A system and appertaining method are described to detect whether a projectile impact occurs on one side of a boundary line or the other. The system utilizes force sensing resistor-based sensors that may be configured in sections or groups and connected to a control system with a display. Sensor installation methods for the sensors and associated electronics are also provided. An impact classification system is provided for distinguishing between various events, including a footstep, ball impact and tennis racquet contact. A sensor monitoring system is provided for determining the health of sensors and providing an error indication if sensor problems exist. A service detection system is provided when the system is used for tennis that permits activation of selected groups of sensors and deactivation of others.
FIG 8A

22 Sensor

40 Wire

102 Control Box

39 Leakage Resistor Approx. 3MOhm

FSR Sensor

+6V

V+

V-

Rd

Approx. 4KOhm

170, 172 A/D, Processor

104 Visual

106 Audio

108 Network

Other Inputs

FIG 8B

22 Sensor

40 Wire

102 Control Box

39 Leakage Resistor Approx. 3MOhm

FSR Sensor

Rd

V+

V-

170, 172 A/D, Processor

104 Visual

106 Audio

108 Network

Other Inputs
FIG 9

Inputs from Sensors

172 A/D CONV

194 Baseline Signal Calc.

188 Health Monitoring

190 Error Notification

122 Error Light

108 Network

192 Listances of Event Classifier Integrator Algorithm

196 Current Game State and Serve Condition

186 Event Integrator

152 Events

124 Doubles/Singles

Auto Serve Detect

194 Signals to Enable or Disable Classifiers

130 Game State Monitor

196 Current Game State

180 Game State Criteria

198 NOT Case and Serve Condition
<table>
<thead>
<tr>
<th>Column 1</th>
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<tr>
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</table>

**Legend:**
- **Name:** Date
- **Group:** Sensor
- **Red:** Sensor OUT (1)
- **Blue:** Sensor IN (1)
- **Yellow:** Sensor different sections and split into IN and OUT (1)
- **Fence:** Split into IN and OUT (1)

*Note: The figure shows the layout of a sensor system with different sections and directions indicated.*
AUTOMATED LINE CALLING SYSTEM

BACKGROUND

[0001] The present invention is directed to a system for determining if a projectile has impacted a surface on one side of a boundary line or another utilizing a force sensing resistor (FSR) or force sensing rubber sensor or other sensor for measuring force. Such a system may be used in a sport such as tennis in which a call must be made as to whether a tennis ball has landed in bounds or out of bounds.

[0002] Various sensor-based systems for monitoring such impacts are known. Many of these revolve around the use of a membrane switch or some form of a switch for the detection. However, such membrane-switch-based systems lack accuracy at the boundary and are not sensitive enough to light ball bounces, and generally utilize debounce circuitry for processing signals. Patents utilizing some form of this technology include, e.g., U.S. Pat. Nos. 5,672,128 (Conn); 3,982,759 (Grant); 4,365,805 (Levine). The lack of sensitivity in the Conn system cannot be corrected by minimizing the amount of "dead" area, because if the openings are made large enough to detect light impacts through a layer of tennis court paint, then even a slight error in manufacturing, or a slight bump in the court surface can cause the sensor to be stuck in the conducting state. This is unacceptable for a commercial system that would be required to work reliably for years in widely varying environmental conditions, and would have players running, sliding, and jumping on it. Furthermore, different versions of the system, with different sensitivities would have to be made for different court surfaces, since they have different thicknesses, and flexibility. Because these systems can only sense the presence or absence of a force above a certain threshold, during the start or end of a footstep, they may produce signals that may be confused with ball bounces. Typically, these systems use debouncing circuitry or algorithms to filter such events. Thus, they ignore signals that look like ball bounces within a predetermined time window before and after the detection of a footstep. Thus, they are unable to detect ball bounces that occur within a short time before or after a foot steps. Furthermore, despite these measures, systems that use membrane switches often misclassify foot steps as ball bounces, and are typically incapable of distinguishing events such as a tennis racquets hitting or scraping the sensors from a ball bounce.

[0003] A number of known systems are based on the use of piezoelectric mechanisms, such as U.S. Pat. Nos. 4,840,377 (Bowser); 4,855,711 (Harrop); and 6,367,332 (Fisher—utilizes two triboelectric cables to detect vibration). Although these systems utilize piezoelectric devices in different shapes that can work well under certain situations, they are quite expensive and can fail to detect a static force applied to them. U.S. Pat. No. 5,954,599 (Lin) teaches a use of two cables that conduct mechanically when pressure is applied; the use of two cables does not provide the necessary area coverage to detect balls farther away from the lines.

[0004] Other systems utilize exposed conductors on the court which can be difficult to install, can interfere with the game, and can be difficult to keep clean. For example, U.S. Pat. No. 4,092,634 (Kohorn) requires the use of a conductive ball. U.S. Pat. No. 5,900,292 (Brace) utilizes conductive pins on the court. U.S. Pat. No. 4,109,911 (Anken) uses wires on the court.

[0005] At present, the only practical and commercially viable line calling systems in use are camera-based systems (and Cyclops™ which uses infrared or similar beams across the service line so that when the ball crosses the beam, the detector is able to tell if it was "out"). Other camera- or laser-based systems are known. The primary disadvantage of camera based systems is that they are expensive and do not actually sense the ball impact. Furthermore, these systems generally require very bright lighting to work effectively and often need to be recalibrated. U.S. Pat. No. 6,816,184 (Har-math) discloses a system that utilizes a camera based system. This system requires many cameras and high-speed computers, and does not actually sense the impact point of the ball. Instead, it extrapolates it from a video feed. Finally, U.S. Pat. No. 5,059,944 (Carmona) discloses a system that utilizes lasers to detect the ball bounce. Such a system is not very accurate because the lasers have to be a certain distance above the court. Thus, they can call a ball that is flying at a shallow angle in, when it is really out. This is a similar problem that plagues the Cyclops system, which is why so many players complain about it. Also, such systems can be disturbed by bugs or debris landing on the court, and this system is prone to misalignment. Furthermore, the devices are visible and obtrusive and must be avoided by players, officials, and spectators that may be on the court.

[0006] U.S. Pat. No. 4,990,897 (Beyma) discloses the use of sensors whose resistance varies with force, but utilizes a constant current source that could consume substantial power when the system is not active if a current were fed through many sensor areas. Furthermore, very high voltages would be needed to drive a sensor such as a typical FSR sensor which has a resistance greater than 1 MD in an inactive state.

[0007] Beyma further utilizes a rate of change for signal calculations, which can make distinguishing a footstep, ball bounce, tennis racquet difficult because these can produce very similar rates of change and cannot be used to determine when a player is standing on the line.

[0008] Furthermore, Beyma uses a signal that is proportional to the resistance of the sensor. However, the resistance of such sensors is inversely proportional to the force applied. As a result, when a player stands on the sensor, the rate of change produced by a bouncing ball will be different from the rate of change produced when a player is not standing on a sensor.

SUMMARY

[0009] The present invention is a system that can be used to make line calls both in un-refereed games as well as assisting referees in making good calls for refereed games.

[0010] In an embodiment of the invention pertaining to a tennis court, the line calling system comprises a plurality of sensors embedded under tennis court paint or other tennis court covering, wiring to connect the sensors, a control box that receives the incoming signals, processes the signals, allows configuration of the system, and notifies players or referees when a ball is detected in or out. Notification may be done using an audio notification when the ball is out, a visual display, or by sending a message over a wired or wireless network. The visual display may show, e.g., six boxes that represent each singles or doubles area and one for each service box.

[0011] According to an embodiment of the invention, a sensor based on force sensing resistors (FSR) is utilized in order to avoid the above mentioned problems of membrane switches. This is because, unlike a membrane switch, an FSR does not produce a simple ON/OFF signal. Instead, an FSR
sensor has a resistance that decreases with the amount of force applied, giving an analog signal that can be analyzed for much more accurate results.

[0012] The resistance of an FSR may range from several mega-ohms when there is no force on the sensor to a few hundred ohms when a ball bounce or a footstep on the sensor occurs. The amount of force on the sensor can be approximated by one over the resistance of the sensor, also known as the conductance, which is approximately proportional to the force applied to the sensor. The conductance can be measured by various means such as applying a constant voltage to the sensor and measuring the current through the sensors, or by using a circuit that generates a voltage that is related to the conductance of the sensor in a known way, and measuring that voltage with an analog to digital converter. By analyzing this signal, one can accurately distinguish between a ball bounce, a footstep, the impact of a tennis racquet, and other types of contacting events.

[0013] In the case of a ball bounce, one can determine whether the ball was IN or OUT with an accuracy of a few millimeters, and one can even detect very light bounces, such as those from a drop shot. Furthermore, because the signal is analog, one can filter out the constant component of the signal which can be affected by sensor manufacturing, court surface material, imperfect installation, bubbles and cracks in the court surface, changing weather, the gradual wear of the sensor, etc.

[0014] Thus, unlike a membrane switch, it is almost impossible for the FSR to get stuck in the ON state. Even though the constant component of the signal may be filtered out, the transient changes which result from ball bounces, footsteps, tennis racquet impacts and the like can still be detected.

[0015] Because the signal is analog, it does not have to be de-bounced, and can be analyzed much more accurately than the ON/OFF signal from a membrane switch. As a further advantage, a sensor problem can be detected if the constant component of the signal is too high, indicating a short, or the signal is too low, indicating a break in the wire. As a further advantage, a base-level "off" signal can be determined. Thus, even small forces can be detected as they will cause an increase above the base-level signal.

[0016] The line calling system can be made where a permanent resistor with a high resistance at each sensor area is used to provide a small leakage current. The absence of such a leakage current can be used to detect a break in the wire. Additionally, an integrating algorithm can be provided to make the correct decision by using the position and timing of events that happen within a small period of time to determine where the ball actually bounced (as described above).

[0017] Furthermore, the FSR sensors can be made with a total thickness of approximately 0.005"-0.050"—thin enough to be completely hidden under tennis court paint, without having to cut the concrete or asphalt base of the court. All of these aspects are advantageous for a commercially viable line calling system, and most of these cannot be accomplished with the older membrane switch technology.

[0018] Advantageously, this approach is very accurate for all types of ball bounces, in a wide variety of weather and lighting conditions, and under all the situations that can occur during a tennis match. The system is exceptionally consistent in that it calls the same ball bounce the same way every time, on either side of the court—therefore, whatever margin of error exists on one side of the court will exist on the other, giving neither side an unfair advantage.

[0019] This system can work on cement or asphalt courts, which are painted with tennis court paint, cushioning system, or covered with a surface such as rubber tiles, rubber carpets or synthetic grass.

[0020] And also advantageously, the present invention can be implemented simply and affordably so that it is commercially viable not only for big tournaments (e.g., grand slams), but also for clubs, universities, and private tennis court owners. It is unobtrusive so that it can work with existing court surfaces, tennis balls, shoes, and other athletic equipment. Players do not detect differences between a regular court and one with the inventive system installed, except for the small device that provides audio/visual indication about whether a ball was in or out.

[0021] The present invention is reliable and durable, so that it may last for many years, and can be configured to automatically detect if there is a problem requiring maintenance or replacement.

DESCRIPTION OF THE DRAWINGS

[0022] FIG. 1 is a top view of a tennis court layout comprising an embodiment of the invention;

[0023] FIG. 2A is a top view of a Section A corner area sensor overlap;

[0024] FIG. 2B is a top view of a Section B T-intersection area sensor overlap;

[0025] FIG. 2C is a top view of a Section C T-intersection of the service lines area sensor overlap;

[0026] FIG. 2D is a top view of a multi sectioned sensor layout in which the out portion is segmented;

[0027] FIG. 3A is a top view illustrating the detail of a bottom layer of the sensor with an interdigitated finger configuration;

[0028] FIG. 3B is a bottom view illustrating the detail of a top layer of the sensor with an interdigitated finger configuration;

[0029] FIG. 3C is a top view of the top layer of an exemplary sensor;

[0030] FIG. 3D is a top view of the bottom layer of the sensor shown in FIG. 3C;

[0031] FIG. 3E is a cross-sectional view of the sensor shown in FIGS. 3C and 3D;

[0032] FIG. 3F is a cross-sectional view of a sensor having an interdigitated finger layout;

[0033] FIG. 3G is a cross-sectional view of a sensor using a force sensing rubber configuration;

[0034] FIGS. 4A-D are top views of various sensor/glue layouts;

[0035] FIG. 5A is an isometric pictorial illustration of the sensor-cable interface using a flex cable connector;

[0036] FIG. 5B is an isometric pictorial illustration of the sensor-cable interface using a soldered ribbon cable;

[0037] FIG. 5C is an isometric pictorial illustration of the sensor-cable interface having an attached circuit board;

[0038] FIG. 5D is an isometric pictorial illustration of the sensor-cable interface using a flex circuit;

[0039] FIG. 5E is a top view of the sensor-cable interface using embedded A/D converters and microprocessors along the length of the sensor;

[0040] FIG. 6 is a cross-section view of the sensors embedded in a tennis court;

[0041] FIG. 7A is a perspective pictorial diagram illustrating an exemplary control box mounted on one side of the net;
FIG. 7B is a pictorial front view control panel of the control box; FIGS. 8A, B illustrate a voltage divider and op-amp embodiment for the control box; FIG. 9 is a block diagram of the system hardware/software components; FIG. 10A is a graph illustrating a typical shape waveform for a light ball impact; FIG. 10B is a graph illustrating a typical shape waveform for a medium ball impact; FIG. 10C is a graph illustrating a typical shape waveform for a hard ball impact; FIG. 10D is a graph illustrating a typical shape waveform for a ball impact at a sharp angle; FIG. 10E is a graph illustrating a typical shape waveform for a foot kick; FIG. 10F is a graph illustrating a typical shape waveform for a foot slide; FIG. 10G is a graph illustrating a typical shape waveform for a hard racquet hit; FIG. 10H is a graph illustrating a typical shape for a normal racquet hit with dual thresholding; FIG. 10I is a graph illustrating a typical shape for a racquet scrape; FIG. 10J is a graph illustrating a typical shape for a simultaneous footstep and ball impact; FIG. 11 is a pictorial top view illustrating sensor areas with channeled resistors; FIG. 12 is a plot of the combined chained section signals received; FIG. 13 is a plot of the calculated isolated ball bounce signal; FIG. 14 is a pictorial diagram illustrating a further embodiment of a court layout; and FIG. 15 is a pictorial diagram illustrating a further embodiment of a court layout.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS OVERVIEW

FIG. 1 illustrates an exemplary embodiment of the invention for a tennis court 10. The court 10 is defined by a rectangular area having boundary lines 14 and a net 12 that bisects the rectangular area. A ball is considered IN if, upon impact, it touches the boundary line 14 of a court that is in play, and OUT if it bounces outside of the court without hitting the line 14. A control box 102, explained in more detail below, is shown in an exemplary configuration located proximate to one end of the net 12.

Although it is preferable to have the sensors along all of the boundary lines of a court as in FIG. 1, to reduce cost, sensors may cover a subset of the boundary lines on a court. For instance, sensors may be placed only along the service area to just call serves, or sensors may be placed only along the singles court and service area and not the doubles court.

Sensors

In the primary embodiments of the invention discussed below, a sensor 22 has two sensing areas, an IN sensing area 24 that it is arranged at and inside of the boundary lines 14, (the “IN side”), and an OUT sensing area 26 that is laid out to go outside of the boundary lines 14 (the “OUT side”). The advantage to having both areas is that a ball bounce that is on the line (and hence “IN”) will produce some signal on the IN sensing area 24 and can therefore be used in conjunction with the signal detected on the OUT area to better classify (with more accuracy) such a bounce as “IN”.

However, additional embodiments are possible that only utilize an OUT sensing area. Such embodiments may be utilized when cost or system simplicity can be traded for accuracy. Without having an IN area to provide a definitive indication of the ball bounce on the boundary line 14, the classification of a curve as being IN or OUT becomes difficult for close calls, and an arbitrary criteria must be established to make the determination that is less likely to be accurate. Nonetheless, the accuracy of such a system will be sufficient for many non-professional situations.

Court Layout

The primary interest is in detecting balls that are OUT—therefore, the OUT side 26 of the sensor 14 should be wide enough to detect all ball bounces that may come under dispute because they are too fast for the human eye to see. The necessary width may depend on the experience of the players, the presence of line judges, and the seriousness of the event. Furthermore, the width may vary depending on the location of the line. For instance, the service line 14.1, since it may receive balls traveling over 100 miles per hour, may need to be wider than the base line 14.2. Typically, the necessary width of the OUT sensors 26 will be around 1’ and no more than around 1.5’, because when a ball bounces more than this distance outside the boundary, it is very easy to judge accurately.

The purpose of the IN side 24 of the sensor 22 is to suppress an OUT call when a ball hits both the IN 24 and the OUT 26 sides of a boundary 14. A ball is considered IN if any portion of it touches the IN side of the boundary, and its presence may be detected by a simultaneous signal on both the IN side 24 and the OUT side 26 of the sensor 22, but also, the ball can just land on the IN part without activating the OUT part.

Thus, the IN side 24 of the sensor 22 may be as narrow as 1”, but may be made wider to cover the entire width of the boundary line, which is typically 2” wide all around the court.

During different stages of play, such as service to the odd or even count, singles rally, or doubles rally, different sections of the boundary lines 14 will have to act as IN/OUT. This is accomplished by dividing the boundary lines 14 into multiple sections (Sections A, B and C), each section having an IN side 24 and an accompanying OUT side 26. See FIGS. 2A-C. Because either side of the centerline may act as the IN side or the OUT side depending on which service court is in play, the centerline, unlike all the other lines, must be divided into three sides: a central IN side, and two outer sides, which become either IN or OUT depending on the direction of service. To prevent dead spots in areas where two (or possibly more) sensor strips meet, the sensors can be designed to overlap in those areas such that when they are overlapped, the entire area at the intersection can be sensed by one or the other sensor. The sensors are designed to be thin enough to permit them to overlap without creating bumps on the court that could interfere with the game and because they are flexible, the sensor on the bottom will still be able to feel forces through the sensor above it.

The sensor section layouts are not limited to being segmented into solely a single IN portion 24 and a single OUT portion 26, but rather can be configured to have multiple
segments, such as that illustrated by FIG. 2D, in which, by way of example, the OUT portion 26 is broken into three distinct segments.

[0070] The sections may be further subdivided into subsections (see FIG. 3A, where each wire is connected to a subsection), each subsection having an IN and an accompanying OUT side in order to allow the detection of a ball bounce even while a player is standing or running over a boundary line. This is necessary because a player standing on a line may create a signal that will “mask” the signal produced by a bouncing ball. Because the OUT side of each subsection may be approximately 1.5 feet wide, it may be divided further into sensor areas of smaller width. Note that it is not necessary to divide the service lines into subsections because a player should never stand on a service line during service. The smaller the sensor areas, the less the chance that a ball could hit a sensor area at the same time that a player is standing or running over it. The sensor areas do not need to be much smaller than 6 in length or width since it is nearly impossible for a foot to be within a 6\times6 area and for a ball to bounce in the same area. At the same time, it is desirable to have as few sensor areas as possible since more sensor areas means that the system will need more wires to conduct signals and more electronics to analyze them. Line calling systems made for professional use may have more of these subsections than those made for amateur or personal use.

[0071] There are several ways to reduce the number of IN sections 24 and OUT sections 26 needed by the system, and/or the number of signals generated by the sensors, although such reductions may also reduce accuracy—three such methods are described in more detail in following sections.

[0072] Additional court layouts are illustrated in FIGS. 14 and 15.

[0073] Sensor Structure

[0074] As described above, the sensors in a preferred embodiment of the invention may utilize force sensing resistor (FSR) technology, although the invention is not limited to this embodiment.

[0075] The enabling component of an FSR is, e.g., a semi-conductive force-sensitive resistive ink. Through a carefully controlled manufacturing process, the ink is created with a rough surface at the microscopic level such that when it is merely touching a conductor or another layer of resistive ink, the conductivity is poor. But when pressure is applied, the surface area of contact increases causing an increase in conductivity. Such inks are available from various manufacturers, and each has a different response curve to pressure. The ink chosen for this application should have a high standoff resistance (i.e., a poor conductivity when no pressure is applied), and sensitivity to forces in the range of forces produced by a players foot and the force of a tennis ball.

[0076] In a preferred embodiment, the FSR switch comprises an upper and lower flexible non-conductive plastic layer (such as Mylar™, a trade name for Polyester). The bottom layer (FIG. 3A) has a series of conductive traces printed on it using a process such as screen printing. The traces are printed in an interdigitated finger pattern 30 with one common trace 33 carrying a positive voltage along the middle, and a plurality of IN sections 37 formed along one side of the boundary line by groups of interdigitated traces, and a plurality of OUT sections 39 formed on the other side of the boundary line by more groups of interdigitated traces. All of the traces are run to one or more edges of the sensor line where they can be attached to sensing electronics via, e.g., IN/OUT connectors 34, 36 through ribbon cables 40 respectively. FIG. 3H, described in more detail below, provides an exemplary layout of one possible embodiment.

[0077] The other (top) nonconductive plastic layer (FIG. 3B) is printed with semi-conductive resistive ink 44, 46 described above such that when the two plastic layers are attached, the resistive ink will face the interdigitated fingers 30 (the top layer, as shown in FIG. 3B, is flipped upside down before being glued to the bottom layer), with ink for the IN side 44 and the OUT side 46 respectively. It should be noted that the terms “glue” and “glued” are herein defined as shorthand nomenclature for any type of adhesive. Thus, when the resistive ink 44, 46 is merely touching the interdigitated fingers 30, the resistance between the interdigitated fingers 30 will be, e.g., several megohms or more.

[0078] However, when a pressure such as a ball hitting the sensor or a foot stepping on the sensor 22 is applied, the resistance will drop approximately proportionally with pressure to a lower value around, e.g., 1 kΩ. The actual resistance values are not particularly relevant as long as there is a substantial and measurable difference between the force applied and no force applied conditions.

[0079] In another embodiment, the FSR can be made in the “through” configuration. In this configuration, the common trace is printed on one layer of nonconductive plastic, and the IN/OUT sensing areas are printed on the other layer. Then, either one or both of these layers is covered with semi-conductive resistive ink. This configuration works as well as the one above, but may be more expensive to manufacture since multiple layers of ink may be printed on top of each other.

[0080] FIGS. 3C through 3E illustrate a through layout of an exemplary multilayer sensor 22 in which the top layer comprises a top layer plastic sheet 220, both FSR ink/paint 222, and a conductor 224, and the bottom layer comprises a bottom layer plastic sheet 220′, both FSR ink/paint 222 and a conductor 224. A layer of glue 250 is provided between the layers and the wires 40′ are present along the outer portion.

[0081] FIG. 31 shows a wiring configuration in which the traces on the bottom layer cascade down to their respective sensor areas. The advantage of these cascading traces is that they are formed by a repeating pattern that is less costly to manufacture since the same pattern can be printed repeatedly for the majority of sensor areas of the sensor. Such a pattern could be printed repeatedly using a silk screening method, or a rotary printing method, and would avoid the use of many different, or one long printing mask. Advantageously, this approach allows for the manufacture of extremely long sensors which have a separate trace; and thus, a separate analog channel connected to each sensor area. Furthermore, all of the sensor areas can be connected to the electronics using a single connection point on one end of the sensor.

[0082] The top diagram of FIG. 3H illustrates a basic trace pattern print mask and a basic sensor plus trace pattern mask that can be repeated, in theory, indefinitely. The width permitted for the trace patterns would ultimately dictate the number of repetitions in a practical application. The middle diagram of FIG. 3H illustrates a sensor and trace pattern that is repeated four times. Accordingly, it is possible to design the mask according to such grouped sensor and trace patterns instead of individual ones. In the case of silk screening, such a pattern could be created on one large silk screen, thus four sensor areas would be created, each time the screen was printed. The bottom diagram of FIG. 3H illustrates an
example of either the top pattern being repeated twelve times, or the middle pattern being repeated three times. This technique results in traces being printed that may be reused (i.e., those not connected to any of the sensor areas), but these unused traces are not problematic.

[0083] After the sensing area is printed, a tail portion which extends the length of the traces can be printed on the same piece of plastic as the sensors themselves. The tail section can be made long enough to reach outside the playing area of the court, so that connections do not have to be made under the court surface. Such connections would be unreliable, and would be difficult to mask with court paint. For a tennis court, the longest sensors that are printed are those for the sidelines. These sensors have a sensing area that is 40 feet long and a tail as long as 20 feet.

[0084] The drawback of printing traces directly on the sensor is that the longer the sensor gets, the greater the width occupied by traces. In the preferred embodiment, with 40 foot long sensors with 20 foot long tails, each foot of the sensor contains two sensing areas, one for the IN and one for the OUT portion, thus there are eighty traces running along the side of each sensor. Each trace is 50 mils wide and there is a 50 mil space between traces, thus 8" of sensor width has to be used for traces. Because we are limited to printing an 18" tall sensor, this would mean that width of the sensing areas would be limited to 10". To avoid wasting 8" of the height of the plastic on traces, we print the sensors in three layers. The first layer is the layer with traces printed using a repeating cascading pattern that is 1" wide, and 5" tall. The next layer is a layer of dielectric which covers the traces. The third layer is the print of interdigitating fingers. Although the traces are mostly covered with dielectric, they come out at the top and bottom and through openings left in the dielectric to connect with the interdigitating fingers from the appropriate sensor area. Thus, by combining the idea of printing a repeating cascading pattern, and the idea of printing multiple layers, we are able to produce sensors that are as long as a tennis court and as wide as the screen printing press we use.

[0085] Other wiring configurations, which are generally known, may also be employed for either the interdigitated or thru embodiments of the device. These may include configurations in which sensor areas are located on an X/Y grid and can be scanned one row or column at a time, or more generally, a configuration in which sensors are grouped into clusters having separate common traces, and shared output traces, allowing the force values of the sensor areas in each cluster to be scanned independently of other clusters. Although such configurations may reduce the amount of wiring needed, extreme care must be taken when engineering such a configuration for use with a line calling system, because during footsteps, current may leak onto un-activated common traces, leading to false activations, missed ball bounces, or incorrect calls.

[0086] Several different conductive inks, such as silver, copper, aluminum or nickel conductive ink, may be used for the traces 30, interdigitated finger and/or conductive pads. The silver ink conducts the best, and is least likely to corrode, but is the most expensive. To reduce the cost of these inks and improve corrosion resistance, an ink that is carbon based, or is a mix of carbon and one of the above inks can be used. The ratio of carbon to silver/copper/aluminum/nickel ink will determine the final resistance. Using a cheaper and more corrosion resistant carbon ink, however, may greatly increase the resistance of the traces, since resistance is proportional to the length of the trace, and the traces are quite long. Thus, to achieve the best price vs. performance ratio, it may be possible to use a more conductive and less corrosion resistant ink such as silver ink for the traces, and less conductive, more corrosion resistive, and cheaper ink such as a silver and carbon mix on the sensor areas (which are comprised of interdigitated fingers 30 or pads).

[0087] Producing sensors having a long length that are well-suited for installation in this application may be performed according to the disclosure of the international patent application filed on even date herewith and identified in the prosecuting attorney's docketing system by the docket number P05,0185-02WO, herein incorporated by reference.

[0088] Sensor Dielectric and Adhesive Layer

[0089] As illustrated in FIGS. 4A-D, the upper and lower layers should be glued or sealed securely all around the edges to prevent moisture from getting in. Furthermore, they should be glued in the pressure sensing area of the sensor 22 to prevent the top of the sensor from moving up and down, causing unevenness on the court and fatiguing the sensor 22 so the sensor 22 will stand up to the forces created when players run and slide over it and when the ball bounces on it. The glue 50 should be applied in a pattern that will accomplish this goal while maximizing the sensing area and minimizing the non-sensing area. The glue or spacer should have a layout that will retain sufficient strength and should generally be evenly distributed around the IN/OUT boundary. The pattern can be printed first with dielectric and then with glue to increase the thickness of the pattern, and thereby increase the minimum force that would cause the sensor to begin conducting current.

[0090] As little glue 50 as possible should be applied around the boundary between the IN 24 and OUT 26 areas, since glue 50 near the boundary may reduce the accuracy and consistency of the sensor 22. In one embodiment, the pattern consists of fingers 51 (FIG. 4A) that go toward the center of the sensor 22, with an open “channel” around the sensor boundary to maximize the resolution at the IN/OUT boundary to accurately call close balls. Other embodiments include those in FIG. 4B which illustrates the use of squares 52 with air passages 53 to promote air movement. FIG. 4C illustrates the use of dots 55 for the glue pattern, which is the preferred embodiment, and FIG. 4D illustrates the use of crosses for the glue pattern. All of these layouts are designed to allow the air trapped between the upper and lower layer of the sensor to move around freely preventing areas between the two layers from having a high or low air pressure.

[0091] Note that these layouts can also be used for the middle nonconductive layers of sensors 22 employing other force sensing technology to increase their accuracy. The glue 50 can either be printed onto the sensor 22 (the preferred glue is a special UV activated glue), or a thin sheet of pressure sensitive adhesive which is cut to the appropriate shape can be used.

[0092] Force Sensing Rubber

[0093] In yet another embodiment of the invention, force sensing rubber may be used to create the sensor 22 by replacing the semi-conductive resistive ink with force sensing rubber in either of the above embodiments.

[0094] Force sensing rubber is made by mixing small conductive particles into rubber before it dries, and is similar to semi-conductive resistor ink in that its resistance decreases as force is applied. However, instead of using a surface effect, the effect is one that occurs within the volume of the rubber.
Because the surface is not involved, this configuration may be more resilient to wear and environmental conditions, but may also create a thicker sensor, since the rubber must have a certain minimum thickness in order to work effectively. To attach the force sensing rubber between the upper and lower sensor layers, layouts of glue such as those described above and illustrated in FIGS. 4A-D may be used. An alternative to this is to use conductive rubber glue which may cover the entire surface of the rubber without reducing the sensing area of the sensor.

An embodiment of the invention contemplates a method for installing a sensor in a surface, comprising providing top and bottom layers of the sensor as separate components at a site of in-ground installation; assembling the top and bottom layers with a laminator at the site; adding waterproofing to the assembled top and bottom layers; flattening the waterproofed top and bottom layers; and installing the sensor comprising the flattened and waterproofed top and bottom layers within or on top of a ground surface. Such an embodiment may comprise affixing the sensor to the ground surface with epoxy or other glue; and applying a resurfacing material with texturing on top of the sensor. The texturing may comprise silica sand. Sensor positioning during installation may comprise attaching a sensor signal output line to a computer via an interface; initiating a signal at the sensor signal output line; obtaining feedback from the computer based on the initiated signal; and adjusting a position of the sensor based on the computer feedback to effect an alignment of the sensor to a boundary line. The same technique may be repeated once a sensor is installed to determine the accurate placement of a boundary line on top of the sensor.

Sensor Interface

FIGS. 5A-E illustrate various embodiments of the sensor interface. The sensors 22 can e.g., (FIG. 5A), be wired to the control box 102 with flat flex cables 40° utilizing a standard connector 34, 36.

The wiring, e.g., ribbon cable 40 (FIG. 5B), can be directly soldered to the sensors 22 or connected to the sensors 22 using standard flex cable connectors 34, 36. Another option (FIG. 5C) is to have a small circuit board 140 between the wiring 40, 40° and sensor 22. The circuit board 140 may have electronics, such as an A/D converter 150 and microprocessor(s) 160 to analyze the signals closer to their source, and to send a digital signal describing what has been picked up, thus lowering the number of wires that need to be run to the control box 102. The connections can be protected from moisture by potting them in or covering them with a liberal layer of plastic, latex, epoxy, or silicone sealant and/or glue 60 or some other form of waterproof enclosure 60°.

In one embodiment illustrated in FIG. 5D, the electronics 150 and microprocessors 160 may be embedded directly into the sensors 22 using flex-circuit technology. Each microprocessor 160 may process the signals from one or more sensing areas. The electronics 150 and microprocessors 160 may be embedded or more ends of a strip of sensors 22 (FIG. 5D), or on the sensor, and may be evenly spread along the length of the sensor (FIG. 5E). The microprocessors 160 can be connected with a common communication and power bus 40° composed of just a few wires (for example: two for power, one for communications). The major advantage of this scheme is simplified wiring, although great care would have to be taken to ensure that the electronics are reliable, especially in areas where they are installed under court paint and might be run over by players.

Installation

The sensors 22 may be transported from the manufacturing/distribution site to the installation site easily. The sensors described above should not be bent appreciably once they are assembled because this could cause stretching of the plastic, and an uneven court surface once the sensors are installed. However, because the top and bottom layers of the sensors 22 as described above are thin and flexible, and comprise long strips, they can be easily rolled onto spoons for shipping after they are manufactured, and assembly can be done at the installation site. The layer of the sensor that has adhesive should be covered with release liner so it will not stick to itself.

Assembly consists of running the top and bottom layers of each sensor off of the spoons and through a laminator which should remove the release liner, and squeeze the two layers together so that they stick. Next, each sensor should be laminated on the top and bottom with a thin, heat activated laminating film which is slightly longer and wider than the sensor. Extra laminating film can be trimmed off as the sensor goes through the laminator. All of this can be done in one step on a custom made laminating machine. The lamination serves two purposes: First, it prevents moisture from entering the sensors. Secondly, it helps keep the sensor from wrinkling even in extreme outdoor heat.

In cases where an installation is a temporary installation, such as in an arena where the floor may also be used as a basketball court or an ice hockey rink, it is desirable to be able to disassemble the sensors and roll them up for storage. In such cases, the sensors may be manufactured with a weaker adhesive or no adhesive between the top and bottom layers, and they may be laminated with a film in such a way that it can be peeled apart when it is time to disassemble the sensors.

After assembly, the desired locations of the sensors should be carefully measured and marked on the court, because the sensors are extremely difficult to move once they are glued. Furthermore, the installer must keep in mind that the sensor ideally are glued with a slight predetermined offset in relationship to each boundary line. This offset could be, e.g., one quarter inch. This is because in tennis, a ball landing near a boundary will often graze the IN side of the court with its fuzz, or will touch it so lightly that it will not produce enough force to be detected by the IN portion of a sensor. Thus, if the IN/OUT sensor boundary is aligned precisely to the boundary of a court, the sensor may systematically call balls that are just barely IN as being OUT. To avoid this problem, the sensor should be installed so that IN/OUT sensor boundary will fall a few millimeters outside the actual court boundary. This offset was determined experimentally to be approximately 6 mm or ¼". With such an offset, a ball landing near a boundary will always produce a detectable force on the IN portion of a sensor, and an activation threshold can be adjusted through software to fine-tune the IN/OUT accuracy of the sensor down to a few millimeters. Marks should be left on and around the court that will allow the court painters to know where to paint the court boundary lines so that they will align with the sensors once they are covered by a court surface.

FIG. 6 illustrates an exemplary sensor 22 installation. Once the sensors 22 are delivered to the site and
assembled, and all sensor positions are carefully marked, they are glued to the top of concrete, asphalt, or existing court paint with a glue that is resilient, bonds well to plastic and to the substrate, can tolerate a wide range of weather conditions, and can dry or stick without the presence of air (since the plastic will seal off air). These adhesives include epoxy, and pressure sensitive acrylic tape.

Once all the sensors are glued down, thin wiring (40, 40', 40", FIGS. 5A-E) is run over to the control box 102, and glued 72 in place to the court 70. Typically, the court paint will be at least 1/3" thick enough to completely cover all the wiring 40, 40', 40". If it is not, a groove can be cut in the surface of the court to make a channel for the wires 40, 40', 40". In order to make the entire area of the lines sensitive, the sensors 22 can overlap each other in the areas where the boundary lines meet, as illustrated in FIGS. 1, 2A-C, and discussed above. Because the sensors 22 are so thin, this can be done without leaving a visible bump on the surface of the court, and without affecting sensor performance. Alternatively, the sensor border can be cut off during manufacture or assembly before lamination takes place in areas where the sensors meet so that only the laminating film will overlap with the neighboring sensor.

Once the sensors 22 are glued 72 to the court, they must be treated in a way that will permit the tennis court paint 79, or cushioning system 76 to stick securely to the top and/or sides of the sensor 22. One way to do this is to first paint the lines with a primer such as GAC 2000 or CalproCorp Hi-Grab. A further way to improve adhesion of the tennis court paint 79 or cushioning system 76 is to first glue a thin mesh 74, or scrim to the top of the sensor 22 before painting with tennis court paint 79 or cushioning system 76. Another way to accomplish this is to manufacture the sensors 22 with a top layer that has a sufficiently rough upper surface to allow tennis court paint 79 to stick securely. The preferred way to accomplish this is to cover the sensors with an acrylic court resurfacer and to then sprinkle silica sand over the resurfacer. Once the resurfacer dries, the silica sand will create a rough upper surface that court paint will readily stick to.

Once sensors are ready, wires 40, 40', 40" from the sensors 22 are run to the area where a control box 102 will be placed that has the necessary electronics to process signals from the sensors 22. The wires can be glued to the court surface near the sensors, and the connector areas should be sealed in the fashion described above.

Next, the sensors are covered with rubberized cushioning court paint, rubber carpets, or other playing surfaces. The surface used should be thick enough to both hide the sensors and to protect them from players' footsteps. Once the surface is ready, the boundary lines should be painted. At this step, it is absolutely critical that the boundary lines fall in the right place with respect to the sensors underneath the court paint. Because the marks made during installation may be lost, or may move, it is desirable to be able to determine the position of a sensor which is hidden under the paint. This can be done by attaching test electronics to the sensor in question, which plot the forces detected by the sensor with respect to time. By applying forces to various points on the court surface and observing the response of each sensor subsection, the precise alignment of each sensor can be determined and marked.

Once the court is ready, the control box and associated electronics should be placed in the appropriate location and connected to the wires coming from the sensors. The control box 102 can be attached securely to one of the net 12 posts in order to fix it in place, and so that it will not interfere with the game. Another option is to locate the control box 102 at the side of the court 10, space permitting, or to locate it near a referee's chair. One or more indicator lights, monitors or displays might be included as part of the control box 102, or placed in desired areas around the court. For example, these indicators can be attached to net posts, can be placed on the court surface below the net, can be attached to the walls or fences surrounding the court, or can be located on a referee's chair.

Finally, the system should be powered up and tested according to prescribed test guidelines.

Control Box and Interface

Referring to FIGS. 7A, B, the control box 102 collects signals from the sensors on the court, interprets them and notifies players whether a ball was IN or OUT when it hits a boundary line 14. The control box 102 is optimally designed for solid enough withstand the impact of a tennis ball traveling at high speed. As noted previously, the control box 102 can be mounted, e.g., via straps 112, to a net post. Optionally, the control box can be a laptop or desktop computer with an appropriate interface for connecting it to the wires coming from the sensors. For outdoor installations, the control box should be either weatherproof, or portable, so it can be kept indoors during periods of cold or rainy weather.

Although in the preferred embodiment, all of the analysis is performed by one control box, additional control boxes may be provided to serve either as back-ups, or to display information at different locations on the court. Furthermore, the functionality of the control box may be split among multiple control boxes on the court (for instance, one for each side of the court, or one for each line on the court). These control boxes may have mechanisms to communicate with each other and exchange information regarding line calls.

The control box 102 can be designed to minimize power consumption for its operation, and can be designed to go into a low power state automatically if it is accidentally left on. In one embodiment, it can be powered by a high capacity battery. Another embodiment might include utilizing a rechargeable battery and a small solar cell 126 that would charge the battery using ambient light. An additional embodiment includes supplying power from an external source, although a power cord on the court 10 could present a safety hazard or a nuisance if it is not properly routed.

The control box 102 may comprise a number of switches 124 that can serve various functions. These switches 124 may be configured on a control panel 120, which could also include the solar cell 126 and a status or indicator display 122 that may be implemented, e.g., with LCDs or any other display technology. Possible switches 124 present may include an on/off switch for power, a switch to select between singles and doubles play, and switches for enabling or disabling communication via sound, lights, or network communications.

The control box 102 may also have indicators 122 to signal when it is working properly, when power is low, and when a problem is detected. The switches and/or indicator lights could be embodied in the form of virtual switches and/or lights which are displayed on a computer screen and controlled with a keyboard, mouse, or other user interface device.
The control box can have the ability to be controlled and to send out data through a network. The network communication may be wired or wireless, and it could allow referees to log in from a laptop or other portable computer to receive IN/OUT decisions as well as more detailed information, such as where the ball bounce occurred, and details about the status of the line calling system. The information may also be distributed in real-time to TV stations broadcasting the event, sport web sites, and to electronic billboards at the stadium. In a networked configuration, any of the user interface functions (i.e., display 122, switches 124) can be performed remotely.

For unrefereed games, audio and visual indications may be used to notify the players when a ball has bounced IN or OUT, although these can be kept enabled during refereed games as well. In general, audio indication is preferable for single courts, but may be distracting if enabled on several adjacent courts. When audio is enabled, the system may beep, or say “out” immediately after a ball bounces out via speakers 106. When a bounce occurs IN, it is optimal for the system to not make any sound to keep from distracting the players, although some other signal can easily be implemented. When enabled, a visual indicator such as a light 104 can also be used to indicate whether a ball was IN or OUT. If lights are used, preferably the lights 104 will be composed of bright LEDs, since LEDs are both durable and energy efficient. For example, a blinking red light may indicate OUT while a steady green light can indicate IN (when a ball hits a court line).

It should be noted that the areas of the courts that are in play vary depending on whether the game is singles or doubles and on whether the players are serving and to which court they are serving. Because the control box 102 is configured via, e.g., a switch 124 for singles or doubles play, it is simple for the control box 102 to know whether to monitor the outer or inner sidelines of the court 10.

However, the control box 102 also needs a way of knowing when players are serving, and which court the players are serving to, and a way to know when service is over and a rally has begun. One solution to this problem is to have a referee or a scorekeeper, using their networked laptop, or a remote control to explicitly tell the system when players are serving and into which court. This is the approach currently used with systems such as Cyclops. The drawback to this approach is that it may be tedious, cannot be used for unrefereed games, and that incorrect calls may be made if the proper button is not pressed in a timely matter.

One approach which does not require user intervention, is to simply use a display screen to display the position along a line where the ball bounced IN or OUT and let the players decide if it hit an area of the court that was in play. An audio beep can be produced when the ball lands outside the sidelines or baseline of the court, since in that case, it is also definitely outside of the service boxes. However, no beep will be made when the ball bounces outside the service boxes, because this can happen during the regular course of the game also. In this case, the players would have to look at the displays to see the result.

Because the display described above may be hard to read at a distance, instead of showing the position along a line where a ball bounce was detected, the display can just show four boxes for each of the four service areas and two larger boxes for each of the two singles or doubles areas of the court (depending on whether a singles or doubles game is being played), to indicate whether the ball bounced IN or OUT with respect to that area. The boxes can be arranged and dimensioned in a fashion similar to the way the areas on a court are laid out, so there would be an obvious one-to-one mapping in the players mind between the six boxes and the six play areas on the court. The boxes would turn green when a ball lands IN on one of the corresponding areas of the court, and red when a ball lands OUT. Where cost or energy consumption is a concern, the display could be replaced with six lights, capable of glowing red or green, arranged in the pattern described above. Other indicator forms will be apparent to those of skill in the art.

A further way to improve upon the indicating system above is to have intelligent software for serve condition detection. With such a system, the system could make correct audible and visual IN/OUT calls without input from a referee, and without requiring players to look at a display to see where the ball landed. The system could be possibly associated with the control box 102, that attempts to determine whether the players are serving and which court they are serving to. This can work because when a player is preparing to serve, he or she typically stands directly behind the baseline 14.2 for an extended period of time. Since some sensors 22 are mounted in the region behind the baseline 14.2, the control box 102 can interpret a steady pressure on a region behind the baseline 14.2 as an indication that a player is about to serve. Additionally, players often bounce the ball several times near the boundary line before they serve. This can be used as further indication that a player is about to serve because it would never happen that a ball would quickly bounce twice in a row on the baseline during a game. Depending on player preference, this repetitive ball bouncing may be an optional or required indication for activating the serve condition detection system. The software can tell whether the player is serving to the left or the right service court based on whether they are standing on the left or the right side of the service line 14.1. Based on this, the system will determine when a player is serving and into which box. When the system detects a service condition, it may make an audible announcement such as “Service” that lets the player know that the system is ready for their serve.

By automatically determining whether a player is serving and into which court they are serving, the system can activate the service lines in the appropriate service court. After the serve, the system will need to deactivate the service lines in the service court. This can be done in several ways. The first is to deactivate the service court after a predetermined period of time. This works in practice but may be distracting to the players, as they would be forced to serve immediately after activating the serve condition detection system. Another approach is to monitor the footsteps on the baseline, and deactivate service a short period of time after the player has moved off of the baseline. A mechanism may be provided that deactivates a serve mode when a person walks away from the sensor or sensor section or after a predetermined amount of time, and the mechanism (or an alternate mechanism) may be provided for keeping service areas of either a singles or doubles configuration active during a serve.

It should be noted that it is possible that the player may stand near or on the area of the baseline 14.2 during a point, and that the system will detect this as a serve condition. Also, if ball bouncing is not required to enable the serve condition, it is possible that the serve condition could be falsely enabled when players are not actually serving.
Because this may occur, it is desirable to call balls that are outside both the service court and the singles/doubles playing court as being OUT, just in case the players aren’t actually serving at the moment. This can be done simply by continuing to keep the singles/doubles lines enabled during a serve. This doesn’t cause any conflict since a ball that is outside of a sideline 14.3 or baseline 14.2 is also outside the service box.

Although the above approach eliminates the possibility that an OUT call would be missed during a rally, there is still the possibility that a ball could hit near a falsely activated service box during a rally, and that the system would call it OUT. Because this would be potentially confusing to the players, it is desirable to have the system say “OUT” when a ball is outside the singles or doubles court, and “Serve OUT” when it is inside the singles/doubles court but outside the service court. This would keep the players from being confused in the unlikely event that the serve condition was detected during a rally, and a player who was standing on the baseline managed to hit a shot that landed just outside the activated service court on the other side.

Because this approach makes assumptions about where the player stands when they serve, it may not work for beginning players that stand far away from the baseline before they serve. This feature may be implemented as an optional feature called “Auto Serve Detect” that can be disabled with a switch 124.

In addition to automatic detection of service, the system could allow the players to keep score by double-bouncing the ball on predetermined areas of the baseline, which could be indicated visually on the surface of the court. Areas could be provided to allow players to increase or decrease either their or their opponent’s score.

It is also possible that the players themselves could have devices (e.g., wireless controls) for remotely communicating with the control box 102 and for indicating the status of who is serving or providing any other status or control signal to the control box 102. However, such remotes could be cumbersome for the players to carry, and could be prone to being lost or damaged.

Control Box Electronics and Software

The control box 102 comprises the hardware and software used to received and process information from the sensors 22, and is illustrated in FIGS. 8A, B. It comprises a plurality of analog to digital converters 172 and their associated circuitry which will convert the analog signals from the sensors 22 into digital values. The values will be fed into one or more microprocessors 170 which analyze the signals to make the line calls.

Because ball bounces occur within a 5 ms time-span, the signals from the sensors should be read at a rate of approximately 1000 to 4000 times per second to capture the characteristic waveform produced by the ball bounce.

The analog to digital converters 172 may be integrated into the microprocessor 170, or may be on separate chips. Each of these chips 172 may also have its own processor that would allow some amount of preprocessing to be done on the data, thereby reducing the computational load on the main microprocessor 170. As described in the above section on sensor construction, these chips 150 may also reside outside the control box 102, and may be attached to the ends of the sensors 22, or may be integrated into the sensors 22 using flex-circuit technology. Additionally, the control box 102 may contain the necessary components to supply power to the sensors 22 using flex-circuit technology. Additionally, the control box 102 may contain the necessary components to allow user configuration, a speaker 106 to produce sound, connections for visual indicators or integrated visual indicators 104, and components 108 to allow communication over a network.

The sensors 22 may be connected to inputs of the analog to digital converter 172 in a simple voltage-divider configuration, as illustrated in FIG. 8A. In an alternate embodiment (FIG. 8B), operational amplifiers 174 connected in known configurations may be used to amplify the signal from the sensors 22 before passing it into the analog to digital converters 172.

After conversion to a digital value by the analog to digital converter, the signal and information about the configuration of the circuitry used to feed the analog to digital converter may be used to calculate the resistance of the sensor. The conductance of the sensor may then be calculated by taking the multiplicative inverse of the resistance. The conductance can then substitute for the raw signals as the input to the rest of the algorithm. The advantage of using the conductance is that it is approximately proportional to the force applied to the sensor.

Furthermore, when two forces are applied simultaneously to a sensor, the conductance is the same as if the two forces were applied separately and then the conductances from the two were added. This guarantees that even if there is a non-zero base-level signal, the conductance will increase by the same amount and at the same rate when a ball bounces as if there were no base-level signal. Furthermore, when it is necessary to determine the total force exerted on two or more sensor areas, the conductances of the two areas can simply be added together. This is typically not true for the raw values obtained from the analog to digital converters.

Typically, when using the voltage-divider configuration, conductance can be calculated by a system calculator as, e.g., G = Vd/(Vsup+Rd)+Vd/(Rd+R1), where Vd is the measured voltage on the A/D converter, Vsup is the power supply voltage, Rd is the resistance of the pull-down resistor and R1 is the resistance of the wiring and interconnects between the electronics and the sensor. By including the resistance of the wiring in the formula, we are able to compensate for the resistance of the traces printed on e.g., the sixty foot sensors.

In an advantageous FSR configuration, the sensor may be comprised of an FSR ink selected such that a resistance of the FSR ink and the sensor pull-down resistor decrease impedance, thereby increasing current, and produces a measured sensor voltage versus impact force curve that is generally linear. Furthermore, the resistance of the sensor pull-down resistor may be lower than a minimum FSR resistance, and the minimum FSR resistance may be larger than a trace resistance.

Because it would be extremely difficult to electrically shield the entire length of our sensors, in order to get the best possible signal, which is not affected by electrical interference, we prefer to minimize the resistance of the sensors, the wires and the pull down resistor. By doing this, we increase the current in the system and reduce the effect of electrical noise. Furthermore, it is well known that A/D converters measure voltages more accurately when connected to a low impedance source, and if the resistance is low enough we can forego amplifiers and use the voltage divider configuration instead. Typically, the resistances of the traces on our sensors vary between 30 and 200 ohms, depending on the length. In order to overcome the random variability in the
trace resistance, which is usually +–10%, we choose an FSR ink that has a lower end resistance, when someone is standing on a sensor which is several times larger than the trace resistance and is approximately 1K ohm. Then, we choose a drop-down resistor with a value that is also slightly larger than the trace resistance with a value of approximately 300 ohms. Analysis of the Vg vs Force curve shows that these are the optimal values given the characteristics of the circuitry, because they result in a curve that is nearly linear. The non-linearity of the curve is small enough that it is corrected accurately by the conductance calculation described above, yielding a linear relationship between Conductance and Force.

[0138] FIG. 9 is a block diagram illustrating the system architecture. After the analog to digital conversion 172, a software algorithm loaded onto the microprocessor(s) and/or hardware circuitry will monitor the tennis lines. This algorithm will do the following task in the background: it establishes a base-level signal 184 that the sensor produces when it is not activated. When the system is first turned on, it sets the signals produced by each sensor or segment as the base-level. The base-levels may be determined for groups of sensors or sensor sections or may be determined on a per sensor basis. Because base-levels of sensors may change during gameplay, the system may continue to adjust the base-level during the game. It will do this by periodically reading the value of the signal from the sensor, and then slowly increasing the base-level value if the signal is larger than the base-level and slowly decreasing the base-level value if the signal is lower than the base-level. Because the adjustment is very gradual, the base-level value will only change over a period of several minutes. Thus, it is not affected appreciably by transient events such as ball bounces or players running on the sensor. Furthermore, the rate at which the base-level decreases can be made larger than the rate at which it increases so that if a player stands on a sensor long enough to increase the base level, it will decrease quickly once they move away. In addition to calculating the base level, the system can also calculate the noise in the signal in a similar gradual way in order to automatically set a threshold above the noise level that indicates that a sensor is activated. It may be provided that a set of sensor signals is further processed only when it contains a value that is higher than a base level and a threshold value, the set comprising one or more sensor signals.

[0139] If the base-level signal is too high (above a pre-set threshold), this may indicate a short in the wiring or significant physical damage to the court, such as a crack or large bubble in the paint. If the signal is too low (below a pre-set threshold), it may indicate a break in the wiring (a resistor 38 with a large resistance value of several MΩ can be placed at each sensor pad to ensure a low signal as long as the wiring is okay, as described in more detail below). If the noise level in the signal is high, it may indicate strong electrical interference, a poor connection, or other problem. If an error is detected in one section of the sensor 22, the health monitoring system 188 can notify the player/official of the error in that section and continue working in the rest. The health monitoring system 188 is described in more detail below.

[0140] Although the system is designed to have an extremely low failure rate, this may still be extremely useful in the unlikely case that a sensor 22 does malfunction. For instance, if, for any reason, a part of the doubles sideline stops working, the players may continue to play a singles game on the court. If a certain section of the court that is in play stops working, an extra line judge may be called in to monitor that part of the line.

[0141] As noted above, in order to detect possible sensor failure, a sensor health monitoring system 188 may be employed. This system 188 compares, via an internal comparator, signal values or ranges with known values or ranges for a properly operating sensor and/or known values or ranges for an improperly operating sensor (these values possibly being stored in a table), and, based on the result of the comparison calculation, can send a signal to an error notification system 190 that can then further relay such error information to, e.g., an indicator such as an error light 122 or to another device via the network 108.

[0142] One mechanism that may be employed for the detection of sensor problems is illustrated in FIGS. 8A, B in which a leakage resistor 38 is employed. The resistor 38 should be of a sufficiently high resistance value, e.g., 3MΩ, that any current drain through it during normal operation is minimal and thus does not represent a significant power loss for the sensor. However, the minimal current through such a resistor 38 should be adequate so that the absence of this current indicates a connection problem with the sensor. The health monitoring circuitry 188 would detect the presence or absence of the current through the leakage resistor 38 in its comparison. The circuitry 188 could further detect the presence of a short circuit or other types of abnormal signal levels, such as signal levels that persistently remain above certain threshold levels or that indicate other abnormal signals. This circuitry 188 could also be set in a programmed test mode in which the sensor sections are activated for testing and signal an error if a signal indicating an event such as a ball bounce, footstep, or racquet hit is not received within some predetermined period of time.

[0143] In the foreground, the system will do the following: first, a game state monitor 180 will determine which set of lines it should monitor based on whether a singles or doubles game is being played based on switch 124 or other parameter settings, and based on which players are currently serving and into which box they are standing. The game state monitor communicates the current game state 196 with the event integrator 186. As described above, this information could be indicated to the control box over the network by a referee or scorekeeper, or it could be determined automatically based on footstep events that are generated when a player is about to serve from the baseline. The event integrator 186 provides information 198 related to IN/OUT calls and the detection of serve conditions to the game state monitor 180, and can be used to ignore certain IN/OUT determinations from sensor sections that are inconsistent or improbable with a known state of play. The event integrator can be used to discriminate between two recorded ball bounces from different areas of the court.

[0144] For each subsection of the court that is in play, the game state monitor 180 runs a separate instance of an algorithm hereafter referred to as classifier 182 which detects an event and classifies it into contact by a ball, contact by a foot, contact by a tennis racquet or some other type of event. In the case of contact by a ball, the classifier then determines whether the ball was IN or OUT. Each classifier then feeds all of its events into an event integrator algorithm 186 which produces a final decision and an indication that uses sound via the speaker 106, a visual indication 104 and/or a message over the network 108. The game state monitor 180 may also send
signals 194 to the classifiers 182 that indicate whether they should be enabled or disabled, based on the game state. The event integrator 186 could further incorporate the serve condition detection system. The classifier may further comprise a peak detector that detects peaks caused by ball bounces on a same section as where a foot stands. The classifier may be utilized by a score-keeping mechanism that utilizes the classifier to ignore footsteps and to only count two bounces on a same area or tapping with a tennis racket as a score-modifying event. A control mechanism may be combined with a sound-producing mechanism where the control mechanism causes the sound-producing mechanism to produce a first type of sound when a ball lands outside of a service area, and a second type of sound auditorially distinct from the first type of sound when a ball lands outside of a play area.

[0145] Classification

[0146] The first part of the algorithm is the detection of an event and its classification into a ball bounce, footstep or tennis racket hit event. As discussed above, according to an embodiment of the invention, one instance of this algorithm 182 is run for each subsection of the court lines. If sensors 22 having IN and OUT portions are used, the combined signals of the sensor portions should be utilized by the instance to make the determination. According to this implementation, if a player is standing or running over one subsection of the sensor 22, a separate classifier instance 182 will still be able to detect a ball bounce in another subsection.

[0147] The classification of ball bounce, footstep and tennis racket hit is performed on the signals produced by the sensor 22. If a signal is present from an IN portion of a sensor (when the sensor is divided into IN and OUT portions), then a signal classified as a ball bounce in the OUT portion will be deemed to be IN bounds, since any part of the ball touching the line should be considered IN, according to the rules. As noted previously, however, it is possible to utilize sensors 22 only on the OUT side of the boundary line, in which case a somewhat less accurate decision will be made solely on the basis of the OUT sensor signal.

[0148] In order to use processors efficiently, the system may run the classifier only for those sections in which the signal has recently increased above the sum of the base level and noise level that has been determined for that section. Furthermore, signal combinations when the processors are networked, and the work is distributed between processors, the processors may be programmed to only send data over the network when one of the sensors that they are connected to has a value that is above the sum of the base level and noise level. Because only a few sensors on a court will be activated at any one time, this approach drastically reduces the amount of processing power, and/or network bandwidth necessary in the system.

[0149] Any number of schemes may be utilized in performing the classification either individually or in any combination. These include:

[0150] signal duration of activation at a given signal threshold level (or multiple threshold levels);

[0151] signal amplitude;

[0152] determination of number of peaks;

[0153] signal frequency analysis (e.g., using Fast Fourier Transforms or similar analytical techniques based on spectral characteristics); and

[0154] signal correlation or matching.

[0155] When viewed on an oscilloscope, the sensor 22 output signals of all of these events typically have different characteristic shapes. As illustrated by the graphs in FIGS. 10A-D a ball bounce looks like a single, smooth, rounded peak, and typically lasts between 4 and 5 milliseconds and always seems to be within a range of 3.5 and 5.5 milliseconds no matter what speed or spin the ball has, provided the measurement threshold has been set at an appropriate level. The appropriate measurement threshold(s) can be manually set based on any form of calibration scheme, or may be defined in some relationship to other signals in the system, which could include the base level signal and the noise level

[0156] FIGS. 10A, B, and C illustrate respectively a light, medium and hard ball impact. FIG. 10D illustrates the asymmetry present when the ball impact occurs at a sharp angle.

[0157] The height of the peak increases with the vertical speed of the ball. Because a ball will always fall from at least net height, which is approximately 42 inches, there is a certain minimum vertical speed with which it will hit the sensor, and thus, it will produce a peak with a minimum height, which can be determined experimentally. Also, the maximum practical velocity of a tennis ball when it hits a court can range between 100 and 150 mph, and therefore a peak of maximum height can be determined experimentally as well. The actual amplitudes obtained for signals will be based on a calibration, and these may be adjusted based on the type of sensor used, variations in drive circuitry, court conditions, etc. It is also possible to schedule calibrations on a periodic basis to ensure the integrity of the system. Such a calibration could utilize firing tennis balls at a known speed on the sensors and having persons of varying weights stand or jump on the sensors.

[0158] As illustrated in FIGS. 10E and 10F a footstep produces a signal that is much longer than that of a ball bounce. These are typically greater than 50 ms in duration, and can be much longer. When a player kicks the line, the signal starts with a sharp peak and then settles to a lower value which lasts until the foot is released. When a player jumps or runs over a line, the signal may also have a peak at the beginning followed by a large hump. We have not observed any way in which a player can produce a peak of the same duration and height as a tennis ball with their foot, given the very different nature of the forces and inertia involved. In FIGS. 10E and 10F, the duration of the footstep is considerably longer than the duration of the ball bounce when the threshold is set at the level illustrated in FIG. 10A-D.

[0159] FIGS. 10G-1 illustrates curves associated with a racquet impact. Due to their rigid construction, the hit of a tennis racquet usually produces one or more peaks which are often jagged, or shorter in duration than that of a tennis ball bounce. On extremely rare occasions, a tennis racquet may produce a single peak which may look like the peak produced by a tennis ball.

[0160] The scrape of a tennis racquet across the court, as illustrated by the graph shown in FIG. 10I, typically produces peaks that are much smaller in height than the smallest peaks produced by a ball, and would therefore not generally be confused with a ball bounce. The issue of false activation of the sensors by the tennis racquet is addressed below.

[0161] FIG. 10I illustrates a resultant curve when a simultaneous ball bounce and footstep occur. As discussed in more detail below, dual thresholds (see FIGS. 10H and 10J) may be utilized for further discrimination.

[0162] Because a ball that is traveling at an angle may skid across the boundary between two sensors as it bounces, it is possible that each sensor in isolation will register a peak that is shorter or smaller than that of a typical ball bounce. For this
reason, the signals from adjacent sensors may be combined in software to create larger “virtual” sensor areas, which will register the full ball bounce. Doing this is especially important at the boundary between IN sensor portions and OUT sensor portions, when these are used, since a ball that bounces on the boundary should be detected reliably and scored as being IN. As explained before, if conductance is used as the signal to the algorithms, then the conductances of the two sensor areas can simply be added to determine the combined signal on the “virtual” sensor area. However, if raw voltage signals are added ignorantly, then the characteristic shape of the summed signal may not look like that of a ball, and may instead have multiple peaks.

[0163] Each of the signals, including the ball bounce has a “tail” region. This is due to hysteresis—in other words, FSR sensors turn on very quickly when activated, but turn off more slowly. This can also be due to vibration of the court surface near the point of impact. Also, the signals may have a small level of electrical noise due to interference from outside devices. To get an accurate timing of the peak, the width is measured at a threshold level which is a pre-determined margin above the base-level signal. This margin should be high enough to avoid detecting signals caused by hysteresis, vibration and electrical noise. However, the threshold should not be too high, since a high threshold may produce inaccurate timings of ball bounces and racquet hits.

[0164] To distinguish a tennis ball bounce from other events, the classification algorithm can measure the width of a peak in milliseconds and its height. If the peak is approximately 3.5 to 5.5 ms in width, and above a threshold height, determined by the lightest bounce a ball can take from the height of the net, it should be classified as a ball. If it is longer than approximately 5.5 ms in duration, it should be classified as a footstep. If it is shorter than approximately 3.5 ms in duration or smaller than the threshold height, it should be classified as a racquet hit. As a further criteria, the classifier may check that the signal has only a single peak. In other words, it should increase approximately monotonically from the start until its maximum value and then decreases approximately monotonically until its end. Because there might be some noise in the signal, only peaks bigger in size than the noise should be detected. More sophisticated algorithms which match the profiles of the peaks to pre-recorded profiles may also be employed to better distinguish between ball bounces and racquet hits, which in rare circumstances may have heights and durations similar to those produced by ball bounces, but are distinguishable due to their jagged shape.

[0165] As discussed above, it is also possible in a further embodiment of the invention to utilize multiple threshold levels as illustrated in FIGS. 10H and 10J. The use of multiple threshold levels permits additional discrimination for the various sensor signals based on the characteristic shapes of the curves. In performing such an analysis, a low threshold (a small percentage larger than the base-level signal) may be used to find the start time at which the sensor was activated and the end time at which it was deactivated. This entire period is treated as a single event. Then, the width of peaks above a higher threshold within that period are analyzed. This second threshold may be set through experimentation just high enough to reliably detect a ball dropping from net height. If more than one peak is found, or if there is a wide peak greater than about 5.5 ms, then this may be indicative of a footstep event. If the peak is shorter than, e.g., about 3.5 ms, the event may be classified as a racquet hit. Any number of thresholds may be utilized in order to better discriminate between various impact events that may occur with respect to the sensors.

[0166] As noted above, the frequency characteristics can be utilized to discriminate between and classify events. These may be calculated by means such as a Fast Fourier Transform (FFT) or a wavelet transform. The racquet hits generally comprise a number of high-frequency components not found in either the footstep or ball bounce. The ball bounce will have a large spectral spike at around 200 Hz (54 ms) and a general absence of the frequency components above and below this. The footstep will, as a rule, have large lower frequency components.

[0167] Furthermore, some form of a correlator may be used to compare the stored waveforms with those measured. In this arrangement, a digitized sampled sensor signal is compared with various stored characteristic curves according to some sampled interval, and a correlation coefficient is established for the sampled sensor signal for each stored characteristic. The stored characteristic having the highest correlation coefficient is deemed to indicate the type of event that occurred.

[0168] In the preferred embodiment of the classifier, a voltage divider configuration as shown in FIG. 8A is used, and the signal, is fed to an A/D converter which samples the signal at a rate of 4000 hertz. The signal is then converted to a conductance value using the mathematical calculation described previously. The conductance value from the last 20 ms of signal are stored in a circular buffer in memory. Although a plot of the conductance might look similar to the plot of the raw output of the sensor, it is scaled differently, and produces more accurate results. Each time a new conductance value becomes available, the oldest one in the circular buffer is removed and the new value is inserted. Then, the classification algorithm analyzes the 20 ms of signal stored in the buffer to determine if a ball bounce occurred there. The classification algorithm first checks that the signal was below the base-level adjusted threshold for the first two milliseconds, above the threshold for the next 3.5 to 5.5 milliseconds, and below the threshold for the remaining time. It then checks that the maximum value of the signal was above the minimum peak value for a ball bounce. Finally, it checks that during those 3.5 to 5.5 ms, the signal had only one peak by verifying that, ignoring small noise, the signal increases for approximately the first half of that period and decreases afterwards. If all of these conditions are satisfied, then the signal is classified as a ball bounce. For detecting footsteps, the amount of time that the signal spends above the threshold is measured. If the signal is above the threshold for over a sufficient length of time, such as 50 ms, the signal is classified as a footstep. If the signal is classified neither as a ball bounce or a footstep, it is classified as a racquet hit.

[0169] Because the timings, amplitudes of the signals, characteristic shapes, peak characteristics and spectral characteristics may change slightly depending on the type of ball used, the speed at which they impact, the type of court surface, environmental factors, and changes in the way tennis is played, a facility should be included in the system to allow calibration and fine-tuning of these parameters and stored characteristics during installation and maintenance. Furthermore, it should be possible to modify any and all parts of the algorithms presented and stored characteristics via a software update.

[0170] Once an event is classified as a ball bounce, the system must then determine if the ball was IN or OUT. In
In tennis, a ball is considered IN if it touches the white of the boundary line 14, even slightly. Thus, if the ball bounce was detected on an IN section, the ball counts as definitely IN. However, if the ball bounce occurs on an OUT section which is adjacent to an IN section, to make the determination, the signal produced by adjacent IN section of the segment is analyzed within a short (around 2 ms) window of the event. If at any time within that window, the signal increased past a preset threshold, the ball is considered IN. That threshold should be similar to the lower threshold used for detection of ball bounces, but can be finely adjusted in order to improve the IN/OUT accuracy of the system.

The algorithms presented above, if properly implemented and adjusted, work with extremely high accuracy for discriminating between ball bounces, footsteps, and tennis racquet hits. A foot step is never confused with the bounce of a ball. However, we found that in extremely rare circumstances, a tennis racquet bouncing off the court can produce a signal that is indistinguishable from a ball bounce. In particular we saw this happen when the racquet was dropped, headfirst onto the sensor, and allowed to bounce. Depending on the particular implementation of the classifier, there may be other situations in which it could, in rare circumstances, detect a tennis racquet hitting or scraping the court as a ball bounce. Such situations and a few others are resolved by the integrator 186, which is presented below.

Previously it was noted that there are three ways to reduce the number of IN sections 24 and OUT sections 26 needed by the system, and/or the number of signals produced by the sensor. The first is to analyze a waveform produced by each sensor 22 to find the approximately 5 ms long peaks created by ball bounces even while they are being “masked” by a footstep. However, as noted above, peaks at the beginning of a footstep (approximately the first 25 ms) may look like a ball bounce and would have to be ignored. Peaks created by a ball bounce can be detected by looking for a large increase in the signal (above a pre-determined threshold) within 2.5 ms, followed by a similarly sized decrease in the signal in the next 2.5 ms. If such a peak is detected the software should then check that the signal within a short period before and after the peak is smooth as seen in FIG. 101. If it is not, it is possible that the foot was sliding over the sensor during the peak, and that the peak was not produced by a ball bounce, and should thus be ignored. This works best when using the conductance of the sensor as the input signal to the classifier, since when looking at the conductance, the signal will be exactly the same as if we had measured the signal from the ball bounce and from the foot step separately and added them together. This method allows one to decrease the number of subsections on the sensor and increase the size of each subsection, while still being able to detect a ball bounce and footstep that occur on the same subsection. Additional processing can be provided to further refine the criteria for distinction.

The second way to accomplish the goals described above is to chain two or more sensor subsections with small resistors Rg (FIG. 11), and to compare the output from the subsections at the two ends. By computing 11*Input/(11+I2), the average position of the force applied to the sensors 22 can be calculated. With such a setup, a ball bounce would cause a peak in the total force signal, plus a sudden shift in the average position of the force that would last as long as the ball bounce (typically around 5 ms). FIG. 13 illustrates the plot of 11/(11+I2) that could potentially be used to draw out the ball bounce while eliminating the footstep.

A third way to reduce the number of signals, described previously, is to connect the sensor areas so that they may be scanned in groups. Such configurations involve having the sensor areas on an X/Y grid or having the sensor areas share separate common traces. Care should be taken in the engineering of such approaches to avoid problems associated with current leaking to un-activated common trace.

Integrator

Returning to FIG. 9, all of the events 192 from each of the independent classifiers 182 are sent to the integrator 186, along with the time of the event, and the location on the court where it occurred. The integrator 186 listens to all of the events and sorts out what happened based on those events. The integrator 186 may be configured to only receive events from subsections of the court that are currently being monitored, since those are the sections that were enabled by the game state monitor.

In the case that a single BALL IN or BALL OUT event 192 is passed from one of the classifiers 186, the job of the integrator 186 is very simple: it simply outputs that event to all of the enabled notification devices (sound 106, visual 104, or network 108). However, when multiple BALL IN/BALL OUT events 192 occur within a very short time, the integrator 186 has to decide what notification to produce. If two BALL IN/BALL OUT events 192 happen simultaneously, or within a small (e.g., 2 ms) window of each other on adjacent subsections, this typically indicates that a ball landed on the boundary of two subsections. In this case, if either of the events 192 were BALL IN, BALL IN should be reported. Otherwise, BALL OUT should be reported.

If the events occur simultaneously on non-adjacent subsections on the same side of the court 10, the multiple events can only have happened because a ball bounce occurred at the same time as a tennis racquet hit which was mistakenly classified by a classifier as a ball bounce. In such a situation, the event that occurred on the subsection closer to the front of the net will be used to produce a notification. This is because balls typically bounce in front of players. In the case that both of these events happen on the baseline, the event that happens closer to the outside of the baseline will be used to produce a notification.

If two or more BALL IN/BALL OUT events occur on one side of the court within a short time of each other (shorter than the time it takes for a ball to be returned to the same side of the court) the events could be produced by a ball that takes multiple bounces (such as during a drop shot), or one of the events could be produced by a tennis racquet hit (which was mistakenly classified by a classifier as a ball bounce). In such a case, the event that was the first to happen will produce the notification, and the second event will be ignored. This works because by carefully analyzing tennis play, it can observed that when a tennis racquet hits the ground, it usually occurs after the ball has already bounced. Furthermore, in the event that the racquet hit and ball bounce happen almost simultaneously in the same or adjacent subsections of the sensor, the result should still be correct. The reason is that if the ball hits the IN section and the racquet hits the OUT section, the ball will be counted as IN, which is correct. In case the ball hits the OUT section, the player will usually also hit the OUT section as they are reaching for it. The only situation in which a wrong call will be made is one in which the player hits an IN section while the ball hits an OUT section. This is very unlikely since players typically swing their racquets toward the ball from the OUT side of the court to the IN side.
produce the correct notification in almost any possible situation that may occur. However, these algorithms could be modified, based on empirical data collected. Furthermore, the system may allow players and or referees to review calls, and to see which events actually happened around the time of the call. Additionally, players and or referees may have the option to disable the automatic integration of events, and receive notification about all the events as they detected.

Accuracy

[0181] The inventive system is designed for high accuracy and consistency. Accuracy is achieved by a combination of different factors. First, the SR based sensors 22 can be made much more sensitive than membrane switches without having false activations and can detect even a light force on the surface of the court. Unlike other sensors, such as piezoelectric vibration sensors, they will not be activated by vibrations that travel through the concrete. Furthermore, analog signals produced by the FSR based sensors can be analyzed using the methods described to distinguish between ball bounces, foot steps and tennis racquet hits much more accurately than could be done with previous approaches, virtually eliminating bad calls due to misclassification of events.

[0182] Second, accuracy comes from the way a ball 80 deforms when it bounces on a court. Experiments and computer simulations have shown that the bottom of the ball will actually inflect upwards during a bounce, such that the majority of the force will be exerted by the edge of the ball. Thus, if the edge of the ball touches a boundary line, the force will be sufficient to be detected by the IN sensor 24 under that line. These sensors 22 are consistent because they are equally sensitive on both sides of the boundary line 14 along their entire length on the court 10. High-speed camera experiments indicated that these sensors 22 had an accuracy better than 4 mm when balls were bounced from above and shot at low angles.

[0183] The present system presents a viable embedded system that succeeds where others have failed. Although this system has been described in terms of tennis court embodiment/implementations, there is nothing that inherently limits the principles of the invention to this application. This system, or parts thereof, may be applied for various other games including volleyball, badminton, etc., and can even be used for non-sports-related applications such as security, robotics and factory automation. Any part of the settings utilized in the system are configurable and do not have to be hard-coded. This system can also be used in conjunction with a camera based system or other ball tracking technology (which may employ sound, radar, laser, or other means) to improve the accuracy of these systems which do not “feel” the impact point, or to provide two independent opinions.

[0184] The term “ball” as used herein can be understood to include any form of game projectile capable of impacting a ground-based sensor, with the appropriate predetermined signal signatures being determined beforehand.

[0185] For the purposes of promoting an understanding of the principles of the invention, reference has been made to the preferred embodiments illustrated in the drawings, and specific language has been used to describe these embodiments. However, no limitation of the scope of the invention is intended by this specific language, and the invention should be construed to encompass all embodiments that would normally occur to one of ordinary skill in the art.

[0186] The present invention may be described in terms of functional block components and various processing steps. Such functional blocks may be realized by any number of hardware and/or software components configured to perform the specified functions. For example, the present invention may employ various integrated circuit components, e.g., memory elements, processing elements, logic elements, look-up tables, and the like, which may carry out a variety of functions under the control of one or more microprocessors or other control devices. Similarly, where the elements of the present invention are implemented using software programming or software elements the invention may be implemented with any programming or scripting language such as C, C++, Java, assembler, or the like, with the various algorithms being implemented with any combination of data structures, objects, processes, routines or other programming elements. Furthermore, the present invention could employ any number of conventional techniques for electronics configuration, signal processing and/or control, data processing and the like.

REFERENCE CHARACTERS

[0188] 10 tennis court
[0189] 12 Net
[0190] 14 boundary lines
[0191] 14.1 service line
[0192] 14.2 Baseline
[0193] 14.3 Baseline
[0194] 22 Sensor
[0195] 24 IN sensing area
[0196] 26 OUT sensing area
[0197] 26.1 left-side OUT sensing area
[0198] 26.2 common OUT sensing area
[0199] 26.3 right-side out sensing area
[0200] 28 glue area (non sensing)
[0201] 30 interdigitated fingers
[0202] 32 protective border
[0203] 33 common trace
[0204] 34 in connector
[0205] 35 out connector
[0206] 37 IN section interdigitated traces
[0207] 38 leakage resistor
[0208] 39 OUT section interdigitated traces
[0209] 40 ribbon cable
[0210] 40' flex cables
[0211] 40" wire (power, communication bus)
[0212] 44 FSR ink for IN side
[0213] 46 FSR ink for OUT side
[0214] 50 Glue
[0215] 51 glue finger pattern
[0216] 52 squares in glue pattern
1. A system for determining whether a ball bounce occurs on an inside of a boundary line or an outside of the boundary line, comprising:
   a) a sensor or sensor sections comprising an output that provides either an analog signal or a multilevel digital signal related to a force present on the sensor or sensor section;
   b) a signal analysis unit comprising:
      b1) an input connected to the sensor signal output;
      b2) circuitry or a memory containing predetermined information related to a footstep characteristic curve and a ball bounce characteristic curve, the characteristic curve information comprising at least one of duration of activation information, amplitude information, peak information, frequency information, or curve shape information;
   b3) a classifier configured to classify a signal received from the sensor as at least one of: 1) a ball bounce by utilizing the ball bounce characteristic curve information, and 2) a footstep by utilizing the footstep characteristic curve information;
   b4) the classifier comprising an event output at which a signal is output, the event output signal comprising at least an OUT event indicating a ball bounce classified outside of the boundary line or an IN event indicating a ball bounce classified inside of the boundary line.
2-10. (canceled)
11. The system as claimed in claim 1, wherein the calculated measurement threshold signal level is calculated based on a relationship with at least one of a base-level signal and noise-level signal.
12-19. (canceled)
20. A system for determining whether a ball bounce occurs on an inside of a boundary line or an outside of the boundary line, comprising:
   a) a sensor or sensor sections comprising an output that provides either an analog signal or a multilevel digital signal related to a force present on the sensor or sensor section;
   b) a health monitoring system comprising:
      b1) an input for monitoring a signal related to each sensor or sensor section;
      b2) at least one of circuitry and an algorithm for distinguishing a properly operating sensor or sensor section from one that is improperly operating indicating an error; and
   b3) an output for providing an indication of a sensor, sensor section, or system error; and
   c) an error notification system comprising an input connected to the output of the health monitoring system and an output connected to a user notification device.
21. The system as claimed in claim 20, further comprising:
   a) a base-level signal calculator, the base-level signal calculator comprising:
      a) an input at which is received a signal from one or more of the sensors;
      b) a calculator configured to establish a base-level sensor signal when the sensor is not under pressure; and
      c) a comparator configured to determine if the base-level sensor signal is above or below a predetermined threshold; and
   an output connected to the input of the health monitoring system at which information related to the base-level sensor signal is provided;
   wherein at least one of the base-level and noise-level signal calculator further comprises:
   a) a timer configured to periodically trigger an adjustment of the at least one of base-level and noise-level signal during play; and
   a memory for holding signal values between periodic triggering of the timer.
22. A system for determining whether a ball bounce occurs on an inside of a boundary line or an outside of the boundary line, comprising:
   a) a sensor or sensor sections comprising an output that provides either an analog signal or a multilevel digital signal related to a force present on the sensor or sensor section;
signal related to a force present on the sensor or sensor section;
b) a serve condition detection system, comprising:
   b1) an input configured to receive an indication of a service and an indication of a service court for which
   the service is to occur; and
   b2) an activation mechanism for activating a sensor group associated with service lines related to the service
   court and deactivating sensor groups associated with service lines unrelated to the service court.
23. The system as claimed in claim 22, wherein:
sensors located under or proximate the baselines provide output to the input of the serve condition detection
system; and
the detection system being configured to determine which service court sensor group to activate based on a criteria
selected from the group consisting of: a) a predetermined prolonged signal from the sensors behind one of
the baselines indicative of a person standing behind the baseline; and
b) detected repetitive ball bounces
24. The system as claimed in claim 22, further comprising
one or more wireless or wired devices configured to provide a signal indicative of a service area to the input of the serve
condition detection system.
25. The system as claimed in claim 22, further comprising
a switch for activating and deactivating the serve condition detection system.
26. The system as claimed in claim 22, further comprising:
a mechanism that deactivates a serve mode when a person
walks away from the sensor or sensor section or after a
predetermined amount of time.
27. The system as claimed in claim 22, further comprising a
mechanism for keeping service areas of either a singles or
doubles configuration active during a serve.
28. The system as claimed in claim 1, wherein the classifier
further comprises a peak detector that detects peaks caused by
ball bounces on a same section as where a foot stands.
29. A method for installing a sensor in a surface, comprising:
   providing top and bottom layers of the sensor as separate
   components at a site of in-ground installation;
   assembling the top and bottom layers with a laminate at
   the site;
   adding waterproofing to the assembled top and bottom
   layers;
   flattening the waterproofed top and bottom layers;
   and installing the sensor comprising the flattened and water-
   proofed top and bottom layers within or on top of a
   ground surface.
30. The method according to claim 29, where installing
comprises:
   affixing the sensor to the ground surface with epoxy or
   other glue; and
   applying a resurfacing material with texturing on top of the
   sensor.
31. The method according to claim 30, wherein the textur-
ing comprises silica sand.
32. The method according to claim 29, further comprising:
   attaching a sensor signal output line to a computer via an
   interface;
   initiating a signal at the sensor signal output line;
   obtaining feedback from the computer based on the initi-
   ated signal; and
   at least one of adjusting a position of the sensor based on
   the computer feedback to effect an alignment of the
   sensor to a boundary line, and adjusting a position of a
   boundary line based on computer feedback indicating a
   sensor boundary position.
33. The system as claimed in claim 1, wherein the sensor or
sensor sections are offset from the boundary line by a pre-
determined distance.
34. The system as claimed in claim 33, wherein the pre-
determined distance is one-quarter inch.
35. The system as claimed in claim 1, further comprising:
a score-keeping mechanism that utilizes the classifier to
ignore footsteps and to only count two or more bounces
on a same area or taps with a racket as a score-modi-
ifying event.
36. The system as claimed in claim 1, further comprising:
a sound-producing mechanism; and
a control mechanism that produces a first type of sound
with the sound-producing mechanism when a ball lands
outside of a service area, and produces a second type of
sound auditorily distinct from the first type of sound
when a ball lands outside of a play area.
37. The system as claimed in claim 1, further comprising:
an output display comprising six boxes that represent each
singles or doubles area and each service box.
38. The system as claimed in claim 1, further comprising:
a calculator that converts a voltage measured on an A/D
converter associated with the sensor to a sensor conduc-
tance and provides a compensation for a wiring and
interconnect resistance between the sensor and associ-
ated electronics.
39. The system as claimed in claim 38, wherein the calcul-
or operates on a formula as follows:
\[ C = \frac{\text{Vad}}{(\text{Vsup} \cdot \text{Rd} - \text{Vad} \cdot (\text{Rd} + \text{RI}))} \]
wherein
C is the calculated conductance;
Vad is a measured voltage on the A/D converter;
Vsup is a power supply voltage to the sensor;
Rd is a resistance of a sensor pull-down resistor; and
RI is a resistance of the wiring and interconnects between the
electronics and the sensor.
40. The system as claimed in claim 1, wherein:
the sensor is comprised of an FSR ink selected such that a
resistance of the FSR ink and a sensor pull-down resistor
decrease impedance, thereby increasing current, and
produces a measured sensor voltage versus impact force
curve that is generally linear.
41. The system as claimed in claim 40, wherein a resistance
of the sensor pull-down resistor is lower than a minimum FSR
resistance expected during normal operation, and the mini-
mum FSR resistance expected during normal operation is
larger than a trace resistance.
42. The system as claimed in claim 1, wherein a set of
sensor signals is further processed only when it contains a
value that is higher than a base level and a threshold value, the
set comprising one or more sensor signals.