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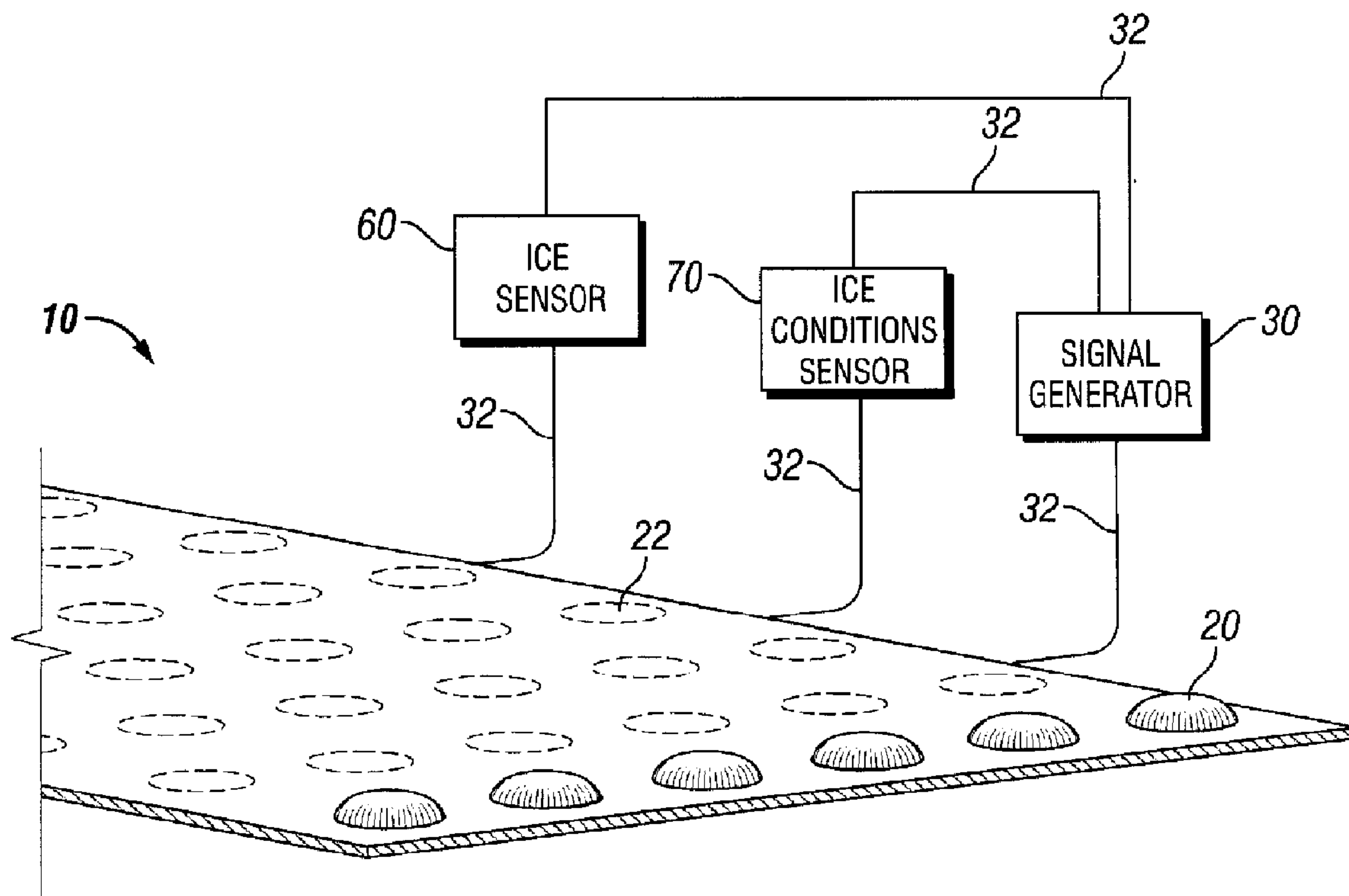
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(54) Titre : DISPOSITIF DE PROTECTION CONTRE LE GIVRE POUR AERONEF UTILISANT DES SURFACES EN
POLYMERE ELECTROACTIVES

(54) Title: ICE PROTECTION FOR AIRCRAFT USING ELECTROACTIVE POLYMER SURFACES



(57) Abrégé/Abstract:

An electro-active polymer (EAP) surface (10) having a plurality of actuators (20) adapted to prevent the formation of ice on an external surface (230), such as a leading edge of an aircraft (100). The EAP surface (10) may also be adapted to remove ice formed on the external surface (260). The actuators of the EAP surface (10) may be oscillated to prevent and/or remove ice from



(57) **Abrégé(suite)/Abstract(continued):**

the surface of an aircraft (100). A signal generator (30) may be used to individually oscillate the actuators (20) in a first mode to prevent the formation of ice(230) and a second mode to break up ice formed on the EAP surface (10). The signal generator (30) may oscillate all of the actuators (20) at the same frequency, may individually oscillate the actuators (20) to form a pattern on the EAP surface (10), or may individually oscillate the actuators (20) to form a wave along the EAP surface (10). The actuators (20) may be dimple actuators, wrinkle actuators, and/or bump actuators.

ABSTRACT

An electro-active polymer (EAP) surface (10) having a plurality of actuators (20) adapted to prevent the formation of ice on an external surface (230), such as a leading edge of an aircraft (100). The EAP surface (10) may also be adapted to remove ice formed on the external surface (260). The actuators of the EAP surface (10) may be oscillated to prevent and/or remove ice from the surface of an aircraft (100). A signal generator (30) may be used to individually oscillate the actuators (20) in a first mode to prevent the formation of ice(230) and a second mode to break up ice formed on the EAP surface (10). The signal generator (30) may oscillate all of the actuators (20) at the same frequency, may individually oscillate the actuators (20) to form a pattern on the EAP surface (10), or may individually oscillate the actuators (20) to form a wave along the EAP surface (10). The actuators (20) may be dimple actuators, wrinkle actuators, and/or bump actuators.

ICE PROTECTION FOR AIRCRAFT USING ELECTROACTIVE POLYMER SURFACES

BACKGROUND

Field of the Disclosure

The embodiments described herein relate to a system for the prevention of the formation of ice and/or the removal of ice from an external surface of a vehicle, such as an aircraft, or another structure using an electro-active polymer (EAP).

Description of the Related Art

The formation of ice on an external surface of a vehicle or another structure can be problematic. As an example, the formation of ice on an external surface of an aircraft, such as the leading edge of a wing or a tail is less than desirable.

There are a number of systems that have been used in an attempt to remove ice from external surfaces, such the leading edges, of aircraft. One type of system is a deicing boot, which is a thick rubber membrane that is installed on the leading edges of a wing. When ice forms on the leading edges, a pneumatic system fills the deicing boot with compressed air, causing the deicing boot to expand and break up the ice. The airflow past the leading edges then removes the ice from the wings. Once the ice has been removed, the deicing boots are deflated until needed again. The rubber membrane may be subject to ultraviolet degradation. Deicing boots are not practical on transonic aircraft because of the potential leaks, limited durability, and variations in surface contour.

Another existing system used to remove ice from the leading edges of an aircraft is a heater system. This system uses heat to melt the ice from the leading edges of the aircraft.

Heater systems use large amounts of energy, which limits ice protection to only the most critical areas. Another problem associated with conventional thermal systems is run-back ice, formed if the melted ice re-freezes on the aircraft.

Shakers or thumpers are other systems used to remove ice from the leading edges of an aircraft. Shakers and thumpers are only used intermittently and may have less than desired results in removing all of the ice accumulated on the leading edges of an aircraft.

The preceding described methods and systems for the prevention and/or removal of ice from an aircraft have less than desired results.

SUMMARY

The present disclosure is directed to providing a system that consumes a low amount of energy to prevent and/or remove ice from external surfaces, such as leading edges, of an aircraft and potentially overcome some of the problems and disadvantages discussed above.

One embodiment of the present disclosure is a method of protecting an external surface from ice, the method comprising preventing the formation of ice on an external surface by oscillating at least a portion of a plurality of actuators on an electro-active polymer (EAP) surface. The method may include applying the EAP surface to an external surface. The method may include detecting that conditions exists that are conducive to the formation of ice on the external surface. The method may include sending a signal to a signal generator to oscillate at least a portion of the plurality of actuators based on detecting conditions conducive to the formation of ice on the external surface. The external surface may be an external surface of an aircraft, such as the leading edge of the aircraft. The method may include oscillating each of the plurality of actuators at the same frequency to prevent the formation of ice. The plurality of actuators may be oscillated at frequencies on

the order of about 1 Hz to more than 1 kHz. The actuators may be dimple actuators, bump actuators, and/or wrinkle actuators. The method may include individually oscillating a portion of the plurality of actuators to form a pattern on the external surface to prevent the formation of ice on the external surface. The method may include individually oscillating the plurality of actuators to form a wave on the external surface to prevent the formation of ice on the external surface.

The method may further include detecting the formation of ice on the external surface, sending a signal to a signal generator based on the detection of the formation of ice, and oscillating at least a portion of the actuators to remove the formation of ice from the external surface. The method may include oscillating each of the plurality of actuators at the same frequency to remove the formation of ice from the external surface. The method may include individually oscillating a portion of the plurality of actuators to form a pattern on the external surface to remove the formation of ice from the external surface. The method may include individually oscillating the plurality of actuators to form a wave on the external surface to remove the formation of ice from the external surface.

One embodiment of the present disclosure is an ice protection system for an external surface comprising an EAP surface having a plurality of actuators and a signal generator connected to the EAP surface. The signal generator may be adapted to individually oscillate the actuators. The EAP surface may be installed on an external surface of a vehicle, such as on a leading edge of the aircraft. The actuators may be dimple actuators, bump actuators, and/or wrinkle actuators. The signal generator may be adapted to oscillate the plurality of dimple actuators in a first mode to prevent the formation of ice on an external surface of the aircraft and to oscillate the plurality of dimple actuators in a second mode to remove ice

formed on an external surface of an aircraft. The first mode of the signal generator may oscillate each of the actuators at the same frequency, may individually oscillate a portion of the actuators to form a pattern, and/or may oscillate the actuators to form a wave. The second mode of the signal generator may oscillate each of the actuators at the same frequency, may individually oscillate a portion of the actuators to form a pattern, and/or may oscillate the actuators to form a wave. The system may include a sensor adapted to detect the formation of ice on an external surface of an aircraft.

In another embodiment of the present invention, there is provided a method of protecting an external surface from ice, the method comprising: controlling respective surface areas of at least some of a plurality of actuators bounded by respective peripheries that resist movement, wherein controlling the surface area of one of the plurality of actuators comprises controlling a thickness of a compression-resistant elastomer in a compliant capacitor of the one of the plurality of actuators and causing the one of the plurality of actuators to move relative to the external surface.

In another embodiment of the present invention, there is provided an ice protection system for an external surface, the system comprising: an electro-active polymer (EAP) comprising a plurality of actuators, each of the plurality of actuators comprising a compression-resistant elastomer bounded by a periphery that resists movement, and each of the plurality of actuators comprising electrodes positioned within the periphery and on opposite sides of the compression-resistant elastomer to control a surface area of the compression-resistant elastomer in response to controlling an electric field between the electrodes; and a controller in communication with the EAP and operable to control the electric field between the electrodes in each of the plurality of actuators.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows EAP on an exterior surface of a vehicle.

FIG. 2 is a perspective view of an EAP surface that may be used to prevent the formation of ice and/or remove ice on an external surface.

5 FIG. 3 is a partial perspective view of an embodiment of an EAP surface with the first row of actuators being actuated as the start of a wave across the EAP surface.

FIG. 4 is a partial perspective view of the embodiment of the EAP surface of FIG. 3 with the second row of actuators being actuated as part of a wave across the EAP surface.

10 FIG. 5 is a partial perspective view of an embodiment of an EAP surface with the actuators being actuated in a pattern on the EAP surface.

FIG. 6 is a partial perspective view of an embodiment of an EAP surface with wrinkle or line actuators.

FIG. 7 is a block diagram of an aircraft.

FIG. 8 is a flow diagram of an ice protection method.

15 While the disclosure is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be

described in detail herein. However, it should be understood that the disclosure is not intended to be limited to the particular forms disclosed. Rather, the intention is to cover all modifications, equivalents and alternatives falling within the scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

The present application involves the use of electro-active polymers (EAPs), which are a category of materials that are well-known in the art. The EAP surface comprises a compliant capacitor that includes an elastomer dielectric film sandwiched between two compliant electrodes. In operation, an electric field is applied to the compliant electrodes creating an electrostatic pressure, also referred to as Maxwell Stress, compressing the elastomer film. The compression of the elastomer film results in an elongation of the elastomer film because of incompressibility of the elastomer film. An application of an electric field between two oppositely charged electrodes causes a mechanical compression between the two electrodes. Likewise, an application of an electric field between two like charged electrodes causes a mechanical expansion between the two electrodes.

The EAP surface may be adapted to create a dimple or depression actuator in the elastomer film upon an application of an electric field to the electrodes. Depending on the configuration of the elastomer film and the electrodes, the elastomer film buckles, bends, or elongates upon the application of an electric field. The electric field may be applied from a signal generator. However, various means may be used to apply an electric field to the elastomer field as would be appreciated by one of ordinary skill in the art having the benefit of this disclosure. Clamps may secure the elastomer film in place and define the dimensions of the actuator. Because the periphery of the actuator is fixed, no in-plane movement of the

elastomer film can occur. Thus, the mechanical force due to the electrostatic pressure causes an out-of-plane movement, such as a depression or dimple as shown in the actuator **50** of FIG. 2. In other examples, described in more detail below, the mechanical force of the elastomer film can create other out-of-plane movements, such as a bump or protrusion, as shown in the bump actuator **20** of FIG. 2 – FIG. 5, or a wrinkle or line as shown in the wrinkle actuator **40** of FIG. 6. Once the application of the electric field is removed, the elastomer film moves back to the initial in-plane flat position. The application of an electric field at a frequency can cause an actuator to rapidly oscillate between its actuated and non-actuated states.

FIG. 1 shows one embodiment of the application of EAP surfaces **10** on selected exterior surfaces of a vehicle. In the embodiment illustrated in FIG. 1, the vehicle comprises an aircraft **100**, and the selected exterior surfaces comprise the leading edges of the wings and tail of the aircraft. In other embodiments, the EAP surfaces **10** may be applied to various other external surfaces to prevent the formation of ice on the external surface or to remove ice from the external surface. For example, in some embodiments, EAP surfaces **10** may be applied to a wide variety of other vehicles, such as helicopters, unmanned aerial vehicles (UAVs), ships, trains, automobiles, etc. In other embodiments, EAP surfaces **10** may be applied to any suitable exterior surface on which the removal and/or prevention of ice may be beneficial, such as, for example, a roof, staircase, sidewalk, or road.

Referring again to the embodiment shown in FIG. 1, a signal generator **30** is connected to the EAP surfaces via lines **32**. A single signal generator **30** is shown for illustrative purposes only. Multiple signal generators and various configurations connecting the signal generators to the actuators of the EAP surfaces **10** may be used as would be

appreciated by one of ordinary skill in the art having the benefit of this disclosure. The EAP surfaces **10** may be applied to any desired surface on the aircraft **100**, such as the leading edges of each wing, empennage, etc. The EAP surface **10** may comprise a film or skin layer applied to the surface of the leading edges of the aircraft **100**. In some embodiments, the EAP surface **10** may have a thickness of about **1** millimeter.

The signal generator **30** is preferably adapted to individually control the oscillation of each actuator **20** on the EAP surfaces **10**. The signal generator **30** may apply a time-varying current to actuate the actuators **20** of the EAP surface **10**. The signal generator **30** may be adapted to actuate the actuators **20** in a first mode to prevent the accumulation of ice on the leading edges of the aircraft **100**. The first mode may comprise applying an electrical pulse at a frequency on the order of **1** Hz to more than one **1** kHz. The electrical pulse may be used to oscillate the actuators **20** of the EAP surface **10**. The first mode may be activated upon the detection of any atmospheric conditions likely to lead to the formation of ice upon the leading edges of the aircraft **100**. The signal generator **30** may be adapted to actuate the actuators **20** in a second mode to remove ice from the EAP surface **10**. The second mode may comprise oscillating the actuators **20** of the EAP surface **10** at a different frequency than the first mode or in a different geometrical pattern than the first mode, to break the bond between the ice and the leading edge of the aircraft **100**.

FIG. **2** shows one embodiment of an EAP surface **10** with all of the actuators **20**, **50** in the actuated position. The signal generator **30** is connected to the actuators **20**, **50** of the EAP surface **10** via connection **32**. The signal generator **30** may oscillate each of the actuators **20**, **50** of the EAP surface **10** at the same frequency so that all of the actuators **20**, **50** are actuated at the same time to prevent the formation of ice on an external surface of an

aircraft and/or to remove ice that has formed on the external surface of an aircraft. Some of the actuators **50** may be depression or dimple actuators and some of the actuators **20** may be bump or protrusion actuators.

FIG. **3** and FIG. **4** show one embodiment of an EAP surface **10** with the actuators **20** being actuated by a signal generator **30** to create a wave that moves along the EAP surface **10**. The signal generator **30** can actuate the actuators **20** to create a standing wave or a moving wave on the EAP surface **10**. FIG. **3** shows a first row of actuators **20** in the actuated position while the remainder of the non-actuated actuators **22** (shown by dashed lines) being in-plane or flat along the EAP surface **10**. FIG. **4** shows the next row of actuators **20** being in the actuated position while the remainder of the non-actuated actuators **22** (including the first row that was previously actuated) being in-plane or flat along the EAP surface **10**. The signal generator **30** will continue to actuate each row in succession until the wave has traveled the length of the EAP surface **10**. The use of an actuator wave along the EAP surface **10** may be beneficial to prevent the formation of ice and/or removal of ice on the EAP surface **10**. The signal generator **30** may be adapted to actuate the actuators **20** to create waves of various shapes to prevent and/or remove ice formed on the EAP surface **10** as would be appreciated by one of ordinary skill in the art having the benefit of this disclosure.

FIG. **5** shows the actuators **20** being actuated by the signal generator **30** in a pattern on the EAP surface **10**. In the example shown in FIG. **5**, the actuators **20** are being activated in a diagonal or zigzag pattern along the EAP surface **10**. The signal generator **30** may be adapted to oscillate the actuators **20** in various patterns on the EAP surface **10** for the prevention and/or removal of ice on the EAP surface **10**. For example, the signal generator

30 may oscillate the actuators **20** in a pattern of concentric circles, a checkerboard, or various other patterns as would be appreciated by one of ordinary skill in the art having the benefit of this disclosure.

FIG. 6 shows the actuation of a wrinkle or line actuator **40** on the EAP surface **10**. The use of a wrinkle actuator **40** may be beneficial to prevent ice from forming on the EAP surface **10** and/or remove ice formed on the EAP surface **10** by breaking the bond between the ice and the EAP surface **10**. A signal generator **30** may be used to actuate a single wrinkle actuator **40** on a first edge of the EAP surface **10** while the remaining non-actuated actuators **42** remained flat. The signal generator **30** may then actuate the next actuator **40** creating a wave that moves along the EAP surface **10**. The wrinkle actuators **40** may also be actuated in a pattern along the EAP surface **10** by the signal generator **30**.

The EAP surface **10** may include dimple actuators **50** (as shown in FIG. 7), bump actuators **20** (as shown in FIG. 3 – FIG. 5), and/or wrinkle actuators **40** (as shown in FIG. 6) and a combination of each of these actuators. The system may include a sensor **60** that detects the formation of ice on the EAP surface **10** or on an external surface of a vehicle or structure, such as the leading edges of an aircraft. The sensor **60** may be connected via line **32** to the signal generator **30** so that upon detection of the formation of ice the signal generator **30** may cause the oscillation of the actuators of the EAP surface **10** at various frequencies and in various patterns to break of the formation of ice. The EAP surface **10** may include an ice conditions sensor **70** that during environmental conditions that are conducive to the formation of ice causes the signal generator to oscillate the actuators to prevent the formation of ice. The ice conditions sensor **70** may be connected via line **32** to the signal generator **30** so that upon the detection of conditions conducive to the formation

of ice the signal generator **30** may cause the oscillation of the actuators of the EAP surface **10** at various frequencies and in various patterns to prevent the formation of ice on the EAP surface **10**. The ice sensor **60** and/or the ice conditions sensor **70** may be integral with the EAP surface **10**.

As shown in FIG. 7, an aircraft **100** may include an airframe **118** with a plurality of systems **130** and an interior **122**. Examples of high-level systems **130** include one or more of a propulsion system **134**, an electrical system **136**, a hydraulic system **138**, and an environmental system **132**. The airframe may also include various systems such as an ice prevention system. Examples of high-level elements of the ice prevention system **120** include an EAP system **110**, a detection system **126**, an electrical system **124**, and a manual activation system **128**. Any number of other systems may be included. Although an aerospace example is shown, the principles of the disclosure may be applied to other industries, such as the automotive industry, the construction industry, etc.

FIG. 8 illustrates an example of a method **200** for protecting an external surface from ice. In the illustrated embodiment, the method **200** begins with an optional first step **210**, in which an EAP surface is applied to the external surface to be protected. In some cases, this first step **210** is unnecessary because, for example, the EAP surface is fabricated as an integral component of the external surface to be protected.

In a next step **220**, the decision may be made to manually oscillate the actuators. If the decision is made to oscillate the actuators of the EAP surface, the actuators may be oscillated at step **230**. The actuators may be oscillated under to control of a signal generator at various frequencies and in various patterns to prevent to formation of ice and/or remove the formation of ice from an external surface. The actuators may oscillate for a short period

of time and the method may return to step **220**. Optionally, the actuators may be turned off in step **270** and the method may return to step **220**.

If the decision at step **220** is to not oscillate the actuators, the next step **240** is whether conditions conducive to the formation of ice are detected. In some embodiments, this detection step **240** is performed by a suitable environmental sensor, such as ice conditions sensor **70**. When ice formation conditions are detected, in a next step **230**, one or more actuators of the EAP surface are oscillated to prevent the formation of ice on the external surface. As described above, the actuators of the EAP surface can be oscillated under the control of a signal generator at various frequencies and in various patterns to prevent ice formation. The actuators may oscillate for a short period of time and the method may return to step **220**. After oscillating the actuators at step **230**, the actuators may optionally be turned off at step **270** and the process may return to step **220**.

Although it is often desirable to prevent the formation of ice on the external surface, in some cases, ice may form despite the attempts to avoid it. In such cases, the method **200** may include a step **250**, in which the formation of ice is detected by a suitable sensor, such as ice sensor **60**. When ice is detected, in a next step **260**, one or more actuators of the EAP surface are oscillated to remove the ice from the external surface. As described above, the actuators of the EAP surface can be oscillated under the control of a signal generator at various frequencies and in various patterns to remove ice from the external surface. The actuators may oscillate for a short period of time and the method may return to step **220**. Optionally, the actuators may be turned off at step **270** after oscillating the actuators at step **260** and the process may return to step **220**.

The method may include a next step to determine whether the ice prevention system has been turned off or remains on. If no formation of ice is detected and the system remains on at step **280**, the method may return to step **220** to determine whether to manually oscillate the actuators. If no formation of ice is detected and the system has been turned off at step **280**, then the method ends at step **290**.

Although various embodiments have been shown and described, the present disclosure is not so limited and will be understood to include all such modifications and variations as would be apparent to one skilled in the art.

**THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:**

1. A method of protecting an external surface from ice, the method comprising:

controlling respective surface areas of at least some of a plurality of
actuators bounded by respective peripheries that resist movement,

wherein controlling the surface area of one of the plurality of actuators
comprises controlling a thickness of a compression-resistant elastomer in a
compliant capacitor of the one of the plurality of actuators and causing the
one of the plurality of actuators to move relative to the external surface.

2. The method of claim 1 wherein controlling the thickness of the compression-resistant
elastomer of the one of the plurality of actuators comprises controlling an electric
field in the compliant capacitor.

3. The method of claim 2 wherein controlling the electric field in the compliant
capacitor comprising the compression-resistant elastomer of the one of the plurality
of actuators comprises controlling the electric field between electrodes positioned
within the periphery of the one of the plurality of actuators and on opposite sides of
the compression-resistant elastomer of the one of the plurality of actuators.

4. The method of claim 1, 2, or 3 wherein controlling the thickness of the compression-
resistant elastomer of the one of the plurality of actuators comprises:

causing the one of the plurality of actuators to exert forces on the periphery
of the one of the plurality of actuators; and

causing the one of the plurality of actuators to move relative to the external
surface in response to the forces exerted on the periphery of the one of the
plurality of actuators.

5. The method of claim 1, 2, 3, or 4 further comprising applying an electro-active polymer comprising the plurality of actuators to the external surface.

6. The method of any one of claims 1 to 5 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises preventing formation of ice on the external surface.

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7. The method of claim 6 further comprising detecting conditions conducive to the formation of ice on the external surface.
8. The method of claim 7 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises controlling the respective surface areas of the at least some of the plurality of actuators in response to detecting the conditions conducive to the formation of ice on the external surface.
9. The method of claim 6, 7, or 8 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises sending a signal to a signal generator.
10. The method of claim 6, 7, 8, or 9 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators to prevent the formation of ice on the external surface.
11. The method of claim 10 wherein oscillating the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators at the same frequency to prevent the formation of ice on the external surface.
12. The method of claim 10 or 11 wherein oscillating the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators at a frequency between about 1 Hz to about 1 kHz.
13. The method of claim 10, 11, or 12 wherein oscillating the at least some of the plurality of actuators comprises oscillating each of the plurality of actuators to prevent the formation of ice on the external surface.
14. The method of claim 10, 11, or 12 wherein oscillating the at least some of the plurality of actuators comprises individually oscillating the at least some of the plurality of actuators to form a pattern on the external surface to prevent the formation of ice on the external surface.

15. The method of claim 14 wherein the pattern comprises a pattern of concentric circles.
16. The method of claim 14 wherein the pattern comprises a checkerboard pattern.
17. The method of claim 10, 11, or 12 wherein oscillating the at least some of the plurality of actuators comprises individually oscillating the at least some of the plurality of actuators to form a wave on the external surface to prevent the formation of ice on the external surface.
18. The method of any one of claims 1 to 17 wherein the plurality of actuators comprises dimple actuators.
19. The method of any one of claims 1 to 18 wherein the plurality of actuators comprises bump actuators.
20. The method of any one of claims 1 to 19, wherein the plurality of actuators comprises wrinkle actuators.
21. The method of any one of claims 1 to 5 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises removing a formation of ice from the external surface.
22. The method of claim 21 further comprising detecting the formation of ice on the external surface.
23. The method of claim 22 wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises controlling the respective surface areas of the at least some of the plurality of actuators in response to detecting the formation of ice on the external surface.
24. The method of claim 21, 22, or 23 wherein controlling the respective surface areas in response to detecting the formation of ice on the external surface comprises sending a signal to a signal generator.

25. The method of claim **21**, **22**, **23**, or **24** wherein controlling the respective surface areas of the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators to remove the formation of ice from the external surface.
- 5 26. The method of claim **25** wherein oscillating the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators at the same frequency to remove the formation of ice from the external surface.
- 10 27. The method of claim **25** or **26** wherein oscillating the at least some of the plurality of actuators comprises oscillating the at least some of the plurality of actuators at a frequency between about 1 Hz to about 1 kHz.
28. The method of claim **25**, **26**, or **27** wherein oscillating the at least some of the plurality of actuators comprises oscillating each of the plurality of actuators to remove the formation of ice from the external surface.
- 15 29. The method of claim **25**, **26**, or **27** wherein oscillating the at least some of the plurality of actuators comprises individually oscillating the at least some of the plurality of actuators to form a pattern on the external surface to remove the formation of ice from the external surface.
30. The method of claim **29** wherein the pattern comprises a pattern of concentric circles.
31. The method of claim **29** wherein the pattern comprises a checkerboard pattern.
- 20 32. The method of claim **25**, **26**, or **27** wherein oscillating the at least some of the plurality of actuators comprises individually oscillating the at least some of the plurality of actuators to form a wave on the external surface to remove the formation of ice from the external surface.

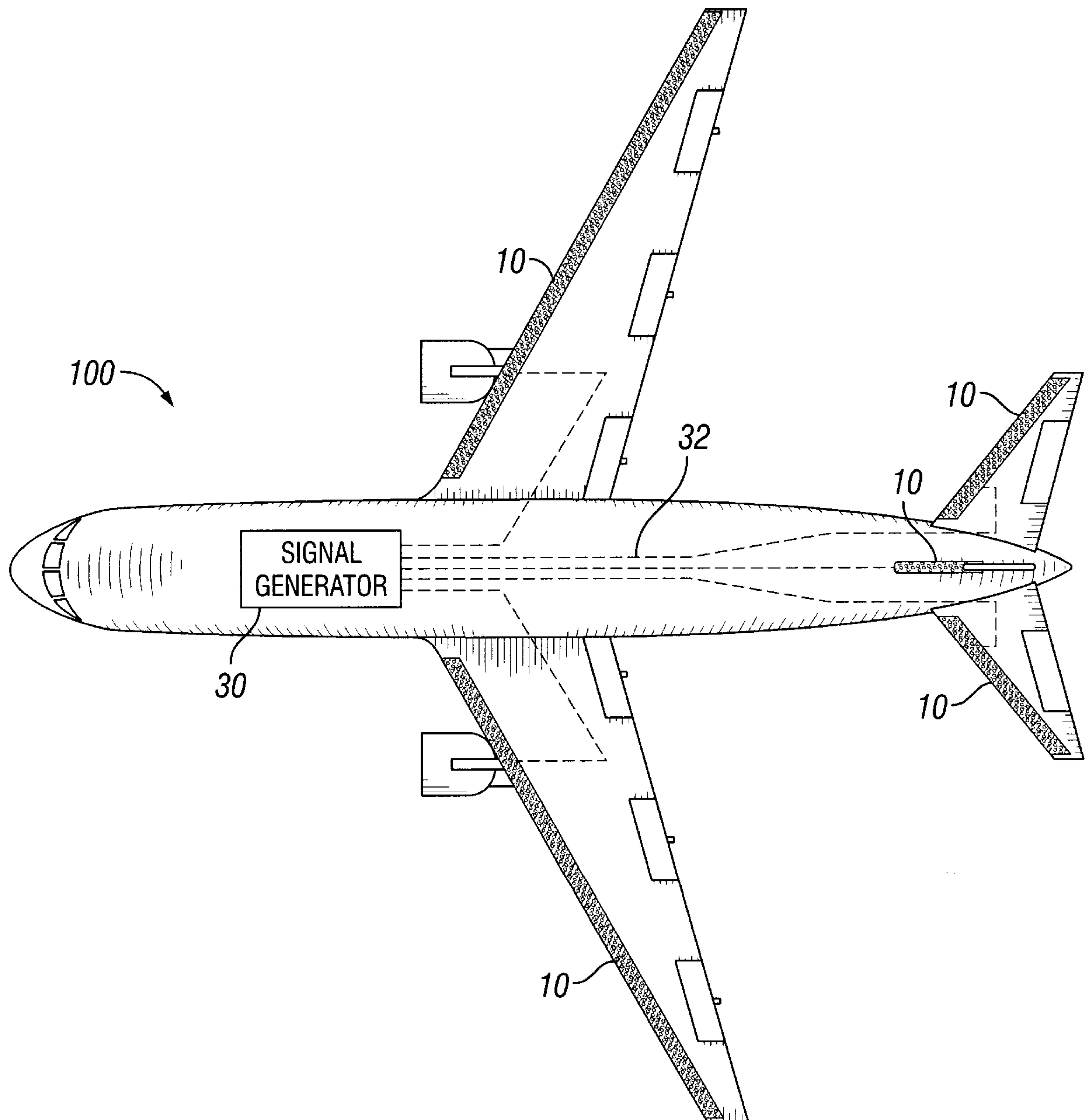
- 33.** The method of any one of claims **21** to **32** wherein the plurality of actuators comprises dimple actuators.
- 34.** The method of any one of claims **21** to **33** wherein the plurality of actuators comprises bump actuators.
- 5 **35.** The method of any one of claims **21** to **34**, wherein the plurality of actuators comprises wrinkle actuators.
- 36.** The method of any one of claims **1** to **35** wherein the external surface is on a vehicle.
- 37.** The method of any one of claims **1** to **35** wherein the external surface is on a leading edge of an aircraft.
- 10 **38.** An ice protection system for an external surface, the system comprising:
- an electro-active polymer (EAP) comprising a plurality of actuators, each of the plurality of actuators comprising a compression-resistant elastomer bounded by a periphery that resists movement, and each of the plurality of actuators comprising electrodes positioned within the periphery and on
- 15 opposite sides of the compression-resistant elastomer to control a surface area of the compression-resistant elastomer in response to controlling an electric field between the electrodes; and
- a controller in communication with the EAP and operable to control the electric field between the electrodes in each of the plurality of actuators.
- 20 **39.** The system of claim **38**, wherein the controller is operable to control the electric field between the electrodes in each of the plurality of actuators independently.
- 40.** The system of claim **38** or **39** wherein the external surface is on an external surface of a vehicle.

41. The system of claim 38 or 39 wherein the external surface is on a leading edge of an aircraft.
- 5 42. The system of claim 38, 39, 40, or 41 wherein the controller is adapted to oscillate a first at least some of the plurality of actuators in a first mode to prevent the formation of ice on the external surface.
43. The system of claim 42 wherein the controller, in the first mode, oscillates the first at least some of the plurality of actuators at a first frequency.
44. The system of claim 43 wherein the first frequency is between about 1 Hz to about 1 kHz.
- 10 45. The system of claim 42, 43, or 44 wherein the controller, in the first mode, individually oscillates the first at least some of the plurality of actuators to form a first pattern.
46. The system of claim 45 wherein the first pattern comprises a pattern of concentric circles.
- 15 47. The system of claim 45 wherein the first pattern comprises a checkerboard pattern.
48. The system of claim 42, 43, or 44 wherein the controller, in the first mode, individually oscillates the first at least some of the plurality of actuators to form a first wave.
- 20 49. The system of any one of claims 42 to 48 wherein the controller, in the first mode, oscillates each of the plurality of actuators.
50. The system of any one of claims 38 to 49 wherein the controller is adapted to oscillate a second at least some of the plurality of actuators in a second mode to remove ice formed on the external surface of the aircraft.

- 51.** The system of claim **50** wherein the controller, in the second mode, oscillates the second at least some of the plurality of actuators at a second frequency.
- 52.** The system of claim **51** wherein the second frequency is between about 1 Hz to about 1 kHz.
- 5 **53.** The system of claim **50**, **51**, or **52** wherein the controller, in the second mode, individually oscillates the second at least some of the plurality of actuators to form a second pattern.
- 54.** The system of claim **53** wherein the second pattern comprises a pattern of concentric circles.
- 10 **55.** The system of claim **53** wherein the second pattern comprises a checkerboard pattern.
- 56.** The system of claim **50**, **51**, or **52** wherein the controller, in the second mode, individually oscillates the second at least some of the plurality of actuators to form a second wave.
- 57.** The system of any one of claims **50** to **56** wherein the controller, in the second mode,
15 oscillates each of the plurality of actuators.
- 58.** The system of any of claims **50** to **57** further comprising a sensor adapted to detect the formation of ice on the external surface.
- 59.** The system of claim **58** wherein the controller is adapted to oscillate the second at least some of the plurality of actuators in the second mode in response to the sensor
20 detecting the formation of ice on the external surface.
- 60.** The system of any one of claims **38** to **59** wherein the plurality of actuators comprise dimple actuators.

- 61.** The system of any one of claims **38** to **60** wherein the plurality of actuators comprise bump actuators.
- 62.** The system of any one of claims **38** to **61**, wherein the plurality of actuators comprise wrinkle actuators.

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**FIG. 1**

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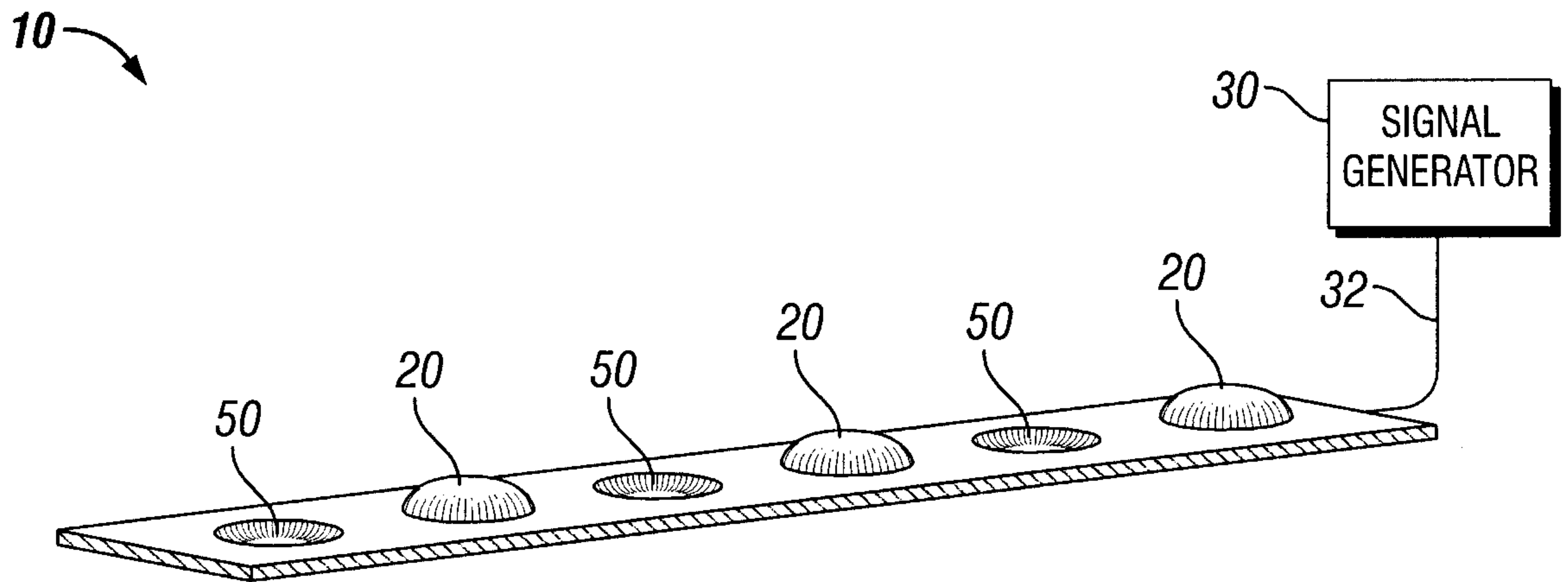


FIG. 2

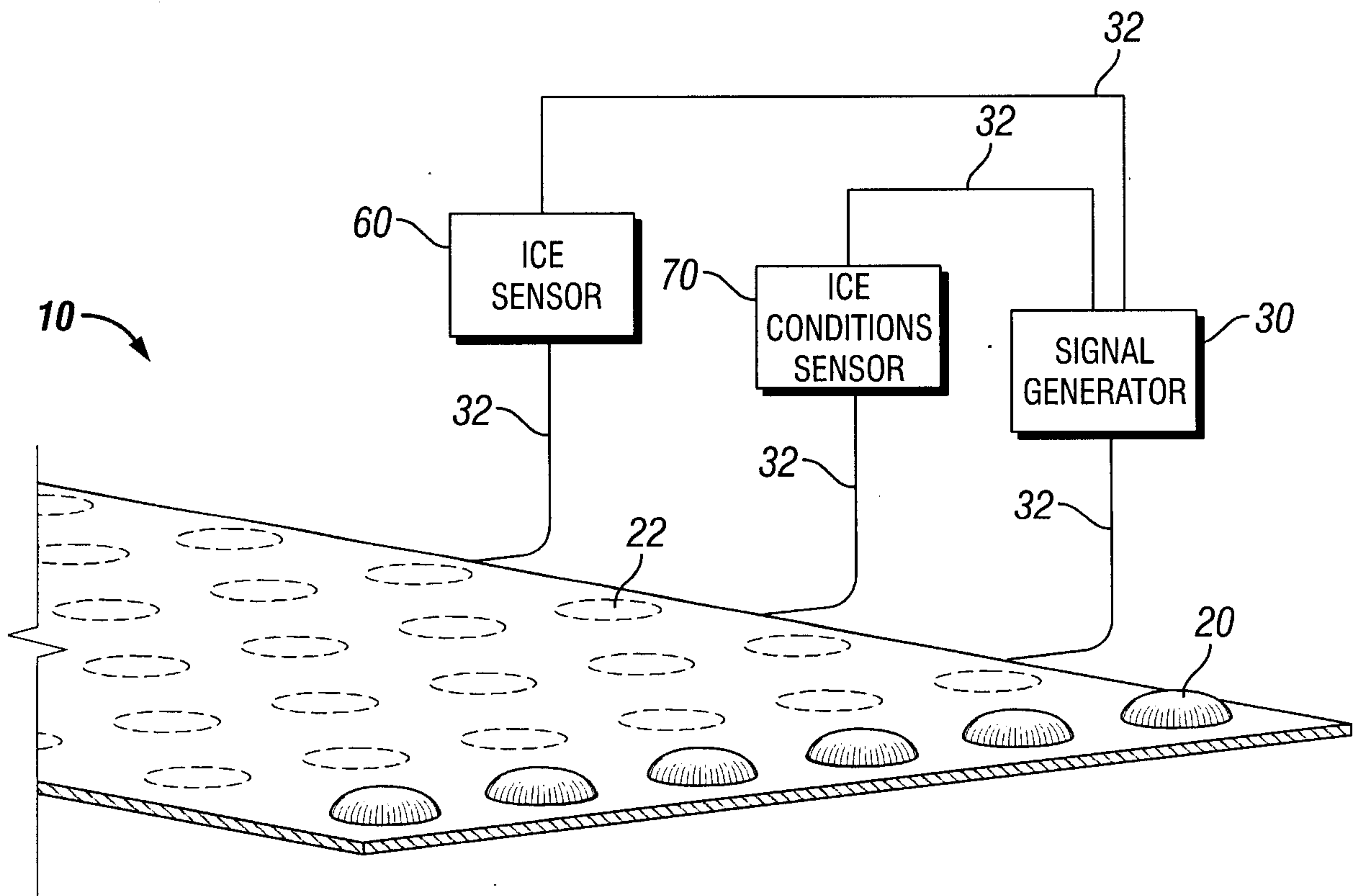


FIG. 3

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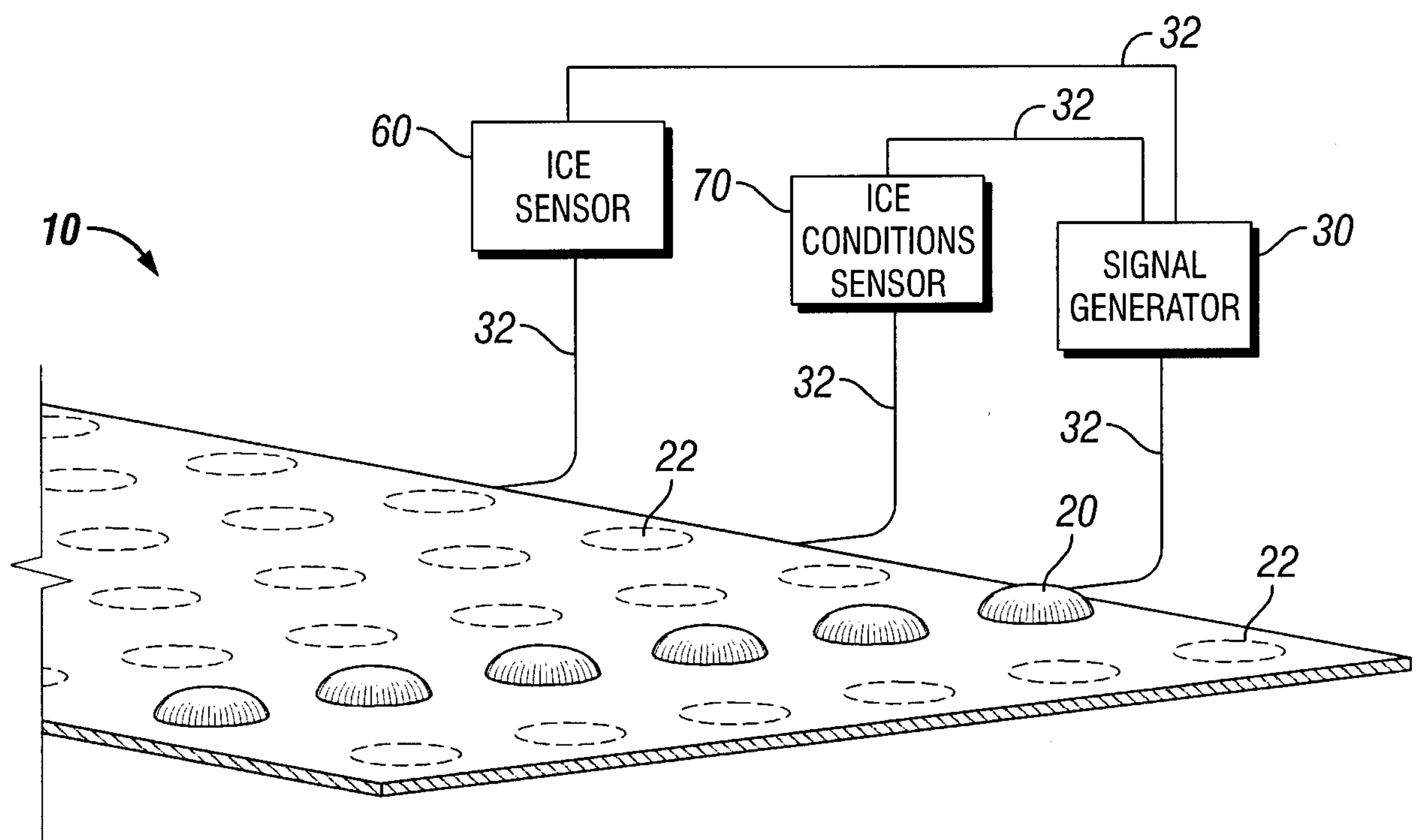


FIG. 4

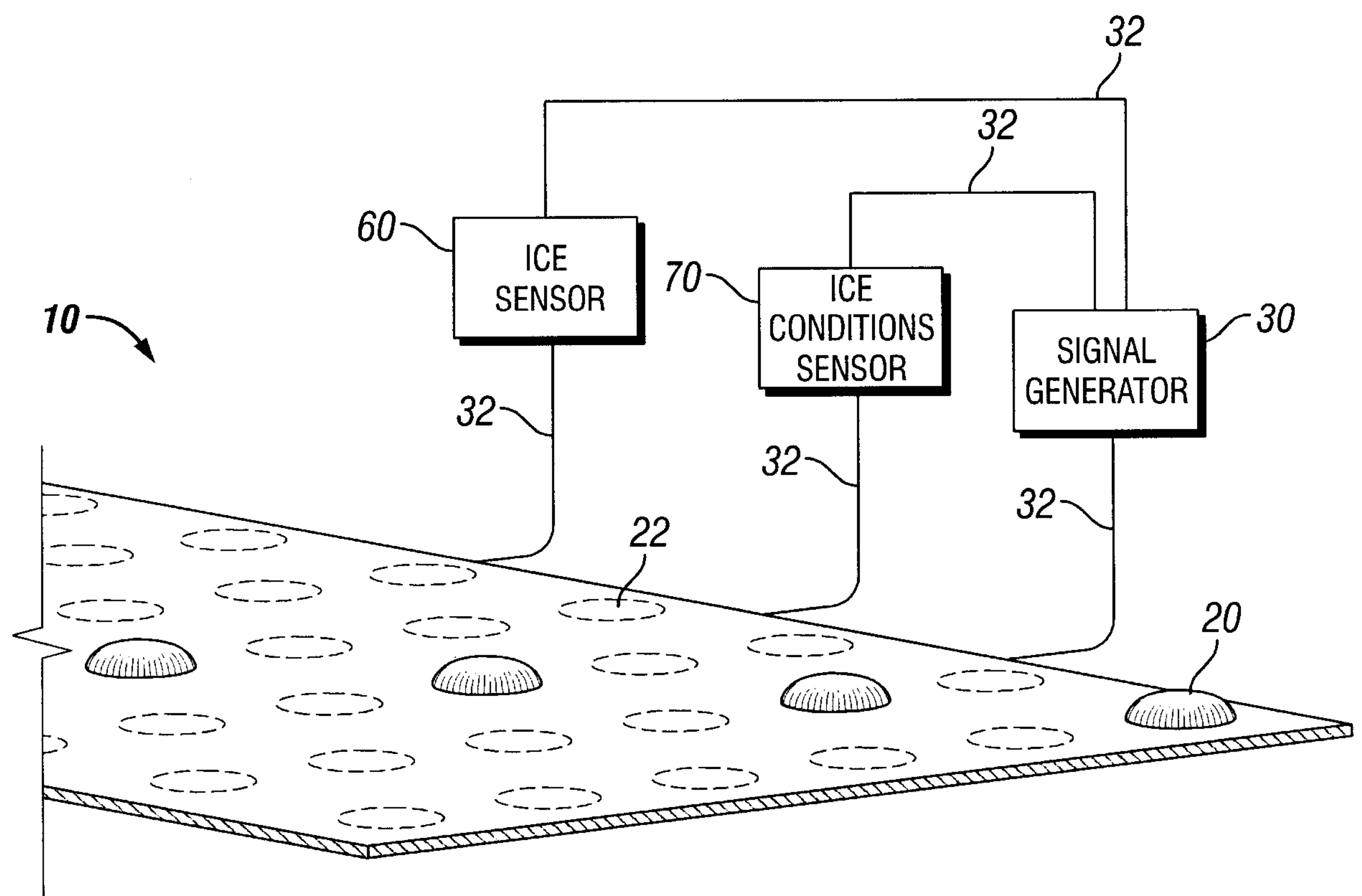


FIG. 5

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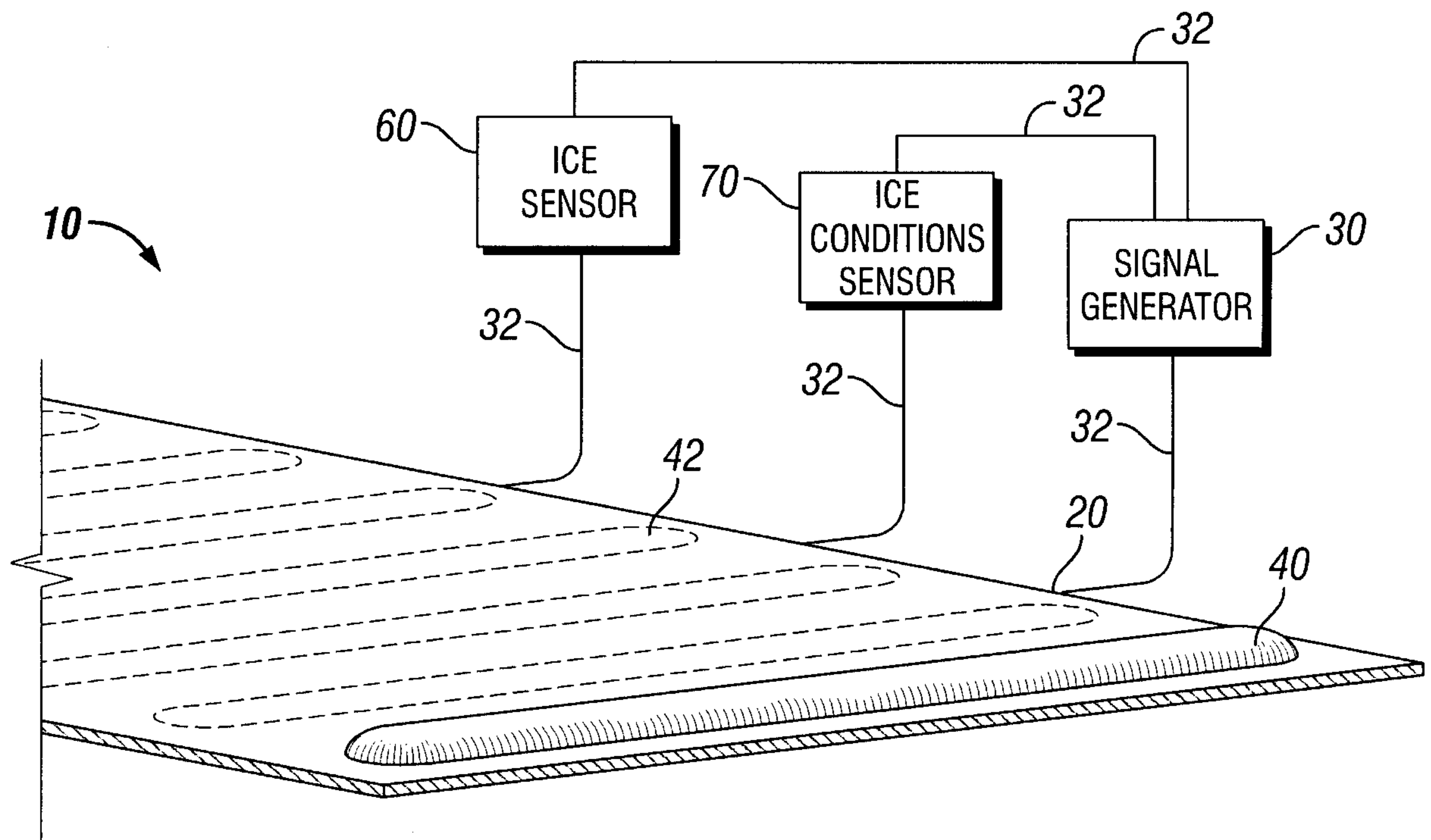


FIG. 6

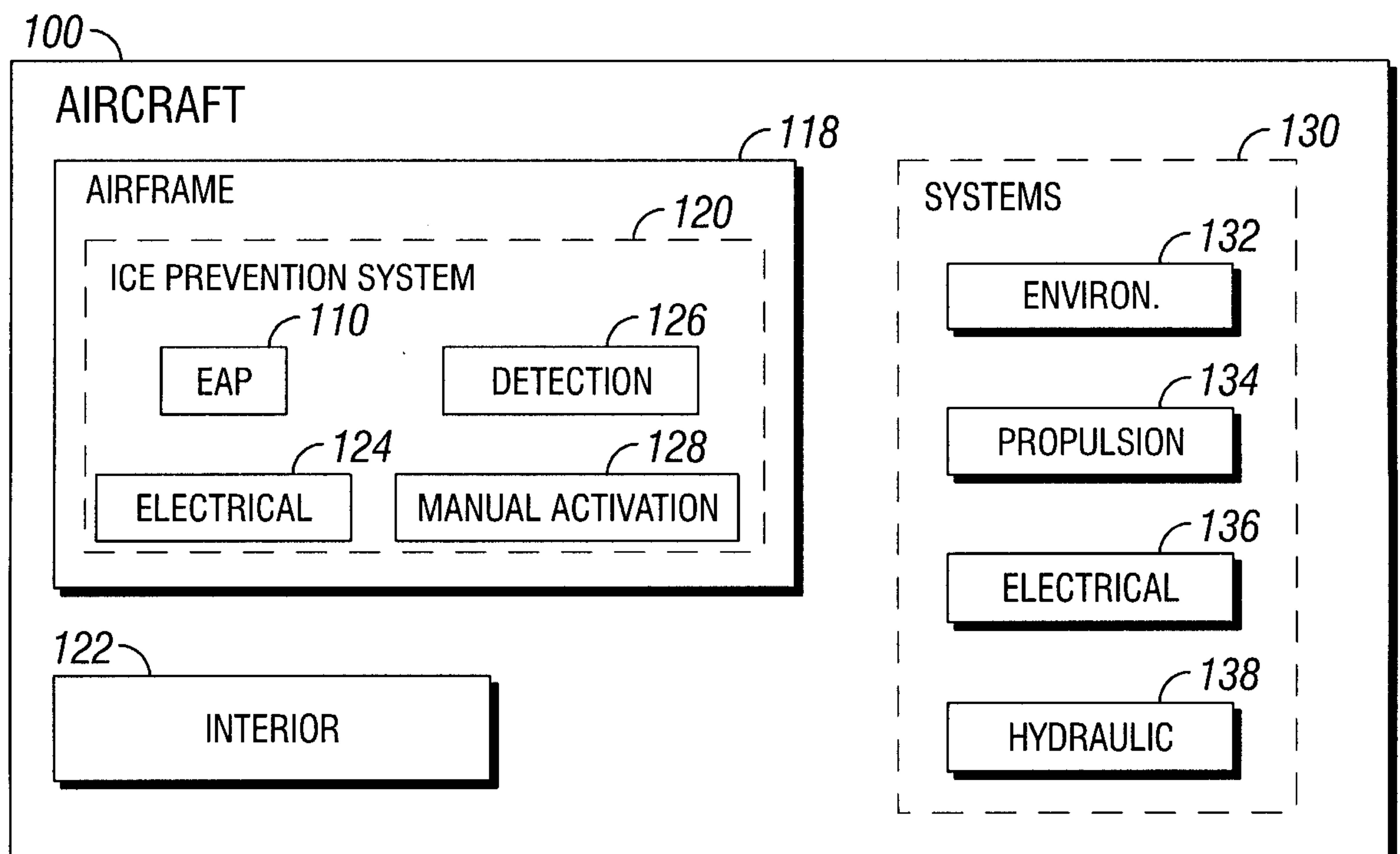


FIG. 7

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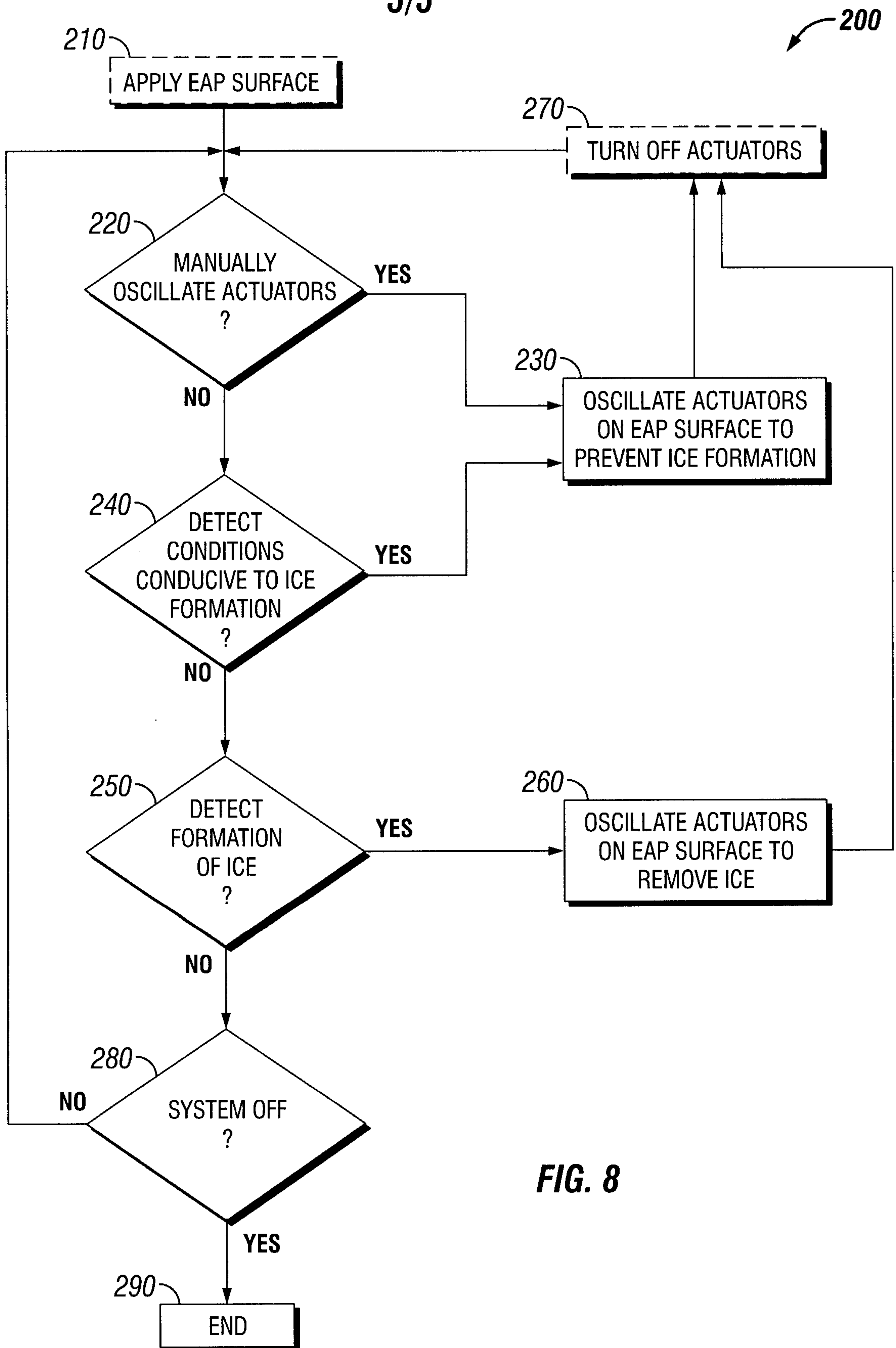


FIG. 8

