

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent	12385794
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Dueweke; Michael et al.

Systems and methods for continuous mode force testing

Abstract

Described herein is a method and system for testing a force or strain sensor in a continuous fashion. The method employs a sensor, a test fixture, a load cell, a mechanical actuator and tester hardware and software to simultaneously record signal outputs from the sensor and load cell as functions of time. The method provides time synchronization events for recording data streams between, for example, a linear ramp of the force on, or displacement of, the sensor and for extracting performance characteristics from the data in post-test processing.

Inventors: Dueweke; Michael (Campbell, CA), Liu; Allan (HsinChu, TW), Benjamin; Dan (Atlanta, GA)

Applicant: NEXTINPUT, INC. (Mountain View, CA)

Family ID: 1000008748899

Assignee: NextInput, Inc. (Mountain View, CA)

Appl. No.: 18/517558

Filed: November 22, 2023

Prior Publication Data

Document Identifier	Publication Date
US 20240159607 A1	May. 16, 2024

Related U.S. Application Data

continuation parent-doc US 17615208 US 11874183 WO PCT/US2020/035531 20200601 child-doc US 18517558
us-provisional-application US 62854422 20190530

Publication Classification

Int. Cl.: G01L5/00 (20060101)

U.S. Cl.:

CPC G01L5/0028 (20130101);

Field of Classification Search

CPC: G01L (5/0028); G01L (5/0038); G01L (25/00)

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
4140008	12/1978	Golembeck	73/806	G01N 3/42
5255562	12/1992	Yamamoto	73/78	G01D 1/02
5447051	12/1994	Hanks et al.	N/A	N/A
5517860	12/1995	Lin	73/789	G01N 3/20
6176117	12/2000	Chen	73/1.15	G01L 25/00
6520004	12/2002	Lin	73/81	G01N 3/46
7395722	12/2007	Lin	73/789	G01L 25/00
7681432	12/2009	Hay	73/1.79	G01B 21/045
8839655	12/2013	Bormann	73/1.15	G01L 25/00
9487388	12/2015	Brosh	N/A	N/A
9493342	12/2015	Brosh	N/A	N/A
9696229	12/2016	Schulz	N/A	G01L 25/00
9880066	12/2017	Larsen et al.	N/A	N/A
9902611	12/2017	Brosh et al.	N/A	N/A
10466119	12/2018	Campbell et al.	N/A	N/A
10921217	12/2020	Ehmke	N/A	G01L 25/00
11118994	12/2020	Tao	N/A	G01G 5/006
11506559	12/2021	Chen	N/A	G01L 25/00
11624648	12/2022	Ohler	177/50	G01G 23/015
11835400	12/2022	Tu	N/A	G01L 5/167
11874183	12/2023	Dueweke et al.	N/A	N/A
2007/0186670	12/2006	Lin	73/789	G01L 25/00
2007/0255509	12/2006	LeFebvre et al.	N/A	N/A
2010/0226203	12/2009	Buttle	367/15	B63B 21/66
2010/0281944	12/2009	Brucke	N/A	N/A
2011/0024192	12/2010	Pastusek et al.	N/A	N/A
2013/0247689	12/2012	Thanigachalam et al.	N/A	N/A
2015/0096348	12/2014	Schulz	73/1.08	G01L 25/00
2016/0273990	12/2015	Larsen	N/A	G01L 25/00
2016/0363490	12/2015	Campbell et al.	N/A	N/A
2018/0238771	12/2017	Ehmke	N/A	B61K 9/08

2019/0383675	12/2018	Tsai et al.	N/A	N/A
2019/0383676	12/2018	Foughi et al.	N/A	N/A
2020/0191622	12/2019	Suga	N/A	G01L 27/007
2022/0228936	12/2021	Dueweke	N/A	G01L 5/0038

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
103021985	12/2012	CN	N/A
103575460	12/2013	CN	N/A
107255544	12/2016	CN	N/A
109000847	12/2017	CN	N/A
H1123401	12/1998	JP	N/A
2013185966	12/2012	JP	N/A
2018148503	12/2017	WO	N/A
2018148510	12/2017	WO	N/A
2019068686	12/2018	WO	N/A

OTHER PUBLICATIONS

Non-Final Office Action for U.S. Appl. No. 17/615,208, mailed May 23, 2023, 8 pages. cited by applicant

Notice of Allowance for U.S. Appl. No. 17/615,208, mailed Sep. 13, 2023, 7 pages. cited by applicant

Extended European Search Report for European Patent Application No. 20812780.3, mailed Apr. 12, 2023, 9 pages. cited by applicant

International Search Report and Written Opinion for International Patent Application No. PCT/US2020/035531, mailed Aug. 20, 2020, 8 pages. cited by applicant

First Office Action for Chinese Patent Application No. 202080054697.4, mailed Jun. 1, 2024, 21 pages. cited by applicant

Intention to Grant for European Patent Application No. 20812780.3, mailed Mar. 15, 2024, 47 pages. cited by applicant

Vidal-Verdu, F. et al., "A Large Area Tactile Sensor Patch Based on Commercial Force Sensors," Sensors, vol. 11, No. 12, May 2011, pp. 5489-5507. cited by applicant

Examination Report for European Patent Application No. 20812780.3, mailed Sep. 24, 2024, 5 pages. cited by applicant

Second Office Action for Chinese Patent Application No. 202080054697.4, mailed Dec. 30, 2024, 24 pages. cited by applicant

Extended European Search Report for European Patent Application No. 25176162.3, mailed Jun. 20, 2024, 10 pages. cited by applicant

Primary Examiner: Kirkland, III; Freddie

Attorney, Agent or Firm: Withrow & Terranova, P.L.L.C.

Background/Summary

RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 17/615,208, filed Nov. 30, 2021, now U.S. Pat. No. 11,874,183, which is a 371 national phase

filing of PCT/US2020/035531, filed Jun. 1, 2020, which claims the benefit of U.S. provisional patent application Ser. No. 62/854,422, the disclosures of which are hereby incorporated herein by reference in their entirety.

FIELD OF THE DISCLOSURE

(1) The present disclosure relates to the testing of force sensors and strain gauges used for converting force or strain into an electrical signal.

BACKGROUND

(2) When testing sensors such as force sensors and strain gauges, it is often required to evaluate sensor response over a range of input values in order to assess performance to specifications. Current techniques for testing require a range of force or strain values to be applied and to stabilize each force or strain mechanically and wait for electrical signal variations to stabilize prior to taking each measurement. The repeated process of applying a force or strain, waiting for mechanical and electrical stabilization, taking a measurement of both force or strain and electrical signal, and applying an additional force or strain value is time consuming and costly.

(3) Accordingly, there is a need in the pertinent art for a less time consuming, lower-cost, test method for force sensors and strain gauges.

SUMMARY

(4) The present disclosure pertains to a method of testing force sensors and strain gauges comprising the application of a mechanical force or strain and measurement of a sensor electrical output. Each force or strain sensor can include a flexure and one or more piezoresistive strain gauges. In one implementation, a mechanical force is applied with a linear ramping of the applied force while simultaneously measuring the electrical output of the force sensor and the amount of force applied. Synchronizing events are introduced in the test sequence to allow for post-processing and analysis of the data taken through various measurement channels. The method enables faster, lower-cost, and more accurate measurements of force sensors and strain gauges.

(5) An example testing system is described herein. The system includes a test fixture configured to provide electrical connection to a force or strain sensor, a mechanical actuator configured to apply force to the force or strain sensor, a load cell configured to measure an amount of the force applied to the force or strain sensor and a controller configured to operate the mechanical actuator and simultaneously record respective output signals from the force or strain sensor and the load cell.

(6) In some implementations, the step of simultaneously recording respective output signals from the force or strain sensor and the load cell optionally includes sampling the respective output signals in a burst mode, where the burst mode is defined by a sampling frequency and a sampling period.

(7) In some implementations, the step of simultaneously recording respective output signals from the force or strain sensor and the load cell optionally includes sampling the respective output signals in a burst mode, where the burst mode is defined by a sampling frequency and a sampling period.

(8) Alternatively or additionally, the force or strain sensor includes one or more piezoresistive, piezoelectric, or capacitive transducers.

(9) Alternatively or additionally, the system further optionally includes a robotic arm, where the mechanical actuator is optionally controlled by the robotic arm. For example, the robotic arm is operably connected to and controlled by the controller.

(10) Alternatively or additionally, the respective output signals from the force or strain sensor and the load cell is stored in memory of the controller.

(11) Alternatively or additionally, the respective output signals from the force or strain sensor and the load cell is recorded as a function of time. In some implementations the controller is configured to operate the mechanical actuator to change the amount of the force applied by the mechanical actuator from a first force value to a second force value, where the first and second force values are

different. Optionally, the controller is further configured to operate the mechanical actuator to hold the first force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time, subsequently ramp the first force value to the second force value while recording the respective output signals from the force or strain sensor and the load cell as a function of time, and hold the second force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time. In some implementations, the controller is further configured to operate the mechanical actuator to use a transition from the first force value to the ramped force and a transition from the ramped force to the second force value as temporal data synchronization points between the respective output signals from the force or strain sensor and the load cell.

(12) Alternatively or additionally, the system can optionally include a flexible substrate can be included, where the force or strain sensor is soldered to the flexible substrate, and the force is applied to the flexible substrate by the mechanical actuator to create displacement and strain within the flexible substrate and strain within the force or strain sensor. In some implementations, the respective output signal of the force or strain sensor is recorded by the controller through electrical routing within the flexible substrate.

(13) In some implementations, the system optionally includes the force or strain sensor.

(14) An example method for testing a force or strain sensor is also described herein. The example method includes providing a test fixture configured to provide electrical connection to the force or strain sensor, connecting the force or strain sensor to the test fixture, and operating a mechanical actuator to apply a force to the force or strain sensor. The example method also includes providing a load cell configured to measure an amount of the force applied to the force or strain sensor, and simultaneously recording respective output signals from the force or strain sensor and the load cell.

(15) Additionally, the step of simultaneously recording respective output signals from the force or strain sensor and the load cell includes sampling the respective output signals in a burst mode, where the burst mode is defined by a sampling frequency and a sampling period.

(16) In some implementations, the respective output signal from the force or strain sensor is sampled with a first sampling frequency and a first sampling period. Additionally, the respective output signal from the load cell is sampled with a second sampling frequency and a second sampling period. Optionally, the first and second sampling frequencies are the same or different.

(17) Alternatively or additionally, the force or strain sensor detects strain through piezoresistive, piezoelectric, or capacitive transducers.

(18) Alternatively or additionally, the mechanical actuator is optionally controlled by a robotic arm. For example, the robotic arm is operably connected to and controlled by a computing device.

(19) Alternatively or additionally, the respective output signals from the force or strain sensor and the load cell are optionally stored in memory of a computing device.

(20) Alternatively or additionally, the respective output signals from the force or strain sensor and the load cell is optionally recorded as a function of time.

(21) Alternatively or additionally, the method further includes changing the amount of the force applied by the mechanical actuator from a first force value to a second force value, where the first and second force values are different. In some implementations, the method further includes holding the first force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time, subsequently ramping the first force value to the second force value while recording the respective output signals from the force or strain sensor and the load cell as a function of time, and subsequently holding the second force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time. Optionally, the method further includes using a transition from the first force value to the ramped force and a transition from the ramped force to the second force value as temporal data synchronization points between the respective output signals from the force or strain sensor and the load cell.

(22) Alternatively or additionally, the force or strain sensor is soldered to a flexible substrate, and the force is applied to the flexible substrate by the mechanical actuator to create displacement and strain within the flexible substrate and strain within the force or strain sensor. Additionally, the respective output signals of the force or strain sensor is recorded through electrical routing within the flexible substrate.

(23) Other systems, methods, features and/or advantages will be or may become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features and/or advantages be included within this description and be protected by the accompanying claims.

(24) Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

Description

BRIEF DESCRIPTION OF THE DRAWING FIGURES

(1) The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

(2) FIG. 1 is an isometric view of the top of an example force sensor.

(3) FIG. 2 is a cross-sectional view of the force sensor shown in FIG. 1.

(4) FIG. 3 shows a cross-sectional view of another example force sensor soldered to a substrate where a force is applied to the top of the force sensor.

(5) FIG. 4 shows a cross-sectional view of another example force sensor soldered to a substrate where a force is applied to the bottom of the substrate.

(6) FIG. 5 shows a typical voltage output response for a force sensor with respect to input force level.

(7) FIG. 6 shows the force applied to a force sensor versus time as measured by a load cell according to an implementation described herein.

(8) FIG. 7 shows an example voltage output signal versus time for a force sensor experiencing the force profile shown in FIG. 6.

(9) FIGS. 8A-8C show an example of the relative timing among force events applied to a force sensor (FIG. 8A) and the resulting load cell force output (FIG. 8C) and force sensor voltage output (FIG. 8B).

(10) FIG. 9 shows a resulting voltage output versus force output measurement based on post processing of load cell voltage output and force sensor voltage output and the synchronization of force events (A and A'/B and B').

(11) FIG. 10 shows a cross-sectional view of a system for testing a force or strain sensor according to an implementation described herein.

(12) FIG. 11 shows a cross-sectional view of a system for testing a force or strain sensor according to an implementation described herein.

DETAILED DESCRIPTION

(13) The present disclosure can be understood more readily by reference to the following detailed description, examples, drawings, and their previous and following description. However, before the present devices, systems, and/or methods are disclosed and described, it is to be understood that this disclosure is not limited to the specific devices, systems, and/or methods disclosed unless otherwise specified, and, as such, can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting.

(14) The following description is provided as an enabling teaching. To this end, those skilled in the relevant art will recognize and appreciate that many changes can be made, while still obtaining beneficial results. It will also be apparent that some of the desired benefits can be obtained by selecting some of the features without utilizing other features. Accordingly, those who work in the art will recognize that many modifications and adaptations may be possible and can even be desirable in certain circumstances, and are contemplated by this disclosure. Thus, the following description is provided as illustrative of the principles and not in limitation thereof.

(15) As used throughout, the singular forms “a,” “an” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a force sensor” can include two or more such force sensors unless the context indicates otherwise.

(16) The term “comprising” and variations thereof as used herein is used synonymously with the term “including” and variations thereof and are open, non-limiting terms.

(17) Ranges can be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another aspect includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another aspect. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

(18) As used herein, the terms “optional” or “optionally” mean that the subsequently described event or circumstance may or may not occur, and that the description includes instances where said event or circumstance occurs and instances where it does not.

(19) Throughout the present disclosure, the terms “force sensor” and “strain sensor” may be used to describe the sensor being tested. The systems and methods disclosed can be used to test force sensors or strain sensors. In some implementations, the force or strain sensor is a microelectromechanical system (“MEMS”) sensor.

(20) The present disclosure relates to systems and methods for testing a force or strain sensor. In the examples below, the systems and methods are described with regard to testing a force sensor. It should be understood that force sensor testing is provided only as an example.

(21) This disclosure contemplates that the systems and methods described herein can be used to test a strain sensor (or strain gauge). With reference to FIG. 1 and FIG. 2, in some implementations the force sensor includes a base **11** and electrical contacts **19**. The electrical contacts **19** can be solder bumps, pillars, or other conductive contacts. It should be understood that the electrical contacts **19** provide the means for applying voltage to and/or recording voltage from the force sensor **10**. A contact surface **15** exists along the top surface of the base **11** for receiving an applied force F and transmitting the force F to at least one mechanical flexure **16**.

(22) It should be understood that the force sensor **10** shown in FIGS. 1 and 2 is provided only as an example of a force sensor. This disclosure contemplates testing force sensors other than those shown in FIGS. 1 and 2. Example MEMS force sensors that can be tested using the systems and methods of this disclosure are described in detail in U.S. Pat. No. 9,487,388, issued Nov. 8, 2016 and titled “Ruggedized MEMS Force Die;” U.S. Pat. No. 9,493,342, issued Nov. 15, 2016 and titled “Wafer Level MEMS Force Dies;” U.S. Pat. No. 9,902,611, issued Feb. 27, 2018 and titled “Miniaturized and ruggedized wafer level mems force sensors;” U.S. Pat. No. 10,466,119, issued Nov. 5, 2019 and titled “Ruggedized wafer level mems force sensor with a tolerance trench;” WO2018/148503, published Aug. 16, 2018 and titled “INTEGRATED DIGITAL FORCE SENSORS AND RELATED METHODS OF MANUFACTURE,” and WO2018/148510, published Aug. 16, 2018 and titled “INTEGRATED PIEZORESISTIVE AND PIEZOELECTRIC FUSION FORCE SENSOR,” the disclosures of which are incorporated by reference in their entireties.

(23) FIGS. 3 and 4 illustrate a force sensor **30** according to another implementation described herein. Optionally, the force sensor **30** is soldered to a substrate **31** through solder balls **32**. Optionally, the substrate **31** can be a flexible substrate, and electrical routing can be positioned

within the flexible substrate. This disclosure contemplates that the force sensor **30** can be any force sensor, including the MEMS force sensors described above. As shown in FIG. 3, the force sensor **30** can be activated from the top surface with force F to measure the force F and output an electrical signal proportional to the applied force. In this implementation, the substrate is optionally held fixed in place with backing material or other support material.

(24) Referring to FIG. 4, the force sensor **30** can optionally be activated by applying a force F from the bottom surface of the substrate **31**. The force F can induce a displacement and strain in the substrate **31** which in turn can impart strain to the force sensor **30** through solder balls **32**. In this implementation, the substrate **31** optionally has some flexibility while the top surface of the sensor **30** is optionally unconstrained by any hard surface. The force sensor **30** can undergo strain and can output an electrical signal proportional to the amount of strain it experiences due to force F .

(25) FIG. 5 illustrates a graph depicting typical output voltage signal versus input force for a force sensor, e.g., a force sensor such as one described above with regard to FIGS. 1-4. According to conventional force sensor testing, a force value is set and held constant while measuring output of the force sensor. This process is repeated at a plurality of force level

(26) increments to establish the response curve (i.e., the dotted line in FIG. 5) of the sensor. At each applied force value, the output of the force sensor is allowed to stabilize before moving to the next incremental force value. The response curve represents the voltage output (y-axis) versus applied force (x-axis). This disclosure contemplates that the force response of a force or strain sensor is monotonic, e.g., the voltage output never decreases as the values of the applied force increase. The linear force response shown in FIG. 5 is provided only as an example. It should be understood that the force response curve for a force or strain sensor may be non-linear. This conventional testing method is time consuming since changing the applied force induces electrical and mechanical noise which requires settling time or averaging to reduce noise and enable measurement accuracy.

(27) FIG. 6 illustrates a graph of force applied to a force sensor as a function of time according to an implementation described herein. In FIG. 6, the force applied (or voltage output) is measured by the load cell. As described herein, a load cell is a transducer that converts applied force into a measurable output voltage. In other words, the voltage output of a load cell is indicative of the force applied to the load cell. The applied force is held at a fixed value F_1 up to time t_1 . At time t_1 , the force begins to ramp with time, corresponding to point A in the graph. As discussed below, the force increases continuously from F_1 to F_2 between point A (at time t_1) to point B (at time t_2). In FIG. 6, the force ramps linearly (e.g., increases linearly) with time. It should be understood that the linearly increasing applied force beginning at time t_1 is provided only as an example. This disclosure contemplates that the increasing applied force beginning at time t_1 may do so in a non-linear fashion. Additionally, it should be understood that the rate of increase shown in FIG. 6 is provided only as an example and that other rates of increase are possible. The force is continually ramped to point B in the graph, where it is held at a fixed value F_2 starting at time t_2 . In FIG. 6, F_2 is greater than F_1 . It should be understood that the values of F_1 and F_2 and times t_1 and t_2 , as well as the relationships therebetween, are provided only as examples. Additionally, a ramped increasing force is used in FIG. 6 as an example. It should be understood that force can be decreased, for example, between F_2 and F_1 over time. The x-axis in FIG. 6 represents time, and the y-axis represents the applied force. It should be understood that the y-axis in FIG. 6 represents the voltage output of a load cell, which is indicative of the applied force.

(28) FIG. 7 illustrates the corresponding voltage output for a linear force sensor experiencing the force profile illustrated in FIG. 6. It should be understood that the force response of a force or strain sensor is not required to be linear. The response of a force or strain sensor, whether linear or non-linear, is expected to be monotonic. The linear force response shown in FIG. 7 is provided only as an example. In FIG. 7, the voltage output is measured by the force sensor. In other words, x-axis in FIG. 7 represents time, and the y-axis in FIG. 7 represents the voltage output of the force sensor. There is a constant voltage output V_1 while the applied force F_1 is constant. When the applied force

begins to ramp linearly at point A in FIG. 6, there is a corresponding change in the voltage output starting at point A' in FIG. 7. This occurs at time t_l' in FIG. 7. It should be understood that the rate of increase shown in FIG. 7 is provided only as an example and that other rates of increase are possible. Further, a delay is present between the input force and the output voltage of the force sensor. For example, a delay can be caused by delays in the signal path and/or differences in the signal path lengths for load cell (FIG. 6) and force sensor (FIG. 7), respectively. Therefore, the time t_l' in FIG. 7 is different than the time t_l in FIG. 6. Similarly, t_2 in FIG. 6 is different than t_2' in FIG. 7.

(29) As the force is ramped linearly as shown in FIG. 6, the voltage output of a force sensor responds proportionally as shown between points A' and B' in FIG. 7. With reference to FIG. 7, the voltage output of the sensor increases until point B' which corresponds to a constant force level F2 being applied. This occurs at time t_2' in FIG. 7. After point B', the voltage output is constant at voltage V2 corresponding to constant force F2. Again, a delay can be caused by delays in the signal path and/or differences in the signal path lengths for load cell (FIG. 6) and force sensor (FIG. 7), respectively.

(30) FIGS. 8A-8C show an example of relative timing among events and measurements according to an implementation described herein. FIG. 8A indicates the timing of an applied force to a force sensor (e.g., the force sensors of any one of FIGS. 1-4), illustrated as a linear ramp in force from point A to point B. The applied force is ramped continuously over time between points A and B (e.g., in contrast to incrementally or with discrete steps). As described above, the linearly increasing applied force and force response in FIGS. 6 and 7 are provided only as examples. As shown in FIG. 8A, the applied force is held constant at times before point A and also held constant at times after point B. Between points A and B, the applied force increases continuously from F1 to F2. FIG. 8B illustrates the timing of voltage measurements from the force sensor (also referred to herein as "force sensor output"). According to the implementation illustrated in FIGS. 8A-8C, the system is configured to sample using a "burst mode." In "burst mode," the sensor and load cell are sampled in "bursts" where each burst includes plurality of voltage measurements (e.g., from either the force sensor or the load cell) acquired in each "burst period." In FIGS. 8A-8C, the vertical arrows represent samples, and the spacing between the vertical arrows represents the sampling period. The sampling rate for both the sensor output (FIG. 8B) and load cell output (FIG. 8C) can be tuned to reduce the measurement noise of a single burst mode reading, for example, by means of averaging the plurality of voltage measurements acquired in a burst. Additionally, the burst period is not fixed, and can be adjusted to account for motor speed (e.g., driver of the mechanical actuator), sensor output sensitivity, and/or other parameters particular to a given measurement implementation. As shown in FIGS. 8A-8C, a plurality of burst measurements are acquired from each of the force sensor and load cell prior to points A and A', a plurality of burst measurements are acquired from each of the force sensor and load cell between points A/A' and B/B', and a plurality of burst measurements are acquired from each of the force sensor and load cell after points B and B'. It should be understood that a plurality of burst measurements are acquired from each of the force sensor and load cell while the applied force increases continuously between points A/A' and B/B'. In other words, according to the implementation shown in FIGS. 8A-8C, the applied force is not increased incrementally (e.g., step-wise) between points A/A' and B/B' with a pause for measurements at an incremental step. FIG. 8C illustrates the timing of measurements from a load cell (also referred to herein as "load cell output"), which quantifies the amount of force applied to the force sensor as a function of time. The load cell is also measured in a burst mode with a force sample period, and a burst period indicated by the time between groups of small vertical arrows. As discussed above, the sampling rate for the load cell output (FIG. 8C) can be tuned to reduce the measurement noise of a single burst mode reading, for example, by means of averaging the plurality of voltage measurements acquired in a burst. Additionally, the burst period is not fixed, and can be adjusted to account for motor speed (e.g., driver of the mechanical actuator), load cell

output sensitivity, and/or other parameters particular to a given measurement implementation. Different combinations of force sensor, load cell, sampling mode, and sampling period are possible, according to implementations described herein. For example, the output data from the force sensor may be sampled with a first sampling frequency/period, and the output data from the load cell may be sampled with a second sampling frequency/period. According to some implementations described herein, the load cell sample period and force sensor sample period can be the same. According to other implementations, the load cell sample period and force sensor sample period can be different. Alternatively or additionally, the load cell sample frequency and force sensor sample frequency can be the same or different.

(31) The actual timing of signal events between load cell measurements and force sensor measurements will not in general be synchronous, but will occur with some relative delay between the different signal paths, which is indicated as Δt relative signal delay below FIG. 8C. After the load cell and force sensor voltage output signals have been measured and recorded through the sequence shown in FIGS. 6 and 7 (e.g., fixed 1st force (F1) until time t_1/t_1' , followed by ramped force until time t_2/t_2' , followed by fixed 2nd force (F2)), the signal data can be post processed to map the events at the beginning and end of the force ramp. Points A/A' and B/B' serve as the temporal data synchronization points. For example, the onset of the load cell voltage output signal increase (e.g., at time t_1 in FIG. 6) is mapped to the onset of the force sensor voltage output signal increase (e.g., at time t_1' in FIG. 7), and similarly the load cell voltage output stabilization (e.g., at time t_2 in FIG. 6) is mapped to the force sensor voltage output stabilization (e.g., at time t_2' in FIG. 7), to obtain a function of force sensor voltage output as a function of load cell voltage output. The measurement times for one signal path can be shifted or scaled appropriately such that the start and end times for the force ramp coincide between load cell voltage output and force sensor voltage output. In some implementations, the load cell and force sensor voltage are sampled at the same rate, such that after scaling times on one variable to match the start and stop events, the intermediate points can also be scaled by the same factor to match values one to one between load cell output and sensor voltage output.

(32) The transition points (e.g., points A/A' and B/B' in FIGS. 6 and 7) can be used as temporal synchronization points. It should be understood that the number and/or relationship between the synchronization points are provided only as an example. For example, by synchronizing the time at which the load cell output begins to change, with the point at which the force sensor output begins to change, the two graphs can be synchronized, accounting for any time delay between the output from the force sensor and the output from the load cell. Accordingly, the force sensor output voltage can be determined as a function of the load cell force measurement. By scaling the measurement times of one signal path, either force sensor voltage output or load cell voltage output, and mapping the start and stop force ramp events, the force sensor voltage output can be determined as a function of the load cell force measurement, providing the desired signal output versus applied force measurement as shown in FIG. 9. This can be accomplished without repeating a plurality of force level increments and measurements to establish the force sensor's response curve according to conventional techniques as discussed above with regard to FIG. 5.

(33) FIG. 10 illustrates a cross-sectional view of a system for testing a force or strain sensor. In FIG. 10, the system includes a test fixture 44, a mechanical actuator 45, and a load cell 46. The system also includes a controller (e.g., computing device 1100 shown in FIG. 11) operably coupled to the mechanical actuator 45 and the load cell 46. Additionally, the controller is operably coupled to a force sensor 40 via the test fixture 44. This disclosure contemplates that the force sensor 40 can be any one of the force sensors as described above, or another other type of force or strain sensor. The controller can be coupled to the mechanical actuator 45, load cell 46, and/or force sensor through one or more communication links. This disclosure contemplates the communication links are any suitable communication link. For example, a communication link may be implemented by any medium that facilitates data exchange including, but not limited to, wired, wireless and optical

links.

(34) The test fixture **44** can be made (or coated with) of an insulating material and include one or more electrical connections **43**. Optionally, as shown in FIG. **10**, the electrical connections **43** are provided in a recess of the test fixture **44**, where the recess is configured to fit the force sensor **40**. This disclosure contemplates that insulating materials include, but are not limited to, polyether ether ketone (PEEK), ceramic, and polyimide. This disclosure also contemplates that the electrical connections **43** can be made of a conductive material (e.g. metal). The electrical connections **43** can be provided to make contact with solder balls (or pillars, terminals, etc.) **42** of the force sensor **40**. It should be understood that the solder balls **42** provide the means for applying voltage to and/or recording response (e.g., voltage output) from the force sensor **40**. The number, size, shape and/or arrangement of the electrical connections **43** can be chosen based on the design of the force sensor **40**. It should be understood that the number, size, shape and/or arrangement of the electrical connections **43** in FIG. **10** are provided only as examples. The test fixture **44** therefore serves as an electrically insulating mechanical fixture with conductive electrical connections **43** for providing source voltage and/or measuring output voltage of the force sensor **40**. The force sensor **40** can be operably coupled to the controller (e.g., computing device **1100** shown in FIG. **11**) via the electrical connections **43**. Accordingly, the system is configured to record the force sensor output voltage (e.g., as shown in FIGS. **7** and **8B**) via the electrical connections **43** while a force is applied to the force sensor **40**.

(35) The system also includes the mechanical actuator **45**. The mechanical actuator **45** is configured to apply the force to the force sensor **40**. For example, the mechanical actuator **45** can be a moveable rigid body. The mechanical actuator **45** can be made of a hard plastic (e.g., an acetal homopolymer such as DELRIN), metal (e.g. aluminum, stainless steel, etc.), or an elastic material (e.g., silicone rubber). This disclosure contemplates the mechanical actuator's size and/or shape are variable. For example, the mechanical actuator **45** can have a flat surface and/or rounded protrusions. Alternatively or additionally, the mechanical actuator **45** can be larger or smaller than the size of the force sensor **40**. Optionally, the mechanical actuator **45** is about the same size as the force sensor **40**. The mechanical actuator **45** can be controlled to make contact with a surface of the force sensor **40** and apply a force **F3**, which can be variable over time as described herein. Mechanical movement can be controlled by means of one or more electrical motors, such as a stepper or servo motor, for example. In some implementations, the system optionally includes a robotic arm, and the mechanical actuator **45** is operably coupled to the robotic arm. For example, the mechanical actuator **45** can be attached to the robotic end effector. The robotic arm can be configured to control the movements (e.g., trajectory, position, orientation, etc.) of the mechanical actuator **45** relative to the test fixture **44** such that a variable force can be applied by the mechanical actuator **45** to the force sensor **40**. as described above, mechanical movement can be controlled by means of one or more electrical motors. Robotic product testing systems are known in the art and are therefore not described in further detail herein.

(36) Additionally, the system includes the load cell **46**. A load cell is a transducer that converts force into a measurable electrical output (e.g., a voltage). A strain gauge is one example type of load cell. It should be understood that other types of load cells can be used in the system described herein. Load cells are known in the art and are therefore not described in further detail herein. The load cell **46** can be arranged in series with the mechanical actuator **45**. The force **F3** applied by the mechanical actuator **45** can be measured by a load cell **46**. Optionally, the load cell **46** can be attached directly or indirectly to the mechanical actuator **45**. Optionally, the load cell **46** is not attached to the mechanical actuator **45**. It should be understood that the arrangement of the load cell **46** in FIG. **10** is provided only as an example.

(37) As described herein, applied force **F3** in FIG. **10** can be variable over time. For example, the mechanical actuator **45** can be controlled to apply a first force (e.g., constant force **F1** in FIG. **6**) while simultaneously recording the respective output signals from the force sensor **40** (e.g., FIG. **7**

prior to time t_1') and the load cell **46** (e.g., FIG. **6** prior to time t_1). The mechanical actuator **45** can be further controlled to subsequently ramp the first force to a second force (e.g., force F_2 in FIG. **6**) while simultaneously recording the respective output signals from the force sensor **40** (e.g., FIG. **7** between times t_1' and t_2') and the load cell **46** (e.g., FIG. **6** between times t_1 and t_2). The mechanical actuator **45** can be further controlled to subsequently apply the second force (e.g., constant force F_2 in FIG. **6**) while simultaneously recording the respective output signals from the force sensor **40** (e.g., FIG. **7** after to time t_2') and the load cell **46** (e.g., FIG. **6** after to time t_2). Additionally, the transition from the first force to the ramped force (e.g., at time t_1 in FIG. **6**/ t_1' in FIG. **7**) and the transition from the ramped force to the second force (e.g., at time t_2 in FIG. **6**/ t_2' in FIG. **7**) serve as temporal data synchronization points between the respective output signals from the force sensor **40** and the load cell **46**. These synchronization points allow the force sensor output voltage to be determined as a function of load cell force measurement. This relationship between force sensor output voltage and applied force is shown, for example, by FIG. **9**.

(38) It should be appreciated that the logical operations described herein with respect to the various figures may be implemented (1) as a sequence of computer implemented acts or program modules (i.e., software) running on a computing device (e.g., the computing device described in FIG. **11**), (2) as interconnected machine logic circuits or circuit modules (i.e., hardware) within the computing device and/or (3) a combination of software and hardware of the computing device. Thus, the logical operations discussed herein are not limited to any specific combination of hardware and software. The implementation is a matter of choice dependent on the performance and other requirements of the computing device. Accordingly, the logical operations described herein are referred to variously as operations, structural devices, acts, or modules. These operations, structural devices, acts and modules may be implemented in software, in firmware, in special purpose digital logic, and any combination thereof. It should also be appreciated that more or fewer operations may be performed than shown in the figures and described herein. These operations may also be performed in a different order than those described herein.

(39) Referring to FIG. **11**, an example computing device **1100** upon which the methods described herein may be implemented is illustrated. The computing device **1100** can be operably coupled to the mechanical actuator and load cell described above, for example, and be configured to control application of the force and record output data (e.g., output signals) from the load cell. Additionally, the computing device **1100** can be operably coupled to the force sensor described above, for example, and be configured to record output data (e.g., output signals) from the force or strain sensor. It should be understood that the example computing device **1100** is only one example of a suitable computing environment upon which the methods described herein may be implemented. Optionally, the computing device **1100** can be a well-known computing system including, but not limited to, personal computers, servers, handheld or laptop devices, multiprocessor systems, microprocessor-based systems, network personal computers (PCs), minicomputers, mainframe computers, embedded systems, and/or distributed computing environments including a plurality of any of the above systems or devices. Distributed computing environments enable remote computing devices, which are connected to a communication network or other data transmission medium, to perform various tasks. In the distributed computing environment, the program modules, applications, and other data may be stored on local and/or remote computer storage media.

(40) In its most basic configuration, computing device **1100** typically includes at least one processing unit **1106** and system memory **1104**. Depending on the exact configuration and type of computing device, system memory **1104** may be volatile (such as random access memory (RAM)), non-volatile (such as read-only memory (ROM), flash memory, etc.), or some combination of the two. This most basic configuration is illustrated in FIG. **11** by dashed line **1102**. The processing unit **1106** may be a standard programmable processor that performs arithmetic and logic operations necessary for operation of the computing device **1100**. The computing device **1100** may also

include a bus or other communication mechanism for communicating information among various components of the computing device **1100**.

(41) Computing device **1100** may have additional features/functionality. For example, computing device **1100** may include additional storage such as removable storage **1108** and non-removable storage **1110** including, but not limited to, magnetic or optical disks or tapes. Computing device **1100** may also contain network connection(s) **1116** that allow the device to communicate with other devices. Computing device **1100** may also have input device(s) **1114** such as a keyboard, mouse, touch screen, etc. Output device(s) **1112** such as a display, speakers, printer, etc. may also be included. The additional devices may be connected to the bus in order to facilitate communication of data among the components of the computing device **1100**. All these devices are well known in the art and need not be discussed at length here.

(42) The processing unit **1106** may be configured to execute program code encoded in tangible, computer-readable media. Tangible, computer-readable media refers to any media that is capable of providing data that causes the computing device **1100** (i.e., a machine) to operate in a particular fashion. Various computer-readable media may be utilized to provide instructions to the processing unit **1106** for execution. Example tangible, computer-readable media may include, but is not limited to, volatile media, non-volatile media, removable media and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data. System memory **1104**, removable storage **1108**, and non-removable storage **1110** are all examples of tangible, computer storage media. Example tangible, computer-readable recording media include, but are not limited to, an integrated circuit (e.g., field-programmable gate array or application-specific IC), a hard disk, an optical disk, a magneto-optical disk, a floppy disk, a magnetic tape, a holographic storage medium, a solid-state device, RAM, ROM, electrically erasable program read-only memory (EEPROM), flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices.

(43) In an example implementation, the processing unit **1106** may execute program code stored in the system memory **1104**. For example, the bus may carry data to the system memory **1104**, from which the processing unit **1106** receives and executes instructions. The data received by the system memory **1104** may optionally be stored on the removable storage **1108** or the non-removable storage **1110** before or after execution by the processing unit **1106**.

(44) It should be understood that the various techniques described herein may be implemented in connection with hardware or software or, where appropriate, with a combination thereof. Thus, the methods and apparatuses of the presently disclosed subject matter, or certain aspects or portions thereof, may take the form of program code (i.e., instructions) embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, or any other machine-readable storage medium wherein, when the program code is loaded into and executed by a machine, such as a computing device, the machine becomes an apparatus for practicing the presently disclosed subject matter. In the case of program code execution on programmable computers, the computing device generally includes a processor, a storage medium readable by the processor (including volatile and non-volatile memory and/or storage elements), at least one input device, and at least one output device. One or more programs may implement or utilize the processes described in connection with the presently disclosed subject matter, e.g., through the use of an application programming interface (API), reusable controls, or the like. Such programs may be implemented in a high level procedural or object-oriented programming language to communicate with a computer system. However, the program(s) can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language and it may be combined with hardware implementations.

(45) Although the subject matter has been described in language specific to structural features

and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.
(46) Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

Claims

1. A testing system, comprising: a test fixture configured to include electrical connection to a force or strain sensor; a mechanical actuator configured to apply a force to the force or strain sensor; a load cell configured to measure an amount of the force applied to the force or strain sensor; a controller configured to operate the mechanical actuator and simultaneously record respective output signals from the force or strain sensor and the load cell; wherein simultaneously recording the respective output signals from the force or strain sensor and the load cell comprises sampling the respective output signals in a burst mode, wherein the burst mode is defined by a sampling frequency and a sampling period; wherein the respective output signals from the force or strain sensor is sampled with a first sampling frequency and a first sampling period; and wherein the respective output signals from the load cell is sampled with a second sampling frequency and a second sampling period, wherein the first sampling frequency is different than the second sampling frequency.
2. The testing system of claim 1, wherein the force or strain sensor comprises one or more piezoresistive, piezoelectric, or capacitive transducers.
3. The testing system of claim 1, further comprising a robotic arm, wherein the mechanical actuator is controlled by the robotic arm.
4. The testing system of claim 3, wherein the robotic arm is operably connected to and controlled by the controller.
5. The testing system of claim 1, wherein the respective output signals recorded by the controller are stored in a memory of the controller.
6. The testing system of claim 1, wherein the respective output signals from the force or strain sensor and the load cell are recorded as a function of time.
7. The testing system of claim 1, wherein the controller is configured to operate the mechanical actuator to continuously change the amount of the force applied by the mechanical actuator from a first force value to a second force value, wherein the first and second force values are different.
8. The testing system of claim 7, wherein the controller is further configured to: hold the first force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time; subsequently ramp the first force value to the second force value while recording the respective output signals from the force or strain sensor and the load cell as the function of time; and hold the second force value constant while recording the respective output signals from the force or strain sensor and the load cell as the function of time.
9. The testing system of 8, wherein the controller is further configured to use a transition from the first force value to a ramped force and a transition from the ramped force to the second force value as temporal data synchronization points between the respective output signals from the force or strain sensor and the load cell.
10. A testing system, comprising: a test fixture configured to include electrical connection to a force or strain sensor; a mechanical actuator configured to apply a force to the force or strain sensor; a load cell configured to measure an amount of the force applied to the force or strain sensor; a controller configured to operate the mechanical actuator and simultaneously record respective output signals from the force or strain sensor and the load cell, simultaneously recording the respective output signals from the force or strain sensor and the load cell comprises sampling

the respective output signals in a burst mode, wherein the burst mode is defined by a sampling frequency and a sampling period, the respective output signals from the force or strain sensor is sampled with a first sampling frequency and a first sampling period, the respective output signals from the load cell is sampled with a second sampling frequency and a second sampling period, and the first sampling frequency is different than the second sampling frequency; and a robotic arm, wherein the mechanical actuator is controlled by the robotic arm.

11. The testing system of claim 10, wherein the controller is configured to operate the mechanical actuator to continuously change the amount of the force applied by the mechanical actuator from a first force value to a second force value, wherein the first and second force values are different.

12. The testing system of claim 11, wherein the controller is further configured to: hold the first force value constant while recording the respective output signals from the force or strain sensor and the load cell as a function of time; subsequently ramp the first force value to the second force value while recording the respective output signals from the force or strain sensor and the load cell as the function of time; and hold the second force value constant while recording the respective output signals from the force or strain sensor and the load cell as the function of time.

13. A method for testing a force or strain sensor, comprising: connecting the force or strain sensor to a test fixture, wherein the test fixture is configured to include electrical connection to the force or strain sensor; operating a mechanical actuator to apply a force to the force or strain sensor; simultaneously recording respective output signals from the force or strain sensor and a load cell, wherein the load cell is configured to measure an amount of the force applied to the force or strain sensor; wherein simultaneously recording the respective output signals from the force or strain sensor and the load cell comprises sampling the respective output signals in a burst mode, wherein the burst mode is defined by a sampling frequency and a sampling period; wherein the respective output signals from the force or strain sensor is sampled with a first sampling frequency and a first sampling period; and wherein the respective output signals from the load cell is sampled with a second sampling frequency and a second sampling period, the first sampling period is different than the second sampling period.
