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Sensor Placement for Control of a Meter-Scale Origami Structure

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Abstract

This study delves into the deployment dynamics of a meter-scale origami pill bug (OPB) structure, a novel design inspired by the morphological characteristics of pill bugs. Monitoring the development of strain within the structure during deployment is crucial for understanding its behavior. To achieve this, strain gauges and load sensors are employed. The objective of this paper is the development of a sensor placement optimization algorithm to ensure efficient and holistic data collection with a limited number of sensors. The results from this analytical study will inform the experimental setup by prioritizing the placement of strain gauges to these critical locations. The optimized placement of the strain gauges will ensure effective and efficient data collection. Additionally, insights gained from this research can provide valuable information on control strategies for the structure. The synergy of analytical and experimental approaches contributes to a comprehensive understanding of the deployment dynamics of the OPB structure, offering potential advancements in the design and control strategies of origami-enabled structures in civil engineering.

Keywords: Origami, actuation, sensor placement, dynamic relaxation

1. Introduction

Adaptive structures, with their ability to modify their properties in response to changing environments, offer a promising avenue for sustainable infrastructure development. Their versatility extends beyond aerospace applications (Pellegrino 1995), holding promise for the civil engineering sector as well. However, their deployable nature introduces geometrically non-linear behavior and large displacements, posing challenges for conventional design tools (Gantes et al. 1989). Due to the application-specific nature of these adaptive structures, there is a pressing need to investigate structural health monitoring methods that can effectively assess their condition and facilitate broader implementation in civil engineering applications.

Origami's influence on engineering design has gained significant traction, inspiring diverse structures from deployable solar panels (Miura et al. 1985) to self-assembling stents and configurable materials. This influence extends beyond simple foldability, as the understanding of origami geometry has been leveraged to design rigid-foldable structures and even provide insight into the kinematics of folded metamaterials (Schenk and Guest 2013). However, while modeling approaches using pin-jointed bars offer valuable insights (Filipov et al. 2017), bridging the gap between theoretical models and real-world applications remains a challenge.

Dynamic relaxation, a vector-based static analysis method by Otter (1965) and Day (1965), offers a valuable tool for analyzing origami-inspired adaptive structures due to its efficient handling of structural nonlinearities. By avoiding matrix inversion, it significantly reduces computational costs of nonlinear analysis. The method was modified to incorporate kinetic damping, improving convergence. While dynamic relaxation method has been used to model the behavior of adaptive structures (Kmet et al. 2012), further investigation is needed to fully explore the viability of dynamic relaxation method in assessing the shape and behavior of mid-scale deployable origami prototypes.

This objective of this paper is to study the deployment of a meter-scale origami pill bug structure using dynamic relaxation analysis to optimize sensor placement for health monitoring. Through an analytical approach, the study aims to identify critical areas within the structure. These results will then guide the placement of sensors in the experimental setup, prioritizing critical locations to ensure efficient and comprehensive data collection while minimizing sensor count.

2. Methodology

2.1 The Origami Pill-Bug Structure

The novel design of the origami pill bug (OPB) structure is inspired by the adaptive behavior of pill bugs from the Armadillidiidae family. A pill bug's ability to roll into a ball in response to external stimuli stems from their sub-cylindrical shape and segmented hard-shell body, enabling them to exhibit conglobation through the contraction of internal musculature, as depicted in Figure-1(A). The OPB structure emulates these morphological traits using origami principles. Comprised of segmented modules, the OPB structure transitions from an unrolled to a rolled configuration when actuated, as shown in Figure-1(B). Actuation is achieved by increasing tension in the actuation cable connected at the structure's base, prompting the segmented modules to fold and roll up, thereby mimicking the pill bug's conglobation behavior.

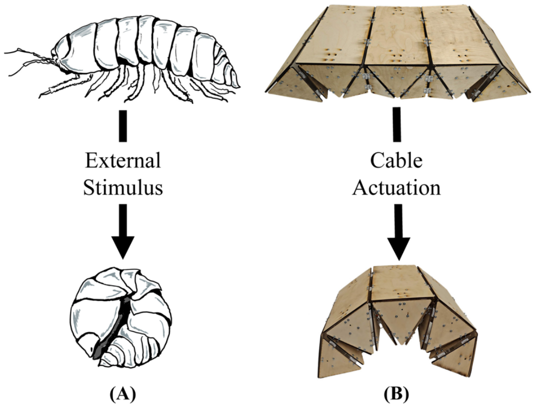

Figure-1: (A) Pill bugs exhibiting conglobation as a result of muscle actuation. (B) Rolling of the OPB structure as a result of cable actuation.

2.2 Simulation using Dynamic Relaxation Method

This study leverages a novel module integrated with the dynamic relaxation (DR) method (Sychterz and Baruah 2021) to simulate the behavior of the OPB structure. This empowers the DR framework with the capability to characterize origami hinge stiffness, rendering it adept for the development of iterative actuation algorithms for such structures. The efficacy of the DR method, in analyzing mid-to-large-scale origami structures was demonstrably validated through a comprehensive comparison of simulation results with experimental data obtained using computer vision (Baruah and Sychterz 2022).

This investigation delves into the non-linear static analysis of the OPB structure under various damage scenarios utilizing the enhanced DR method. For damaged instances, the model assumes a complete loss of stiffness in a designated bar element, rendering it incapable of withstanding any stress. This is implemented within the DR framework by assigning a value of zero to the affected bar's area, effectively removing the element from the computational model. It is crucial to emphasize that this study focuses solely on the failure of a single element at a time and does not encompass the simultaneous failure of multiple elements within the same model.

2.3 Strain Energy-Based Stability Assessment

The internal force distribution in each element is determined using the Dynamic Relaxation (DR) method at each deployment step. To evaluate the stability of the damaged structure, a strain energy density-based approach is employed.

For each damage case (k), the strain energy density ($U_{k,ij}$) within each member (i) at each deployment stage (j) is calculated using the following equation:

$$U_{k,ij} = \frac{\left(F_{k,ij}\right)^2}{2\, A_i{}^2 E_i} \tag{1}$$

where:

$U_{k,ij}$: Strain energy density of member i in damage case k at deployment stage j
$F_{k,ij}$: Internal force in member i obtained using DR method in damage case k at deployment stage j
A_i: Cross-sectional area of member i
E_i: Young's modulus of member i

The strain energy density represents the energy stored per unit volume of the material due to deformation. By summing the strain energy density of all members (i) for a specific damage case (k) at each deployment step (j), the total energy ($E_{k,j}$) is obtained:

$$E_{k,j} = \sum_i U_{k,ij} \tag{2}$$

This value reflects the overall internal energy stored within the structure under that particular damage scenario and deployment stage. To capture the most critical effect of damage on the structure's stability, the system energy (W_k), which is the maximum total energy across all deployment stages (j) for a given damage case (k), is considered:

$$W_k \ = max_j \left(E_{k,j}\right) \tag{3}$$

This system energy serves as an indicator of the structure's ability to withstand damage and maintain stability during deployment.

3. Results

To analyze the impact of damage on structural stability, the net change in system energy compared to the healthy structure was investigated for all damage cases. This metric provides valuable insight into the relative impact of different damage scenarios on overall structural stability. Figure-2 presents a bar plot showing the net change in system energy for all investigated damage cases. The top 15% of cases exhibiting the most significant changes in system energy compared to the healthy structure are highlighted in red. The corresponding elements, therefore, are referred to as critical elements as damaging these elements has the most significant effect on the structure's overall stability.

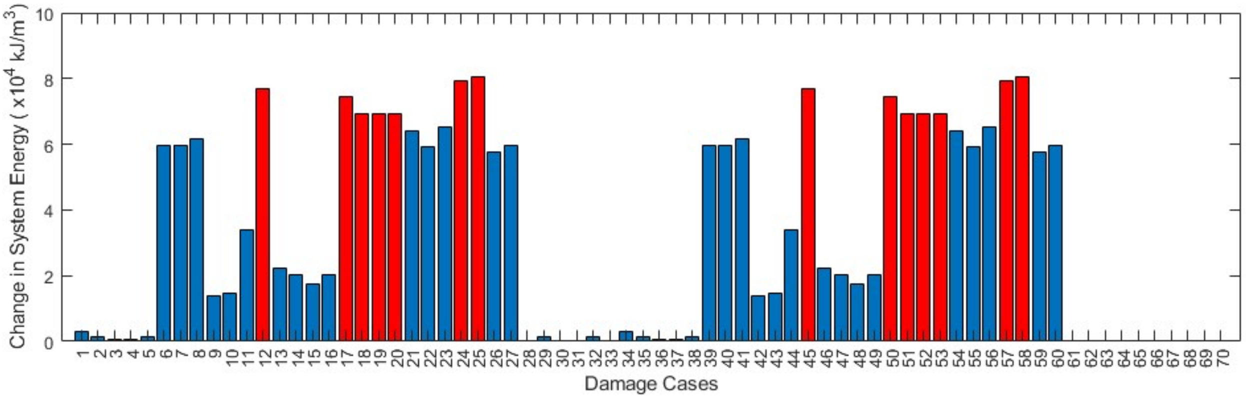

Figure 2:Change in system energy for each damage case compared to the healthy structure. The top 15 % (red) represent critical scenarios with the most change.

Figure-3 depicts the OPB structure with the critical elements (elements number 12, 17, 18, 19, 20, 24, 25, 45, 50, 51, 52, 53, 57 and 58) highlighted by the red solid lines, indicating their location within the structure. For targeted monitoring, sensor placement in the experimental model focuses on these critical locations.

Leveraging this damage-centric analysis, a strategic structural health monitoring approach can be implemented. Prioritizing critical elements identified through this process allows for the optimization of sensor deployment, focusing on high-impact zones. This minimizes redundancy while maximizing information gain, providing an efficient framework for complex origami systems. Correlating sensor data with established critical element behavior enables engineers to make informed decisions about maintenance needs, facilitating early detection of potential issues and ensuring the reliability in real-life applications of deployable origami structures.

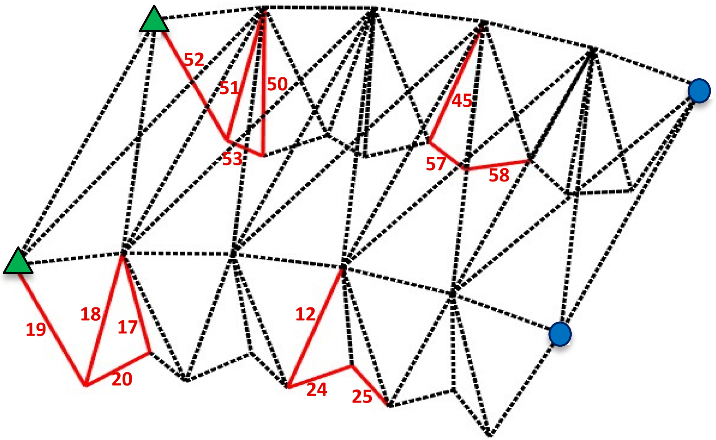

Figure 3: Critical elements (12, 17, 18, 19, 20, 24, 25, 45, 50, 51, 52, 53, 57, and 58) highlighted by the red solid lines in the OPB structure. Pinned supports are shown as green triangles and roller supports are shown as blue circles.

4. Conclusions

The study successfully identifies critical locations within the origami pill bug structure for optimal sensor placement. Concentrating sensors in these critical regions enables comprehensive structural health monitoring while minimizing the number of required sensors. This strategic approach successfully enhances data quality for assessing structural integrity and performance and demonstrates an efficient framework for sensor deployment in complex origami systems. The successful implementation paves the way for further research into the durability and reliability of origami-based structures in real-world applications.

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