Piezoelectric sensors for taxiway airport traffic control system

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Piezoelectric Sensors for Taxiway Airport Traffic Control System.

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***Abstract*—This paper reviews the operation principles of piezoelectric sensors for airport surface movement control. Using an array of sensors, it enables the detection of moving objects as well as their classification according to their tire configurations, velocity, and direction of movement. Preliminary experimental results using thin film piezoelectric sensors confirm the predicted operation characteristics and show the applicability of piezoelectric sensors for monitoring airport surface movement. A preliminary version using piezoresistive thin film sensors has been presented and published [1]. This paper also provides an approach to eliminate the insensitive zone and reveals more insights on feasible design.**

***Index Terms*—Airport surface movement, piezoelectric sensors, piezoresistive thin film sensors, taxiway.**

I. Introduction

ACCORDING to the Federal Aviation Administration (FAA) more than one thousand incursion occur in the US airports each year [2]. An incursion is any unauthorized presence on an airport taxiway. In order to increase the safety of airport taxiways and the awareness of air traffic controllers monitoring the taxiways, the primary objective is to determine an aircraft's velocity, model, number of axles, and direction through the use of piezoelectric sensors and microcontrollers. The acquired information needs to be encrypted and wirelessly transmitted to a host computer.

This paper reviews the design challenge of taxiway safety and taxiway incursions by outlining the operation principles with the piezoelectric sensors for airport surface movement control. Recently, piezoelectric sensors have gained popularity for axle counting on highways [3-5]**;** same technology can be used to monitor aircraft on the ground. This type of sensor enables reduced power consumption to a level acceptable by sustainable sensor networks, but more importantly they enable the system to perform moving object detection and automatic classification of objects according to their tire arrangements, speed, and direction of movement. The main engineering objective is to increase the situational awareness of ground traffic on the airfield, particularly when it is flog.

With the popularity in flying, there is a big demand for new and more safety requirements over the taxiway airport traffic control system [6-8]. The Federal Aviation Administration (FAA) has been emphasizing the awareness of ground operation as a major challenge [9-10]. Currently, the Airport Surface Detection Equipment, Model X (ASDE-X) system [11], which is based on surface movement radar and transponder multilateration sensors, is installed in 32 major airports in the United States, but its performance has been degraded by factors like snow or rain. A system to supplement ASDE-X during normal operation hours, but especially during not-so-nice weather, like snowy or rainy weather, is greatly needed. Of course, when the weather is bad, all the flights will be cancelled.

The scope of this paper is obviously limited by our test model. All of the obtained data and the conclusions based on the results are drawn from tests performed on system prototype. Another limitation on this research is the hardware that is used to implement the prototype system. The Force Sensitive Resistor (FSR) was used on the prototype system instead of the piezoelectric sensor. Due to the large size of taxiways, our system had to be scaled down to a size that would allow for realistic laboratory testing. Since all the testing was done in the laboratory, our system would not susceptible to realistic weather like the actual system implementation would be. Another limitation of this research is that our prototype will not be subjected to the same mechanical stresses as the actual system implementation. Piezoresistive thin film is a light weight version of piezoelectric sensor and has similar characteristics. Preliminary experimental results are compared with the predicted operation characteristics of piezoelectric sensor.

II. Current Traffic Management System for Airport Surface [11]

The FAA has identified 35 major airports in the United States as candidates for ASDE-X systems. Now, 32 airports have deployed with ASDE-X systems. The features of this system include a combination of surface movement radar and transponder multilateration sensors. More reliable data can be obtained from the integration of radar and different types of sensors. Complex and advanced algorithms also enable conflict detection, alerting algorithm, and safety logic in ASDE-X systems. However, ASDE-X system may not be cost effective for some

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airports, and there are still about 400 airports in the US dependent on the Air Traffic Controller (ATC).

A. Materials

Piezoelectric sensors [12-15] come in a variety of shapes and sizes, but for axle counting, they generally come in long narrow strips as shown in Figs. 1 & 2. These sensors are generally used in permanent installations, where they are installed just below the road surface. These sensors have the ability to measure the pressure signal, so they find use in weigh-in-motion applications. A voltage signal is generated when the piezoelectric sensor is pressed. This type of signal can be used to calculate speed of the vehicle as the axle rolls over the sensor array. Fig. 3 represents the first sensor that the front and rear axle for vehicle counting. Fig. 4 represents the second sensor which is 11.5 inches apart from the first sensor. As shown in Figs. 3 & 4, the time lapse between these two figures is 9.6 msec. The speed of the vehicle is the distance divided by the time. The vehicle speed = 11.5 in. / 9.6 ms = 68.06 mph. The spikes in Figs. 3 & 4 represent the triggering pulse from the front and rear axle. As shown in Figs. 3 & 4, the time lapse between the two spikes is 100.8 ms. The wheelbase = 100.8 ms×68.06 mph = 120.75 in, and the actual wheelbase of the Ford Windstar used in the experiment is 120.7 in.

Fig. 1: Piezoelectric sensor for vehicle counting [15].

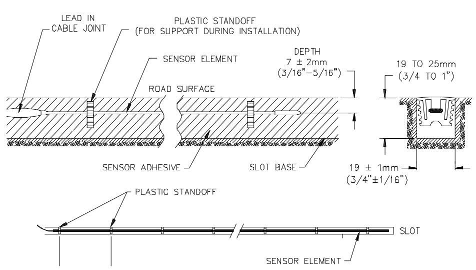

Fig. 2: Piezoelectric sensor for axle counting [15].

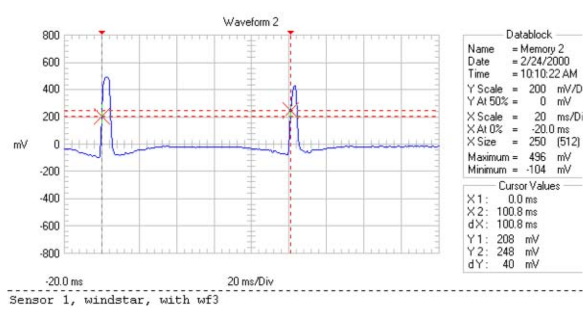

Fig. 3: Axle counting: Output of the first piezoelectric sensor [15].

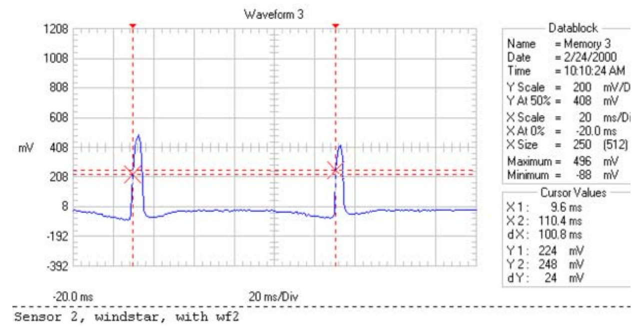

Fig. 4: Axle counting: Output of the second piezoelectric sensor [15].

“The width of taxiways is from 100 to 400 feet. The maximum length of piezoelectric sensor is between 15 to 20 feet. Arrays of sensors are used to span wide taxiways to provide complete coverage. If the sensors are arranged in a straight line, as shown in Fig. 5, an insensitive zone is left between each sensor in the array. Each sensor has two wires to connect with the sampling circuit; the connection of the adjacent sensors is as shown in Figs. 5 & 6. The insensitive zone is approximately five inches away from the sensor connector, and two inches from the tip of adjacent sensor, as shown in Fig. 7. An insensitive zone (6~8 in.) is smaller than the typical width of the landing gear of a large aircraft, but a small single engine aircraft can roll over the insensitive zone of the sensor without triggering the sensor. If two rows of sensor arrays are installed as shown in Figs. 8 or 9, the insensitive zone can be eliminated, but this allows the possibility of triggering two sensors (one sensor in each row, e.g. sensors 1 & 2 or sensors 1 & 3 as in Fig. 8) within a short interval like a fraction of a second. This issue can be easily corrected by programming the microcontroller to ignore the double spikes. The effective length of 172 inches out of 180 inches or 15 feet of piezoelectric sensor is determined from Fig. 8, and the number of sensors listed in Table 1 is also determined by using the effective length (172 inches or 14.33 feet) for each sensor. The sensors should be installed in slots cut into the taxiway as shown in Fig. 2. Additional slots will be necessary if the number of sensors increase. By setting the threshold at 200 mV, the microcontroller can be programmed to monitor the ground speed and direction of the plane.” [1]

Table 1: Number of sensors for various width of taxiway [1]

Taxiway Width	Sensor Length	Number of Sensors
100 ft	15 ft	7
250 ft	15 ft	18
400 ft	15 ft	28

In general, most small aircraft have three sets of wheels in one of two configurations: the conventional, or taildragger undercarriage and the tricycle undercarriage.

The wheel or tire arrangements of some commercial aircraft are as shown in Fig. 10. The four-wheel bogie under each wing and the two set of six-wheel bogies under the fuselage of an Airbus A380 will trigger a sensor with six spikes: one spike from the nose landing gear, two spikes from the four-wheel bogie and three spikes from the six-wheel bogie. The aircraft can be classified by calculating the distance between the nose landing gear and the multiple wheel bogies either under each wing or the fuselage from the time differences between voltage spikes produced by the sensor array. The aircraft speed limit on taxiway is 30 mph, and the normal speed for most of the taxiing aircraft is between 15~20 mph. As an aircraft rolls over a sensor array as shown in Fig. 9, it will trigger at least two output voltage spikes. The cluster of spikes should occur within a certain time frame, and that time frame can be computed as the following:

$$\text{Time Frame} \geq \frac{2+x}{\text{Aircraft ground speed}} \qquad (1)$$

where x is the distance in feet between the nose landing gear and the last wheel bogies as shown in Fig. 11. In order to estimate the time frame as in Eq. 1, without knowing the aircraft ground speed, we can analyze the waiting zone before the aircraft enters the junction. The distance of the waiting zone should be about $4x$ feet (about twice the length of the aircraft). Assuming the aircraft ground speed is 15 mph or 22 ft/sec, the time frame estimation should be as follows:

$$\text{Time Frame} \approx \frac{2x}{22\text{ ft/sec.}} = \frac{x}{11}\text{sec}. \qquad (2)$$

The runway length determines the type of aircraft that particular airport can accommodate. Knowing the type of aircraft, there will be a set of x values and using the maximum value of x to determine the time frame as in Eq. 2. The microcontroller will be able to count the cluster of spikes within a time frame as one spike from the sensor array.

An upgraded sensor array is necessary to measure the aircraft ground speed and to categorize the aircraft model. An example of this sensor array configuration is shown in Fig. 12. The sensors around the central portion of the taxiway are installed in the same pattern as shown in Fig.5, and the area on each side of the taxiway is back to the configuration as shown in Fig. 9. The only drawback is for the single-engine aircraft, the width of the tire is just about eight inches, which may not trigger the sensor if one of tires rolls over the insensitive zone. If the nose landing gear or multiple wheel bogie can trigger one sensor on each row (24 inches apart), the aircraft ground speed can be determined with the microcontroller timer function. The aircraft model can be confirmed by the spikes pattern on the sensor array. By knowing the aircraft ground speed, we can determine the distance between the nose landing gear and the multiple-wheel bogie. The distance between the nose landing gear and the multiple-wheel bogie for all aircraft models and also the number of wheels in that type of aircraft will be loaded into a database to perform the pattern recognition match. Although the width between the bogies under the wings or fuselage cannot be determined accurately, the address of the sensor in a sensor array will provide a rough estimate of their separation. The number of spikes created by the multiple-wheel bogie also provides information on the number of wheels in the bogie. The distance measurement can be done with the microcontroller timer function; the number of ticks from the E clock times the distance travelled within one tick gives a good measurement of distance.

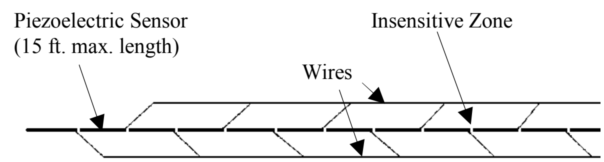

Fig. 5: Sensors array to span wide taxiway [15].

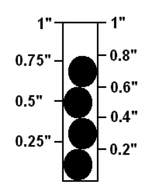

Fig. 6: Leads/wires from every other sensor are running in slots on each side of the sensor array which is as in Fig. 2 [15].

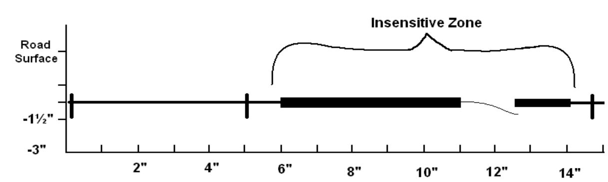

Fig. 7: The insensitive zone between each sensor in the array [15].

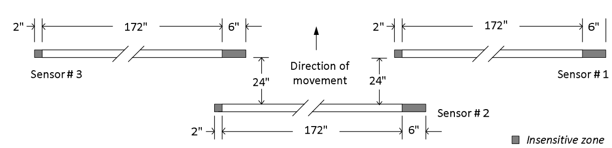

Fig. 8: Configuration of sensors to eliminate the insensitive zone.

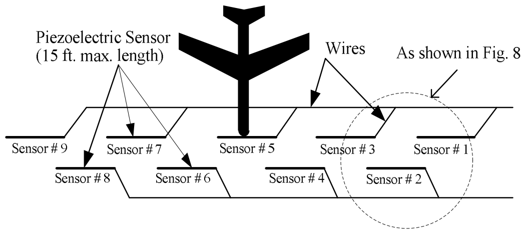

Fig. 9: An alternative configuration of sensors array to span wide taxiway and eliminate the insensitive zones.

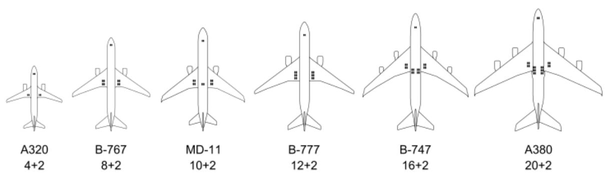

Fig. 10: Tire arrangements of large aircraft [16].

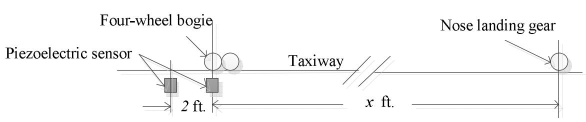

Fig. 11: Compute time frame for sensor array.

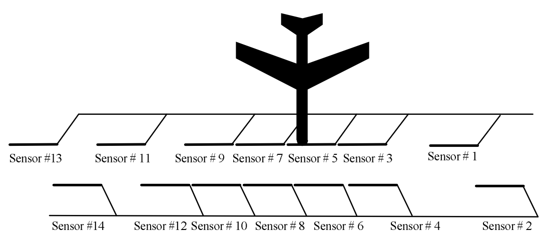

Fig. 12: A configuration of sensors array to span taxiway for ground speed and aircraft model estimation.

B. Analog-to-Digital Interface

The output of each piezoelectric sensor is a differential voltage pulse similar to those shown in Fig. 3. Several architectures are possible to interface the differential output of each sensor to the single-ended input of the microcontroller's analog-to-digital converter depending on the sensor compensation and signal conditioning required. Since a maximum of 28 sensors is required to span a 400 ft. wide path, the system requires a large analog multiplexer, controlled by the microcontroller. Such a large analog multiplexer is not available commercially as a single integrated circuit; thus a composite switch would have to be built as a two-level matrix. The architecture shown in Fig. 13 performs the differential to single-ended conversion using one instrumentation amplifier per sensor strip and feeds the analog-to-digital converter via a 32-to-1 multiplexer. The architecture shown in Fig. 14, by contrast, uses a 64-to-2 multiplexer and one instrumentation amplifier for the entire bank of sensors.

The design begins with the selection of the instrumentation amplifier. For this application a good amplifier such as TI's INA333 or Linear's LT1167 provides sufficient gain and linearity. The single-ended analog multiplexer can be composed of four 8-to-1 SN74LV4051 and a 2-to-1 SN74LV4053, available from TI. The 8-to-1 switch could be replaced with HMC183s from Hittite. The differential multiplexer can be implemented using the same devices, but using MC74HC4052 ICs from ON Semiconductor would result in a cleaner board layout even though more ICs would be needed for a three level switch matrix.

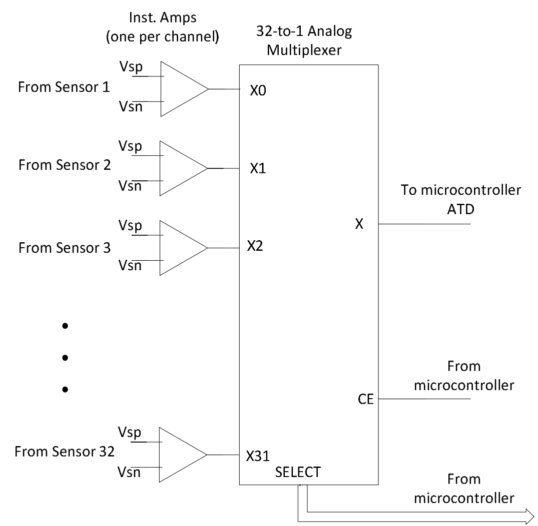

Fig. 13: Block diagram for using 32 amplifiers and a 32-to-1 multiplexer.

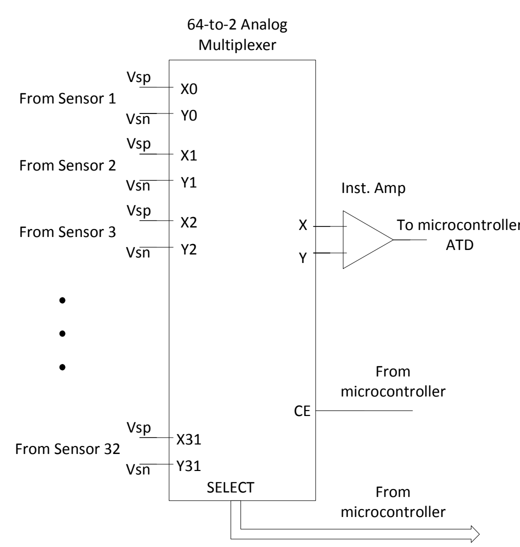

Fig. 14: Block diagram for using 64-to-2 multiplexer and one amplifier.

To evaluate the applicability of piezoelectric sensors to airport ground traffic control, a prototype scaled model taxiway junction was built. It used piezoresistive thin film sensors to monitor the traffic at the junction. Piezoelectric thin films are considered emergent materials for integration within Micro Systems Technology (MST) or Micro Electro Mechanical (MEM) devices. Plenty of research activities for the piezoresistive thin film has been shown worldwide [17-20]. While the strain sensitivity of piezoelectric is 50,000 times the one of piezoresistive thin film [14], piezoresistive thin film is appropriate in a lab setting to detect the moving objects that weights much less than the airplanes or moving vehicles in airport field.

C. Method

"The piezoresistive thin film sensor provides a low resistance when it is pressed; the harder the force, the lower the resistance. When no pressure is being applied, its resistance can be greater than 1 MΩ. This type of sensors can sense any pressed force in the range of 0.1~10 kg. We will use a circuit to measure the voltage drop across a resistor into which the current generated from piezo thin film sensor injects, and apply the input capture function of a microcontroller to capture the falling edge of the waveform. The waveform generated by the sensor is just the opposite of the piezoelectric sensor, currently used in axle counting. With two parallel sensor arrays, using the input capture function from a microcontroller, the ground speed can be determined. The direction of travel can also be determined by analyzing which sensor array has been triggered first. The generated voltage from the piezoelectric sensor is proportional to the pressure on the sensor. The higher the pressure, the higher the amplitude of the signal generated.

With each sensor interfaced with a microcontroller, the area of activity can be monitored. The data is sent through a USB or RS-232 interface to the graphic software running on a personal computer to illustrate the area of activity on the screen (similar to the GPS system in our vehicles except the display is for the air traffic controller, not for the pilot on the plane). This can be done in wireless communication with encryption for security purpose. The graphic software will be customized for the layout of a particular airport. Each sensor array will be connected to one input pin in a microcontroller and assigned an address. If the sensor is triggered by a plane rolling over the sensor, the triggering pulse will send to the microcontroller, and the microcontroller in turn will monitor the sensors in the nearby area. The output signal from the microcontroller will send the address of the triggered sensor array to the graphic software. The microcontroller will provide a higher priority for the graphic software to focus on the area with most activity. The next highest priority will be displayed in a smaller window on the upper right corner of the screen. In such a way, the air traffic controller will be monitoring the ground activity for several nearby junctions on the computer screen, instead of using the binoculars to confirm the activity visually at the junction. The block diagram is shown in Fig. 15." [1]

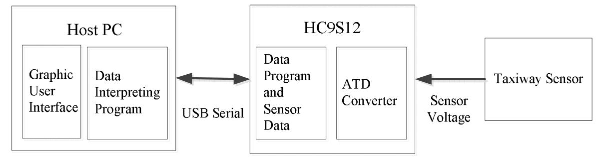

Fig. 15: Block diagram of the methodology.

Airport Surface Detection Equipment, Model X (ASDE-X), uses a combination of surface movement radar and transponder sensors to detect any airport surface movement. The system may not be cost effective for some airports, but the method proposed in this paper can improve the taxiway incursion prevention for those airports. Lastly, the FAA and the Commerce Department have raised concerns about a new high-speed wireless network that could cause conflicts with GPS systems [21]. The transponder sensors in the ASDE-X are using the GPS systems to monitor the airport ground movement.

D. Experimental Setup

A prototype of taxiway junction embedded with piezoresistive thin film sensors was built according to the layout of an airport in Corpus Christi, Texas, as shown in Fig. 16. Initially we decided on the main components to be used in the model for the Taxiway Airport Traffic Control System. The model being built from wood was constructed in order to take advantage of the versatility it brought in being able to modify and adjust the model when compared to harder materials such as metal. After the base model was complete, the Force Sensitive Resistors (FSRs) were added onto the board in a pattern to simulate the taxiway in an airport. The sensors would allow us to program in assembly how to distinguish the model of the aircraft that went over the FSR's by counting the number of axles as well as allow for the calculation of velocity of the aircraft. After verifying that each FSR worked individually, a program was written in both assembly and Visual Studio C# to interface with the sensors. After many tests of running the model plane over our model of the Airport Taxiway to make sure the data gathered was correct and accurate within our desired parameters, then we moved on to interfacing the base model with a Graphical User Interface (GUI) which was created from Microsoft Visual Studio C# which used XNA Game Studio, a sub program of Visual Studio. When the GUI was complete, we linked together and interface all of our models and codes together into one unit to be tested. It could be seen when running the tests of our model and GUI linked together the aircraft could be seen individually on the GUI going at a scaled speed in relation to how fast the sensors were triggered and in the proper direction. The final task was to have the microcontroller that handles the information about the plane transmit the data wirelessly to the microcontroller that will display the aircrafts location and relative scaled velocity on the GUI. The *XBee* wireless transmitter/receiver was chosen for the wireless transmission of the data upon linking them together via asynchronous serial communication and wiring them correctly on each respective microcontroller the data could be transmitted wirelessly.

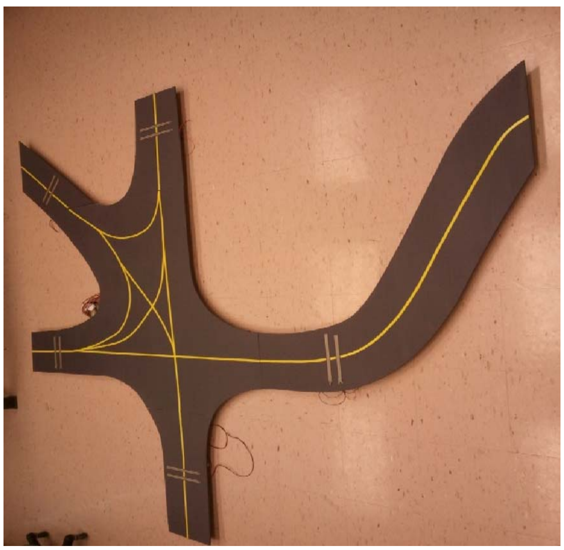

Fig. 16: The prototype of a taxiway junction.

Fig. 17: The layout of a junction in Corpus Christi International Airport, TX, USA.

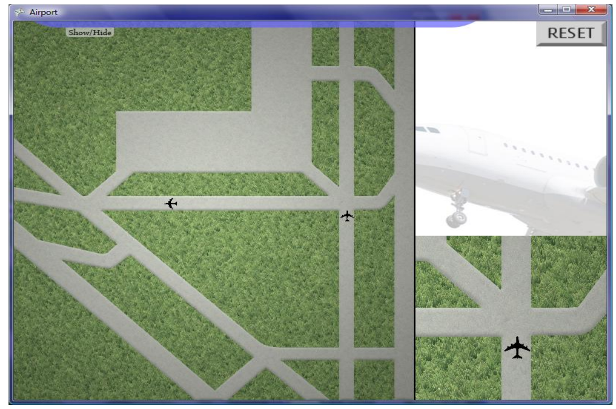

Fig. 18: The graphic display of a junction on the monitor.

"The distance between the two sensor arrays on a taxiway should be greater than the distance between the front landing gear and the rear landing gears of any plane." [1]

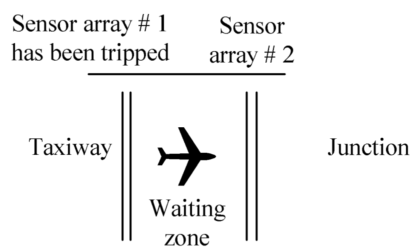

Fig. 19: The plane is heading to the junction.

"Assume the junction is to the right of sensor # 2 in Fig. 19. If the plane has rolled over sensor # 1, the microcontroller will acknowledge sensor # 1 has been tripped. The signal will be similar to the waveform as shown in Figs. 3 or 4. If the sensor # 2 has not been rolled over by the plane, then the plane is in the location as shown in Fig. 19. Similarly, if the plane has rolled over sensor # 2, but has not rolled over sensor # 1, then the plane is in the location as shown in Fig. 20. Using two sensors in each taxiway will be able to monitor the plane direction." [1]

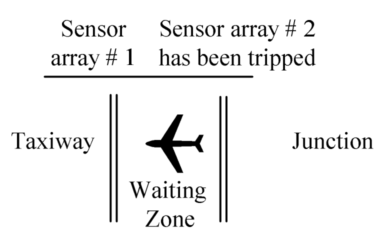

Fig. 20: The plane is coming in from the junction.

"The area between the two sensor arrays on the taxiway can be named as the waiting zone. As soon as the plane rolls over the first sensor, the microcontroller can keep track of time in the waiting zone. The air traffic controller can refer to the time the plane has been waiting within the waiting zone, and be able to control the traffic at the junction." [1]

The primary goal of an Air Traffic Controller is to move aircraft to and from the runways as safely and as efficiently as possible. There is a local controller (LC) and a ground controller (GC). The LC is responsible for aircraft and vehicles on the runways. The GC is responsible for aircraft and vehicles on the taxiways. When an aircraft requests to proceed on to the taxiway, either to or from the runway, the aircraft calls GC and advises GC of his position and intention. The GC determines the best route for the aircraft and issues taxi instructions. The GC is also responsible to insure the aircraft follows the instructions. This system could aid in low visibility conditions to verify the aircraft followed instructions.

E. *Experimental Procedure and Preliminary Results*

For the prototype, the model taxiway junction shown in Fig. 16 was built. The original intent was to use a remote controlled (RC) airplane, car, or truck to roll over the piezo thin film sensor or force sensitive resistor (FSR). When a force is applied to the FSR, a better connection is made between the contacts, thus the conductivity is increased. There are many types and models of RC vehicles; unfortunately none met our requirements. They were either running too fast or were too light in weight. Thus, a manual procedure was implemented to do the rolling.

"The circuit used to interface the FSR with the analog-to-digital (ATD) on the microcontroller is shown in Fig. 21. The simple set-up for interfacing FSR with the microcontroller is shown in Fig. 21." [1]

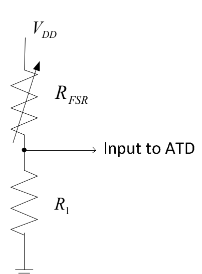

Fig. 21: Using a voltage divider to interface the FSR with the microcontroller.

"The FSR behaves like a variable resistor. When a plane rolls over the FSR, the resistance of the FSR will drop. The voltage divider will cause a bigger voltage drop across R_1. The expression for the voltage divider is as shown below:

$$V_{R_1} = \frac{R_1}{R_1 + R_{FSR}} \times V_{DD} \tag{3}$$

The V_{DD} for the microcontroller is 5 volts, but for other microcontrollers the supply voltage can be 3.3 volts. The value of R_1 can be any value between 200 KΩ ~ 1 MΩ. As the voltage cross R_1 is digitized by the analog-to-digital (ATD) converter in the microcontroller, the assembly program sets the threshold voltage to capture any object rolled on the FSR through the input to ATD." [1]

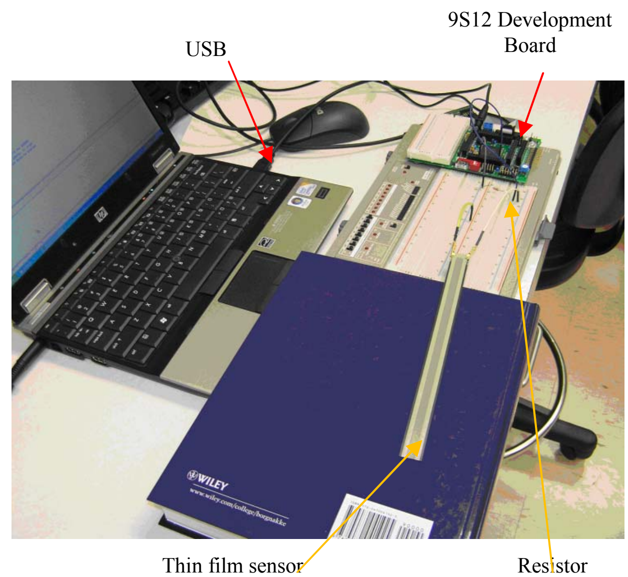

Fig. 22: Network for testing the force sensitive resistor (FSR).

III. Conclusions

"This paper presented a piezoelectric sensor network for use in monitoring ground movement at airports. This sensor network can be used as a stand-alone system or as a supplement to current ground traffic monitoring systems such as ASDE-X. Much work remains before a fully deployable system is finalized. For instance, the interface between each sensor in the array and the microcontroller in the node will be different. Since the output signal of the piezoelectric sensors is of small amplitude, the signal will need to be conditioned and amplified prior to digitization. Also, in a real world implementation, there will be more than one taxiway junction to monitor. And since the distance from the taxiway function to the control tower may be more than a mile, a wired or wireless communication system will also need to be implemented. Preliminary results are encouraging for continued research in using piezoelectric sensors for airport ground movement detection, monitoring, and control. A real-time traffic monitoring and graphic display software system to process the data for visualization is also part of future work. Our long term goal is to deploy piezoelectric sensor networks at airports to supplement ASDE-X with a comprehensive real-time traffic monitoring and controlling software package for staff working at airport control towers." [1]

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