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Soft deformable surface based on origami structures

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Resumen

Este trabajo presenta el diseño de una superficie deformable compuesta por módulos hexagonales de origami basados en el patrón de Kresling. Estos módulos actúan simultáneamente como elementos estructurales y sensores de deformación, con la capacidad de detectar cargas externas aplicadas sobre la superficie. El proceso de validación experimental incluye una serie de pruebas. Entre ellas figuran la configuración de los módulos en diferentes topologías, la evaluación del comportamiento estático bajo cargas controladas y el análisis del movimiento dinámico de objetos. Los resultados obtenidos demuestran la viabilidad y efectividad de los módulos de origami para la implementación de superficies deformables sensorizadas, destacando su potencial en una variedad de aplicaciones.

Palabras clave: Superficie blanda deformable, Sistemas sensorizados, Estructuras de origami.

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Abstract

The present paper proposes a design for a deformable surface using hexagonal origami modules based on the Kresling pattern. These modules function as structural elements and deformation sensors, with the capacity to detect external loads. The experimental validation process involves a series of tests. These include the configuration of modules in different arrangements, the evaluation of static behavior under controlled loads, and the analysis of dynamic object movement. The findings of the study demonstrate the viability and effectiveness of origami modules for sensorised surfaces, highlighting their potential across a range of practical applications.

Keywords: Soft deformable surface, Sensorized systems, Origami structures.

1. Introduction

Shape-changing deformable surfaces represent a technological frontier that is evolving rapidly, with materials and structures that dynamically adapt their geometry in response to external stimuli or programmed commands. These surfaces, capable of transforming between multiple configurations, are driving innovations in robotics, biomedical engineering, human interfaces and even architecture.

The ability of these surfaces to change shape depends on sophisticated mechanical designs, smart materials and novel actuation strategies. Interfaces that are capable of altering their configuration are emerging as a significant medium for both input and output in the domain of human-computer interaction. In the context of interaction, Rasmussen et al. (2012) identifies three primary approaches: 1. No interaction, the shape transformation occurs only as an output. 2. Indirect interaction, the shape responds to implicit inputs from the user or the environment. 3. Direct interaction, the shape simultaneously provides user input and system output through its physical transformation. Examples of such systems include Topobo (Raffle et al. (2004)) and the Origami Mouse

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(Mintchev et al. (2019)), which illustrate how physical transformation can serve both to control the system and to receive feedback. The versatility of these surfaces allows for their integration into a variety of applications. In the case of reconfigurable displays, systems have the capacity to transform their configuration in a matter of seconds, thereby dynamically adapting to the type of content displayed, by Dand and Hemsley (2013); Everitt and Alexander (2017). In the field of soft robotics, Shah et al. (2021) has developed a soft robot capable of changing its shape to move more efficiently across different terrains. The system exhibits superior performance in comparison to a rigid one, due to its capacity for automatic adaptation to different environments. Interconnected panel systems using 3D printing technology also generate such surfaces. Consisting of rigid panels connected by flexible links, they enable liquid-like deformations with far fewer actuators. Made from photopolymer resins, they can achieve large-scale curved changes with 80% greater efficiency than traditional vertical pin systems, by Everitt and Alexander (2019).

The present study proposes the creation of a deformable surface employing hexagonal origami modules based on the Kresling pattern (Kresling and Abel (2008)). These modules have the capacity to generate honeycomb-like surfaces, resulting in a range of possible configurations. The basis for this proposal is the non-interacting surface, it means passive behaviour. The proposal exploits the metamaterial properties of polypropylene (MP-PC146 sheet) when structured into a three-dimensional Kresling pattern, as previously demonstrated in Mena et al. (2023). The resulting configuration allows for analogue motion throughout the folding and unfolding cycles, a consequence of the shape-memory characteristics of the material and its intrinsic multi-stable behavior. It is therefore proposed to employ the origami module as a deformation sensor, with the objective of registering the influence of a load when it is placed on the top cover of the origami module.

The objective of this study is to demonstrate the reconfigurability, scalability and modularity of the modules based on origami structures. Several factors must be taken into consideration: The surface may contain an arbitrary number of modules, provided that the hexagonal geometry of the modules generates uniform planes in the shape of a honeycomb. Secondly, the construction of the modules is scalable in both size and strength, and the dimensions do not influence the behavior of the module as long as the Kresling pattern is maintained. It is evident that the sensorised soft surface in a variety of applications holds considerable potential. These applications include the measurement and analysis of footstep, posture and forces generated in the feet for the purpose of performance analysis of athletes. Additionally, the coating of skin as a touch sensor for robots or for the modeling of complex object shapes is a promising development.

The document is organized as follows. The design, fabrication and sensor tuning of the prototype are described in Section 2. The results of the tests carried out are presented in Section 3. Finally, conclusions and future work are summarized in Section 4.

2. Materials and methods

The main module to create a deformable surface consists of an origami Kresling pattern. The structure exhibits a configuration of triangular panels that are identical, showing cyclic symmetry. The triangulated polyhedron geometry is based on the constant values a, α, and β. Kresling structure enables folding and unfolding states, which change the height of the module, including the continuous rotation around angle θ (see Figure 1).

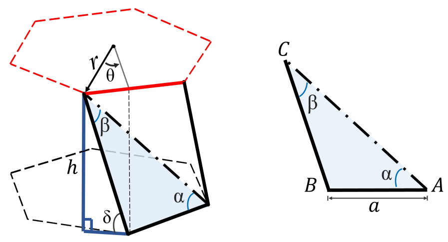


Figure 1: Triangulated polyhedron geometry of origami Kresling pattern.

The deformation of the module (represented by the value h) is measured using a VL6180X Time-of-Flight (ToF) sensor, which accurately determines distance using a miniature laser source and an integrated coincidence sensor. The sensor employs a Class 1 laser, compliant with IEC 60825-1:2014. The VL6180X is able to detect the time of flight, which is defined as the time taken for the laser light to bounce off the sensor. As it employs a narrow light source, the sensor is only capable of determining the distance to the surface directly in front of it. In contrast to sonars that emit ultrasonic waves, the detection cone is narrow. Unlike infrared distance sensors that attempt to measure the amount of light reflected, the VL6180X is more accurate and does not suffer from linearity or double image problems, where it is difficult to identify the distance of an object. The measurement range is between 5mm and 100mm, and the device features an I2C protocol for data readout. It is powered from 3V to 5V.

The construction of the module includes a base to enclose the ToF sensor. The base is hexagonal in shape and contains the holes for mounting the sensor and the origami module. The base design is 42.5mm in height, comprising two supports at the base and an internal cavity to facilitate access to the ToF sensor connector, while allowing the cables to exit through the space between the supports. Thereby, several modules can be placed next to each other, without the cables disturbing the creation of the honeycomb surface.

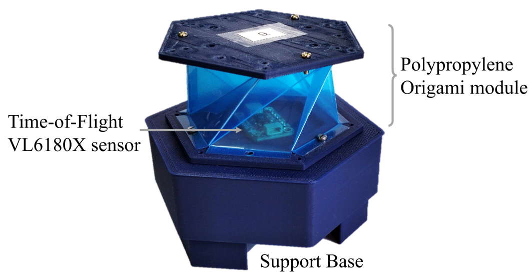


Figure 2: Prototype of an origami module for deformable surfaces, comprising a polypropylene structure integrated with a time-of-flight sensor and a stable support base.

The fully assembled prototype, comprising the base, the time-of-flight sensor and the polypropylene origami module corresponding to the Kresling pattern designed with $\alpha = 38°$, $\beta = 30°$, and $a = 30mm$, which results in $h = 29.5mm$, is shown in Figure 2.

This modular design enables the creation of surfaces with a wide range of configurations, from a single module up to n modules. Figure 3 illustrates various configurations using three, six, seven, and nine modules, highlighting the versatility of the soft surface approach.

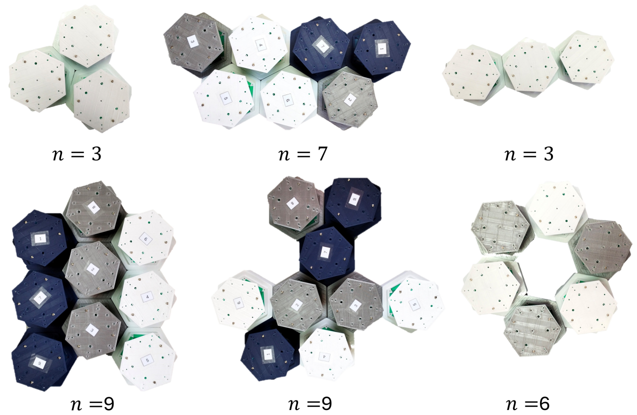


Figure 3: Soft surface with different configurations including three, six, seven and nine modules.

Subsequent to the fabrication of the module that is able to generate surfaces with multiple configurations, the following step involves the connection of the appropriate sensors in order to obtain accurate surface data. Sensor communication is managed via the SCL and SDA pins associated with the I2C protocol on an Arduino Mega board. Communication is simple when employing a single VL6180X sensor, thanks to the use of the Adafruit_VL6180X.h library. This specialized library simplifies sensor interaction by providing direct and convenient access to distance measurements, streamlining data acquisition, and significantly reducing the complexity typically associated with sensor integration, programming, and implementation.

For applications involving multiple VL6180X sensors, the XSHUT pin is used to individually enable or disable each sensor via separate digital output pins on the Arduino board. This method is essential for managing multiple sensors simultaneously, as it allows the assignment of unique I2C addresses and prevents communication conflicts during initialization.

In order to ensure reliable communication and to avoid interference between devices, sensor readings are carried out in a sequential manner. Each sensor is activated individually, with a delay of 10 milliseconds between activations, allowing adequate time for initialization and measurement. Once the data from all sensors is collected, it is transmitted via serial communication to a connected device or computer. The transmitted values are then stored in a comma-separated values (CSV) file, enabling easy handling and later analysis. The system operates with a fixed sampling interval of 300 milliseconds, achieving a balance between responsiveness and data stability. The complete algorithm responsible for managing sensor detection, activation, and data acquisition is detailed in Algorithm 1.

Algorithm 1 Sensor Initialization and Reading

```
procedure InitializeSensors
    Set all sensor shutdown pins (XSHUT) to LOW
    Wait 10 ms
    Set all sensor shutdown pins (XSHUT) to HIGH
    Wait 10 ms
    for sensorIndex = 1 to n do
        Set current sensor pin HIGH
        Set other sensor pins LOW
        Wait 10 ms
        Initialize sensor at predefined I2C address
    end for
end procedure
procedure ReadSensor(sensor)
    lux ← sensor.readLux()
    range ← sensor.readRange()
    status ← sensor.readRangeStatus()
end procedure
procedure ReadAllSensors
    for each sensor i from 1 to n do
        ReadSensor(sensors[i])
        Save the temporary range value to sensor_ranges[i]
    end for
end procedure
procedure MainLoop
    InitializeSensors
    while true do
        ReadAllSensors
        Print sensor_ranges array
        Wait 100 ms
    end while
end procedure
```

3. Tests and results

After the prototype was fully developed, a series of experimental tests were designed to evaluate the performance and behavior of the proposed soft surface system, composed of seven interconnected origami-based modules. Three different tests were carried out in order to evaluate the responsiveness and deformation capabilities of the system under various conditions. Test 1 and Test 2 were conducted using a circular configuration of the modules, as illustrated in Figure 4, to observe coordinated motion and deformation across the surface.

Figure 4: Soft surface circular configuration with seven modules, for Tests 1 and 2.

The first test evaluates the behaviour of individual modules by manually folding each one in sequence, from module 1 to module 7. As the folding process is performed manually, the duration of each fold is not standardized or considered in the analysis. The results, shown in Figure 5, indicate a total test duration of 27 seconds, during which the height variations of all modules were continuously recorded. Minor discrepancies were observed in the initial distance readings from the sensors, which may have slightly influenced the accuracy of the deformation measurements. Despite this, the deformation range of each module was successfully determined, with an average linear displacement of 24.7 mm. This initial test validates the accurate performance of each module and confirms the effectiveness of the deformation measurement system integrated into the soft surface.

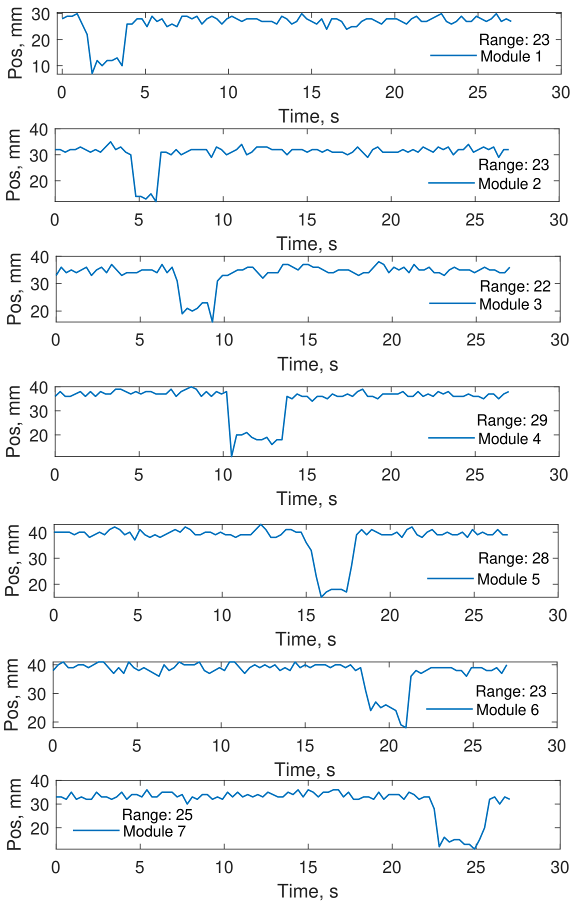


Figure 5: Soft surface circular configuration. Test 1 position results.

The second test involves the simultaneous application of a 200g payload to modules 1 and 4 to evaluate their displacement behavior under load. Module 4 supports a single 200g payload, while module 1 is loaded with two separate 100g payload to ensure consistent mass distribution. The other modules remain fully deployed and unloaded throughout the test. The effects of these applied loads on the deformation of the targeted modules are illustrated in Figure 6, highlighting the response of the system to localized weight and the consistency of the deformation range reading with 19mm and 18mm for the modules 1 and 4, respectively.

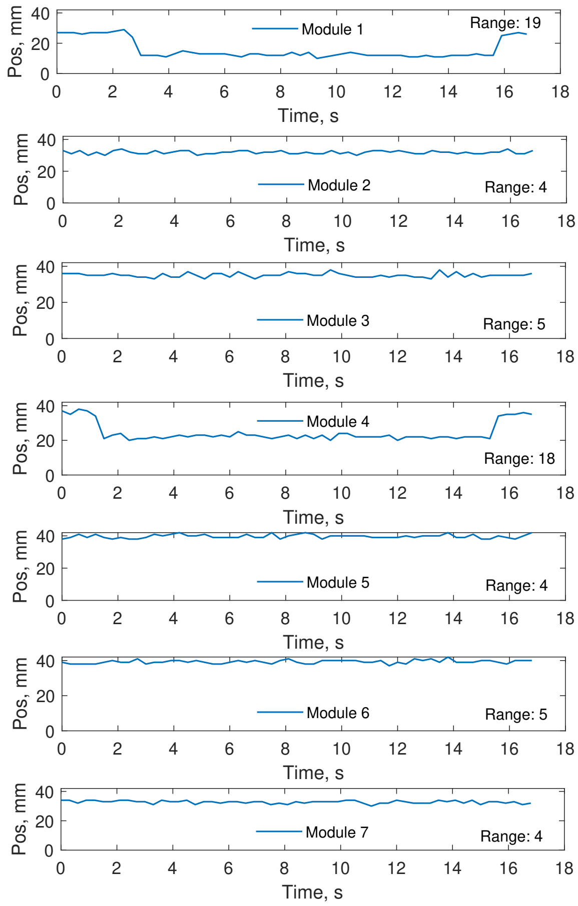
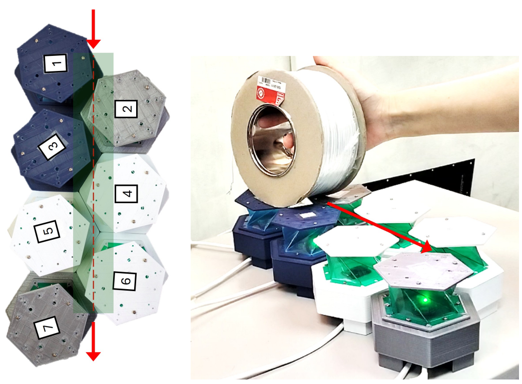


Figure 6: Soft surface circular configuration. Test 2 position results.

The two previous tests were performed statically by individually folding the modules. For the third test, a dynamic assessment is proposed involving the displacement of a load across the soft surface. A surface configuration consisting of seven modules aligned in two rows is employed, as shown in Figure 7 (a). A cable reel serves as the test object, which is rolled over the soft origami module surface following the path indicated by red arrows in Figure 7. The purpose is to measure and analyze the deformations induced by object movement over the surface.



(a) (b)

Figure 7: Test 3 setup. (a) Soft surface of two rows configuration with seven modules. (b) The cable reel as test object rolling over the surface.

The test was carried out, and the results are presented in

Figure 8, Figure 9, and Figure 10. As the object rolls across the surface, it interacts with the modules through manual contact, resulting in varying force distributions. This interaction triggers sequences of folding and unfolding among the modules, generating a deformation pattern that reflects the distribution and magnitude of the forces exerted by the moving object.

Figure 8 illustrates the ToF sensor readings across all modules during the test. Similar to Test 1, a sequential deformation pattern is observed; however, in this dynamic scenario, multiple modules may deform simultaneously in response to the moving load. This test effectively highlights the soft surface's capability to adapt to dynamic interactions, confirming its responsiveness to varying force distributions over time.

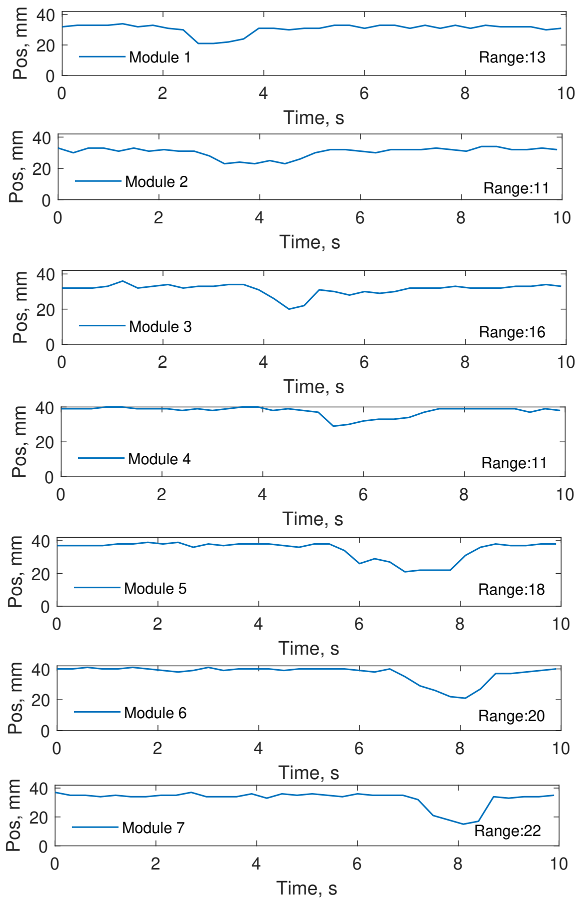


Figure 8: Soft surface of two rows configuration with seven modules. Test 3 position results.

The displacement range for each module has been calculated to evaluate the mechanical response of the system. Table 1 summarizes the deformation ranges recorded during Tests 1, 2, and 3, providing a basis for comparative analysis of the behavior of the soft surface under both static and dynamic loading conditions. This comparison provides valuable insight into the consistency and adaptability of the surface across different test scenarios.

To illustrate the sequence of movement and deformation of the soft surface, Figure 9 presents a two-dimensional visualization. A color bar indicates the magnitude of deformation, while the X-axis represents time and the Y-axis corresponds to the module number.

Table 1: Deformation ranges of each module in Tests 1, 2, and 3.

	Module						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Test 1 (mm)	23	23	22	29	28	23	25
Test 2 (mm)	19	4	5	18	4	5	4
Test 3 (mm)	13	11	22	18	20	11	16

In contrast, Figure 10 displays the same data in a three-dimensional format, enabling a more comprehensive representation of module behavior during Test 3. Both figures clearly depict the progression of displacement and surface deformation caused by the object, as well as the subsequent recovery of the modules to their initial positions.

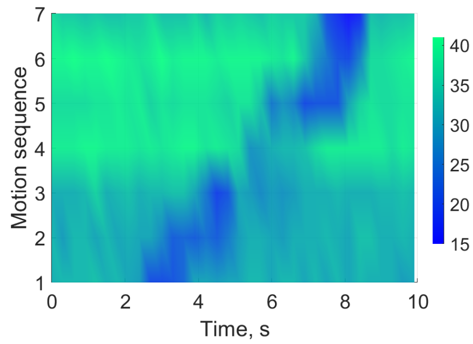


Figure 9: Soft surface of two rows configuration with seven modules. Test 3 motion sequence results in 2D.

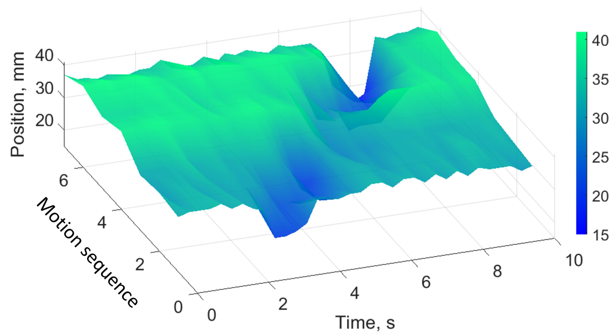


Figure 10: Soft surface of two rows configuration with seven modules. Test 3 motion sequence results in 3D.

The results of Test 3 fully validate the proposed method for measuring deformations using origami modules based on the Kresling pattern. Deformation occurs in a continuous, analog manner, and thanks to the shape memory properties of the polypropylene material, the modules reliably return to their original configuration after deformation. These findings confirm the effectiveness of the system under dynamic conditions.

4. Conclusions

In conclusion, the proposed soft surface demonstrates the scalability of the origami-based modules and validates their effectiveness as a deformation sensing mesh. The system has demonstrated its capacity to accurately detect and respond to both static loads and dynamic displacements across the surface.

Three experimental tests were conducted to validate the performance of the proposed deformable surface. The first test confirmed dynamic adaptability through sequential folding in a circular module arrangement. The second demonstrated static stability under applied loads. The third and most extensive test evaluated the surface's ability to track dynamic object movement, successfully generating detailed deformation maps. These results confirm the feasibility of using origami-inspired modules for responsive, sensorized surfaces.

Future work will focus on scaling the system for applications such as footprint detection, pressure mapping, and tactile sensing in robotic skin systems.

Acknowledgements

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