Research Article

Dynamic Simulation of Space Debris Cloud Capture Using the Tethered Net

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Space debris, especially the space debris cloud, has threatened severely the safety of future space missions. In the framework of multibody system dynamics, a computational approach is proposed in this study to investigate the dynamics of net deployment and capture of space debris cloud using this net subject to large overall motions and large deformations. To obtain high simulation fidelity of capturing space debris cloud, the gradient deficient beam element of the absolute nodal coordinate formulation (ANCF) is employed to discretize threads which are woven into the net. The normal contact force between the net and the debris cloud and among debris particles is computed by using the penalty method. Some deployment examples are presented to investigate the influences of shooting velocity of bullets and microgravity as well as the angle between the traveling direction of the net and the microgravity direction on the deployment characteristics of the tethered net. Other capturing examples are given to clarify the effect of the deployment area of the net at the moment it starts to contact with the debris cloud on the capture rate and to demonstrate the effectiveness of the proposed approach for capturing space debris cloud using the net in microgravity conditions.

1. Introduction

Space debris in orbit around the Earth is produced by space activities and has been growing by nearly geometric progression [1]. These space debris may strike other space objects in use, significantly increase the number of small debris, and severely threaten the safety of future space missions [2–4]. Even more seriously, the chain reaction of collisions between space debris and other space objects possibly leads to a debris cloud composed of many tiny debris particles which may trigger the disastrous cascade effects of debris, named “Kessler syndrome” [5–7].

To mitigate this situation and keep safe space exploration, the space debris capturing and removal technique from overpopulated orbital regions has been one of the hot spots in space research for the entire international space community, and the past decades have witnessed significant theoretical and technical developments in this exciting research field [3, 8, 9]. Compared to the tentacle capturing method [10], single and multiple robotic arm capturing method [11, 12], tether-gripper capturing method [13], and harpoon capturing method [14], the tethered net capturing method is regarded as one of the most promising capturing methods due to its features of flexibility, lightweight, efficient cost, and compatibility with various dimensions and shapes of space debris [8, 15].

Compared with the elastic continuum approach [16] and cubic B-spline approach [17], the mass-spring model [18] and the absolute nodal coordinate formulation (ANCF) [19] are the most commonly used modeling approaches of the net. Benvenuto et al. modeled the net via the mass-spring approach and studied different phases of the debris capture and disposal [20]. Botta et al. presented a scheme of contact detection between the net and the target based on the mass-spring approach and established a normal and frictional contact dynamic model [18]. Huang et al. and Zhang et al. proposed a mass-spring approach based on a maneuverable tethered space net used for noncooperative space
target capture and removal, and the position and configuration of this net are controllable via four maneuvering units located at four corners of a square net [21, 22]. The mass-spring model exhibits linearity of dynamic ordinary differential equations and computational efficiency in net modeling. However, the approach is not an ideal modeling method for the net due to its low accuracy in net dynamic deployment and the lack of ability to describe the nonlinear and large deformation of the tether.

The finite elements of ANCF introduce the global position vector and position vector gradients as nodal coordinates, leading to a constant mass matrix and zero centrifugal and Coriolis forces [23]. Numerous important applications have been identified for the potential use of ANCF on the deformation of fibrous soft tissue [24], underwater vehicle [25], fluid-structure interaction [26], and topology optimization [27], just to name a few. Recently, ANCF has been employed to establish the dynamic model of a space net [28]. Shan et al. compared the ANCF model and mass-spring model of the space net by using a parabolic flight experiment and concluded that the ANCF model is superior to the mass-spring model in describing the dynamics of the inner knots of the net [29, 30]. Qing-quan et al. investigated the dynamic modeling and ground test of the tethered net and showed that the ANCF model is more capable of describing the flexibility of the net with fewer nodes than the mass-spring model [31].

In addition to the dynamic modeling of the space net, researchers have focused their attention on the capture process of space debris, including net deployment [30], contact between the net and the target [32], and closing of the net [33]. Botta et al. established the models of the chaser, net, target, contact dynamics, and closing mechanism used for tethered net capture of space debris and simulated the process of capturing a small asteroid [34]. Si et al. established the self-contact dynamic model of the tethered net based on its geometric characteristics [35]. They also proposed a new split closing mechanism model by using the thread-ring sliding joint and validated the effectiveness of the model by comparing the simulation results and the experimental ones [36]. Zhang and Huang improved the net capture performance by controlling the thrusters installed on the bullets [37]. To test the performance of active debris removal technologies on mock targets in low Earth orbit, Forshaw et al. and Aglietti et al. have developed techniques and devices, for example, navigation, hardware, and software, to capture noncooperative targets in their RemoveDEBRIS demonstration mission [38–40]. Furthermore, they captured a CubeSat in orbit successfully in 2018 using a net launched from another CubeSat.

The aforementioned literature focuses attention on the debris capture with only one target. Moreover, the target is assumed to be infinitely massive, and as a result, forces and moments transmitted to the target upon the impact of the net have a negligible effect on its motion [18]. Little attention has been paid to the capture of the space debris cloud, which could be produced when space debris impacts other debris or space targets, for example, the Whipple shield of spacecraft [41], as shown in Figure 1. The masses of these debris particles in the cloud are very small, and their dynamic responses upon the impact of the net cannot be neglected. The description of the space debris cloud is generally based on the finite element method and smoothed particle hydrodynamics by simplifying the tiny debris particles in the cloud into spheres with masses and radii [7]. Therefore, this paper is aimed at proposing a computational approach in the framework of multibody system dynamics to simulate the net deployment and capture of space debris cloud and to investigate the response of the debris cloud in the capture process.

The remaining part of the paper is organized as follows. In Section 2, the ANCF gradient deficient beam element is described to establish the dynamic model of the threads which are woven into the net. In Section 3, the multizone contact detection strategy and the penalty method are introduced to establish the normal contact model between the net and the debris cloud. Section 4 presents some numerical examples to investigate the influences of shooting velocity of bullets, microgravity, and the deployment area of the net at the contact moment on the deployment characteristics of the net and on the capture rate. In Section 5, some concluding remarks are made.

2. System Modeling

As threads woven into the net are usually very thin, it is very suitable to establish the dynamic model of the net undergoing large deformations and large overall motions in space based on the ANCF gradient deficient beam element [19]. Compared to the mass-spring model, the ANCF model exhibits a constant mass matrix of the dynamic system, geometric nonlinearity, zero centrifugal and Coriolis forces, and, consequently, good capability of describing the flexibility of the net [23].

Shan et al. applied the ANCF to model the net by introducing the local coordinate $x \in [0, 1]$ to obtain the position of an arbitrary point within only one element [30], which is not convenient for the multizone contact detection strategy used in this paper to detect the contact between the net and the debris cloud [19] as in this strategy the detecting point

![Figure 1: The numerical and experimental results of debris cloud morphology [41].](image-url)
may skip from one element to its adjacent one. Moreover, in their work [30], only the elastic forces due to the longitudinal deformation of threads are taken into account. The bending deformation which is very important for contact detection is not considered. So in this paper, the ANCF gradient deficient beam element suitable for the contact detection is introduced, both the longitudinal and bending deformations are taken into consideration, and the elastic force and Jacobians due to these deformations are derived in detail.

For the convenience of further discussion on contact detection, as shown in Figure 2, a new body-fixed arc coordinate $\zeta$ is introduced to describe the global position of an arbitrary point on a thread meshed by the ANCF gradient deficient beam. Thus, the global position vector $r$ of an arbitrary point $P$ on the centerline of the entire thread yields

$$r(\zeta) = S(\bar{\zeta}) e_\zeta,$$

where $\zeta \in [0, L]$ is the arc coordinate of the thread and $L$ is its length in the undeformed configuration. $\bar{\zeta} \in [1, N_e]$ and $\zeta \in [0, 1]$ are the integer part and decimal part of the dimensionless value $\zeta/l$, denoting the element the point $P$ belongs to and the position on the element the point locates, respectively. $N_e$ and $l = L/N_e$ are the total element number used to discretize the thread and element length in the undeformed configuration, respectively.

$e_\zeta$ is the global nodal coordinate vector of the element $\zeta$, composed of the positions and gradient coordinates, as

$$e_\zeta = \begin{bmatrix} r^T_{\zeta} & r^T_{\zeta+1} & r^T_{\zeta+1} & r^T_{\zeta+1} \end{bmatrix}^T,$$

where both $r_\zeta$ and $r_{\zeta+1}$ are global position vectors of two nodes (red dots in Figure 2) of the element; $r^\prime_\zeta = l \partial r_\zeta / \partial \zeta$ and $r^\prime_{\zeta+1} = l \partial r_{\zeta+1} / \partial \zeta$ are gradient coordinates of the two ends.

$S(\bar{\zeta}) \in R^{3 \times 12}$ is the shape function matrix of the element, expressed as

$$S = \begin{bmatrix} S_1 I_3 & S_2 I_3 & S_3 I_3 & S_4 I_3 \end{bmatrix},$$

where $S_1 = 1 - 3\bar{\zeta}^2 + 2\bar{\zeta}^3$, $S_2 = l(\bar{\zeta} - 2\bar{\zeta}^2 + \bar{\zeta}^3)$, $S_3 = 3\bar{\zeta}^2 - 2\bar{\zeta}^3$, and $S_4 = l(3\bar{\zeta}^2 - \bar{\zeta}^3)$; $I_3$ is the identity matrix of order 3.

The constant element mass matrix $M^e$ of the thread can be written as [30]

$$M^e = \rho A l \int_0^1 S^T S \partial \zeta,$$

where both $\rho$ and $A$ are the density of the thread material and the area of the thread cross-section, respectively.

The gravitational force acting on the thread element, $F_G$, is deduced by using the virtual work principle, as

$$F_G = \mu \rho A l \int_0^1 S^T r \partial \zeta,$$

where $\mu = 3.986e14$ m/s$^2$ is the geocentric gravitational constant.

The Jacobian $J^e_1$ of $F_G$, which is needed in solving the system dynamic equations using the implicit integration algorithm, yields

$$J^e_1 = \mu \rho A l \int_0^1 \left[ \left\| r^\prime \right\|^2 S^T S + S^T r r^\prime S \right] \partial \zeta,$$

The strain energy of the thread element is deduced as [23]

$$U = U_1 + U_b = \frac{1}{2} E Al \int_0^1 \epsilon^2 d\bar{\zeta} + \frac{1}{2} E l \int_0^1 \kappa^2 d\bar{\zeta},$$

where both $U_1$ and $U_b$ represent the longitudinal strain energy and the bending strain energy of the thread element, respectively. $E$ and $l$ are Young’s modulus of the thread material and the second moment of the area of the thread cross-section, respectively. Besides, $\epsilon = (r^\prime r^T r^\prime - 1)/2$ and $\kappa = \left\| r^\prime \times r^\prime \right\|/\|r^\prime\|$ are the longitudinal strain and the curvature of an arbitrary point in the element. $r^\prime = l \partial r / \partial \zeta$ is the gradient vector, and $r^\prime\prime = l^2 \partial^2 r / \partial \zeta^2$.

The nonlinear elastic force $F^e_l$ associated with the longitudinal deformation of the element can be expressed as

$$F^e_l = \left( \frac{\partial U_1}{\partial e_\zeta} \right)^T = E Al \int_0^1 \epsilon \Gamma e_\zeta d\zeta,$$

where $\Gamma = S^T S / l^3$ and $\epsilon = \partial S / \partial \zeta$.

The Jacobian $J^e_l$ of the elastic force is derived as

$$J^e_l = \frac{\partial F^e_l}{\partial e_\zeta} = E Al \int_0^1 \left( \epsilon \Gamma + \Gamma e_\zeta e_\zeta^T \right) d\zeta.$$

Accordingly, the elastic force $F^e_b$ and the Jacobian $J^e_b$ of the element due to the bending deformation can be cast as

$$F^e_b = \left( \frac{\partial U_b}{\partial e_\zeta} \right)^T = E l \int_0^1 \Psi_1 e_\zeta d\zeta,$$

where $\Psi_1$ is a constant.
The space debris cloud is generally described based on the finite element method and smoothed particle hydrodynamics by simplifying the tiny debris particles in the cloud into spheres with masses and radii, each of which has 3 degrees of freedom [7]. So for an arbitrary debris particle with the global position $r_p$, its mass matrix can be expressed as

$$M_p = m_p I_3,$$

where $m_p$ is the mass of this particle.

The gravitational force acting on the debris particle, $G_p$, can be written as

$$G_p = \mu m_p \frac{r_p}{||r_p||^3}.$$  

Its Jacobian with respect to the $r_p$ is deduced as

$$J_p = \mu m_p \left( \frac{I_3}{||r_p||^3} - \frac{r_r r_r^T}{||r_p||^5} \right).$$  

### 3. Contact Dynamic Modeling

In the process of capturing space debris cloud using the tethered net, contact occurs between the net and the debris cloud and the contact force will influence their dynamic responses. So accurate contact detection is critical to the accuracy of contact force calculation and, as a consequence, to the simulation fidelity in the capture phase. The mass-spring model used to establish the net [18, 32] can detect the contact between mass points of the net and the target but is incapable of detecting the contact between the thread segments and the target, leading to the low fidelity of capture simulation. This study investigates the capture of space debris cloud using the net discretized by the ANCF gradient deficient beam. This type of element can describe the tension, bending, and large deformation of an arbitrary point of the net. Therefore, it can detect contacts between the net and the debris cloud accurately. The tiny debris particles in the cloud are commonly simplified into spheres with masses and radii [7]. So only the contact detection between the net and the spheres should be operated in this study. Wang et al. developed a multizone contact detection strategy between two thin beams based on ANCF [19]. The degenerated form of this model is applied to the contact detection between threads and debris particles in this study. The reader interested in the details of this model may refer to the work by Wang et al. [19].

In this study, the contact force model between the net and the debris cloud neglecting friction is based on the penalty method, which has been widely used to study the contact problems because of its simplicity, no introduction of additional equations, and easy interpretation from a viewpoint of physics [42]. According to the penalty method, the contact force acted at an arbitrary point in the thread by debris particles is defined as

$$F_T = -pg \tau n,$$

where $p$ is the penalty parameter.

### Table 1: Input parameters for the deployment and capture simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread Young’s modulus (GPa)</td>
<td>131</td>
</tr>
<tr>
<td>Thread diameter (m)</td>
<td>0.001</td>
</tr>
<tr>
<td>Thread density (kg/m$^3$)</td>
<td>1440</td>
</tr>
<tr>
<td>Net size (m$^2$)</td>
<td>4 x 4</td>
</tr>
<tr>
<td>Net mesh (m)</td>
<td>0.2</td>
</tr>
<tr>
<td>Bullet mass (kg)</td>
<td>5</td>
</tr>
<tr>
<td>Particle mass (kg)</td>
<td>0.1</td>
</tr>
<tr>
<td>Particle radius (m)</td>
<td>0.15</td>
</tr>
<tr>
<td>Shooting velocity (m/s)</td>
<td>21</td>
</tr>
<tr>
<td>Penality parameter (N/m)</td>
<td>1e6</td>
</tr>
<tr>
<td>Shooting angle (deg)</td>
<td>30</td>
</tr>
</tbody>
</table>

![Figure 3: Schematic view of effective and traveling distances during net deployment.](image-url)
\( g_T \) in Equation (17) is the normal penetration between the thread and the particle, defined as

\[
g_T = \|r - r_p\| - R_T - R_p, \tag{18}\]

where \( r \) and \( r_p \) are the global positions of the contact point in a thread and debris particle, respectively; \( R_T \) and \( R_p \) are the radii of the thread and the particle.

\( \mathbf{n} \) denotes the normal contact direction at contact points and yields

\[
\mathbf{n} = \frac{r - r_p}{\|r - r_p\|}. \tag{19}\]

According to the principle of virtual work, the generalized contact force acted at the thread point and debris particle can be written as...
\[ \mathbf{P}_T = \mathbf{S}^T \mathbf{F}_T, \]

where \( \mathbf{S} = \begin{bmatrix} \mathbf{S}^T( \hat{\zeta}_m - \mathbf{I}_3) \end{bmatrix} \). Accordingly, the Jacobian of the generalized contact force can be deduced as

\[ \mathbf{J}_T = \frac{\partial \mathbf{P}_T}{\partial \hat{\mathbf{e}}} = \frac{-\mathbf{P}}{||\mathbf{r} - \mathbf{r}_p||} \mathbf{S}^T \left( \mathbf{g}_T \mathbf{I}_3 + (\mathbf{R}_T + \mathbf{R}_p) \mathbf{n} \mathbf{n}^T \right) \mathbf{S}, \]

where \( \hat{\mathbf{e}} = \begin{bmatrix} \mathbf{e}^T \hat{\zeta} \\ \mathbf{r}_p^T \end{bmatrix} \) is the assembly of the element nodal coordinate and the global position of the debris particle.

The derivation process of the contact force between debris particles is omitted in this study as it is similar to that between threads and debris particles.

4. Deployment and Capture Simulation

In this section, simulations of deployment of a square net and the capture of space debris cloud using this net in microgravity conditions are, respectively, performed based on the ANCF model and the penalty method. The software MATLAB is used to implement these simulations. Each thread is discretized into 8 ANCF gradient deficient beam elements to obtain high simulation fidelity. The four bullets which are shot by the shooting mechanism to deploy the net are assumed to be lumped masses attached at the four corners of the net. The debris cloud is right above the net in the initial configuration. In the work by He et al. [7], the debris cloud shape is represented by the distribution of the particles in SPH. So in this study, the debris cloud is composed of four layers with \( 7 \times 7 \) uniformly distributed particles for each layer. The relative distance between the net and the bottom layer of the debris cloud above the net is set to be 5 m. The distances of adjacent layers and adjacent particles are set to be 0.45 m and 0.35 m, respectively. The net has an initial orbit altitude of 43164 km with an orbit angular velocity of 0.704 rad/s to maintain the circular orbit. The traveling direction of the net is parallel with the microgravity direction. The folding scheme of the net is the same as that by Shan et al. [30]. Some other input parameters for the simulations are shown in Table 1. In this table, the shooting angle is defined as the angle between the direction of the shooting velocity and the traveling direction of the net relative to the debris cloud [30].

4.1. Deployment Phase. Shan et al. studied in detail the influence of initial parameters, such as shooting velocity, shooting angle, and mass of bullets, on the deployment characteristics of the tethered net, namely, maximum area, deployment time, traveling distance, and effective period [30]. In this study, a new parameter to describe the dynamic characteristics of the net deployment phase, effective distance, is introduced. Similar to the definition of the effective period [30], the effective distance is defined as the distance in which the deployment area of a net is beyond 80% of its designed maximum area, as shown in Figure 3. To increase the probability of success of capturing debris cloud, it is expected that the debris cloud is within the effective distance which is as larger as possible.

The influence of the shooting velocity of bullets relative to the debris cloud on the deployment area of the net at the deployment phase is investigated in this study. The dimensionless deployment areas, calculated by dividing the deployment area by the designed maximum area (16 m² in this study), versus both time and relative displacement with different shooting velocities, are shown in Figures 4 and 5, respectively. It can be seen from the two figures that with the increase of the shooting velocity, the maximum area is increasing, the deployment time is decreasing, and, accordingly, the capture is more efficient, which coincides with the conclusions in Shan et al. [30]. While the effective distance is increasing with the increase of the shooting velocity, as shown in Figure 5, the effective period for capturing is...
decreasing, as depicted in Figure 4. Shan et al. [30] pointed out that a shorter effective period leads the capturing to a higher risk of failing and is less reliable. Therefore, a reasonable shooting velocity should be adopted so as to achieve an optimal combination of efficient capture and high reliability. So in the next study, the shooting velocity is chosen as 21 m/s.

**Figure 7:** Dimensionless deployment area versus relative displacement with and without microgravity.

**Figure 8:** The dynamic configurations of the net at six specific moments at the deployment phase.
The influences of both the microgravity acted on the net by the Earth and the angle between the traveling direction of the net and the microgravity direction on the deployment area are also investigated in this study. The dimensionless deployment areas versus both time and relative displacement with and without microgravity are shown in Figures 6 and 7, respectively. In the two figures, the red curves depict the deployment area of the net considering microgravity, with whose direction the net traveling direction is parallel. The green curves, on the other hand, depict that with the microgravity direction perpendicular to the net traveling direction. It can be concluded that compared to the results without consideration of microgravity, the maximum deployment area of the net with the traveling direction parallel with the microgravity direction is smaller, while that with the traveling direction perpendicular to the microgravity direction is larger. Both the deployment time and the traveling distance become longer and larger for the two cases. The effective period and effective distance for the first case almost do not change, while those for the second case become longer and larger. It can also be seen from the two figures that all the abovementioned differences are very slight.

Figure 9: The system dynamic configurations at eight specific moments at the capture phase.
The dynamic configurations of the net at six specific moments at the deployment phase are depicted in Figure 8. It can be seen from the figure that at the initial moment, the four bullets with a shooting velocity of 21 m/s drive threads at four corners of the net to deploy and then the rest of the threads of the net deploy successively. The relative velocities of bullets to the debris cloud decrease with time, and when their components in the plane perpendicular to the relative traveling direction decrease to zero (0.341 s, as shown in Figure 7), the deployment area of the net reaches its maximum value and the net starts to shrink due to the tensions of the threads. The figure also indicates that the ANCF model can describe the large flexibility and large deformation of the net.

4.2. Capture Phase. After the deployment of the net with a shooting velocity of 21 m/s and a traveling distance of 5 m, as shown in Figure 5, the net reaches its maximum area and starts to contact the debris cloud. The system dynamic configurations at eight specific moments at the capture phase are depicted in Figure 9. It can be seen from the figure that at 0.3 s, the net has not yet contacted the debris cloud, while at 0.35 s, the net contacted the first layer of the debris cloud. Later debris particles impact each other, causing the debris cloud a state of disorder, as shown in Figure 9 at the moment of 0.4 s. As the four bullets move with one velocity component towards the center of the net and the other one in the traveling direction, the deployment area of the net is decreased and the envelope surface made up of the net wraps some debris particles from the moment 0.5 s to the moment 0.7 s. In this process, more and more debris particles escape from the envelope surface due to the impact between particles and would not be captured successfully. With the bullets moving away from the center of the net after the moment the deployment area of the net reaches its maximum value, some other debris particles escape from the envelope surface successively while the rest of the particles are wrapped by the net more tightly and captured successfully, as shown in Figure 9 from the moment 0.8 s to the moment 0.9 s. From this viewpoint, it is difficult to capture the whole debris cloud due to the impact of particles. Increasing the designed maximum area of the net may be an effective way to capture more debris particles because the net can make a larger envelope space and can wrap more particles.

A debris particle that may be captured should be located within an envelope space made up of the net and a surface containing the four bullets. It should be noted that some of the debris particles within the envelope space can also escape from the space as this space is not closed, as shown in Figure 9. Moreover, the deployment area of the net at the moment it starts to contact with the debris cloud may affect the number of debris particles captured by the net. So the initial relative distance between the net and the bottom layer of the debris cloud is changed from 5 m to 4 m to investigate this influence. It can be seen from Figure 5 that the initial relative distance of 5 m is corresponding to the maximum deployment area of the net, about 92% of the designed maximum area, while the 4 m is corresponding to 80% of the designed one.

The comparison of the time histories of the number of debris particles that may be captured by the net with 92% (maximum deployment area) of the designed maximum area of the net and with 80% of that at the moment it starts to contact with the debris cloud is shown in Figure 10. It can be seen from the figure that after the moment the deployment area of the net is 92% (80%) of the designed maximum area, the number of debris particles that may be captured is increased sharply to 49 because all the particles of the first layer of the debris cloud are located in the interior of the envelope space.
The rest of the layers of the debris cloud are captured successively, but the increasing rate of the number of captured particles becomes slow as some debris particles escape from the envelope space. At the moment of 0.47 s (0.36 s), the number reaches its maximum value and starts to decrease due to the impact among particles within the envelope space. From the moment about 0.95 s (1.05 s), the number of debris particles captured remains unchanged, about 72 (32), as particles are wrapped by the net tightly, as shown in Figure 9. These debris particles are the particles that are captured successfully by the net in the final configuration. Furthermore, it can be seen clearly that the net with 92% (maximum deployment area) of the designed maximum area at the contact moment can capture more debris particles than the net with 80% of that.

5. Concluding Remarks

A computational approach is proposed in this study to simulate the dynamics of net deployment and capture of space debris cloud using this net subject to large overall motions and large deformations. To obtain high simulation fidelity of capturing space debris cloud, the gradient deficient beam element of the absolute nodal coordinate formulation (ANCF) is employed to discretize threads which are woven into the net. The multizone contact detection strategy proposed by the authors in their previous work is used to detect contacts between threads and debris particles. The normal contact force between the net and the debris cloud and among debris particles is computed by using the penalty method.

A numerical example is made to investigate the influences of shooting velocity of bullets and microgravity on the deployment characteristics of the tethered net. The numerical results indicate that with the increase of the shooting velocity, the maximum area and the effective distance are increasing while the deployment time and the numerical results indicate that with the increase of the method.

References


