Claims

What is claimed is:

1. A method of determining a force exerted by an object onto a surface under the object using at least one optical fiber located below or adjacent to the surface, the method including:

measuring distributed fiber-optic sensing (DFOS) data arising from strain in the at least one optical fiber responsive to the force;

determining at least one relationship between the measured DFOS data and the force and

processing the measured DFOS data and the at least one relationship to determine the force.

2. The method of claim 1, wherein determining the force includes determining a force distribution including magnitude and location of the force, the method further including deriving object information of the object based on the force distribution.

3. The method of claim 2, wherein the object information includes at least one of a footprint area of the object and a mass distribution of the object.

4. The method of any one of claims 2-3, wherein the object information includes at least one of a velocity of the object, an acceleration of the object, a momentum of the object, a speed of the object, an identity of the object and a travelling direction of the object.

5. The method of any one of claims 1-4, wherein the at least one relationship between the measured DFOS data and the force is determined by training a machine learning network using at least one of DFOS data and the physical relationship between DFOS measurements and force distribution.

6. The method of any one of claims 1-4, wherein the at least one relationship between the measured DFOS data and the force corresponds to at least one transfer function of a medium between at least one location on the surface and at least one sensing segment on the at least one optical fiber.

7. The method of claim 6, wherein the at least one location on the surface includes multiple locations corresponding to a mesh or matrix of nodes on the surface.

8. The method of claim 7, wherein the DFOS data and the at least one transfer function are used to determine the force distribution at specific locations within the mesh of nodes over the at least one sensing segment on the at least one optical fiber.

9. The method of claim 6, wherein determining the force distribution includes using at least one statistical optimization method and inverting a matrix related to the at least one transfer function, wherein inverting the matrix related to the at least one transfer function is performed before performing DFOS.

10. The method of claim 9, wherein the at least one statistical optimization method is conducted in real-time while performing DFOS.

11. The method of any one of claims 6-10, wherein determining the at least one transfer function of the medium between at least one location on the surface and at least one sensing segment on the at least one optical fiber is based on at least two of the material(s) of the medium, the geometry of the at least one optical fiber relative to the at least one location on the surface, and local geological information.

12. The method of any one of claims 6-11, further including selecting at least one gauge length of the at least one optical fiber for performing DFOS, the gauge length corresponding to the at least one segment on the at least one optical fiber.

13. The method of any one of claims 1-12, wherein the object includes a vehicle.

14. The method of claim 13, wherein the object information includes at least one of a count of axles of the vehicle and occupancy of the vehicle.

15. The method of any one of claims 1-14, wherein the surface includes multiple lanes.

16. The method of claim 15, further including determining lane quantization of the multiple lanes.

17. A method of determining a force exerted by an object onto a surface under the object, the method comprising:

measuring DFOS data in an optical fiber located below or adjacent to the surface; and

calculating the force based on the measured DFOS data.

18. The method according to claim 17, wherein

the measuring the DFOS data includes measuring strain.

19. The method according to claim 17, wherein

the measuring the DFOS data includes measuring ground motion.

20. The method according to claim 17, further comprising:

generating an alert in response to the calculating of the force.

21. The method according to claim 17, further comprising:

determining a location of the object on the surface.

22. The method according to claim 17, further comprising:

calculating a horizontal offset between the object and the optical fiber.

23. The method according any of claims 17-22, further comprising:

storing in a storage table the measured DFOS data.

24. The method according to claim 23, further comprising:

storing in the storage table the calculated force.

25. A method of detecting objects on a surface, the method comprising:

measuring DFOS data in an optical fiber located substantially below or adjacent to the surface;

calculating a force based on the measured DFOS data; and

determining that the force is exerted by the objects on the surface.

26. The method according to claim 25, wherein

the DFOS data includes at least one of strain and ground motion.

27. The method according to claim 25, further comprising:

estimating characteristics of the objects detected on the surface.

28. The method according to claim 25, wherein the characteristics include

at least one of the object's X position and the object's Y position.

29. The method according to claim 27, wherein

the surface includes at least one of a roadway, driveway, parking lot, garage floor, airport taxi ways and run ways, building or warehouse floor, trail, sidewalk, field, and an agricultural yard,

the objects include a vehicle, and

the characteristics include at least one of vehicle location and vehicle properties.

30. The method according to claim 29, wherein

the roadway includes multiple lanes, and

the vehicle location indicates a position of a vehicle along the roadway and a lane position.

31. The method according to claim 27, wherein

the characteristics include vehicle properties.

32. The method according to any one of claims 25-31, wherein

the vehicle properties include at least one of a footprint area of the vehicle, a count of axles of the vehicle, a mass of the vehicle, a velocity of the vehicle, an acceleration of the vehicle, a momentum of the vehicle, a mass distribution of the vehicle, occupancy of the vehicle, a speed of the vehicle, and a direction of travel of the vehicle.

33. The method according to any one of claims 25-32, wherein

the vehicle is one of a passenger vehicle, motorcycle, scooter, light-truck/SUV, truck, heavy machinery, and 4-wheeled ATV.

34. A method of estimating vehicle information of one or more vehicles on a surface, the method comprising:

performing quantitative distributed fiber-optic sensing (DFOS) with one or more optical fibers buried along the surface to estimate the vehicle information of the one or more vehicles on the surface.

35. The method according to claim 34, wherein

the surface includes a road extending along a length and having a width,

the vehicle information includes individual vehicle positions along the length of the road.

36. The method according to any one of claim 34-35, wherein

the vehicle information includes individual vehicle positions along the width of the road.

37. The method according to any one of claims 34-36, wherein

the vehicle information includes a vehicle footprint area.

38. The method according to any one of claims 34-37, wherein

the vehicle information includes a count of axles of a vehicle.

39. The method according to any one of claims 34-38, wherein

the vehicle information includes a mass of a vehicle.

40. The method according to any one of claims 34-39, wherein

the vehicle information includes a mass distribution of a vehicle.

41. The method according to any one of claims 34-40, wherein

the vehicle information includes occupancy of a vehicle.

42. The method according to any one of claims 34-41, wherein

the vehicle information includes a load of a vehicle.

43. The method according to any one of claims 34-41, wherein

the vehicle information includes at least one of a speed of a vehicle and a direction of travel of the vehicle.

44. A method of tracking individual vehicles traveling on a roadway, the method comprising:

performing distributed fiber-optic sensing (DFOS) with one or more optical fibers buried along the roadway to estimate vehicle information of the individual vehicles; and

combining the estimated vehicle information to generate tracking information for each of the individual vehicles.

45. The method according to claim 44, wherein

the generating of the tracking information includes calculating lane quantization.

46. The method according to any one of claims 44-45, wherein

the generating of the tracking information includes calculating a distance between two vehicles in the X direction.

47. The method according to any one of claims 44-46, wherein

the generating of the tracking information includes calculating a distance between two vehicles in the Y direction.

48. The method according to any one of claims 44-47, further comprising:

generating one or more alerts based on the generated tracking information.

49. The method according to claim 48, further comprising:

storing the one or more alerts in a storage device.

50. A method of selecting gauge length for performing DFOS, comprising:

identifying a length, in a direction substantially parallel to an optical fiber, of an object on a surface to be detected;

estimating a weight of the object;

calculating a dimension of an area of the surface that is deformed by the object based on a model of a first depth of material under the surface; and

selecting the gauge length based on calculated dimension.

51. The method according to claim 50, wherein

the selecting the gauge length is further based on at least one of

a pulse width of light injected into the optical fiber,

a total length of the optical fiber,

frequency of the light, and

index of refraction of the optical fiber.

52. The method according to claim 50, wherein

the model includes a Boussinesq approximation of deformation of the surface.

53. A system for performing DFOS configured to perform any of the methods recited in any one of claims 1-52.

54. A system for performing DFOS, comprising:

a device configured to emit a laser light into an optical cable and to receive light transmitted by the optical cable; and

one or more processors configured to perform any of the method recited in any one of claims 1-52.

55. A system comprising:

a DFOS instrument including

a light source,

a modulator configured to modulate light generated by the light source,

a photoreceiver,

a controller configured to control at least the light source and the photoreceiver; and

an optical fiber, wherein

the DFOS instrument is optically coupled to the optical fiber.

56. The system according to claim 55,

wherein the light source is a laser.

57. The system according to claim 55, wherein

the controller is further configured to execute a method of selecting gauge length for performing DFOS, comprising:

identifying a length, in a direction substantially parallel to an optical fiber, of an object on a surface to be detected;

estimating a weight of the object;

calculating a dimension of an area of the surface that is deformed by the object based on a model of a first depth of material under the surface; and

selecting the gauge length based on calculated dimension.

58. The system according to claim 55, wherein

the controller is further configured to execute a method of tracking individual vehicles traveling on a roadway, the method comprising:

performing distributed fiber-optic sensing (DFOS) with one or more optical fibers buried along the roadway to estimate vehicle information of the individual vehicles; and

combining the estimated vehicle information to generate tracking information for each of the individual vehicles.

59. The system according to claim 55, wherein

the controller is further configured to execute a method of estimating vehicle information of one or more vehicles on a surface, the method comprising:

performing quantitative distributed fiber-optic sensing (DFOS) with one or more optical fibers buried along the surface to estimate the vehicle information of the one or more vehicles on the surface.

60. The system according to claim 55, wherein

the controller is further configured to execute a method of detecting objects on a surface, the method comprising:

measuring DFOS data in an optical fiber located substantially below or adjacent to the surface;

calculating a force based on the measured DFOS data; and

determining that the force is exerted by the objects on the surface.

61. The system according to claim 55, wherein

the controller is further configured to execute a method of determining a force exerted by an object onto a surface under the object, the method comprising:

measuring DFOS data in an optical fiber located below or adjacent to the surface; and

calculating the force based on the measured DFOS data.

62. A DFOS instrument, comprising:

a light source;

a modulator configured to modulate light generated by the light source;

a photoreceiver;

a controller configured to control at least the light source and the photoreceiver, wherein

the controller is configured to perform a method of any one of claims 1-52.

Claims

What is claimed is:

1. A method of determining a force exerted by at least one object onto a surface under the at least one object using at least one optical fiber located below or adjacent to the surface, the method including:

measuring distributed fiber-optic sensing (DFOS) data arising from strain in the at least one optical fiber responsive to the force;

determining at least one relationship between the measured DFOS data and the force; and

processing the measured DFOS data and the at least one relationship to determine the force.

2. The method of claim 1, wherein determining the force includes determining a force distribution including magnitude and location of the force, the method further including deriving object information of the at least one object based on the force distribution.

3. The method of claim 2, wherein the object information includes at least one of: a footprint area of the at least one object, a mass distribution of the at least one object, a velocity of the at least one object, an acceleration of the at least one object, a momentum of the at least one object, a speed of the at least one object, an identity of the at least one object, and a travelling direction of the at least one object.

4. The method of any one of claims 1-3, wherein the at least one relationship between the measured DFOS data and the force is determined by training a machine learning network using at least one of DFOS data and the physical relationship between DFOS measurements and force distribution.

5. The method of any one of claims 1-3, wherein the at least one relationship between the measured DFOS data and the force corresponds to at least one transfer function of a medium between at least one location on the surface and at least one sensing segment on the at least one optical fiber.

6. The method of claim 5, wherein the at least one location on the surface includes multiple locations corresponding to a mesh or matrix of nodes on the surface, and wherein the DFOS data and the at least one transfer function are used to determine the force distribution at specific locations within the mesh of nodes over the at least one sensing segment on the at least one optical fiber.

7. The method of claim 5, wherein determining the force distribution includes using at least one statistical optimization method and inverting a matrix related to the at least one transfer function, wherein inverting the matrix related to the at least one transfer function is performed before performing DFOS.

8. The method of claim 7, wherein the at least one statistical optimization method is conducted in real-time while performing DFOS.

9. The method of any one of claims 5-8, wherein determining the at least one transfer function of the medium between at least one location on the surface and at least one sensing segment on the at least one optical fiber is based on at least two of the material(s) of the medium, the geometry of the at least one optical fiber relative to the at least one location on the surface, and local geological information.

10. The method of any one of claims 5-9, further including selecting at least one gauge length of the at least one optical fiber for performing DFOS, the gauge length corresponding to the at least one segment on the at least one optical fiber.

11. The method of any one of claims 1-10, wherein the at least one object includes a vehicle, and wherein the at least one object information includes at least one of: a count of axles of the vehicle and occupancy of the vehicle.

12. The method of any one of claims 1-11, wherein the surface includes multiple lanes, and the method further includes determining lane quantization of the multiple lanes.

13. The method of any one of claims 11-12, wherein the at least one object comprises multiple vehicles and the at least one object information includes calculating a distance between the multiple vehicles in the X direction and/or in the Y direction.

14. The method according to any one of the preceding claims, further comprising:

generating an alert in response to the calculating of the force.

15. A system for performing DFOS, comprising:

a device configured to emit a laser light into an optical cable and to receive light transmitted by the optical cable; and

one or more processors configured to perform any of the method recited in any one of claims 1-14.

16. A DFOS instrument, comprising:

a light source;

a modulator configured to modulate light generated by the light source;

a photoreceiver;

a controller configured to control at least the light source and the photoreceiver, wherein

the controller is configured to perform a method of any one of claims 1-14.