Design of A Wireless Sensor Network Based Automatic Light Controller in Theater Arts

Chuan Feng, Lizhi Yang, Jerzy W. Rozenblit
Electrical and Computer Engineering Department
The University of Arizona
Tucson, Arizona 85721
Email: {fengc, lyang, jr}@ece.arizona.edu

Peter Beudert
School of Theatre Arts
The University of Arizona
Tucson, Arizona 85721
Email: pbeudert@email.arizona.edu

Abstract

In this paper, an automatic lighting controller designed and built using a wireless sensor network indoor positioning technology is described. This controller can autonomously track actors during a real-time theatrical performance. Kalman filter and 3-D trilateration technologies were used with Cricket wireless sensors to implement this system. In addition, an entertainment industry standard protocol DMX-512 and an efficient calibration method were applied to realize remote computerized fixture control. As far as we know, this controller is the first application of wireless sensor networks in the theater arts area. A successful public performance concert at the University of Arizona validated the performance of the system.

1 Introduction

In this paper, we propose an automatic moving light controller which was built using a wireless sensor network (WSN for short) based indoor positioning technology. WSN is an interconnected wireless system of typically small low power electronic sensors that provide ubiquitous sensing and computing capabilities, through which the controller tracks the position of actors on the stage. It controls the light instruments to illuminate the actors as needed [2]. In contrast with traditional systems that rely on pre-programmed sequences, this system provides autonomous abilities to control the moving lights in real-time.

Modern stage lighting plays an important part in a performance. The director can use the lights to alter the perception of shapes, direct audiences' attention, set the mood of a scene, establish position in time and day, and trigger a variety of events.

To achieve these various objectives, different types of lighting instruments and related control systems are implemented. One modern instruments which appeared in theaters in the early 1980's is an intelligent fixture (or moving light) . An intelligent fixture allows remote control of the movement of a light beam either by moving a mirror that reflects the beam in front of the lens, or by moving the whole fixture itself.

Traditionally, the moving light is pre-programmed by the lighting designer before a real time performance [9]. It is like an industrial manipulator that can only play-back what has been memorized during a training session. There are no automatic lighting devices that can track and follow actors during a show because they lack real time position information. We wanted to build a system which obtains the position of actors in real time and controls the beam of the intelligent fixture automatically.

In the next section, we briefly review previous work. In Section 3 we describe the High Accurate Positioning subsystem including the wireless sensor network, Kalman filter, and the 3-D trilateration algorithm. In Section 4, we present the automatic lighting control subsystem. Section 5 describes the whole system setup and implementation. In Section 6, the experiment and real performance results in the theater of the University of Arizona are presented. Section 7 discusses future work.

2 Related Work

Theater lighting is one of the most important features in modern theater performance. In Disney's "Beauty and the Beast", which opened at the Dominion Theater in London 1998, there were 1240 lighting units, with different levels of intensity, changing color and focus on moving objects at different times [6]. In that performance, sixty seven automated fixtures were used, which communicated with the control desk via the DMX 512 protocol, an entertainment industry standard based on RS485 to change the pan, tilt, intensity, color and gobo. These fixtures usually utilize com-

Proceedings of the 14th Annual IEEE International Conference and
Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE

pact arc lamps as light sources. They use servo motors or stepper motors connected to mechanical and optical devices to manipulate light before it emerges from the fixture's front lens. Currently, there are several different manufacturers working in the market, such as Highend, Vari Lites, SGM Light Technology etc. In our project, a Highend Studio Beam system was used.

Besides the lighting system, another necessary component of the automatic lighting device is the positioning system. Today, thanks to satellite navigation systems such as GPS, the outdoor positioning is reliable and convenient [10]. However, although GPS signals are free to everyone, there are blind spots, especially inside buildings, and the accuracy of a GPS tracking system is inadequate for indoor applications.

There are several indoor positioning technologies available [3] [4] [5] that can offer higher accuracy than the outdoor location systems within a confined space. One system uses an RF signal of wireless AP or Bluetooth devices to locate objects. They measure distance between the transmitter and the receiver based on Received Signal Strength Information (RSSI). Another measurement technology is called Time Difference of Arrival (TDOA), which can be implemented by ultra wide band (UWB) technology or ultrasonic pulse. Image processing is another method. Among all the available techniques, a wireless sensor network is a relatively new and advanced technology because the wireless sensor networks integrate technologies from sensing, communications and computing to small individual sensors which can be deployed into the indoor environment flexibly.

The location accuracy requirements of an indoor positioning system can be grouped into three classes: low accuracy at room-scale, medium accuracy around 1 meter and high centimeter-scale accuracy. The requirements of the automatic lighting system are reliable coverage and high accuracy within 10 centimeters. RSSI technology does not require complex hardware, but it is difficult to measure precise distance and estimated position. Image processing technology cannot adapt to complex lighting and background variations in a theater environment. Ultrasonic pulse TDOA devices offer high accuracy at a few centimeters without requiring complicated hardware such as UWB. Thus, they are a suitable positioning part of the lighting system. The Active Bat and Cricket systems are two successful products of this type. For this project, we used the Cricket system.

The Cricket Location-Support System was first developed at MIT's Artificial Intelligence Laboratory and is now distributed by Crossbow Technology. The Cricket system is a decentralized wireless sensor network which tracks objects using the TDOA between radio frequency and ultrasonic signals, which provides high accuracy distance measurement (within 1 cm). By using MICA2 platform [11], we can build a small wireless sensor network that consists of several fixed mounted beacons, and one listener which can be carried by the actor to achieve tracking goals. Detailed information about the Cricket application will be provided later in this paper.

3 High Accuracy Positioning

Because theater applications have high tracking accuracy requirements, Cricket is used as the positioning sensors in the automatic lighting project. Cricket consists of nodes which are small wireless sensors. Each node consists of a radio frequency (RF) transceiver, an ultrasonic sender and receiver, and a microcontroller. The positioning system uses distance information acquired from Cricket nodes to estimate the exact 3-D coordinates of the actor.

3.1 Wireless sensor network

There are two kinds of Cricket nodes: 1) beacons that usually act as reference points of the location system and are typically attached to the ceiling of a building, and 2) listeners that are attached to actors so that the system can determine their location. Beacons periodically transmit RF messages containing the unique beacon-identifier (ID). At the same time, they also send an ultrasonic pulse. The transmission is not centrally coordinated. Listeners listen to beacon transmissions and measure distances to nearby beacons by comparing the time difference of the RF message and the ultrasonic pulse. Then the listener transfers the estimated distances to a super node through a bluetooth adaptor. The super node is a computer that has computational power for further operations including trilateration and lighting control. Fig. 1 is the schematic diagram of the wireless sensor network.

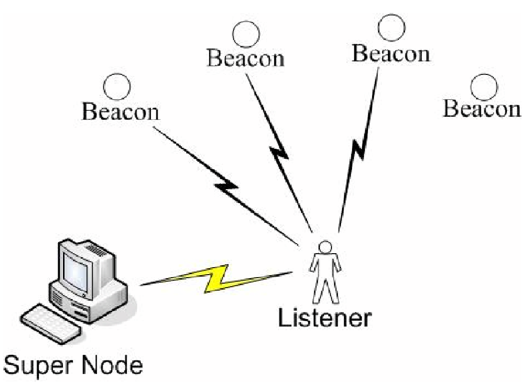

Figure 1. Cricket Sensor Network

Proceedings of the 14th Annual IEEE International Conference and
Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE

3.2 Kalman filter

The Kalman filter is one of the most popular mathematical tools used for noisy sensor measurement by stochastic estimation [11]. In practice, it is difficult to get the an exact solution because of noise and device errors. The noise of the distance time difference of ultrasonic and RF signals mainly comes from sound reflection or other effects. The Kalman filter is an efficient recursive filter that estimates system states from sequential noisy measurements by exploiting the dynamic of the target. The system maintains a table of the distance estimations between a listener and beacons in realtime. When a listener receives distance information from a beacon, the system uses the error between the current distance information and the new one to update the distance table. A Kalman filter is implemented as the correction phase.

Following are the system time update equations.

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k \tag{1}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{2}$$

$$z_k = Hx_k + v_k \tag{3}$$

Where x_k is the system state, $\hat{x}_k^-$ is a priori state estimate at step k, and $\hat{x}_k$ is the posteriori state estimate at step k. P_k^- is a priori estimate error covariance and P_k is the posteriori estimate error covariance. A is the state equation that describes the relation of the previous state and current estimated state. B relates the previous distance difference u to the state x. In this application, the matrix A and B are I; Q is the process noise covariance; z_k is the measurement value, v_k is the measurement noise and H is the measurement matrix, which is also equal to I in this application. In practice, z_k can be measured directly, so equation (3) is not necessary, but the measurement innovation $z_k - H\hat{x}_k^-$ is important in the measurement update step.

The Kalman gain equation is shown in the following:

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{4}$$

Where R is the measurement noise covariance.

According to the time update equations and the Kalman gain K_k, the estimate state and error covariance can be updated by equations (5) and (6).

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \tag{5}$$

$$P_k = (I - K_kH)P_k^- \tag{6}$$

Fig. 2 is the graph of a simulation of distance measurement. The x-axis is simulation time and the y-axis is distance information. The "+" indicates information got from the sensors, the curve shows the estimated distance. The Kalman filter can indicate distance without being influenced by noise.

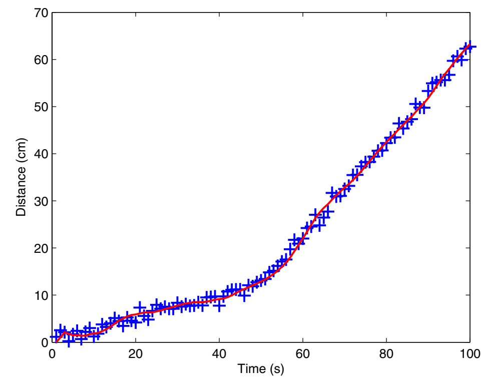

Figure 2. Kalman Filter Diagram

If error is significant, there will be a big shock wave as shown in Fig. 3. In that simulation, at t=10s, an error measurement of around 100 centimeters was received. Although the system steadied after a while, the big shock is not acceptable.

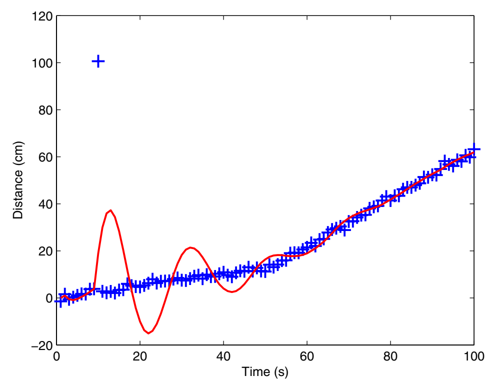

Figure 3. Error Data Effect to Kalman Filter

To minimize such effects, a logical estimation is applied in addition to the complete computation iteration of the Kalman filter. The distance from the sensor will be considered as incorrect and removed if it is too far away from the estimated distance. However, from [1], a serial small distance error may cause the Kalman filter to go into a bad state that treats all of the correct distance information as incorrect. So if continuous incorrect distance information is detected, the filter will know it is in the bad state because the integration of the error will be greater than a predefined threshold. Therefore, the system will clear all the information and start the filter from the initial state again. Using the self-reset mechanism, the filter can eliminate the serious infection from incorrect data.

Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE

3.3 3-D trilateration

The object of the positioning system is to acquire the coordinates of the target. When using the Kalman filter, the distances of the target (listener) and reference points (beacons) can be known. Trilateration is a method to determine the object position by some reference points with known locations. Like a GPS, the 3-D space tracking system needs trilateration to detect the position of an object. Assume the object is at position P_0, there are known reference points P_1 to P_n, and all of these points are in 3-D Cartesian coordinate system. If the precise distances from the reference points to the object are known, equations can be derived as follows:

$$\left\{\begin{array}{lcl} |P_0 - P_1| & = & D_1 \\ |P_0 - P_2| & = & D_2 \\ & \cdots & \\ |P_0 - P_n| & = & D_n \end{array}\right. \tag{7}$$

Where $P_0 \ldots P_n$ are the coordinate vectors of the object and reference points and $D_1 \ldots D_n$ are the distances between the object and reference points. In a general 3-D application, 4 reference points are needed to solve the equations. If the redundant solution can be eliminated easily, 3 reference points are enough, e.g., mounting the sensors on the roof and tracking people walking on the floor, two different coordinates will be observed by the trilateration of the 3 reference points, but one of them will be removed because it is over the roof.

Theoretically, the coordinate information of the target can be obtained by solving the equations 7. But device errors or inaccuracy cannot be eliminated by the Kalman filter. There is an example in Fig. 4.

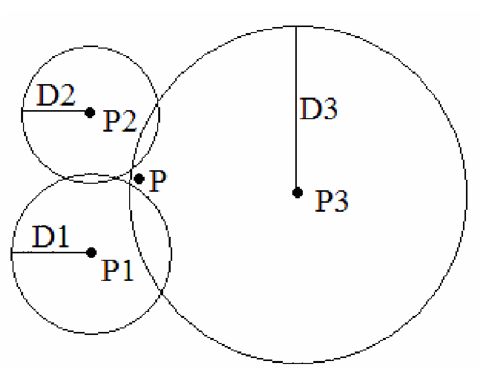

Figure 4. Trilateration Problem

There are many algorithms that have been proposed for solving nonlinear equations. The least square algorithm is a popular one that can be adopted to acquire the approximated solution of trilateration. In order to estimate the 3-D position from three measured distances D_i, the algorithm updates the position estimate $\hat{P}$ to minimize the cost function E. The cost function is the sum of the errors between the measured and the estimated distance.

$$E(\hat{x}) := \sum_{n=1}^{3} (D_i - |P_{\hat{x}} - P_i|)^2 \tag{8}$$

In equation (8), D_i is the distance information obtained from the sensor, $P_{\hat{x}}$ is the estimated position of the target and P_i is the position of the reference points. In order to solve the nonlinear problem, the Newton method is applied.

The Newton method is an efficient root-finding algorithm for solving nonlinear equations. The idea is as follows: one point is selected from the equations and then the functions are replaced by their gradients. The roots of the gradients are a better approximation than the original point. This iterated equation is:

$$\hat{x}_{k+1} = \hat{x}_k - J_k^{-1} E(\hat{x}_k) \tag{9}$$

In equation (9), $\hat{x}_k$ is the estimated position of the target in kth iteration, $E(\hat{x}_k)$ is the cost function, and J_k is the Jacobean matrix $\partial E(\hat{x}_k)/\partial \hat{x}_k$.

For the application mentioned earlier, in which three reference points are required, the Jacobean matrix is:

$$J = \begin{pmatrix} 2(\hat{x} - x_1) & 2(\hat{y} - y_1) & 2(\hat{z} - z_1) \\ 2(\hat{x} - x_2) & 2(\hat{y} - y_2) & 2(\hat{z} - z_2) \\ 2(\hat{x} - x_3) & 2(\hat{y} - y_3) & 2(\hat{z} - z_3) \end{pmatrix} \tag{10}$$

Where $\hat{x}, \hat{y}, \hat{z}$ are the Cartesian coordinate of estimated position. x_k, y_k, z_k are the coordinate of reference points.

In this application, the inversion of the Jacobean matrix has been computed offline and embedded inside the tracking program to speed up the processing time. This makes 3-D tracking in real time become reality. The Newton method is quite simple, so it is easy to embed it into the sensor nodes without massive computational power consumption.

4 Automatic Lighting Control

To control the beam pointing to the known spot obtained from the positioning system, coordinate transfer and a DMX-512 controller are used.

Fig. 5 shows the coordinate transfer process. Because the intelligent fixture has two degrees of freedoms, pan and tilt, while the positioning system provides the target information with Cartesian coordinates (x,y,z), a mapping is needed to transfer the coordinates.

4.0.1 Global coordinate

As shown in Fig. 5, a global coordinate can be set up in the theater, so the position of the target is $P_t = (x_t, y_t, z_t)$

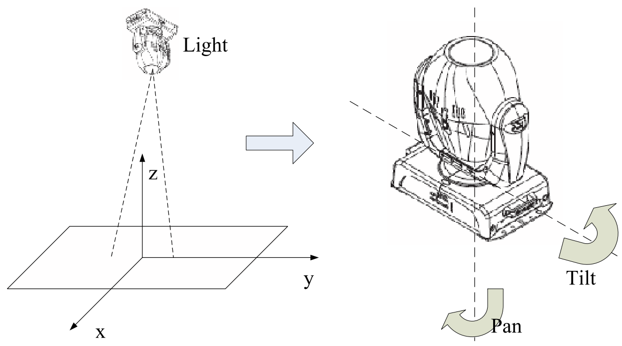

Figure 5. Coordinate Transfer

and the position of the light is $P_l = (x_l, y_l, z_l)$. Because the light position is fixed, the mapping relation is only a function of target position P_t to the Pan and Tilt.

$$Pan = \arctan \frac{x_t - x_l}{y_t - y_l} + Pan_{offset} \tag{11}$$

$$Tilt = \arctan \frac{\sqrt{(x_t - x_l)^2 + (y_t - y_l)^2}}{z_t - z_l} + Tilt_{offset} \tag{12}$$

Where the Pan_{offset} and $Tilt_{offset}$ are the offsets of the device input that makes the intelligent fixture fit the global coordinate exactly.

4.0.2 Calibration

An issue with equation (11) is that it assumes the position of the light $P_l = (x_l, y_l, z_l)$ as a known parameter. In practice, it is hard to measure the exact position of the moving lights, which are quite heavy, because they are usually fixed on the ceiling, unlike the wireless sensors which can be mounted flexibly. Calibration is an easy solution in this situation. Calibration is the process setting the magnitude of the output to the magnitude of the input property. In this application, the calibration process is defined as follows:

1. Build the global coordinate system, set up the original spot.
2. Mount the wireless sensors carefully, making sure they can get the position information correctly.
3. Fix the moving light on the roof.
4. Select three points in the theater, get the coordinates by the positioning system.
5. Control the light beam to point to the selected points manually, recording the Pan and Tilt respectively.
6. Use the coordinate of points and the direction of the moving fixture as known parameters in equation (11).
7. Solve the equations by numerical function and get the position of the light which is $P_l = (x_l, y_l, z_l)$.

4.1 DMX-512 controller

There is a special protocol used by intelligent lighting devices, namely DMX 512 [8]. DMX 512 is an entertainment industry standard based on RS485, which is mainly used to control stage lighting. Each DMX cable can support 512 channels. Thus, the controller can transmit up to 512 8-bit values at one time. Depending on the kind of device, each intelligent fixture requires 20 to 40 channels. Data are transmitted at the speed of 250kbps. There are 513 bytes in one package, which are 512 byte values of the 512 channels and 1 byte start code. Therefore, the refresh rate of the light device is 44Hz, which is enough because the mechanical delay of the intelligent light is relative large.

In our application, a USB to DMX converter is used to help the computer send and receive DMX packages.

5 System Setup

The entire system is the integration of the positioning subsystem and the lighting control subsystem. The system framework is shown in Fig. 6.

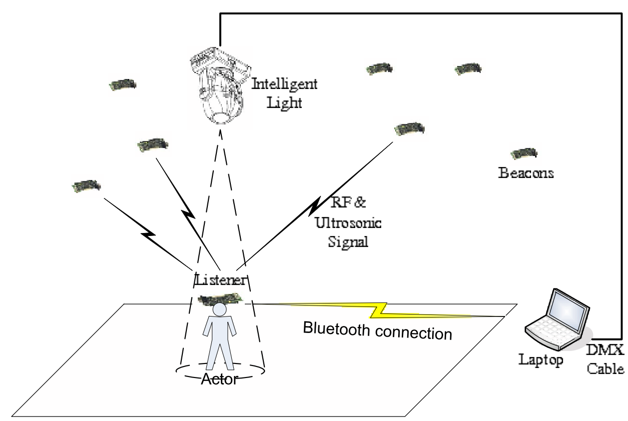

Figure 6. System Framework

5.1 Cricket sensors

Eight Cricket sensor nodes were used to build the positioning system. One of them is configured as the listener, which is carried by the actor. The other seven nodes are beacons that send RF ID and ultrasonic pulses periodically. The time interval of each transmission is pre-configured between 400 ms and 800 ms to provide enough refresh frequency with a low collision rate. The basic Cricket sensor

Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE

system requires the listener to connect to a computer directly through a serial cable. In our application, this is not acceptable in our application because an actor cannot carry a long cable during the performance. To solve this problem, a serial to bluetooth converter was used to build a wireless communication channel.

5.2 Highend Studio Beam

Highend Studio Spot 250 [7] is the intelligent fixture used in the automatic lighting system. The fixture can rotate $540°$ in pan and $270°$ in tilt. An optical encoder guarantees position accuracy. The fixture uses 18 DMX channels to control position, light, color, gobo, etc. During the performance, the data related to light, color and gobo can be changed remotely on the computer, and the pan and tilt data will change automatically.

6 Experiment and Performance

To validate the automatic lighting system, some experiments and performance results are presented. The listener sensor and the bluetooth converter were carried by the actor. The sensor was on the shoulder and faced up so that it could receive the ultrasonic signals without problems. The other devices were mounted on the waist, which is similar to carrying a wireless microphone. Another bluetooth receiver was plugged into the control laptop. A special hexangular frame was made by a stainless steel pipe, each side of which was 9 feet (272.7 cm). The seven beacons were mounted on the vertexes and the center of the frame. The frame was hung on the top of the theater so that the sensors covered a large round area. When the actor entered the area, the beam of the intelligent fixture tracked him or her. The experimental program GUI is shown in Fig. 7. It was written in C++ and displays the position of the target in real time.

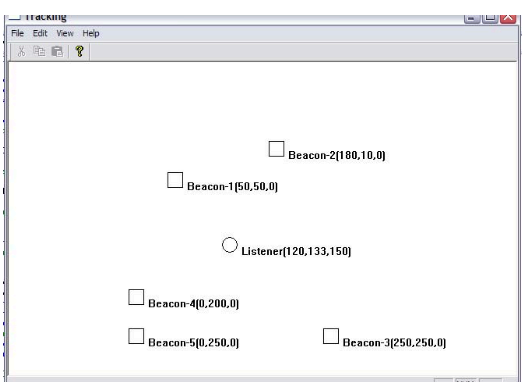

Figure 7. Tracking Program GUI

Table 1. DMX channel setup of the fixture

Channel	Description	Value
1	Pan, coarse adjustment	0-255
2	Pan, fine adjustment	0-255
3	Tilt, coarse adjustment	0-255
4	Tilt, fine adjustment	0-255
12	Shutter, close or open	0-23, 232-255
13	Dim, close or open	0, 255

6.1 Fixture setup

The bottom-up fixture was hung from the ceiling. One long DMX cable was used for communication between the fixture and the laptop. The start DMX channel number of the fixture was set to 1, so that the channels used during the performance were as in Table 1. The other channels were not used and were set to 0. As an example, if the position requirement of the fixture is that Pan equals $270°$, Tilt equals $135°$ and the beam is on, then the data of channel one and three should be set to 127; the data of channel 12 and 13 should be set to 255, and so on.

6.2 Experiment and Performance results

In the experiment, as soon as the actor carrying the listener sensor entered the sensing area, the automatic lighting system would illuminate him until he left the valid field. The experiment results show that the tracking system achieved accurate indoor wireless tracking. Tracking error was within 5 centimeters and the average system latency was 60 ms.

After several experiments, the automatic lighting system was used in the Crosstalk concert performance at the University of Arizona on May 6th, 2006, shown in Fig. 8. The performance was the first attempt ever to use an automated fixture in a real time performance.

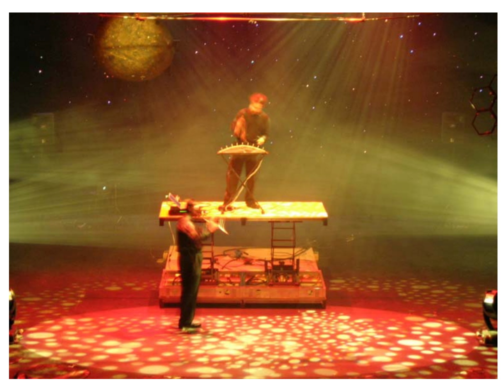

Figure 8. Crosstalk Performance

Proceedings of the 14th Annual IEEE International Conference and
Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE

7 Future work

The wireless sensor network based automatic lighting controller described in this paper is the first autonomous lighting system based on wireless sensor networks used in a real performance. The performance was successful and validated the system. A drawback of the system is relatively long latency, especially when an actor is moving at a high speed. Another issue is that the sonar sensor can be blocked by obstacles causing the tracking system to lose the target. Our future work is to minimize the latency of the system and to try to utilize a more robust sensor setup.

References

[1] Cricket Project, "Cricket v2 User Manual," MIT Computer Science and Artificial Intelligence Laboratory, 2004.

[2] S. Das, C. Gleason, and et al., "2-D Tracking Performance Evaluation Using the Cricket Location-Support System," *2005 IEEE International Conference on Electro Information Technology*, pp. 1-6, 2005.

[3] R. Singh, M. Gandetto, and et al., "A novel positioning system for static location estimation employing WLAN in indoor environment," *15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Vol. 3, pp. 1762 - 1766, 2004.

[4] K. Hida, M. Mizutani, and et al., "Design of Goods Tracking System with Mobile Detectors," *1st International Symposium on Wireless Pervasive Computing*, pp. 1-6, 2006.

[5] Y. Fukuju, M. Minami, and et al., "DOLPHIN: an autonomous indoor positioning system in ubiquitous computing environment," *2003. IEEE Workshop on Software Technologies for Future Embedded Systems*, pp. 53-56, 2003.

[6] M. Odam, "Theatre lighting control for Beauty and the Beast," *Power Engineering Journal*, Vol. 12, pp. 89-94, 1998.

[7] High End System, "Studio Beam User Manual," High End Systems, Inc., 2004.

[8] Enttec, `http://www.enttec.com/opendmxusb.php`, 2006

[9] Wikipedia, `http://en.wikipedia.org/wiki/Intelligent_lighting`, 2006

[10] H. Karimi, J. Lockhart, "GPS-based tracking systems for taxi cab fleet operations," *Proceedings of the IEEE-IEE Vehicle Navigation and Information Systems Conference, 1993*, pp. 679-682, 1993.

[11] Crossbow Technology, `http://www.xbow.com/wireless_home.aspx`, 2006 Crossbow Technology, Inc.

[12] P. Maycheck, "Stochastic Models, Estimation, and Control," *Academic Press*, Vol 1. Chapter 1.

Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS'07)
0-7695-2772-8/07 $20.00 © 2007 IEEE