Investigation of Multi-Physical Sensing in Soft Robots via Signal Transduction Mechanisms

Senhao She

{ss2468@sussex.ac.uk}

School of Engineering and Informatics, University of Sussex, Brighton, East Sussex, BN1 9RH, UK

Abstract. The recent days of Soft robots exhibit unique advantages in complex interaction scenarios due to their compliance and inherent safety. However, the unique advantages substantially increase the difficulty of designing reliable perception systems. In practical applications, a single sensing mechanism often fails to ensure stable and robust perception. Therefore, this work presents a systematic analysis of multi-physics perception approaches in soft robotics from the perspective of signal transduction mechanisms. This article will concentrate on the topic of the features and uses of three common sensing systems, which are electrical, optical, and sound, in terms of real-time response and deep information acquisition. Looked at are the roles of multimodal integration and intelligent decoding in reducing signal uncertainty and making perception more reliable. It is shown that multi-physics perception can effectively compensate for the limitations of single-modality sensing, providing system-level theoretical insights for the design and application of soft robotic perception systems.

Keywords: Soft robotics, compliant robotic systems, Intelligent tactile perception, signal decoding, Multimodal sensing

1 Introduction

Soft robots rely on their capabilities such as compliance, adaptability and extensiveness. The situation that they provide increases the safety in the interaction with the human and environment. One more common sphere of application of soft robots is medical rehabilitation, industrial assistance and control in complex environments [1-3]. But at the same time, these very flexible properties make it difficult to have an accurate perception of the state. The soft structures are usually subjected to huge deformations and have strong material nonlinearities and are structurally continuous, so that only a single sensing mechanism can hardly yield real time and dependable strain data or state of the structures. Consequently, there is a possibility of sensing delays or misunderstandings. Thus, the evolution of the complementary multimodal perception systems has been identified as the critical component of the enhancement of the intelligence of the soft robots[4-6].

Multi physics perception is a field of study that seeks to combine those senses that are rooted in dissimilar physical phenomena into a versatile organism that can concurrently obtain and transfer multisource data. Electrical sensing is simplicity in its structure and easy to incorporate

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enabling measurements of quantitative strain and tactile pressure. However, it has a restricted functionality through the spatial resolution and vulnerability to electromagnetic interference, which promotes the lack of capability in identifying elaborate tactile details or gross anatomical alterations. By contrast, optical sensing is very sensitive and even resistant to interference effects, providing a platform to overcome the weaknesses of the electrical methods and has extensive application in the areas of shape recognition and reconstruction of tactile sensation.

However in the same time, the situation is that the difficulty that the complexity of optical path deployment and limited compatibility with highly deformable structures restrict its application in flexible systems [7-9].

In recent years, acoustic sensing has attracted increasing attention. The propagation and reflection of acoustic waves in soft materials can be exploited to detect strain, internal structural variations, and non-contact targets, offering strong penetration capability and environmental robustness. As such, acoustic sensing serves as an important complement to electrical and optical approaches [6]. When it was combined with electrical and optical sensing. The acoustic censoring would enable more reliable acquisition of internal states and contact information in dynamic and complex environments [9].

Based on the above considerations. This work presents a recent scientific research which is about the systematic analysis of multi-physics perception methods in soft robotics from the perspective of signal transduction mechanisms.

The electrical, optical and acoustic sensing characteristics and complementary functions of flexible systems are also discussed with special focus on their functionality in conditions of complex deformation and interactions. In addition, based on the multimodal perception and intelligent decoding, existing issues and development perspectives are mentioned within the frames of exemplary application situations.

2 Hardware Integration for Multimodal Perception in Soft Robotics

2.1 Research on Electrical Sensing Tactile and Strain Detection

Tactile and deformation sensors of soft robots are dominated by electrical sensors in the center stage because they have mature formations, they respond swiftly and they are easy to integrate with flexible materials. Traditional flexible resistive or capacitance sensors can deliver useable strain feedback under straightforward circumstances, but in the case of the highly stretchable more complicated-contact more cyclic loading conditions of soft robotics, the signals of such sensors are prone to drift, hysteresis and signal degradation due to the formation of microcracks. These drawbacks place a considerable limitation on the situation, which is, the applicability of electrical sensing in the cases where such a demand as it needs high long-term stability.

To date, changes have occurred in the field of computational materials science. As computation-guided design became more common in the design of soft electronics, the electrical strain sensors have evidently improved the strength of the design. Yang (2024) proposed a structure that integrates a topology optimization strategy with a multiphysics model when improving the conductive-network geometry. The sensors demonstrated almost linear change of resistance (R 2 > 0.99) up to strains beyond 300 wt, and their signal drift was less than 3 percent even after

10,000 cycles, which is better than standard flex-based flexible implementations. The results of experiments also demonstrate that. The optimized sensing units maintain a constant gauge factor in high-frequency dynamic bending action. And real-time state-of-the-art prediction of deformations on the average with an error percentage less than 5 in the tasks of estimating soft fingers shape. These results vividly depict the gains of performance made possible by the shift in the process of empirical design to computation-based design paradigm in electrical sensing materials [1].

In addition to material-level improvements, another pressing problem to electrical sensing in soft robotics is the issue of sensor placement, in which both scientific and efficient layout methods are demanded to enhance the overall observability without considering scaling up their hardware. Due to the continuum topology, infinite number of degrees of freedom, and nonlinear geometry of deformable robots, homogeneous or arbitrary positioning of sensors frequently implies redundancy, information blindness or waste, and causes information ghosts. The sensor placement within the MakeSense system suggested by Tapia (2020) has taken the sensor placement as an approximation problem formulated as a differentiable optimization. The design process is integrated with deformation characteristics, observability as well as sensor sensitivity and it is possible to compute sensor distributions without manually tuning it. Although the method preserves the accuracy of shape reconstruction, it also uses a 40-60 percent smaller number of sensors and reconstructs shape error of soft fingers is no more than 3 percent, which is much lower than the error in a traditional experience-based or even uniform placement strategy. In practice experiments also show that in three dimensional type deformation tasks, the MakeSense-based method is much more accurate in detecting highly deformed areas and allocating sensors to those areas accordingly and hence the error made in curvature estimation is more than 30% lower during dynamic motion. The piece of work also makes known the calculational power of sensor layout optimization but also solidifies electrical sensing as one of the most scalable, most cost-effective, and most mature technologies when it comes to intrinsic state perception of soft robots [2].

Attempting to combine both material-level innovations in ultra-robust sensing behavior with system-level optimization of sensing topology [1,2], electrical sensing is transforming out of isolated flexible electronic elements into intelligent distributed sensing systems. In the context of multimodal perception, electrical sensing remains a central element as it gives quick and delicate tactile and strain data. Optical and acoustic sensing can be integrated with these measurements to help in guaranteeing more accurate state estimation and control in soft robots.

2.2 Research on Optical Sensing Modalities and Spatial Perception

At the level of structural integration, Ham et al. (2022) have demonstrated a situation that the stretchable optical and electrical hybrid sensing network fabricated which is using UV laser processing.

The optical paths are laid in this design which is deformed along with the flexible substrate without attenuating the intensity of the light greatly. The resultant 50 x 50mm flexible sensing network was capable of holding constant optical signals even with large tensile strain and changes in its resistive and capacitive response were much smaller than the drift recently found in traditional flexible sensors operating in the same conditions. In real-life samples, the network incorporated three temperature sensors and six proximity sensors and allowed tracking contacts with cold and hot objects, i.e., 5.5 o C cold bottle and 55.7 o C hot bottle, and local events occurring during contacts of hands and objects [3]. Such experiments are the beginning of high compatibility that lies between optical pathways and elastic substrates. It aids in the viability of the implementation of optical sensing in the soft robotic materials.

After optical structures were aptly modified towards flexible applications, later research was directed to the enhancement of spatial and temporal resolution. Bai et al. (2023) have provided an optical sensing system. Able to solve the fine physiological and surface texture structures by tracking tiny differences in the optical field produced at the point of contact. The method does not use individual sensing elements, but the geometry of the surface is recreated by optical perturbations. The dimensions show a 15 μm spatial sampling interval and approximate of 6 μm height resolution, which can be used to measure details on the surfaces that are normally out of reach to the standard form of electrical sensor arrays. This gave a sensing bandwidth under rapid sliding which spanned dynamic stimuli of stationary contact to approximately 400 Hz, but with a frequency resolution of approximately 0.02 Hz. Overwhelmingly perfect accuracy was obtained under fixed set of the conditions of contact, and the mean accuracy was about 98.9 per cent at the situation where the speed at which the sliding took place or a contact pressure was varied widely [4]. These indications depict the outcome of a study which is that the natural benefits of optical sensing of high-frequency interactions and fine tactile discrimination.

Getting beyond spot-sized high-resolution sensing. Global deformations patterns also can be acquired in optical methods by observing variations in the optical field distributions. The experiment was explored by Wang et al. (2025). The speckle patterns form. In the case of change when optical waveguide is in a flexible form, the structure must deform. Distinct deformation such as bending, twisting and stretching. They have created typical speckle changes. Small deformations resulted in quantifiable variations in the reflection of the powerful sensitivity of speckle patterns to optical path variations. The system with the convolutional neural network designing a decoding proved near ideal accuracy in classification which did not change with the course of several days of tests. The method is also used to remove optimal location of sensors in dense arrays because a single waveguide is used to acquire information on deformation[5].

Taken collectively, these works indicate the linear advancement of optical sensing in the field of soft robotics. Ham et al. discussed the incorporation of optical pathways in flexible constructions, when the sensor that will make optical senses work efficiently in soft materials. Bai et al. also demonstrated that optical techniques could provide much higher spatial and temporal resolution as compared to traditional tactile arrays, particularly when there were high-speed interactions. The specklegram-based one by Wang et al. also demonstrated that optical patterns could be natural encoders. Enabling the use of one flexible waveguide to obtain multiple modalities of deformation. These innovations make a logical order of structure integration to performance improvement. And likewise encoding expansion, which will build a strong experimental and mechanistic base of multimodal perception systems of soft robotics in the future.

2.3 Research on Acoustic Sensing for Deep and Dynamic State Recognition

Shi et al. introduced a multimodal soft robotic sensing system that integrates ultrasonic sensing and triboelectric signals in the field of position-aware acoustic perception. To measure the position of contact and surface pressure in real-time, the system measures time-of-flight separations of ultrasonic waves in a flexible material. The localization error was kept to within a range of 13 mm and the level of accuracy was equally satisfactory given that it was in an experimental mode and thus applicable to deformable structures. Another benefit of the ultrasonic modality is that acoustic signals have an adequate signal-to-noise ratio while transducing through flexible bodies several centimeters in thickness. This will allow the system to identify not only the contact points on the surface, but also internal state changes. Upon the application of multimodal fusion. The performance on the object recognition was toward complete recognition. When it is a definite advancement on the approximately 80% accuracy that can be obtained with the acoustic sensing alone [6]. These findings indicate that acoustic localization is capable of facilitating accurate positioning of contacts as well as consistent multimodal recognition.

Handling the nonlinear strong behavior of acoustic waves propagation in soft materials. Yin and Muller have shown a data-driven approach where deep learning models have been applied to the acoustic responses to decode them directly. When it circumvents the constraints of paradigms of conventional physics-based modeling in large nonlinear deformation. Neural networks in their experiments have the capacity to differentiate between various modes of deformation, bending, twisting, and localized compression and classification rates of between 90 to 98. Learning-based inference was found to outperform traditional model-based estimates of recognition accuracy by an average of 15%25 with the difference between the two performance metrics increasing with deformation magnitudes [7]. On-the-fly tests also demonstrated that network prediction latency was suitable to standard control rates of soft robotics, or data-based acoustic state estimation can be implemented in reality.

2.4 Complementary Relationship and Integration Trends Among the Three Mechanisms

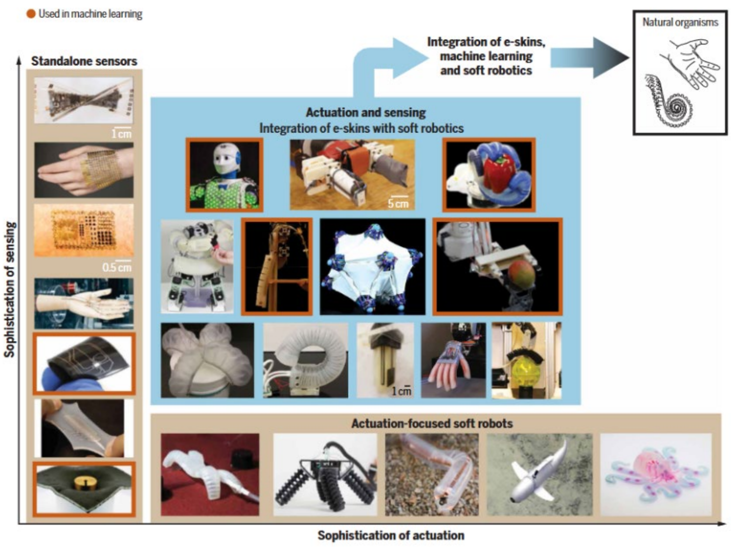

Fig. 1 Development Trends in the Interdisciplinary Field of Electronic Skin, Soft Robotics, and Machine Learning [8].

Fig. 1 below shows that work in the area of soft robotics cuts across a number of related directions, some of which are; improving the performance of flexible sensors, soft robotic systems based on sensing and actuation, and actuation-based designs. In other studies, the method of machine learning is presented as part of the processing of sensory information. Regarding the system-level insight, the recent advances in electronic skin studies provide a feasible direction in the way of integrating optical, electrical, and acoustic sensations into a single framework.

A review of the article by Shih et al., published in Science Robotics. They analyzed the current developments in integrating electronic skin technologies and machine learning in intelligent robots that are soft in nature. The authors suggested that electrical, optical and acoustic sensing would no longer be viewed independently as units of perception in the future. Multimodal sensing arrays Multimodal sensing arrays Multimodal sensors are likely to be able to measure the things in two or more dimensions; the pressure, strain, and vibration, or temperature. In cases when they are embedded within a single layer of skin. Deep learning features are used to extract meaningful features and fuse modalities in high-dimensional spaces of data. With the help of this approach, the representation of the sense of tactile sensing and proprioception is unified.

This was a cross-sensitivity beginning with this review. And redundancy of signals caused by multimodal sensing arrays can not be discussed as a disadvantage. Learning-based approaches can use these characteristics to enhance robustness in detecting complex contacts, unknown materials and states of large-deformation. In this regards, the work offers a rough perceptual interface and algorithmic architecture of incorporating a variety of physical senses, such as optical, electrical and acoustic senses [8].

3 Multimodal Intelligent Fusion Algorithm

3.1 Multimodal Signal Feature Fusion

In optical–electrical–acoustic cooperative perception, multimodal feature fusion aims to map temporal signals and spatial information from different physical channels into a shared feature space.

This will enable complementary information to be stored and minimized redundancy and noise. In most applications, electrical strain signals, optical images or optical fields and acoustic waveforms are initially normalized and encoded individually, and feature concatenation, weighted fusion or attention-based state estimation and behavior recognition are used.

Loo et al. found a latent space that directly predicts soft robots posture and contact states using a learning-based method to project embedded pressure and strain signals into the latent space. The fused representation compared to single-modality sensing had smaller errors of estimation in noisy conditions and was more generalized. The same application is to joint encoding of optical, electrical, and acoustic signals, which is able to give more stable inputs on higher-level decision making and adaptive control of soft robots [9].

3.2 Selective Fusion

Noise and stability under varying operating conditions of distinct sensors are frequently highly different in optical-electrical-acoustic multi-physics perception. Equal consideration of all modalities at once by fusion can result in victory of noisy channels and reduction of the overall accuracy of perception. Consequently, the fusion procedure must explicitly simulate the comparative dependability of every signal and selectively decrease high noisational modalities.

An exemplar of such concept is the Uncertainty-Aware Depth Network (UD-Net) suggested by Song et al. Under a visual inertial odometry framework, the network will provide a depth map as well as the matching uncertainty map, which is then filtered in the depth estimation to provide fusion results. Pixels that have large variance are considered unreliable and exist in pose estimation as down-weighted or discarded. It was demonstrated through experimental methods that the inclusion of the awareness of uncertainty decreased significantly the errors in the trajectories in essentially noisy or less significant-quality texture scenarios. To apply the same strategies to strain signals, electrical measurements, and acoustic echoes in optical-electrical-acoustic cooperative perception one may apply the same to the strain signals, electrical measurements, and acoustic echoes. Multimodal fusion robustness can be enhanced with the help of noise modeling and dynamic weighting without augmenting the complexity of hardware [10].

4 Typical Application Scenarios

4.1 Flexible Life Capture

Soft grippers are commonly used every day with objects of smooth, uneven masses or those that are easily deformed. Common examples would be plastic bottles, fruits and normal household items. There isa complication in discerning is the realization of a slip. Gripping force can be timely adjusted when it is at a young stage. Objects can fall or be ruined in case a slip is not spotted promptly.

The Electrical sensors could be a good choice in this task, as it has the capability of giving real time data on the normal and shear forces. This renders them usable in the tracking of variations in contact force on grasping. The optical tactile sensing is different. It responds violently to minute relative motions and variations of the optical field. Consequently, it is able to record early slip signals that are not readily recorded by electrical sensors. It has been shown that in previous research high-accurate contact geometry can be re-created by printing fingers onto optical tactile structures that serve to detect slip reliably when incorporated into robotic grippers through fingerprints. The structures result in a markedly constant grasp stability during tasks of household manipulation [11].

Docsjugment at the time of grasping can be enhanced by optical sensing with the aid of electrical feedback. Fine spatial details can be found using optical signals. Although the electrical signals are fast in responding to changes of force. Such a combination enables soft grippers to work in a safer way. And be adjusted to changing conditions in daily conditions.

4.2 Medical Rehabilitation Grasping

Soft robots, which are mainly used in medical rehabilitation are mainly used to help patients perform grasping exercises.

These activities involve recovery of grip strength, fine hand movements and training of the upper limbs. The rehabilitation is low force, and safe interaction unlike the industrial manipulation. The robot should consequently be able to detect contact and potential slip on very low loads.

In this case, acoustic sensing can be used since the sound waves penetrate soft substances. Changes in the travel time of ultrasound, reflected ultrasound, or attenuation may be used to provide some information. This will enable identification of deformation within the loose framework and not just in the signals of surface contacts. Consequently, it makes force feedback easier to interpret.

In the article by Shi et al., ultrasonic transducers were implemented right within a soft robot. Their experiments were able to accomplish contact localization with millimeter accuracy. The sensing performance was also constant in case of intricate deformations to the robot. This justifies the application of acoustic sensing in soft robotic systems in rehabilitation [6].

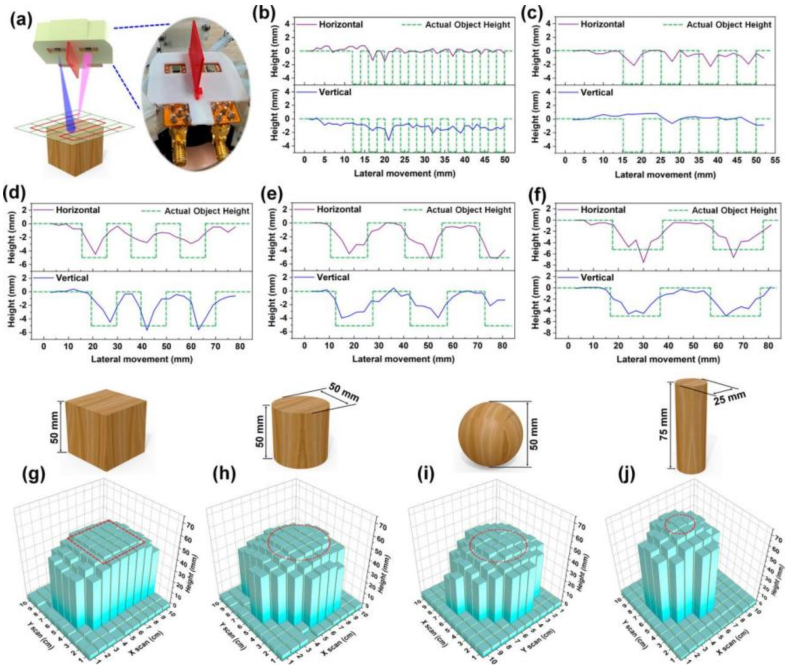

Fig. 2 Demonstration of three-dimensional shape recognition performance for soft robots based on ultrasonic autonomous localization and multimodal perception [6]

The soft robotic system scans the countenance height of various objects and recreates the three-dimensional form of the object as exemplified in Fig. 2 by the application of the ultrasonic auto-positioning. The scans made by the system are horizontal and vertical. This is to have height variation profiles across object surface. These solution height curves are compared with ground truth values. It can be seen that the predicted profiles are stable and reflect major geometric characteristics of a variety of objects including steps, inclined surfaces, and curved structures.

According to the data of the scanning, there are three-dimensional models of reconstruction. To a great extent, these models demonstrate the correspondence with the shapes of real objects. This shows that the proposed ultrasonic sensing system will have the capability of identifying object geometry and the 3D contours of a variety of structural forms. This kind of ability gives soft robots a good geometric awareness in the unknown world.

The same can be used in the rehabilitation training. The unintended excessive force, fatigue or lack of grip strength when interacting with the patient are behaviors that can be detected using acoustic-assisted perception by the system. In return, the robot is capable of leveraging this by adjusting the assistance levels and training difficulty to enhance rehabilitation safety and adaptability, respectively [6].

4.3 Industrial Flexible Grasping

Flexible grasping is frequently performed in industrial production lines with a high frequency of cycles and a broad range of objects of interest. The quality of products must also have tracking. Such conditions demand soft grippers to complete grasp testing and defects checking in tens of milliseconds.

High-speed cameras or fiber-based arrays can be used in optical sensing channels to detect object pose, surface defects and slip trajectories quickly. This renders them to be appropriate to work in tandem with conveyor belt movement. Electrical sensor arrays give high bandwidth measurements of normal and shear forces. These cues come in handy to check the grip force that may be either too great or too small during the grasping. Other acoustic methods of assisting with the inspection process may include examining impact sounds, structure-borne vibrations, or even ultrasonic echoes. With such signals, these internal cracks, voids, or abnormal contacts may be identified at an early stage.

More recently, multimodal tactile modules have incorporated multiple measures into planar sensor arrays of parallel grippers, including three-axis force, vibration and temperature. These systems provide rapid identification of states, constant control in the process of grasping of challenging industrial components. These designs provide a convenient hardware platform to extend optical, electrical and acoustic senses to the flexible industrial grasping operations [12].

5 Current Challenges and Future Outlook

5.1 Current Challenges

The perception of soft robots has been enhanced by the optical, electrical and acoustic multimodal sensing. But many challenges remain. The nonlinear behavior is one of the main problems that arise in the specific usage. It occurs when one stretches and bends. These nonlineartroubles usually bring in signal drift or instability. It is now difficult to determine its own posture or the forces exerted on the environment.

Integration of sensors is another problem. It is not easy to embed several sensing components into soft structure and maintaining compliance at the same time. Wiring is complicated, and the cross interference of sensors is hard to prevent. Also, various sensing modalities generate signals that are very different in nature. Often, optical data are large. Electrical signals are noise sensitive. Sound signals are extremely reliant on the wave propagation within the material. These disparities advance the complexity of cross-modal integration.

The issue is also complicated by the environmental variation. The behavior of soft robots can be highly transferable through tasks and environments thus making trained models difficult to implement in new environments without deterioration of performance. These factors are the reason why a reliable multimodal perception is a central problem towards deployment of soft robot systems in the real world [13].

5.2 Future Outlook

The soft robot sensing continues to evolve with the development of materials or flexible electronics and means of learning. Even the designs in the future will put the sensors within soft structures, rather than considering sensing and structure as two distinct entities. There could be optical, electrical and acoustic signals which can be gathered together in a single material layer. This can minimise the wiring and make the system more stable.

Sensing systems are also easier to adapt to using learning-based methods. The sensor drift is fixable as its operation progresses. Complicated touch patterns can be identified other than through manual adjustment. Even when the environment is varied the performance can be held still. Ways of fusing are also moving. Higher-level representations are becoming widespread in place of manual design functions. This assists the robot in developing a more detailed picture of the contact and deformation.

Soft robots are more actively applied outside of the laboratory. Examples are medical aid, difficult jobs, and fine-tuning. Under such circumstances, more autonomous perception of robots is required. This has contributed to stronger connection between sensing and control on soft robotic systems [14].

6 Conclusion

The use of a soft robot may imply the necessity to work with large deformations and unstable sensory signals. Under such conditions, researchers consider the possibilities of electrical, optical and acoustic sensing to complement. Electrical sensing is quick to respond and easy to build in thus it is suitable in simple strain response and contact feedback. The spatial and temporal information of optical sensing is very fine, and these details will be useful to record surface texture and deformation. Another benefit is acoustic sensing. Soft materials are not able to stop sound waves. This would enable the internal changes to be detected and the localization to be more stable.

When these signals are added together and their uncertainty is taken into consideration, the perception of noisy environment will be more accurate. Practical evidence indicates that the combination of optical, electrical and acoustic sensory responses results in having a better grasp stability during daily activities. It is also safer during rehabilitation training and helps to quickly inspect situations in the industry. Altogether, the multi-physics sensing in combination with learning-based decoding present an opportunity to have a reliable, more adaptive and comprehends the surrounding world of soft robots better.

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