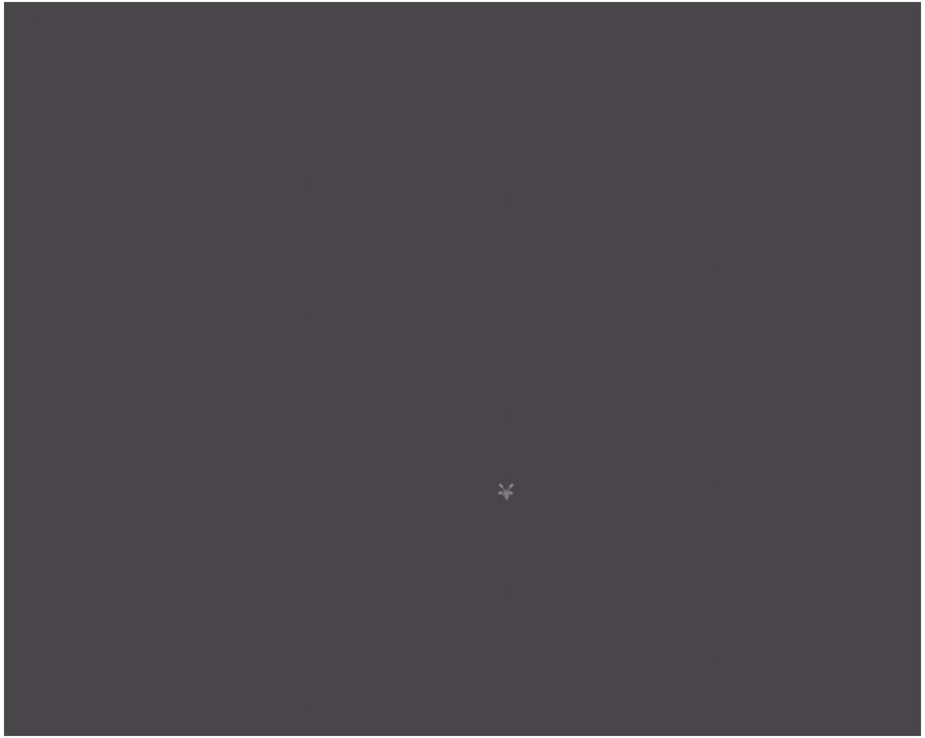


Proposed tether-net

4.3.1 Simulation Results (30deg)

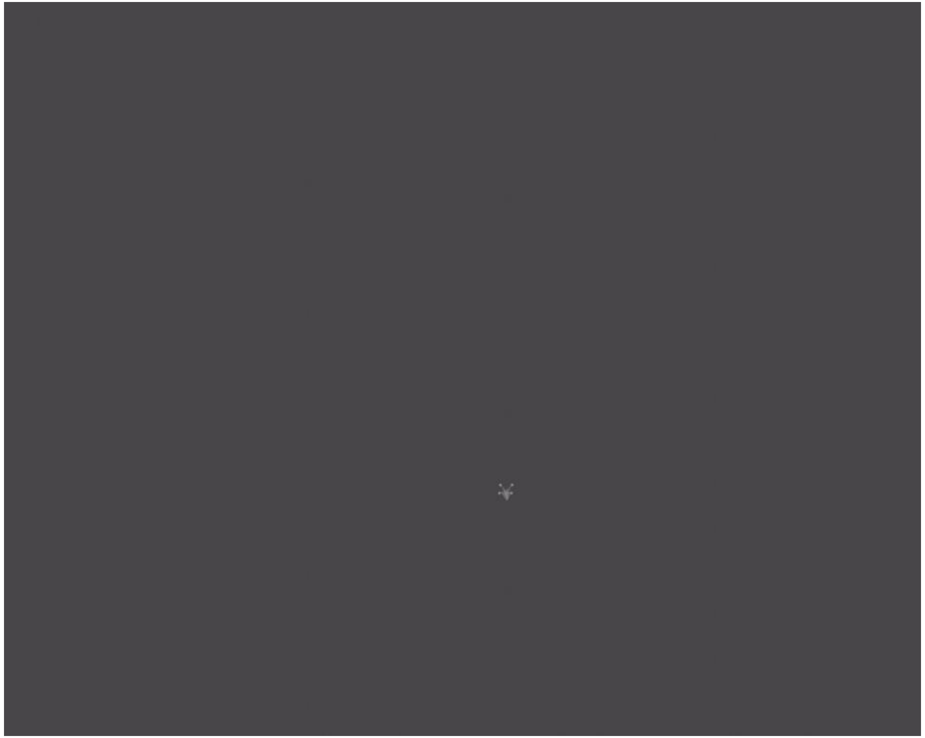


Conventional tether-net

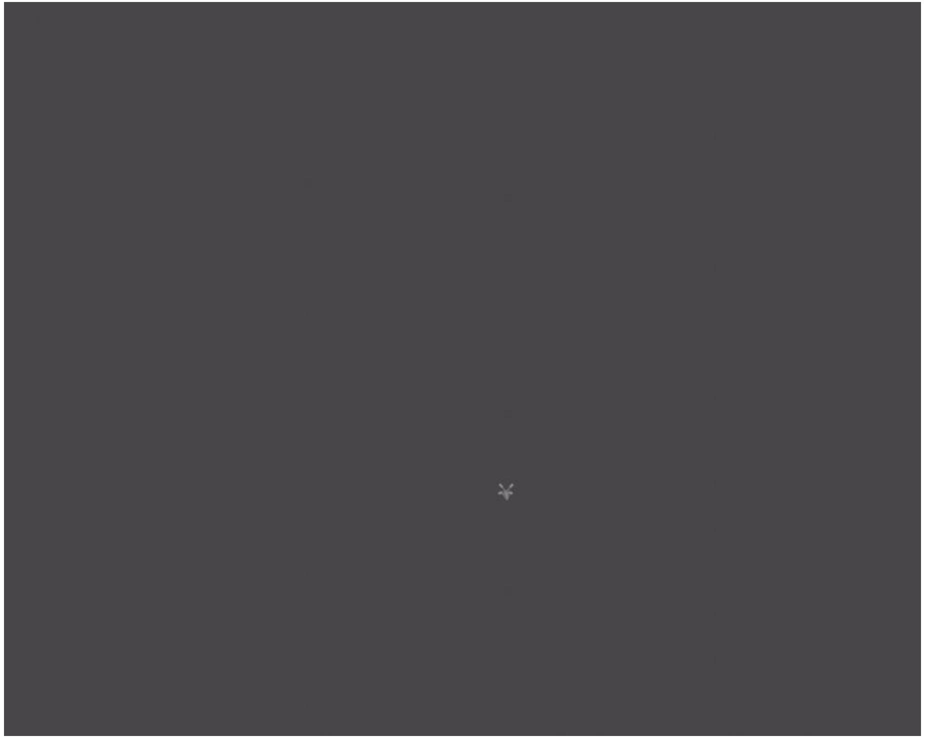


Proposed tether-net

4.3.1 Simulation Results (45deg)

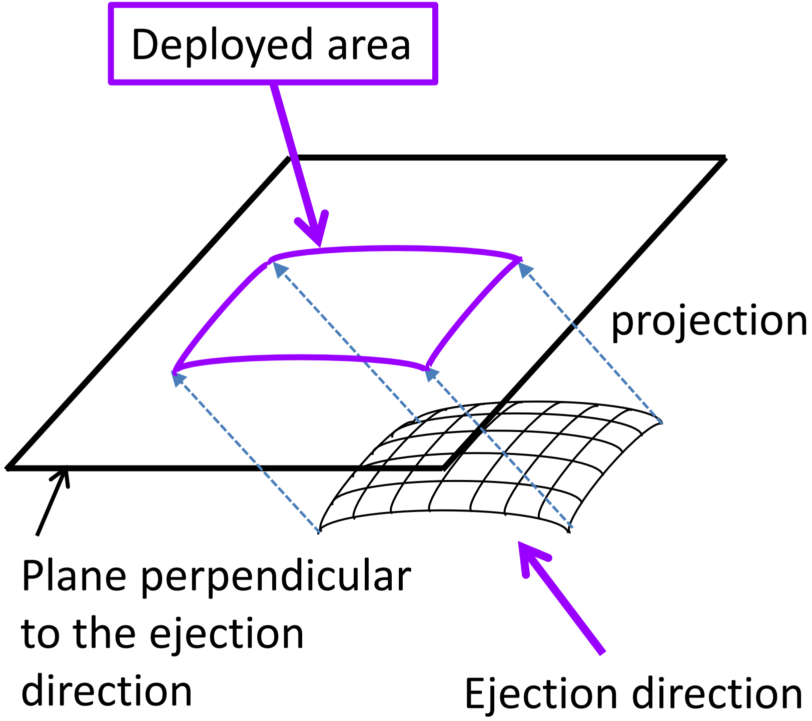


Conventional tether-net



Proposed tether-net

4.3.2 Simulation Results (1)



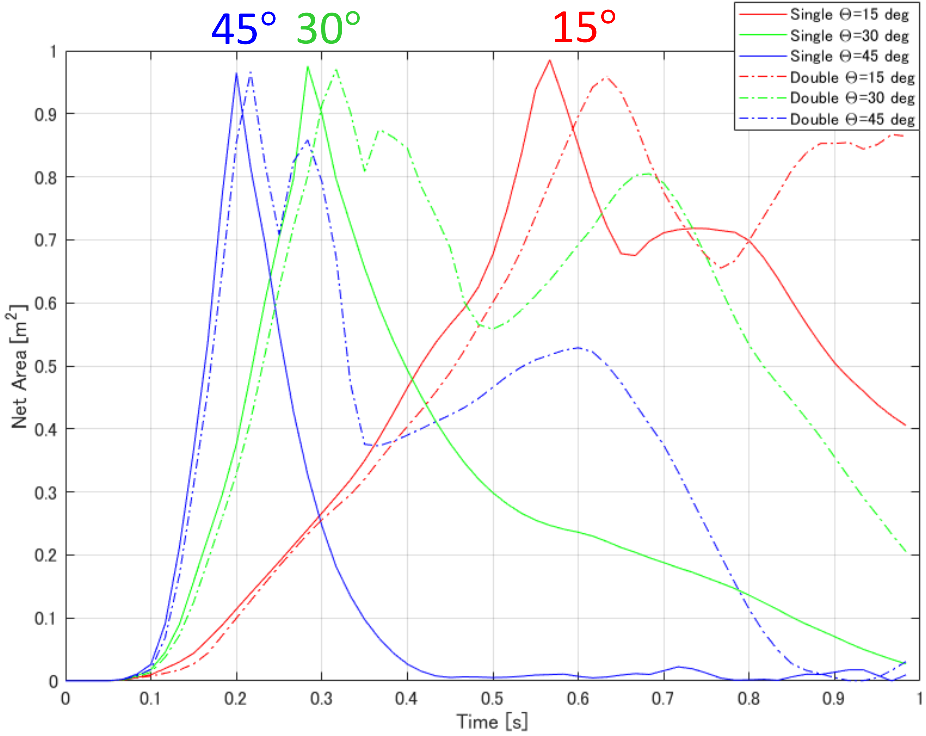


Fig. 8. Time histories of deployed area

4.3.2 Simulation Results (2)

Table 5. Average deployment and reshrinking Speed

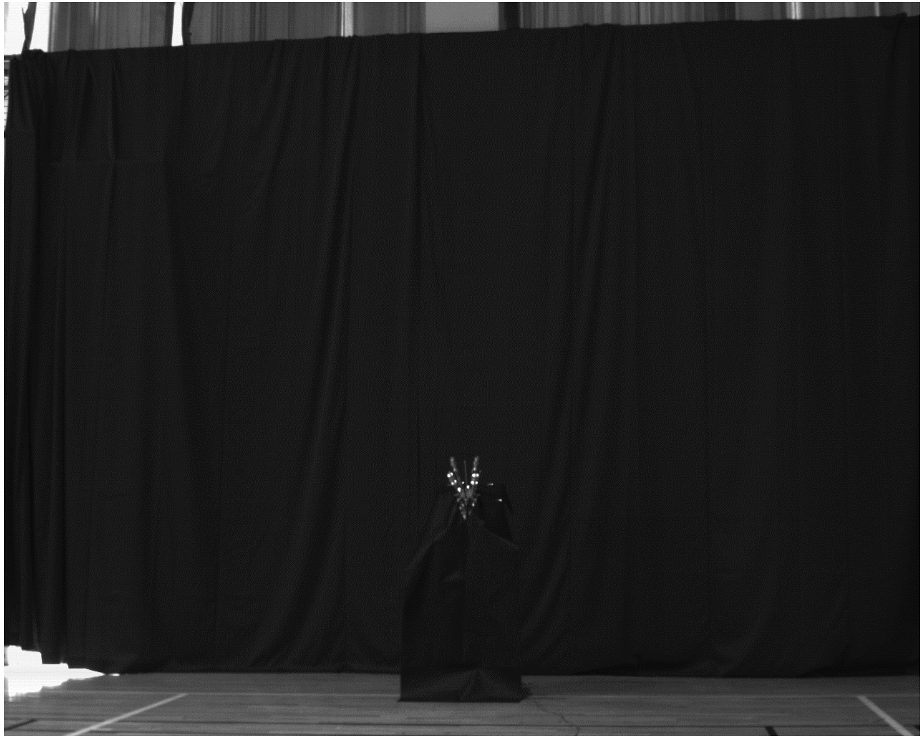
Conventional tether-net

	Deployment speed	Reshrinking speed	Rebounding factor
15deg	3.935 m^2/s	3.103 m^2/s	78.85 %
30deg	6.804 m^2/s	4.352 m^2/s	63.95 %
45deg	9.384 m^2/s	7.188 m^2/s	76.60 %

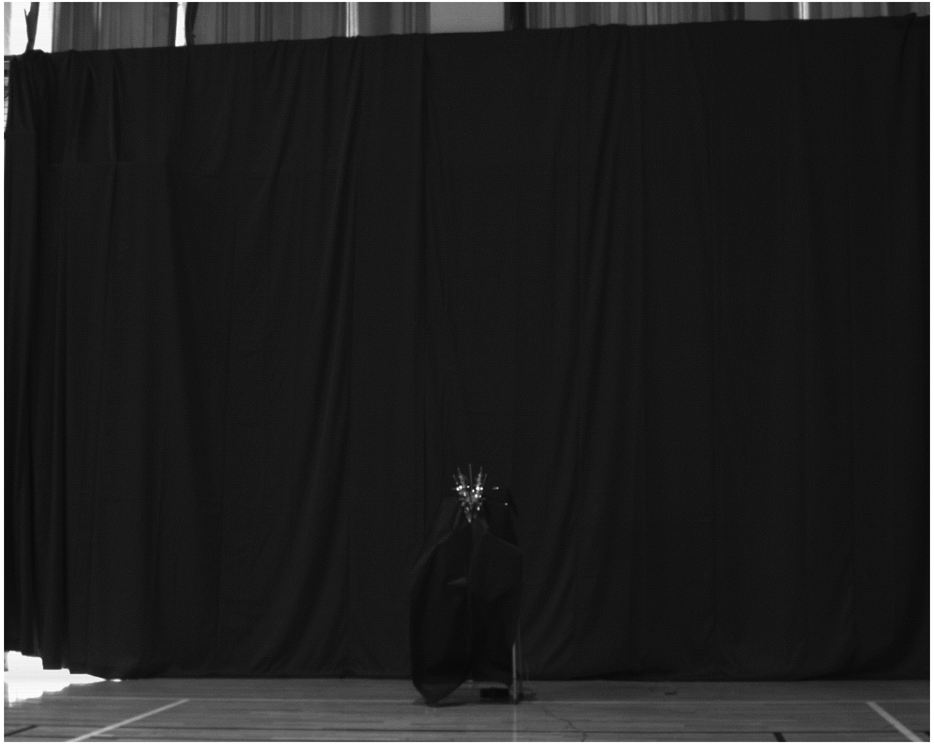
Proposed tether-net

	Deployment speed	Reshrinking speed	Rebounding factor
15deg	2.751 m^2/s	2.566 m^2/s	93.28 %
30deg	5.568 m^2/s	1.870 m^2/s	33.58 %
45deg	8.975 m^2/s	2.938 m^2/s	32.74 %

4.4.1 Experimental Results (15deg)

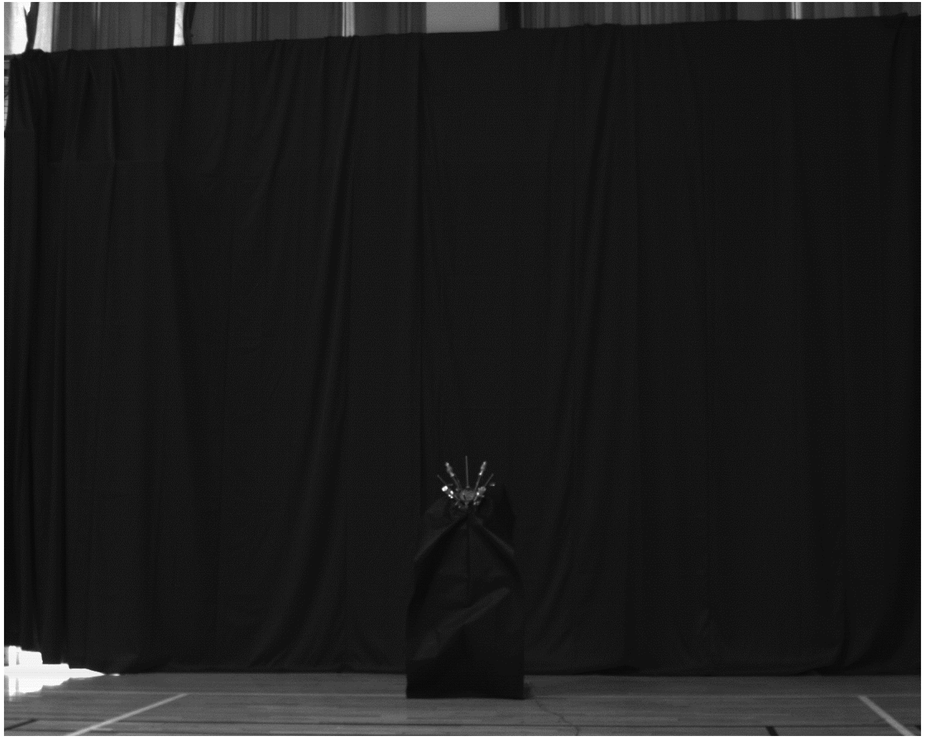


Conventional tether-net

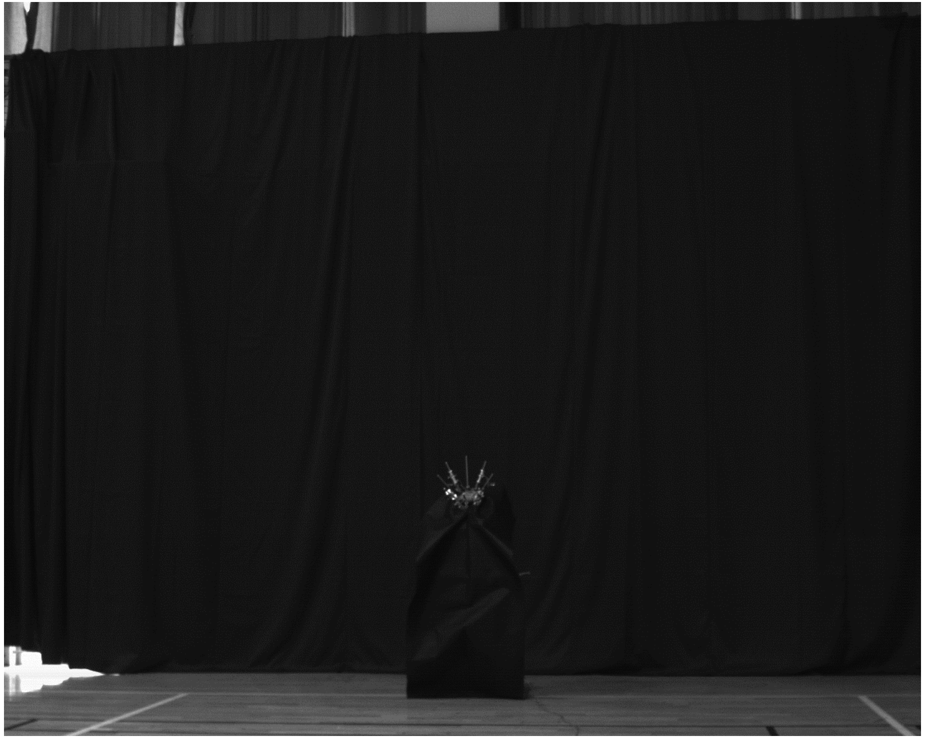


Proposed tether-net

4.4.2 Experimental Results (30deg)

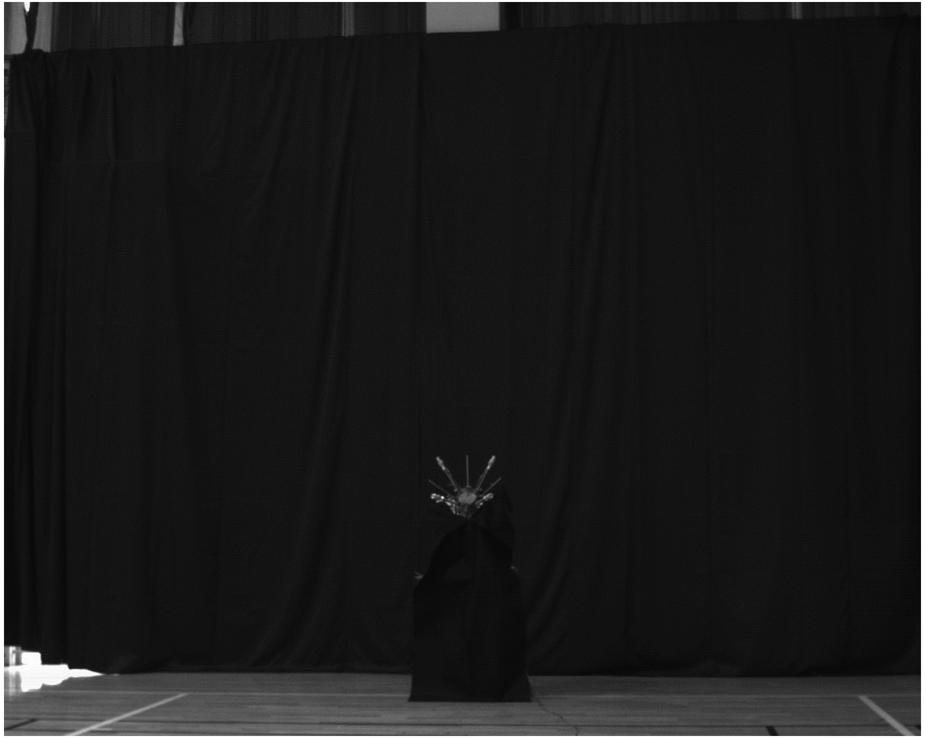


Conventional tether-net

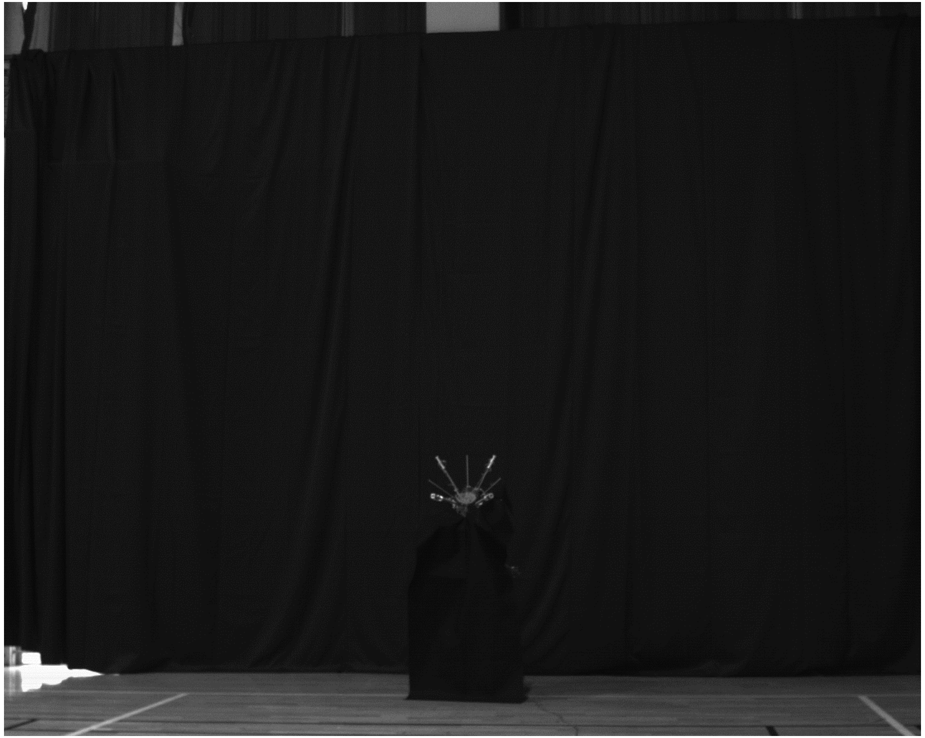


Proposed tether-net

4.4.3 Experimental Results (45deg)



Conventional tether-net



Proposed tether-net

5.1 Conclusions

- A tether-net with double-linked bullets was proposed as a solution to the problem of tether-net reshrinking motion.
- The effectiveness of the proposed tether-net for suppressing the reshrinking motion was confirmed numerically and experimentally.

5.2 Future Study

- The optimization of inner and outer bullet mass ratio and outer tether length that can effectively suppress the reshrinking motion after the tether-net full deployment is of interest, thus should be studied in future.