Strain Sensor Survey for Parachute Canopy Load Measurements

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The parachute failures during the National Aeronautics and Space Administration Low-Density Supersonic Decelerator project revealed many of the complications of using parachutes for atmospheric entry missions and prompted the need for a more in-depth understanding of parachutes. Validation data for point loads on parachute canopies would contribute greatly to this understanding; however, such data does not exist because of a lack in practical sensing technologies capable of measuring the canopy strain. Few commercially available sensing technologies exist that can measure the total strain range of the parachute broadcloth materials, and even fewer can be easily integrated into the canopy. Additionally, many of these options are not at a technology readiness level suitable for flight-testing. This survey presents and compares the latest sensing capabilities that have potential in instrumenting parachute canopies for atmospheric entry and highlights the challenges particular to this application. Each sensor is evaluated for its performance and suitability towards parachute canopy instrumentation. Specifically, sensors are evaluated on their capabilities in measuring maximum strain, strain rate, hysteresis, drift, adherence and integration options, durability, environmental conditions, and technology maturation. Additionally, future work that is needed to assess sensor technologies for this application is provided.

I. Nomenclature

ε	=	Elongation, $\Delta L/L$
ε_{max}	=	maximum elongation
Y	=	sensor output

II. Introduction

Parachutes are used for a variety of high-risk and safety applications; whether for supersonic planetary landings on Mars or subsonic capsules returning astronauts to Earth, parachutes play a critical role in many of the National Aeronautics and Space Administration (NASA) missions. There are many commercial and recreational use cases, such as payload deliveries and sky diving, where the parachute is an essential mission safety item. Despite the critical role of the parachute, its unpredictable nature and reliability continue to introduce a variety of challenges to many missions. One such challenge is that the structural margins of a deploying parachute canopy are not well understood, which casts doubt on the safety factor of the parachute design [1]. To validate structural margins or parachute models, flight data from a deploying parachute would need to be acquired; however, no proven methods have been established for making an in-flight measurement of the canopy strain during deployment or descent.

Currently, parachute performance is evaluated using a combination of wind tunnel and flight-tests to investigate drag, loading, and inflation. Flight-tests are conducted in the last stage of parachute qualification for planned missions

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and are used to gather load data on the payload through instrumentation of strain sensors and load cells on the suspension lines [2]. This method of testing has uncovered that there is unequal loading of suspension lines, which is of significance to simulation, modeling, and design work [3,4]. This method, however, does not allow canopy loads and movement to be measured directly; thus, image-based methods are used during many wind tunnel and flight-tests. Stereophotogrammetry is one image-based method that tracks key markers on the parachute [5,6]. The resulting data are usually low resolution depending on how many markers are applied to the canopy. Stereophotogrammetry has primarily been used for gross motion data rather than localized strain. Advanced image processing techniques such as digital image correlation (DIC) [7] and three-dimensional (3D) point cloud reconstruction [8] have also been used; data from these efforts are typically used for gross motion or projected area measurements. Some drawbacks to using image-based methods are the need for multiple high-speed cameras and direct line of sight; occlusion from the suspension lines, canopy folding, or parts of the payload degrade the data. To address the challenges and cost of the testing methods mentioned, there is a desire for the development of localized strain sensors that can be placed on the canopy broadcloth and on areas of stress concentration to better characterize the performance of the parachute.

Two projects using in-situ canopy strain measurements have been attempted through the NASA Small Business Innovation Research (SBIR) program: Redondo Optics, Inc. (Redondo Beach, California, U.S.A.) using their plastic optical fiber [9], and Katabasis Aerospace, LLC (Murray, Kentucky, U.S.A.) using their Textile Strain Measurement System (TSMS) [10]. Although initial results are promising, hysteresis and sensitivity still hinder obtaining accurate data. The NASA Space Technology Mission Directorate is now funding an Early Career Initiative project, titled "Enhancing Parachutes by Instrumenting the Canopy (EPIC)," to identify and characterize sensors that are capable of gathering strain data on the canopy during deployment and flight. This project will assess the current state of stretchable strain sensor technologies, select viable sensor candidates, and perform various tests to analyze sensor performance. The end goal of the project is to have data that supports the further development of one or more sensors for this application. This survey documents the beginning stages of the EPIC project and presents a review of the latest technologies that are potentially suitable to parachute canopy broadcloth instrumentation, provides quantitative metrics for evaluation of their performance, and discusses the key challenges to canopy measurements including sensor integration. Instrumentation on suspension lines and/or risers of a parachute is outside the scope of this survey and is being addressed using solutions such as: the Cord Tension Measurement Device (C-Gauge) developed at Johnson Space Center (JSC) (Houston, Texas, U.S.A.); the Tension Measurement System (TMS) developed by Invocon Inc. (Conroe, Texas, U.S.A.); and the wireless sensor developed for the NASA Low-Density Supersonic Decelerator (LDSD) project [11].

III. Challenges to Parachute Canopy Instrumentation

The immediate challenges to measuring strain on a parachute canopy are the nature of the fabric and the highly dynamic environment during parachute deployment and descent. Making a direct measurement in this environment requires flexible, high-elongation sensors that are a relatively new technology with applications in medical and biomonitoring [12], soft robotics [13], flexible circuits [14], smart fabrics [15], and other soft goods industries [16]. Very few sensors, however, have been applied to a parachute for a drop test or in a wind tunnel, and, although strain measurements were made in these tests, reliably calculating the load from the strain data is difficult. Most of this difficulty comes from sensor calibration challenges related to fabric variations, anisotropic properties, hysteresis, rate of loading, and differences between on- and off-fabric calibration that may result from clamping, or a distortion in the strain field as a result of the presence of the sensor [17–19]. An additional challenge, and perhaps more important, is the fact that parachutes are mission-critical items; therefore, parachute mechanical properties cannot be altered in a way that would degrade performance or behavior during deployment. Naturally, the goal is to measure the behavior of the parachute, and not the effects caused by the addition of sensors.

A major challenge with physical instrumentation of the parachute canopy involves the weight and potential dynamics of the wiring and placement of the data acquisition system. Proper sensor excitation, data logging, and compatible hardware must be chosen to reliably gather data of a sufficient resolution and rate. Moreover, the data acquisition must be integrated into the decelerator system without hindering deployment and the parachute operation itself. The data acquisition system (DAS) will vary based on the sensor and wiring or wireless capability. Although data acquisition is a critical aspect in obtaining load data from the sensors, the EPIC project focuses on the first aspect of this problem: making accurate load measurements from available strain sensing technologies. For this reason, this survey focuses on examining relevant state-of-the-art sensor capabilities; the DAS will be included in future work.

A. Fabric Material

Typically, parachutes are made from ripstop nylon, and although certain sections are reinforced with stronger and stiffer materials like Kevlar®, the scope of this review is aimed towards the canopy broadcloth; accordingly, ripstop nylon is the substrate of choice for evaluating sensor integration. Figure 1 shows a magnified image of the fabric depicting the ripstop weave pattern under a microscope. A key challenge in parachute instrumentation relates to the maximum strain for ripstop nylon, which is approximately 40 percent; this large strain range presents a challenge for traditional metal foil strain gauges (SGs) and piezoelectric crystal SGs, which are too stiff and cannot reach the expected elongation of the fabric material.

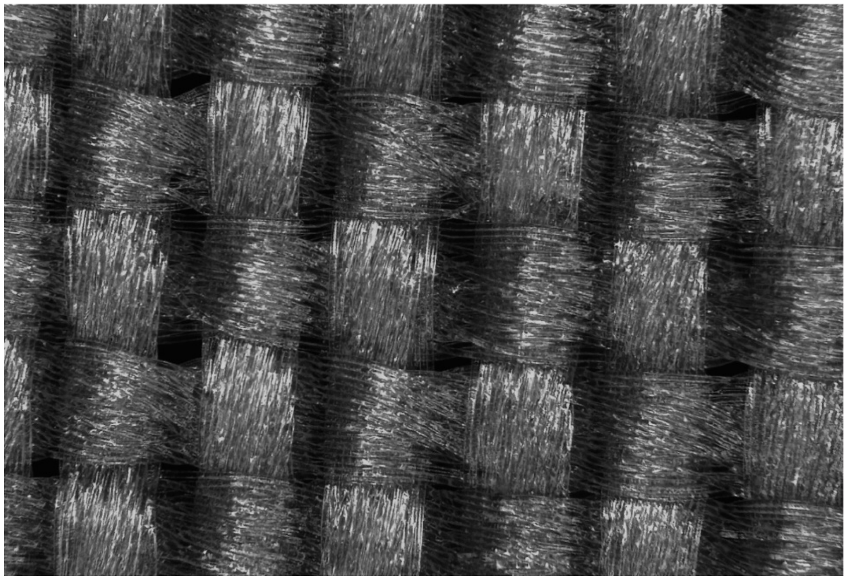

Fig. 1 Ripstop weave magnified in microscope image. [20].

Whereas there are many variations in fabric design that affect aspects like fabric strength and permeability, the overall characteristics are similar. Fabric research has shown that woven materials like ripstop nylon exhibit unique hysteresis patterns over multiple cycles, as shown in Fig. 2. This result means that factors such as pre-stretching can greatly affect the strains of the fabric [21] and complicates separating the natural hysteresis of the fabric from the hysteresis of the sensor. Additionally, proper sizing of sensors must be determined to ensure that peak strains are not overlooked while ensuring that a sufficient representative amount of the weave is covered. Although standards such as the ASTM D5035-11R19, ASTM International (West Conshohocken, Pennsylvania, U.S.A.) Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method) exist for evaluating fabrics, this method does not scale for fabric widths that would be used in canopy gores. Moreover, there is no available data for relevant nylon variants, and the material is not fully characterized. To better size these sensors, full-field strain data is required to determine the expected strain gradient magnitude.

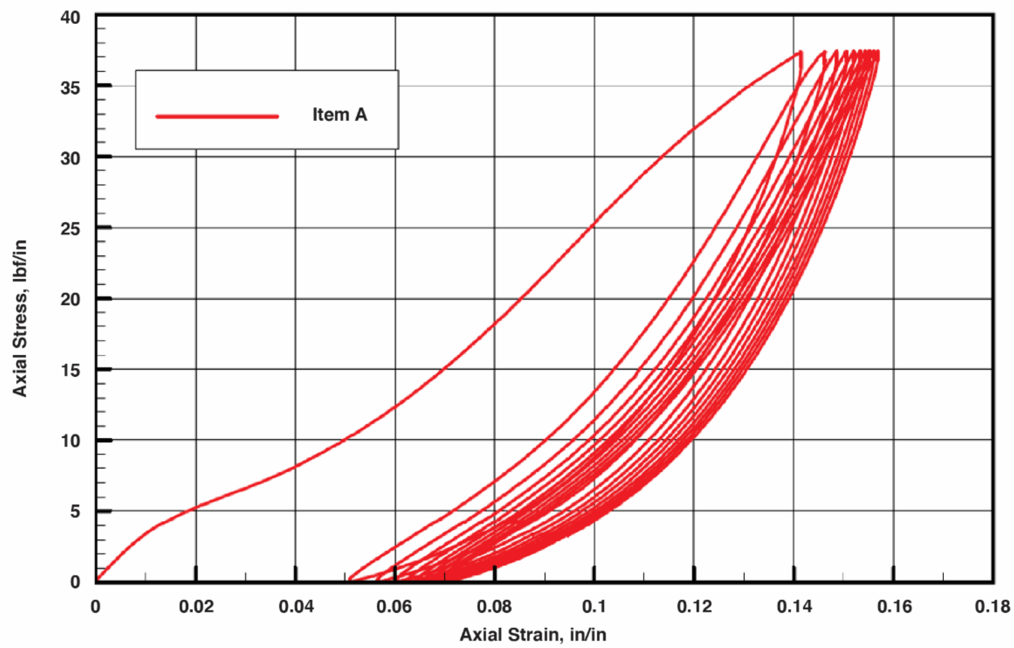

Fig. 2 Hysteresis in F-111 nylon over 10 cycles, measured by Intstron®, Instron (Norwood, Massachusetts, U.S.A.), in uniaxial strip test [21].

Lastly, aside from the mechanics of the material, there is the challenge of adhering a sensor to the fabric so that the sensor moves with the fabric in order to measure the actual elongation of the fabric itself. If the adherence method adds too much stiffness or is too compliant compared to the fabric, the sensor could break or debond from the fabric during elongation [22].

B. Parachute Environment and Sensor Effects

The parachute environment introduces sensor design challenges from the beginning of the mission, with tight pressurized packing, to deployment, with highly dynamic and chaotic forces, to descent through a variety of temperature and humidity environments. There are two questions for concern: 1) can the sensor make the measurement on the canopy material, and of equal importance; 2) can the sensor survive the environment of the measurand?

All parachutes pack down by being carefully folded and enclosed in some sort of container. Parachutes that travel to space are vacuum packed in a canister to conserve space. As a result, the sensor and any wiring and interrogation equipment that is affixed to the canopy must be able to withstand folding of the canopy; sensor equipment needs to be extremely flexible and able to make sharp turns or must be placed on the canopy at intervals such that the folds do not crease the sensor. The sensor interrogation methods should not interfere with the parachute lines, which might result in parachute malfunction. The sensor cannot add significant mass or volume if it is to be used on a space-rated parachute. Additionally, space-rated parachutes undergo high-temperature sequences to sanitize against introducing any microbes before sending the parachute to space.

The next stage of a parachute mission is the deployment of the parachute. Whether the parachute is deployed at supersonic speeds or not, the deployment is a rapid event with chaotic motion and undetermined forces on the local canopy environment. The sensor and corresponding wiring must be robust enough to withstand this type of motion. During supersonic deployment, if the canopy failed at its maximum elongation, the corresponding estimated maximum strain rate could be between 250- to 420-percent elongation per second - based on loading data from the NASA Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) test flights of disk-gap-band (DGB) parachutes and actual Mars Entry, Decent and Landing (EDL) flight load data from the NASA MARS InSight and Phoenix Landers [2, 23, 24].

During parachute deployment and descent, the sensor is subject to strain in all directions of the broadcloth. Furthermore, the ratio of the measured transverse strain to longitudinal strain (analogous to the Poisson's ratio) during uniaxial testing of ripstop nylon is relatively high when compared to that of metals; therefore, particular attention must be paid to the transverse sensitivity of the sensor, and appropriate corrections must be made. The output of the strain gauge can be broken down into two components: axial strain and transverse strain, each with a corresponding gauge factor [25]. The sensors must be tested in a biaxial strain field to characterize sensitivity or determine that it is negligible. If it is determined that the transvers sensitivity is not negligible, the sensors can be arranged in a strain gauge rosette that permits the factoring out of the transverse sensitivity using readings from multiple sensors that are orientated in different directions.

Throughout an entire mission, the parachute will experience substantial environmental changes. During a Mars atmospheric entry, the parachute is deployed at high altitudes that correspond to approximately -100° F [23, 26]. During Mars parachute testing, the Mars EDL conditions are simulated via Earth atmospheric entry at similar Mach numbers and temperatures; for example, as done in the ASPIRE test series [2]. Depending on the mission and usage for flight-testing, temperatures may vary and need to be verified for further material and operational considerations. Specifically, for Mars EDL parachute tests in the Earth's atmosphere, the sensors must demonstrate the ability to make accurate strain measurements at low temperatures. It is known that resistance-based strain gauges are sensitive to temperature changes, sometimes to the degree that the thermal output is greater than the mechanical component of the indicated strain measurement [27]. The thermal output has multiple components, one clearly being a result of expansion or contraction of the test article. The gauge factor, however, is also a function of temperature: as the temperature changes, the resistance of the grid conductor changes; and the transverse sensitivity of the strain gauge changes; and the Poisson's ratio of the material changes. All components are temperature sensitive and contribute to thermal output. Additionally, there is an aspect of measurement error due to mismatch between the coefficient of thermal expansion of the sensing element and the bonding interface to the ripstop nylon; thus, thermal effects must be characterized for each sensor and bonding methodology for a particular substrate of nylon so that they can be corrected for or demonstrated as negligible. Some elastomers used in highly elastic sensors have a relatively high glass transition temperature where the material becomes brittle at low temperatures. Finally, during atmospheric entry, humidity will need to be addressed because many of the sensors identified below are constructed using exposed conductors.

The challenges concerning direct strain measurements on a parachute canopy are summarized by the unique nonlinear behavior of the fabric material; sensor measurement uncertainties; effects of sensor integration on the fabric properties; and the external effects of environmental conditions on both sensors and fabric. All of these factors are coupled with influences of the test set up from varying clamping conditions that affect calibration. Although overcoming these challenges is difficult, new sensing technologies are available that show significant promise as viable paths to address them. These sensors allow small form factors and large strain ranges, often referred to as elastic or stretch sensors. A survey of these sensors is presented and discussed in Section IV. Sensor Technologies below. The survey intends to identify the most suitable sensors for parachute canopy instrumentation. Future efforts of the EPIC project are aimed at evaluating sensor performance via a test campaign that will develop methods to integrate the sensors with minimal effects on the fabric, and address calibration techniques to calculate local stress.

IV. Sensor Technologies

The following subsections categorize sensors relevant to parachute canopy instrumentation based on the basic measuring principle of the sensors: resistance, capacitance, inductance, optics, and passive concepts. The descriptions are intended to provide an overview of the types of technologies available or that are currently being developed, with references to relevant research. The authors recognize that in the case of some of these technologies there are many individual sensors with similar operating concepts. Listing every instance of a sensor, however, is outside the scope of this paper. For extensive comparisons of additional stretchable strain sensors that include variations of the sensors discussed below, the reader is referred to [16, 28].

A. Resistance-Based Sensors

Strain sensing has traditionally been done by measuring the change in resistance in a material caused by deformation. Some highly elastic strain sensing solutions employing this method have taken form by making elastic materials conductive. Metal Rubber™ by NanoSonic, Inc. (Pembroke, Virginia, U.S.A.) is a metal coated elastomer for strain sensing. Another example is the simple conductive polymer cord stretch sensor produced by Images Scientific Instruments, SI Inc. (Staten Island, New York, U.S.A.). Other variations on resistive measurements are conductive elastic materials such as conductive paints and room temperature vulcanizing (RTV), or flexible circuits and sensors made from conductive gel such as those produced by Liquid Wire Inc. (Portland, Orgon). A NASA effort for the evaluation of strain measurement devices for inflatable structures [22] showed that the performance of conductive coatings is poor as a result of cracking of the surface under large strains (50 percent). Additionally, the Metal Rubber™ sensor had a similar reliability drawback because the metal coated conductive layer was not very resistant to wear and had signal cutout at a given peak loading.

Novel innovations are also emerging from flexible electronics and biomonitoring research using silver nanowire (AgNW) or carbon nanotube (CNT) additives in composites to create an elastic conductive material or provide piezoelectric properties [29–34]. These recent developments in polymer nanocomposite are very promising for application in parachute instrumentation because they have the advantage of tailoring the material properties for a given sensing application; however, they exhibit different drawbacks based on the composite structure used. Hysteresis and drift are caused by the relaxation of an elastomeric substrate or nanocomposite matrix. Carbon nanocomposite sensors degrade in performance during cyclic deformation because of crack formation, and AgNW resistance and electromechanical properties change from fatigue and bending cycles of mechanical deformations [12]. In general, these types of sensors suffer from the competing metrics for desired performance of high elasticity, high sensitivity, and linear response, noted in [28]. There have also been applications of reduced graphene oxide (rGO) on cotton [35] and nylon fabric [20], that have piezoresistive properties. The work of [20] is of particular interest because of its application on nylon. The performance of these sensors, however, has only been evaluated for bending or when used as pressure sensors; more testing is needed to evaluate their performance in tensile strain.

The e-textile field has also produced coated or embedded conductive yarns such as those produced by Shieldex, (Bremen, Germany), that can be used as a resistance-based sensor. This sensor can be used either as a single thread [36, 37], or a stitch pattern to form a strain gauge [38–40]. The primary mechanism of the stitched conductive thread is to create a change in overall resistance from shorted circuit paths by opening and elongating the conductive path, as shown in Fig. 3. Expandable shorted patterns are used to increase the elasticity of the conductive elements of the sensor and promote a linear response despite having stiffer components. For sensors made with conductive threads, there are many stitch patterns to choose from that affect the sensor performance. The design space increases with the various conductive yarns that are available in different sizes, plies, and coating methods. The repeatability and reliability of these sensors are very dependent on the sewing machine settings and thread tension because the stitching will naturally cause friction and minor abrasions to the thread. Since the conductive elements of the sensor are exposed, a suitable coating would also need to be applied to prevent detrimental humidity effects or additional abrasion during packing and deployment. Conductive composites and textiles can also be combined with e-textiles to produce sensor systems such as in [41], which demonstrates how these kinds of sensors can be integrated into fabrics.

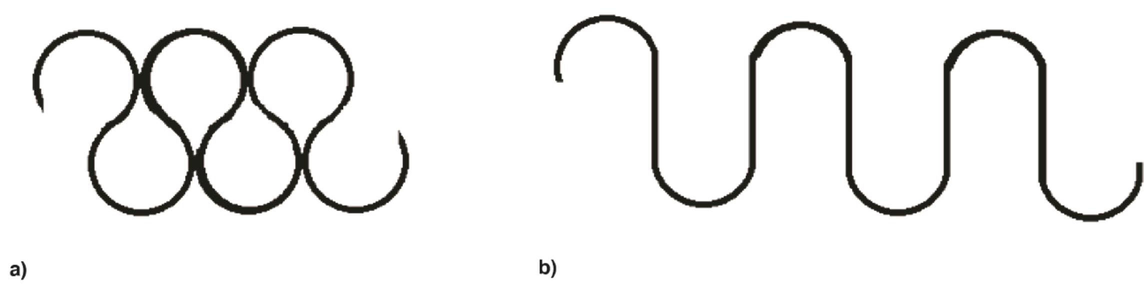

Fig. 3 (a) Ohmic contact example of a stitched circuit in the relaxed position with shorted connections; and (b) in the stretched position with no shorted connections [40].

Ohmic contact sensors are not limited to conductive thread patterns. The mechanical design has been used to achieve elongation benefits in the strain-mediated contact in anisotropically resistive structures (SCARS) sensor [42], and the electrohydrodynamic printed AgNW pattern sensor [43]. A variation on Ohmic contact has also been used with single-walled CNT films arranged in an accordion pattern [44]. During elongation the sensor expands and fractures the films into distinct patterns of gaps and islands; film bundles bridge those gaps and provide a nonlinear response that can be modeled as two linear regions.

Another promising resistive technology is conductive fluid strain gauges. One example is a soft strain sensor based on ionic and metal liquids in embedded microchannels in silicone elastomer [45, 46]. Eutectic Gallium Indium (eGaIn) is a popular liquid metal conductor with desirable properties that mimic the typical structure of traditional metal film gauges, with elastic components [47]. Moreover, the liquid-metal strain gauge (LMSG) showed a lot of promise during mechanical testing of the NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD) torus [48]. Whereas parachute inflation occurs more rapidly than the HIAD torus - torus material being significantly stiffer than nylon - the LMSG was specifically developed to sense strain on low elastic modulus materials and already has a methodology developed for bonding onto fabrics.

Various attempts at direct printing of flexible strain sensors have been attempted as well. This technology is enticing for the parachute application, and fabric sensors in general, because it directly adheres the sensor to the fabric. Direct printing methods are well-suited to scaling the sensor and can create sensors from micron- to centimeter-range. Printing through metal deposition such as vacuum-sputtered thin-film electronics are being explored by the NASA Glenn Research Center (GRC) (Cleveland, Ohio) [49, 50] but have yet to be applied to and tested on fabric. Others are using plasma jet printing [51] and ink jet printing [52–54] of various materials. As well, some are investigating more typical 3D printing methods of TPU composites such as [55]. Similarly, the previously mentioned work [43] printed AgNW on many different materials using electrohydrodynamic printing. To effectively use this approach, the proper ink or material selected must be suitable to the given printing method. Investigation into effective materials is currently underway to eliminate any concern with using these methods for parachute canopy instrumentation. The main concerns are: 1) the thin film metals or other available inks are too stiff and will crack or fracture when subjected to the relevant strain; and 2) modification to material formulas will be required to ensure they properly bond to the nylon material. There are, however, some promising high-strain ink formulations such as [56, 57] and others inks that have been used for making an ammonia sensor on coated yarn [58].

It should be noted that for conductive polymer composites, regardless of the sensing type, there are concerns with soft-sensor wiring connections. Disparity in stiffness is known to cause delamination from rigid electrodes [46], and care must be taken to ensure proper and reliable wiring.

B. Capacitance-Based Sensors

Sensors can employ any type of electrical change that occurs because of a change in tensile strain for measurements. Some commercial off-the-shelf (COTS) solutions, like those from StretchSense (Penrose Auckland, New Zealand), Bend Labs (Farmington, Utah, U.S.A.), and Bando Chemical Industries, Ltd. (Kobe, Japan) use a capacitance-based sensing approach specifically designed for measuring strain on elastic substrates for bending and biomonitoring. For these types of bend and stretch sensors, conducting surfaces are embedded in an elastomeric material that acts as the dielectric component of a capacitor. As the sensor is stretched, the area of the conducting surfaces deforms and the distance between them changes; thus, changing the capacitance of the new geometry in the sensor, as shown in Fig. 4.

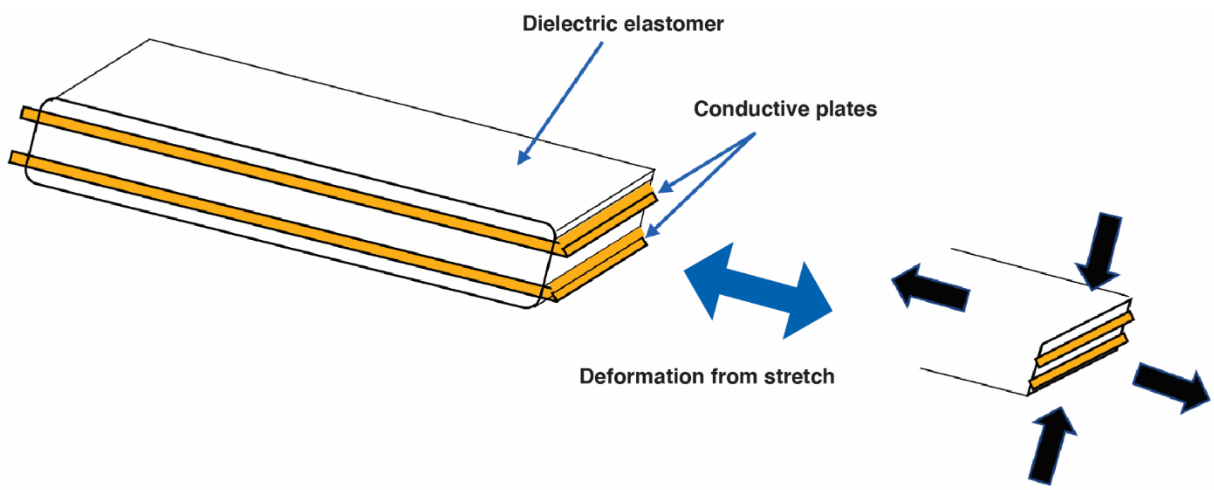

Fig. 4 Capacitive plate sensor diagram.

These sensors are currently in use for various industries and are readily available; they have well-developed interfaces, and some can transmit data via Bluetooth, which could simplify in-situ data collection on a parachute. These sensors have been tested thoroughly by their manufacturers and have shown good accuracy with minimal sensor hysteresis and drift; thus, they are considered to have significant potential for parachute instrumentation. One potential downfall for these sensors, however, would be the temperature environment; cold temperatures could cause the elastomer to become brittle and fail when stretched. Additionally, because these COTS sensors have been developed for biomonitoring and joint motion measurement, they are not optimized for parachute applications and will need to be integrated onto the parachute reliably.

Capacitive stretch sensors are not limited to the commercially available variants. There has been a lot of work with novel nanomaterials and e-textiles to produce capacitive sensors in new formulations. This is done by varying the electrode and dielectric materials, such as using conductive textiles [59, 60], or using CNT films with polydimethylsiloxane (PDMS) or silicone [61].

C. Inductance-Based Sensors
One sensor that comes from the soft robotics discipline, where there is a need for measuring the motion of elastic and soft pneumatic actuators and linkages, is an inductance-based braided cord of wires. The sensor expands and contracts like a muscle with the soft structure [62]. Although a promising technology in its field, there is currently no clear path to miniaturize the sensor and integrate it into a parachute canopy; however, there may be alternative methods of structural integration or alteration to adapt it to the proposed application.

D. Optical Sensors
Fiber-optic technologies are also well known for use in strain measurements and are based on fiber Bragg grating technologies. Although these technologies can be embedded in textiles as displayed in [63], the glass gratings limit the amount of bending and elongation of the system and induce stiffness to the fabric. Plastic fiber optics have also been considered because they extend the range of possible elongation and have even been integrated into parachute canopy fabric, but they can exhibit severe hysteresis [9].

E. Electrical Resistance/Impedance Tomography
Electrical impedance tomography (EIT) has also been considered as a sensor option given its use cases for structural health monitoring applications that can also be used explicitly as a strain sensor [64, 65]. EIT sensors map out potential changes in a conductive substrate from excitation across different points around the sensor, which correspond to the material impedance change from the change in strain. This technology would provide an additional benefit of visualizing the strain from image reconstruction of the impedance changes throughout the material. Moreover, these kinds of sensors have also been applied to thin substrates such as paper [66]. Electrical impedance tomography, however, needs to have the sensor and strain field well characterized for sensing use and would require a large test campaign with a proper truth source such as DIC; therefore, the technology has potential for implementation into a representative environment but poses challenges (as previously mentioned).

F. Passive Sensors
Although a time history of the deformation provides more useful data, a measurement of the peak strain on the canopy would provide significant benefits in determining the maximum load experienced during deployment. Peak strain data at critical points on the canopy would help validate safety margins and provide critical bounding data for model validation. Reducing the problem to capturing peak strain data allows passive measurement methods to be considered. Passive methods are attractive because they do not require wiring or power, a significant challenge for all active measurements discussed in this work.

One such method requires implanting strands of materials with different breaking strains at a single location to get discrete intervals of load, based on which pieces are broken. Figure 5 illustrates this concept using three materials for three discrete maximum strain values; in the figure, the broken material has a maximum elongation of 10 percent, so we infer that the maximum strain experienced at the location of the sensor was between 10 percent and 20 percent, the maximum elongation of the unbroken material. Alternatively, shape memory alloys that change phase, based on strain, could be used by applying the same concept. An obvious limitation, however, is that the maximum strain would only be inferred from the discrete levels of maximum strain that are feasibly applied to a local area. The resolution would be based on the number of sensors placed and the discrete failure strain levels of those sensors, which would have to be selected with usable form factors and specific material properties, potentially varying the material for each strain level. A major drawback of this method is that the sensors would have to be inspected postflight. This means the parachute would have to be recovered, limiting the use case to parachutes on Earth. Additionally, it would be necessary to ensure that the sensors do not sustain breakage as a result of strain during packing; this may further limit use to less common packing methods, which do not significantly compress the parachute.

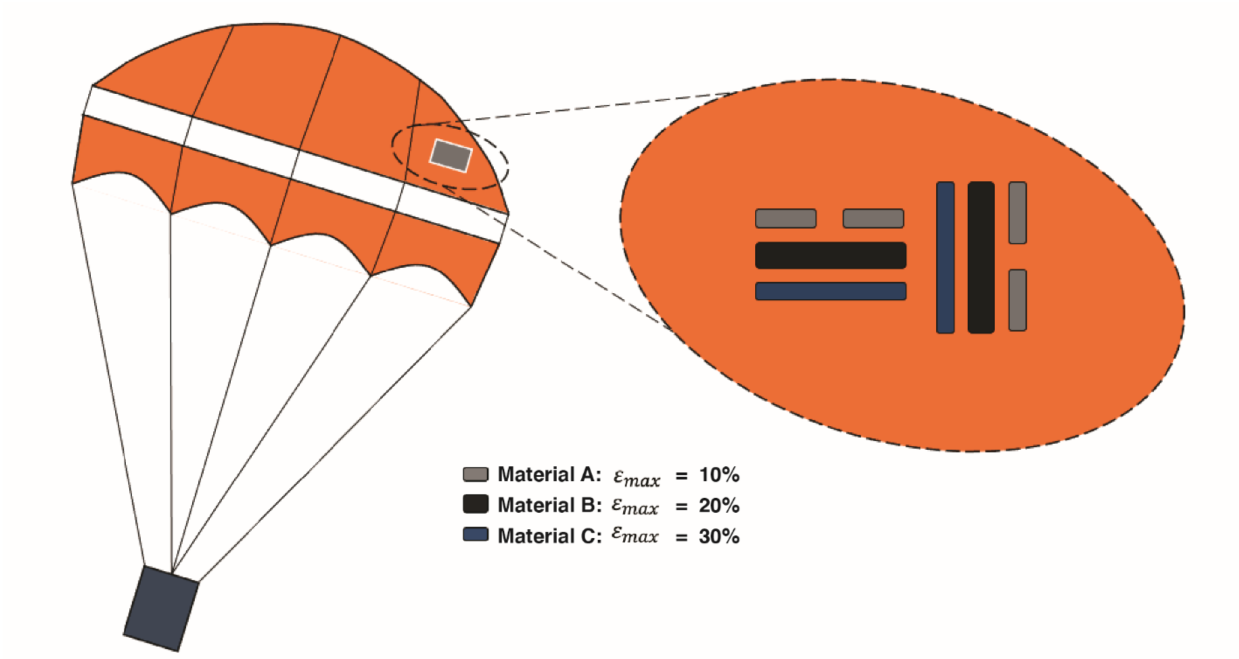

Fig. 5 Passive sensing methodology which would determine peak strain.

V. Sensor Performance Comparison

This section compares the performance of the aforementioned sensor technologies that have been developed past a conceptualized technology to an actual strain sensor. Table 1 presents the sensors and their performance characteristics: maximum elongation, gauge factor, and hysteresis.

Table 1 Strain sensor performance comparison.

Sensor	Max Elongation	GF	Hysteresis %	Meas. Type	TRL	Ref
Conductive Paint/ RTV	50%	na	Severe	Resistance	6	[22]
Conductive Thread 304 Zig Zag	50%	1.6	6.3	Resistance	7	[40]
Conductive Thread 602 Coverstitch	19%	0.4 ‡	10.6 ‡	Resistance	7	[38]
Conductive Thread 602 Bottom Coverstitch	50%	6.76	na	Resistance	7	[39]
Piezoresistive Fabric Sensor	65%	0.3 ‡ course NonLin. Wale	na	Piezoresistive	7	[41]
OFSETH	3%	na	na	Optical	8	[63]
SWCNT Film	280%	NonLin	12 ‡	Resistance	7	[44]
VAgNPN on Silicon	460%	NonLin	na	Resistance	5	[31]
Artificial Skin liquid conductor microchannels	250%	3.93	negligble	Resistance	5	[46]
Ionic Liquid Strain Gauge†,	100%	0.97	na	Resistance	5	[45]
Liquid Metal Strain Gauge†,	100%	3.08	na	Resistance	5	[45]
Printed Liquid Metal Strain Gauge	350%	na	na	Resistance	6	[47]
SCARS	70% *	85500*	Noticible	Piezoresistive	7	[42]
Silicon-Textile Composite	125%	1.23	None	Capacitance	7	[59]
AgNW in PDMS	50%	na	Slight	Resistance	6	[29]
TPE Carbon Black	80%	20	7	Resistance	5	[30]
CNT-Elastomer Capacitor	130%, 300%	~1	Base RΔ, None	Capacitance	5	[61]
Conductive Polymer Chord	50%	na	Slight	Resistance	9	Imagesco.com
Nanosonic Metal Rubber	250%	na	Slight	Resistance	9	Nanosonic.com
Bend Labs	75%	na	None	Capacitance	9	Bendlabs.com
StretchSense	100%	na	None	Capacitance	9	Stretchsense.com
WO3-AgNW in PDMS	50%	13‡	na	Resistance	4	[32]
Electrical Impedance Tomography (EIT) Printed Sensor	41.6%§	na	na	Impedance	5	[65]
Plastic Optical Fiber	35%	na	Severe	Optical	6	[9]
AgNW on Hydrogel	59%	na	na	Resistance	4	[33]
AgNP Ink	400%	na	na	Resistance	4	[56]
MWCNT in PDMS	70%	56	na	Piezoresistive	5	[34]
TPU/MWCNT	120%	8.6 - 176	Significant	Piezoresistive	4	[55]
AgNW EHD Printing	30%	na	na	Resistance	5	[43]

*, Elongation achievable with passive material added, max GF without passive material
†, each entry is one component for a complete sensor that uses both materials
‡, approximated from source graph or data table
§, Volumetric Strain
Base RΔ: Base resistance change

The maximum elongation, ε_{max}, is defined as the maximum change in elongation, ΔL_{max}, over the original length, L_o. For sensors with a linear response, the sensitivity of the sensor is reported by listing the gauge factor, as shown in Eq. (1),

$$GF = \frac{\Delta R}{R_o \varepsilon} \quad or \quad GF = \frac{\Delta C}{C_o \varepsilon} \tag{1}$$

where ΔR is the change in resistance and ΔC is the change in capacitance of the sensor respectively, and where R_o and C_o are the original values. For sensors that do not have a linear response the gauge factor is listed as nonlinear. Hysteresis, when possible, is reported as the max deviation between the upscale output Y_{up} (extension) and downscale output Y_{down} (relaxation) as a percentage of the working range of the measurand defined as hysteresis uncertainty in Eq. (2),

$$u_h = \frac{max\left|Y_{up} - Y_{down}\right|}{\Delta_{FS}}. \tag{2}$$

Because the measurand ranges vary from sensor to sensor, the upscale and downscale difference is normalized by the full-scale range Δ_{FS}. Some sources do not provide tabulated data; therefore, values are generously approximated from the figures provided in these cases. For cases when data is not provided for a given sensor to reliably calculate hysteresis, a qualitative value based on the source literature description will be provided. Some sensors have anisotropic characteristics, primarily those made of fabrics, for these types of sensors, data will be provided for the course and wale directions when available.

In addition to performance characteristics, Table 1 reports the measurement type and technology readiness level (TRL) of the sensor. The TRL gives insight into the specific development stage of the sensor, and the extent to which the technology has been tested in its current application. The TRL scale is from 1 to 9, where 1 indicates that the technology is in concept phase and 9 means the technology has proven successful for its intended task. While high TRL does not inherently mean that the item is readily available for purchase, it is a strong indicator of the availability of the sensor.

VI. Conclusion

Many strain sensors that are capable of being applied to a parachute canopy are in development in the rapidly evolving fields of soft robotics and smart fabrics. With such a large and changing innovation landscape, it is impossible to capture every development in progress; however, the research presented here assists in consolidating the major relevant sensor technologies and gives an overview of the fundamental concepts that show promise for a parachute application. Key performance metrics for these sensors are compared for use case of parachute canopy instrumentation. The drawbacks, in terms of the reliability of sensor measurements as a result of hysteresis and drift from structural changes in the sensor material, are addressed for each sensor type.

The next steps for the Enhancing Parachutes by Instrumenting Canopy project will include further evaluation of the presented sensor technologies and selection of a subset of sensors that are representative of the most promising, available sensor types. Sensors will be attached to ripstop nylon samples and tested in different loading environments including static uniaxial, static biaxial, and dynamic loading environments. In addition to characterizing the performance of the sensors in these environments, future work will investigate how sensor adherence methods affect the canopy material, e.g., altering the fabric breaking strength and inducing stiffness. These future efforts will specifically focus on obtaining an accurate strain measurement with minimum distortion to the parachute and address calibration methods for fabric stress calculations.

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