Robustness evaluation for rolling gaits of a six-strut tensegrity robot

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Abstract
Locomotive robots based on tensegrities have recently drawn much attention from various communities. A common strategy to realize long-distance locomotion is combining several basic gaits that are designed in advance. Considering the unavoidable uncertainties of the environment and the real locomotive system, selecting the gaits with high robustness is essential to the implementation of long-distance locomotion of tensegrity robots. However, no quantitative approach for robustness evaluation of rolling gaits is reported in recent research work. In this study, a practical and quantitative method is proposed for the robustness evaluation of rolling gaits of tensegrity robots. A mathematical model is built to describe the evaluation process, and the success rate of rolling is adopted as an indicator of robustness. Sensitivity analysis and robust evaluation are conducted on the rolling gaits of a typical six-strut tensegrity robot. Specifically, the sensitivities of the rolling gaits to five uncertain parameters (i.e. tendon stiffness, initial tendon prestress, the equivalent mass of nodes, actuation lengths of actuators, and slope of ground) are investigated and discussed in detail, and the robustness of the rolling gaits is evaluated by correlated random sampling. Experiments on a physical prototype of the six-strut tensegrity robot are carried out to verify the proposed concept and method.

Keywords
Tensegrity robot, rolling gait, robustness, parameter sensitivity, experimental validation

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Introduction
A tensegrity system is a special self-equilibrated pin-jointed structural system comprising a discontinuous set of compressed components inside a continuous set of tensioned components.¹ The shape of a tensegrity system can be actively controlled by adjusting the prestress in the components, making it a good candidate for structural systems that require controllable shapes, such as smart structures,²,³ deployable structures,⁴,⁵ and locomotive robots.⁶⁻⁸

More attention has been paid to tensegrity-based robots due to their features of lightweight, efficiency, and high deformability. Paul et al.⁹ investigated the dynamic characteristics and control strategies of tensegrity robots and...
Conducted experimental validation using physical prototypes. Shibata et al.\textsuperscript{10} designed and experimentally validated the crawling behaviors of tensegrity robots based on body deformation. Boehm and Zimmermann\textsuperscript{11} proposed vibration-driven mobile robots based on single actuated tensegrities. Among various types of tensegrity robots, spherical tensegrity robots with rolling gait have attracted the most attention due to their excellent locomotion ability. Spherical tensegrity robots have excellent locomotion ability and thus have potential application in fields such as planetary exploration. Koizumi et al.\textsuperscript{12} designed and tested a spherical tensegrity robot driven by a set of pneumatic soft actuators, which can perform rolling over flat ground. Caluwaerts et al.\textsuperscript{13} developed a physical prototype of a six-strut spherical tensegrity robot. Kim et al.\textsuperscript{14} presented a spherical tensegrity robot that can deliver payloads over a long distance by combining cable-driven rolling and thruster-based hopping. Chen et al.\textsuperscript{15} demonstrated a tele-operated spherical tensegrity robot capable of performing locomotion on steeply inclined surfaces. Luo and Liu\textsuperscript{16} set up a mathematical model of spherical tensegrity robots and analyzed the relationship between the deformation and the trajectory of the tensegrity centroid. Böhm et al.\textsuperscript{17} proposed a locomotion system based on a spherical tensegrity consisting of two compressed curved members and a continuous net of tensioned members. Zhang et al.\textsuperscript{18} achieved automatic learning of rolling gait for a tensegrity robot based on mirror descent guided policy search. It is worth noting that automatic learning is a hot topic in the robot field. For example, Tutsoy et al.\textsuperscript{19} modeled the legged NAO humanoid robot and developed a reduced-order reinforcement learning-based robot adaptive control algorithm for the balancing task.

Rolling is the main locomotion form of spherical tensegrity robots to achieve long-distance movements. The long-distance rolling of a spherical tensegrity robot is usually composed of a series of rolling gait. Cai et al.\textsuperscript{20} generated a series of repeatable rolling gait with identical initial and final states for possible long-distance rolling. Lu et al.\textsuperscript{7} proposed a Dijkstra algorithm-based path planning approach to combine rolling gait for long-distance locomotion. Chang et al.\textsuperscript{21} presented a path planning method based on basic rolling gait using the A* algorithm. Littlefield et al.\textsuperscript{22} proposed approaches to produce long-term locomotion using rolling gait, in which a standard search method is used for simple environments and an informed sampling-based planner for complex environments.

The robustness of rolling gait should be considered when applying the tensegrity robots in practice. The rolling gait obtained from numerical simulation might deviate from expectations when applying in practice due to the uncertainties of the environment and the real locomotive system. Therefore, robust rolling gaits capable of executing the expected motions under the uncertainties are needed for a real tensegrity robot. There have been some research on generating robust motion of tensegrity robots. For example, Işcenoğlu et al.\textsuperscript{23} proposed a coevolution algorithm to generate robust goal-directed motion for a six-strut tensegrity robot. A learning algorithm together with form-finding-based simulation was used to generate robust movement for a six-strut tensegrity robot (Kim et al.\textsuperscript{24}). These kinds of research provide effective ways for generating robust motion of tensegrity robots. However, the robustness mentioned in both the above studies is conceptual and qualitative, and no quantitative uncertainties of parameters have been considered and no quantifiable definition of gait or motion robustness has been proposed. A quantitative approach is needed to better understand and evaluated the robustness of tensegrity robots.

In this study, the robustness of spherical tensegrity robots that achieve long-distance movement by combining several basic rolling gaits is quantitatively investigated. A definition for the robustness of the motion gaits is proposed, and a procedure evaluating the robustness involving the uncertainties of physical parameters and environment is developed. The proposed definition and procedure are numerically and experimentally employed on a six-strut spherical tensegrity robot.

The layout of the article is as follows. The definition and evaluation procedure of the robustness for rolling gaits of spherical tensegrity robots are presented in the second section. The third section presents the structural configuration of a six-strut tensegrity robot and a number of typical rolling gaits of it. The fourth section investigates the sensitivities of structural and environmental parameters and then selects the parameters involved in robustness evaluation. In the fifth section, the robustness of the rolling gaits of the six-strut tensegrity robot is evaluated by the proposed approach. Experimental validation based on a physical prototype of the six-strut tensegrity robot is carried out in the sixth section. Finally, the seventh section concludes the article. Figure 1 shows the main steps of the robustness evaluation of rolling gait.

**Definition and method**

**Rolling gait**

Tension members of a tensegrity are assumed to be only able to bear tensile forces, while compression members are assumed to be rigid and able to bear both compressive and tensile forces. Spherical tensegrity robots that achieve long-distance movement by combining a number of basic rolling gait are considered. A rolling gait denoted as \(B_i\) can be determined by the actuations of actuators and the initial state of the tensegrity system, that is

\[
B_i = B_i(e(t_i), s_i)
\]

where \(e(t_i)\) is an \(n_a\)-length vector of actuations of the gait \(i\) and \(n_a\) is the number of actuators; \(t_i\) is the actuation time;
Six-strut tensegrity robot

Prototype

Manufacturing

Modeling

Experimental

Parameters

Numerical model

Sensitivity analysis

Simulation

Target

Parameter selection

Validation

Pool of rolling gaits

Robustness evaluation

Figure 1. Steps of robustness evaluation.

and $s_i$ is the initial state of the tensegrity system. $e_i(t_i)$ must satisfy that

$$e_i(t_i) \in [e', e'']$$

where $e'$ and $e''$ represent $n_a$-length vectors of the lower and upper limits of the actuations, respectively. The initial state $s_i$ is expressed as

$$s_i = s_i(e, C_i)$$

where $e$ is an $n_a$-length vector of the initial elongations of actuators of the rolling gait $i$ and $C_i$ is the initial contact condition of the rolling gait $i$.

The internal force vector $T_i(t_i)$ of a spherical tensegrity robot can be expressed as

$$T_i(t_i) = [T_{i,1}(t_i), T_{i,2}(t_i), T_{i,3}(t_i), \ldots, T_{i,q}(t_i)]$$

where $T_{i,j}(t_i)$ is the internal force of the $j$'th member and $q$ is the number of structural members. The internal forces of members should not exceed the corresponding design strengths. During the deployment of a gait, the compression members can bear compressive or tensile forces, and the tensile members may slacken temporarily. As a result, the internal forces of members must satisfy

$$\begin{cases} T_{i,j}(t_i) \in [-T_{j}', T_{j}''], & \text{for compression members} \\ T_{i,j}(t_i) \in [0, T_{j}''], & \text{for tension members} \end{cases}$$

Gait robustness and evaluation procedure

The relationship between the robustness of rolling gaits and the uncertainties of environmental and structural parameters might be highly nonlinear, and finding an explicit solution can be quite difficult or even impossible. Monte Carlo sampling provides a simple and direct way to estimate the robustness by repeated tests. Therefore, it is adopted here to obtain a preliminary and global insight on the robustness of rolling gaits of tensegrity robots. The parameters of a tensegrity robot are randomly sampled using given distributions. A rolling gait is tested using various sampling results, and the success rate of the gait is calculated and used as an index of the robustness, that is

$$\text{ROBST}_i = \frac{\text{NUM}_{i, \text{su}}}{\text{NUM}_{i, \text{to}}}$$

where $\text{ROBST}_i$ is the robustness of gait $i$; $\text{NUM}_{i, \text{su}}$ is the number of times that gait $i$ successfully achieves the expected locomotion; and $\text{NUM}_{i, \text{to}}$ is the total number of tests of gait $i$. Note that the robustness defined above is used to scale the effectiveness of the gait design under the uncertainties of the numerical model used in the design, which is not the same as the one considered in robust control.
Six-strut tensegrity robot

Structural configuration

The six-strut tensegrity robot is a typical kind of spherical tensegrity robots, which have potential application in the exploration of complex environments due to their excellent locomotion ability. The six-strut tensegrity robot is adopted here because of its simplicity and representativeness. The robustness of the numerically generated rolling gaits of the six-strut tensegrity robot under the uncertainties of the environment and the real locomotive system is evaluated. This study will be helpful in the design or selection of more robust locomotive gaits based on numerical simulations. As shown in Figure 2, the tensegrity is composed of 6 struts, 12 nodes, and 24 tendons. Each node is connected to a strut and four tendons. The six struts are divided into three pairs, and the struts in each pair are parallel to each other at the reference state. The outside surface of the tensegrity is a pseudo-icosahedron that consists of eight closed triangles (TCs) and 12 open triangles (TOs). A TC has three tendon edges, and a TO has two tendon edges and a virtual edge without structural members. These triangles are numbered for the convenience of rolling gait descriptions, as listed in Table 1. According to the types of touching-ground triangles, there are two basic states for the tensegrity: TC state and TO state, as shown in Figure 2. In a rolling gait, the tensegrity moves from one state to the other state. To ensure the repeatability of the rolling gaits, the initial state and final state of a rolling gait are required to be identical to one of the basic states. As a result, the rolling gaits can be classified by the type of touching-ground triangles. The struts labeled with the prefix “A” in Figure 2(a) are used as active members whose rest lengths can be actively changed by actuators. The rest length of the actuated struts is assumed as 200 mm at the initial state and it is able to change within 156–256 mm at a speed of 14 mm/s. Hence, in this typical case, \( n_a = 6 \), \( e_i(t_i = 0) = 200 \text{ mm} \), and \( e_i(t_i) \in [156, 256] \text{ mm} \). The properties assumed for all the structural members are given in Table 2. To consider the control system and power supply, it is further assumed that a rectangle control box with a size of 50 \( \times \) 50 \( \times \) 60 mm\(^3\) and a mass of

![Figure 2. Six-strut dynamic tensegrity: (a) TC state and (b) TO state. TC: closed triangle; TO: open triangle.](image)

To evaluate the robustness with the above definition, a procedure including four steps is developed as follows:

1. Define a pool of gaits \( B_{eva}^{\text{str}} = [B_1^{\text{eva}}, B_2^{\text{eva}}, B_3^{\text{eva}}, \ldots B_n^{\text{eva}}] \) that are included in the evaluation, where \( B_i^{\text{eva}} \) represents the rolling gait \( i \) that is selected as a typical rolling gait used in the robustness evaluation and \( n \) is the number of gaits.

2. Set the standard values of parameters \( S_{str}^0(\varphi_1, \varphi_2, \varphi_3, \ldots, \varphi_m) \) according to the gait design, where \( \varphi_i \) represents the design value of the \( i \)th parameter involved in robustness evaluation and \( m \) is the number of parameters.

3. Define the random samples of parameters \( S_{str}^0 = [S_{str}^0, S_{str}^1, S_{str}^2, \ldots, S_{str}^p] \), where \( p \) is the number of samples and \( S_{str}^p(\varphi_1, \varphi_2, \varphi_3, \ldots, \varphi_m) \) is sampled values of the parameters of the \( i \)th sample, which is obtained by correlated random sampling on the parameters.

4. For each gait \( B_i^{\text{eva}} \), test all the \( p \) samples and calculate the robustness using equation (7).

### Table 1. Number of triangles.

| Type                  | Triangle number | Nodes |
|-----------------------|-----------------|-------|
| Closed triangle (TC-) | 1               | 1, 5, 10 |
|                       | 2               | 1, 8, 9 |
|                       | 3               | 2, 5, 11 |
|                       | 4               | 2, 8, 12 |
|                       | 5               | 3, 6, 11 |
|                       | 6               | 3, 7, 12 |
|                       | 7               | 4, 6, 10 |
|                       | 8               | 4, 7, 9 |
| Open triangle (TO-)   | 1               | 1, 2, 5 |
|                       | 2               | 1, 2, 8 |
|                       | 3               | 1, 9, 10 |
|                       | 4               | 2, 11, 12 |
|                       | 5               | 3, 11, 12 |
|                       | 6               | 3, 4, 6 |
|                       | 7               | 3, 4, 7 |
|                       | 8               | 4, 9, 10 |
|                       | 9               | 5, 6, 10 |
|                       | 10              | 5, 6, 11 |
|                       | 11              | 7, 8, 9 |
|                       | 12              | 7, 8, 12 |

### Table 2. Properties of members.

| Properties            | Struts | Tendons |
|-----------------------|--------|---------|
| Initial rest length (m) | 0.20   | 0.06    |
| Mass (kg)             | 0.065  | 0.001   |
| Stiffness (N/m)       | 2 \( \times \) \( 10^3 \) | 104     |
| Prestress (N)         | -23.49 | 6.50    |
| Compression strength (N) | -80   | 0       |
| Tension strength (N)  | 100    | 100     |
127.6 g are suspended at the center of the system by 24 additional tendons connected to the nodes.

**Pool of rolling gaits**

Various rolling gaits for the six-strut tensegrity robot can be generated by an approach based on a genetic algorithm incorporated with the incremental dynamic relaxation method. Parameters with significant influences on the rolling gaits are opted to be involved in the robustness evaluation. In this section, sensitivity analysis of parameters is conducted to identify the main parameters that have significant influences on the rolling gaits.

**Sensitivity analysis of parameters**

Parameters with significant influences on the rolling gaits are opted to be involved in the robustness evaluation. In this section, sensitivity analysis of parameters is conducted to identify the main parameters that have significant influences on the rolling gaits.

**Analysis method**

The tornado diagram is utilized for the sensitivity analysis of parameters. In the tornado diagram, the sensitive parameter is modeled as an uncertain value while all the other parameters are held at baseline values, and thus, the effect of the sensitive parameter on the target variable can be obtained. The relative importance of parameters can be evaluated according to the effects of each parameter. A target variable should be selected to evaluate the influence of parameters. Since the objective of a rolling gait is to achieve motion of the tensegrity system and the traveling distance of the tensegrity centroid can be used to indicate the...
whether the expected motion does happen, the traveling distance of the tensegrity centroid is taken as the target variable in the sensitivity analysis.

The main steps of sensitivity analysis are detailed as follows:

1. Select uncertain parameters \( \varphi \) with design values of \( \varphi_{50} \) for analysis, where \( \varphi \) is an \( m \)-length vector and \( m \) is the number of parameters. The \( i \)th parameter and the corresponding design value are denoted as \( \varphi_i \) and \( \varphi_{50,i} \), respectively.
2. Set the values of \( \varphi \) to their design values \( \varphi_{50} \), perform locomotion tracking analysis using incremental DRM, and calculate the mean and standard deviation values of the target variable for all the gaits in \( \mathbf{B}^{\text{eva}} \). The results are recorded as \( \text{Tar}_i \text{Value}_{50} \).
3. Assume that \( \varphi_i \) conforms to the normal distribution \( \varphi_i(\mu_i, \sigma_i^2) \), where \( \mu_i = \varphi_{50,i} \).
4. Determine \( \varphi_{i,10} \) and \( \varphi_{i,90} \) according to \( \varphi_i(\mu_i, \sigma_i^2) \), where \( \varphi_{i,10} \) and \( \varphi_{i,90} \) indicate the values for which 10% and 90% of the data are less than them, respectively.
5. Replace \( \varphi_i \) with \( \varphi_{i,10} \) and \( \varphi_{i,90} \), respectively, perform analysis and calculate the mean and standard deviation values of the target variable for all the gaits in \( \mathbf{B}^{\text{eva}} \). The results are recorded as \( \text{Tar}_i \text{Value}_{10} \) and \( \text{Tar}_i \text{Value}_{90} \), respectively.
6. Draw a tornado diagram using \( \text{Tar}_i \text{Value}_{50} \), \( \text{Tar}_i \text{Value}_{10} \), and \( \text{Tar}_i \text{Value}_{90} \), in which \( \text{Tar}_i \text{Value}_{50} \) is taken as a reference. Determine the main sensitive parameters based on the tornado diagram.

**Parameters participated in sensitivity analysis**

According to the authors’ experience on the design, manufacture, and test of a physical prototype for the six-strut tensegrity robot,\(^7,20,26\) the tendon stiffness \( \varphi_k \), the initial tendon prestress \( \varphi_p \), the equivalent mass of nodes \( \varphi_m \), the actuation lengths of actuators \( \varphi_a \) (with a vector length of \( n_a \)), and the slope \( \varphi_s \) of ground are selected as interested parameters for sensitivity analysis. Specifically, the equivalent mass of nodes is calculated by \( \varphi_m = \frac{F}{g} \), where \( F \) is the equivalent load applied on each node and \( g = 9.81 \, \text{m/s}^2 \) is the gravitational acceleration. Among these parameters, \( \varphi_s \) is an environmental parameter, and the others are structural parameters.

The initial orientations of the tensegrity system in TC-state and TO-state on a slope are shown in Figure 3. The slope direction is perpendicular to \( y \)-axis, and the changeable slope angle \( \varphi_s \) of ground is defined as the angle from the plane \( z = 0 \) to the slope. The initial orientations of the tensegrity system reference to the slope direction are fixed. For examples, for the initial state with a touching-ground triangle TC-6 (3, 7, 12), the edge 12-7 is parallel to the slope direction and points to the positive \( x \)-direction, as shown in Figure 3(a); and for the initial state with a touching-ground triangle TO-5 (3, 11, 12), the edge 12-3 is parallel to the slope direction and points to the positive \( x \)-direction, as shown in Figure 3(b).

**Tornado diagram**

The mean and standard deviation of the target variable are calculated based on Table 4 and recorded in \( \text{Tar}\_\text{Value}_{10} \) and \( \text{Tar}\_\text{Value}_{90} \), as listed in Table 5. The tornado diagram is shown in Figure 4, in which the yellow and blue bars represent \( \text{Tar}\_\text{Value}_{90} \) and \( \text{Tar}\_\text{Value}_{10} \), respectively, and the green bar denotes the overlapping
portion of them. It is found that the variation ranges of the target variable due to the uncertainties of the four structural parameters are comparable to each other. The variation due to the uncertainty of $\varphi_k$ in gait TO → TC is larger than those due to the uncertainties of the other three structural parameters. While in gait TC → TO, the variation due to the uncertainty of $\varphi_k$ is close to the others. Therefore, all the four structural parameters (i.e. $\varphi_k$, $\varphi_p$, $\varphi_m$, and $\varphi_a$) are taken into consideration in correlated random sampling for robustness evaluation. It is also observed that the influence of the uncertainty of the environmental parameter (i.e. $\varphi_s$) is more significant than the influences of the uncertainties of the structural parameters, especially in gait TC → TO. Therefore, $\varphi_s$ is also considered in correlated random sampling. It is worth noting that when the uncertainty of $\varphi_s$ is considered, the mean value of the traveling distances of all TC → TO gaits dramatically increases from 0.0695 m to 0.13 m. A further check reveals that a gait that generates a single rolling on a plane may generate double or even multiple rollings on a slope. These double or multiple rollings lead to the significant increment of traveling distance, which indicates that there is a significant effect of the slope of the ground on the robustness of rolling gaits.

Robustness evaluation of rolling gaits

Fifty samples are generated by correlated random sampling on the five uncertain parameters to build the state library $S_{str}$. For each rolling gait listed in Table 3, each state of $S_{str}$ is tested and the robustness of the gait is evaluated using equation (7). The results of the robustness evaluation are listed in Table 6. Note that the superscript $s$ represents simulation results, and $\text{NUM}_{s,50} = 50$ for all gaits. It is found that the robustness of rolling gaits increases as the number of used actuators increases. For a TC → TO gait, rolling cannot be achieved if there are only one or two used actuators, as given
in Table 3, indicating that the corresponding ROBUST^s_i is zero. For TC→TO gaits using three to five actuators, ROBUST^s_i is zero if the scale factor of actuation lengths equals to 0.9 or 0.8 (i.e. gaits 2, 3, 5, 6, 8, and 9), while for TC→TO type gaits using six actuators, ROBUST^s_i is 0.98 even if the scale factor is smaller than 1.0 (i.e. gaits 11 and 12). For TO→TC type gaits, ROBUST^s_i increases from 0.94 to 0.98 when the number of used actuators increases from 1 to 5. The average ROBUST^s_i of TO→TC type gaits using one to three actuators is 0.96, smaller than the average value 0.98 of the gaits using four to six actuators.

It is also found that the robustness of rolling gaits decreases or remains unchanged as the scale factor of actuation lengths decreases when the same number of actuators is used. As given in Table 6, for gaits 1–3, 4–6, and 7–9, which use three, four, and five actuators, respectively, ROBUST^s_i becomes zero if the scale factor decreases from 1.0 to 0.9 or 0.8; for gaits 16–18 which use two actuators, ROBUST^s_i decreases from 0.96 to 0.94 if the scale factor decreases from 0.9 to 0.8; and for gaits 28–30 which use six actuators, ROBUST^s_i becomes zero if the scale factor decreases from 0.9 to 0.8. The robustness of TC→TO type gaits is lower than the robustness of TO→TC type gaits. Many of the TC→TO type gaits cannot achieve rolling if a scale factor of actuation lengths smaller than 1.0 is applied, while most of the TO→TC type gaits with the same scale factor can achieve rolling successfully. This indicates that the actuation margins of TC→TO type gaits are generally smaller than the margins of TO→TC type gaits. The number of actuators, the scale factor, and the gait type has combined effects on the robustness of gaits. For example, gait 30 has six actuators and a scale factor of 0.8, but the robustness of it is smaller than gait 27, which has five actuators and a scale factor of 0.8. This might be due to the relatively small actuation margins of gait 30.

Table 6. Results of robustness evaluation.

| Gait no. | NUM^s_i | ROBUST^s_i | Gait no. | NUM^s_i | ROBUST^s_i |
|----------|---------|------------|----------|---------|------------|
| 1        | 49      | 0.98       | 16       | 48      | 0.96       |
| 2        | 0       | 0          | 17       | 48      | 0.96       |
| 3        | 0       | 0          | 18       | 47      | 0.94       |
| 4        | 48      | 0.96       | 19       | 49      | 0.98       |
| 5        | 0       | 0          | 20       | 49      | 0.98       |
| 6        | 0       | 0          | 21       | 49      | 0.98       |
| 7        | 50      | 1          | 22       | 49      | 0.98       |
| 8        | 0       | 0          | 23       | 49      | 0.98       |
| 9        | 0       | 0          | 24       | 49      | 0.98       |
| 10       | 49      | 0.96       | 25       | 49      | 0.98       |
| 11       | 49      | 0.98       | 26       | 49      | 0.98       |
| 12       | 49      | 0.98       | 27       | 49      | 0.98       |
| 13       | 47      | 0.94       | 28       | 48      | 0.96       |
| 14       | 47      | 0.94       | 29       | 48      | 0.96       |
| 15       | 47      | 0.94       | 30       | 0       | 0          |

Experiments

Physical prototype

Experiments on a physical prototype of the six-strut spherical tensegrity robot are carried out to verify the proposed concept and method. The physical prototype that is based on the configuration detailed in the third section was manufactured, as shown in Figure 5. The properties of the members used in the prototype are identical to those given in Table 2. Six servo linear actuators are used as active struts, and 24 rubber ropes are used as tendons, and the actuators and rubber ropes are connected with 3D printed nodes. The servo linear actuators each have an initial length of 15.6 cm and able to actively change to 25.6 cm at a rate of 14 mm/s. At the initial state, they extend to 20 cm to prestress the system. The weight of each servo linear actuator is 56.0 g and the weight of each 3D printed node is 4.0 g. Hence, a servo linear actuator plus two nodes at the ends of it has a total weight of 65.0 g. The rubber ropes each have an initial length of 6.0 cm, a stiffness of 104 N/m, and a weight of 1.0 g. In the center of the prototype system, a control box consisting of a Bluetooth communication module, a servo control module, and a lithium battery is attached to the nodes with 24 rubber ropes the same as those used for tendons. It has a size of 50 x 50 x 60 mm$^3$ and a weight of 127.6 g. Note that the nominal properties of the structural members and the control components given above are identical to the corresponding assumed properties used in the numerical simulations.

The prototype is wirelessly controlled through Bluetooth communication with a control program installed in a personal computer. The control program with a graphic user interface (GUI) is developed base on the stm32 platform. Each actuator can be controlled by executing an input command, and multiple actuators can be actuated simultaneously by this program to achieve a rolling gait. By inputting a series of commands, multiple step control of the actuators can be conducted to achieve a series of rolling
gaits for long-distance locomotion. The real-time actuation can be read on the GUI.

**Experiment scheme**

The rolling gaits listed in Table 3 are tested using the physical prototype. Though the rolling gaits listed in Table 3 are all represented as using TC-6 or TO-5 as the initial touching-ground triangle, they are also applicable to other initial states due to the pyritohedral symmetry of the structure with order $S = 24$, which means that there are 24 unique combinations of rotations and reflections that result in an equivalent configuration. As a result, the repeated tests for each gait are conducted by switching the starting touching-ground triangle according to the pyritohedral symmetry of the structure. Specifically, six tests are conducted for each gait in gaits 1–12, and the corresponding starting touching-ground triangles are TC-1, TC-2, TC-3, TC-4, TC-6, and TC-7, respectively, in which TC-2, TC-3, and TC-7 can be transformed into each other by a rotation operation with a rotation angle of 120°, and TC-1 and TC-6 can be transformed into each other by a combined rotation(60°)-reflection operation, while six tests are conducted for each gait in gaits 13–30, and the corresponding starting touching-ground triangles are TO-1, TO-2, TO-3, TO-4, TO-5, and TO-6, respectively, in which TO-1 and TO-2 (as well as TO-4 and TO-5) can be transformed into each other by a reflection operation, and TO-3 and TO-5 (as well as TO-6 and TO-2) can be transformed into each other by a rotation operation with a rotation angle of 180°. The robustness of gaits in the experiment is calculated using equation (7).

**Experimental results**

A typical successful rolling is shown in Figure 6. The tensegrity robot starts with a touching-ground triangle of TO-2 and achieves the rolling by using a control strategy corresponding to the gait 13. The experimental results of robustness evaluation are listed in Table 7. Note that the superscript $p$ denotes experimental results, and NUM$_{i, su}$ = 6 for all gaits. It is shown that the robustness of gaits increases as the number of used actuators increases. For gaits 1–12, ROBUST$_{p}$ of gaits 1, 4, 7, and 10 (i.e. the gaits with the same scale factor of 1.0) are 0.33, 0.33, 0.00, and 0.50, respectively, indicating that the robustness of the gaits with six actuators is greater than the robustness of the gaits with fewer actuators. For gaits 13–30, ROBUST$_{p}$ increases from 0.33 to 0.67 as the number of actuators increases. The robustness of most of the gaits follows this trend, although the robustness of some gaits (e.g. gaits 7–9) deviates. The decreasing of the scale factor of actuation lengths may lead to a decreasing in the robustness. For example, in gaits 10–12, ROBUST$_{p}$ decreases from 0.5 to 0.17 as the scale factor decreases from 1.0 to 0.8. The robustness of TO→TC type gaits is higher than the robustness of TC→TO type gaits. The average value of ROBUST$_{p}$ of gaits 1–12 is 0.19, much smaller than the average value of 0.44 of gaits 13–30. The above findings from the experimental results are qualitatively consistent with the findings from the numerical simulations in general. However, there are nonignorable quantitative differences between the experimental and numerical results. The possible reasons for the differences are as follows. The physical prototype is different from the numerical model.
In the numerical model, the size of the nodes and the sectional sizes of the struts and tendons are ignored, resulting in a geometrical deviation from the physical prototype. Moreover, in the numerical model, the control box is simulated by adding equivalent mass to the nodes, and thus, the eccentric effect of the control box during motion cannot be considered. The distributions of the uncertain parameters used in numerical simulations are ideally assumed and different from the real distributions in the experiments.

Conclusions

A practical method is proposed for the robustness evaluation of rolling gaits of tensegrity robots. A mathematical model is built to describe the evaluation process, and the success rate of rolling is adopted as an indicator of robustness. Sensitivity analysis and robustness evaluation are conducted on the rolling gaits of a six-strut tensegrity robot. Specifically, the sensitivities of rolling gaits to five uncertain parameters, that is, tendon stiffness, initial tendon prestress, the equivalent mass of nodes, actuation lengths of actuators, and slope of the ground, are analyzed, and then, the robustness of rolling gaits is evaluated by correlated random sampling on the five uncertain parameters. Experiments are carried out using a physical prototype of the six-strut tensegrity robot. Based on the numerical and experimental results, it is found that the robustness of rolling gaits increases as the number of used actuators increases; and reducing the actuation lengths proportionally is observed to lead to the decreasing of the gait robustness. Moreover, the robustness of TC→TO type gait is usually lower than the robustness of TO→TC type gait, and the robustness of the gaits might be combinedly affected by the number of actuators, the actuation lengths, and the gait type.

The qualitative agreements between the numerical results and the experimental results indicate that the proposed robustness evaluation method is effective in both simulated cases and physical cases. There are still quantitative differences between the experimental and numerical results. This is caused by the unavoidable difference between the numerical model and the physical prototype: (1) the numerical model simplifies the real three-dimensional components and joints of the tensegrity robot by lower-dimensional idealized virtual components and volume-less nodes, which makes the numerical touching-ground triangle deviate from the experimental one; (2) the self-weight of the system is applied by equivalent nodal masses in the numerical model, ignoring the change of mass distribution during rolling; and (3) the magnitudes and distributions of the uncertainties are ideally assumed. Using a more elaborate physical prototype and an improved numerical model will be able to reduce the differences between the numerical and experimental results. For example, the stability of the contact between the joints and the ground can be improved using ball-like plastic joints as used by the Reservoir Compliant Tensegrity Robot, and the magnitudes and distributions of some uncertainties such as the tendon stiffness, the initial tendon prestress, the equivalent mass of nodes, and actuation lengths of actuators can be determined by repeated tests in advance. These improvements will be adopted in the authors’ future works. It is also worth noting that since the magnitudes of the uncertainties is assumed in advance, the effect of the magnitude of the uncertainties on the robustness of a given rolling gait is not shown in this study and needs further investigation.

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