# A real-time system for monitoring pedestrians

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## Abstract

*In this research, we propose a novel system of monitoring pedestrians and tracking their trajectories in a wide and open area, such as shopping mall, exhibition hall, railway station and so on. A network of single-row laser range scanners is exploited, which are set on the floor doing horizontal scan at an elevation of about 15cm above the floor. A pedestrian's walking model on the horizontal cross section of ground level is defined and a tracking algorithm is developed to detect and trace the rhythmic swing feet. On the other hand, video cameras are integrated with the network of laser scanners, which focus on some spots inside laser scanner's measurement coverage, and get image data for pedestrian's trajectories. An experiment for real-timely monitoring visitor's flow was conducted in a large exhibition, which had totally 30,000 visitors during three exhibition days. Four LMS200 (by SICK) and a video camera were located near a crossing point, covering a floor area of about 30m*30m and 5m*6m respectively. Visitors inside and nearby video camera's vision field were tracked in a real-time mode. Their trajectories as well as the laser points on their feet were back projected onto the video images on the air. On the other hand, visitor's flow nearby the crossing point, and its change along with time is examined by analyzing the motion behavior of each visitor in an off-line mode.*

## 1. Introduction

Analyzing or monitoring human activities, such as counting the number of passengers, measuring their trajectories, finding or/and following a specific pedestrian in a large area is considered very useful in various fields such as building security, surveillance, planning and management assistant in shopping mall, railway station and so on. So far, motion analysis with video data has been a major method to accomplish such a task. A good survey for visual-based surveillance can be found in Gavrila, 1999. Followings are several examples that targeting at tracking a relatively large crowd in a large area. Regazzoni and Tesei, 1996 described a video-based system for people counting over time and detecting overcrowded situations in underground railway stations. Schofield et al., 1997 developed a lift aiding system by counting the number of passengers waiting at each floor. Uchida et al., 2000 tracked pedestrians on street. Sacchi et al., 2001 proposed a monitoring application, where crowd flow in an outdoor tourist site is counted from video image. Pai et al., 2004 proposed a system of detecting and tracking pedestrians on crossroad to prevent traffic accidents. Heikkila and Silven, 2004 developed a real-time system for monitoring cyclists and pedestrians. In such systems, video cameras are set in restricted positions to reduce occlusions. Image resolutions and viewing angles are quite limited due to such camera setting, so that the moving object that has less image pixels might be failed in tracking. Still, the always change of illumination and weather condition is another major obstacle to the reliability and robustness of visual-based system. In order to cover a large area, multiple cameras are used. Whereas, the data from different cameras are difficult to be combined especially in real-time process, since it requires accurate calibration and complicated calculation between different perspective coordinate systems. Up to now, applications of visual-based surveillance are subjected to the extraction of rather few objects in limited environments.

On the other hand, single-row laser (range) scanner is a new sensor technology, which profiles surroundings using eye-safe laser (class 1A, near-infrared spectrum), measures range distances to target objects according to e.g. time-of-flight at each controlled beam direction. In recent years, single-row laser (range) scanner (simplified to "laser scanner" in the followings) with high scanning rate, wide viewing angle and long-range distance has been developed, and can be bought with rather low price on market. It attracts more and more attentions in the field of moving object detection and



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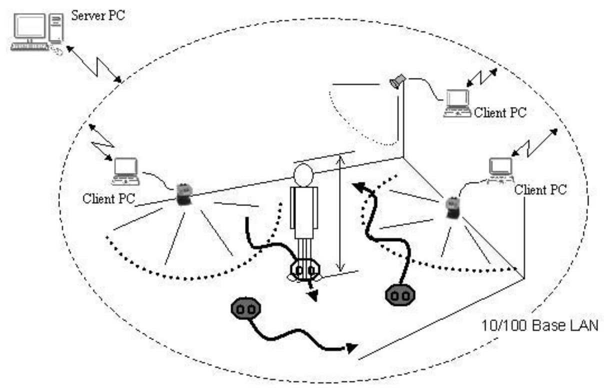


Figure 1: An image of the system for pedestrian's tracking

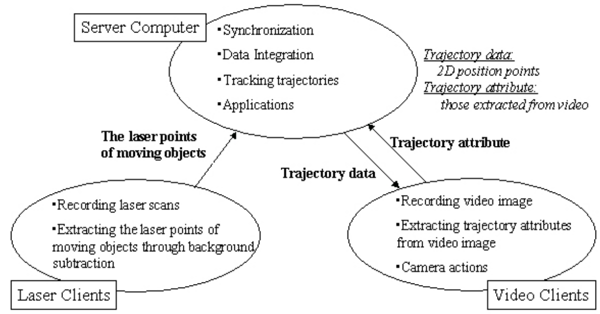


Figure 2: Processing modules of the system

tracking. Applications can be found in Streller et al., 2002, where a laser scanner is set on a car to monitor a traffic scene; in Prassler et al., 1999, where a laser scanner is set on a wheel-chair to track surrounding people, aiming at helping handicapped person traveling through a crowded environment, such as railway station during rush-hour; in Fod et al., 2002, where a laser-based people tracking is presented.

In our previous research [13], a tracking system aiming at real-timely monitoring pedestrian's behaviors in an environment such as railway station, shopping mall, exhibition hall, etc. is developed using a network of laser scanners. In this system, laser scanners are put on the ground, horizontally scanning pedestrian's feet at ground level. A pedestrian's walking model is defined and a Kalman filter based tracking is developed. The laser points of moving feets from different laser scanners are spatially and temporally integrated on the air, and pedestrians are tracked from the integrated frames in a real-time mode. However, since laser scanner measures points only, there are following limitations of the tracking systems based on such a data. When tracking a large and dense crowd using laser scanners only, it is difficult to tell exactly which feet belongs to the same pedestrian. If a trajectory is broken due to occlusion, it is difficult to link the fragments together. Also, it is impossible to attach other status, such as sex, height, age, face, cloth, etc. to such a trajectory. In this research, a hybrid tracking system is developed by introducing video cameras to the tracking system to solve the above limitations. In the followings, section 2 outlines the system for sensing; section 3 describes the tracking algorithm; section 4 shows an experiment at a three-day exhibition; section 5 gives conclusion and future study.

# 2 The System for Sensing

## 2.1 Architecture of the System

Fig.1 shows an image of the system for pedestrian's tracking. A network of laser scanners is composed, so that a relatively large area can be covered, while occlusions are reduced. Each of the laser scanners is located at a separate position on the ground, does horizontal scanning. The measurement coverage of each laser scanner has an overlay with at least one another, so that all laser scans can be integrated into a global coordinate system by matching the measurements to the common objects (Section 2.2). On the other hand, a number of video cameras are exploited. Each of the video camera is set on a high spot, monitoring the ground at a slant angle. The vision field of each video camera at ground level has an overlay with the measurement coverage of integrated laser scans, so that its coordinate systm can be associated independently with those of laser scanners (Section 2.3).

Each laser scanner and each video camera is controlled by a single client computer, called laser client and video client respectively. All client computers are connected through network to a server computer, which synchronizes and integrates the data from all client computers, and tracks trajectories. For data synchronization, each laser scan and each video stream is stamped with a time log at the moment it is captured or it starts to be captured using the client computer's local clock, which is corrected periodically according to that of server computer. The data measured by different client computers, and stamped with a time log of the same period are aligned to make up an integrated frame. Some major processing modules as well as data flow between client and server computers are shown in Fig.2.



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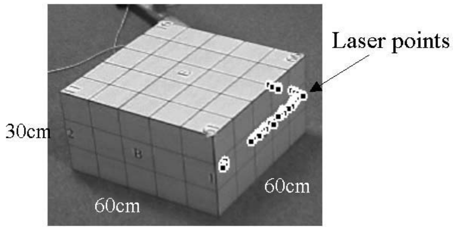


Figure 3: A calibration block

## 2.2 Registration of laser scans

Locations of laser scanners are elaborately planned. All laser scanners form an inter-connected network. Laser scans keep a degree of overlay between each others. Relative transformations between the local coordinate system of neighboring laser scanners are calculated by pair-wisely matching their background images using the measurements to common objects. In the case common features in overlapping area are too few for automated registration, an initial value is first assigned through manual operation, followed by an automated fine-tuning. Assigning an initial value to laser scanners' relative pose is not a tough task here, as two-dimensional laser scans are assumed to coincide in the same horizontal plane, operators can shift and rotate one laser scan on the other one to find the best matching between them. Specifying one local coordinate system as the global one, transformations from each local coordinate system to the global one are calculated by sequentially aligning the relative transformations, followed by a least-square based adjustment to solve the error accumulation problem. A detailed address on registering multiple laser scanners can be found in [12].

## 2.3 Calibration of a video camera with laser scanners

The vision field of each video camera has a degree of overlay with the coverage of laser scans. Each video camera is calibrated independently to the global coordinate system using Tsai's model [15], where both internal and external parameters are calculated using at least 11 control points. A global coordinate system is defined with its XY-axes coincident with those of the integrated coordinate system of laser scanners, with its Z-axis vertically upward, and its origin on the ground surface. The elevation of laser scanning plane is detected using the sensor chip that is developed in [16], so that Z-coordinate is associated to each laser point. Control points are obtained by putting markers on the vertical edges of wall, desks, chairs, boxes and so on, with themselves visiable on video image and the vertical edges be measured by laser scanners. Z-coordinate of each marker is its elevation from the ground surface, which is physically measured previously. XY-coordinates of each marker comes from the laser scans measured vertical edge. In addition, calibration blocks, e.g. shown in Fig.3, can be used to increase the number of control points. Put the calibration block directly on the ground, a horizontal transformation is necessary to associate its local coordinate system of the global one. Let at least two facades be measured by laser scans, which are represented by two-dimensional lines on the horizontal plane of laser scans. A horizontal transformation can be thus calculated, so that the coordinates of all grid points can be converted to the global coordinate system.

# 3 The Method for Pedestrian's Tracking

Pedestrians are tracked from laser scans. Implementing video image to assist for laser-based tracking will be addressed in future study. The laser points of moving objects are extracted from each laser scan by client computers through background subtraction (see Fig.4). They are sent to the server computer, where they are aligned into a global coordinate system, assambled into integrated frames according to their time log, and processed to find and track pedestrians.

A tracking algorithm is developed assuming that the moving objects are the feet of normal pedestrians only. In the followings, flow of the tracking process is first introduced aiming at a global view of the algorithm. A tracking algorithm utilizing Kalman filter is then focused on, where a pedestrian's walking model based on the typical appearance of moving feet is defined.

## 3.1 Flow of the tracking process

A tracking algorithm is designed as shown in Fig.5. In each iteration, server computer gather the data of moving feet in the latest range frames from all client computers and integrates them into a global coordinate system. Since there might be many points shooting upon the same foot, a process is first conducted clustering the moving points of the integrated range frame that has a radius less than a normal foot (e.g. 15cm). The center points of which are treated as foot candidates. Trajectory tracking is conducted by first extending the trajectories that have been extracted in previous frames, then looking for the seeds of new trajectories from the foot candidates that are not associ-



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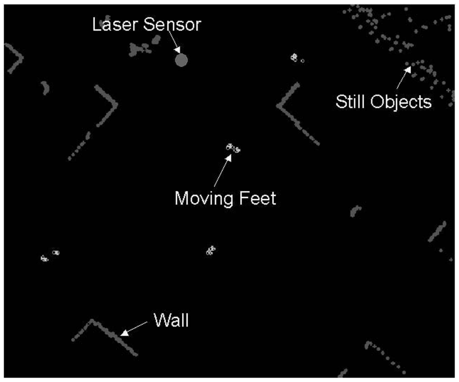


Figure 4: A sample laser scan, colored by background subtraction

ated to any existing trajectories.

A tracing algorithm utilizing Kalman filter is developed extending the existing trajectories to current range frame. It will be addressed in detail in the later sections. Seeds of new trajectories are extracted in two steps. The foot candidates, who are not associated to any trajectories, are first paired up into step candidates (a possible pedestrian) if the Euclidean distance between them is less than a normal step size (e.g. 50cm). A foot candidate may belong to a number of step candidates, if there are multiple options. A seed trajectory is then extracted along a certain number ($N > 3$) of previous frames, which satisfies the following two conditions. First, two step candidates in successive frames overlap at the position of at least one foot candidate. Secondly, the motion vector decided by the other pair of non-overlapping foot candidates changes smoothly along the frame sequence.

## 3.2 Pedestrian's walking model

When a normal pedestrian steps forward, one of the typical appearances is, at any moment, one foot swings by pivoting on the other one. Two feet interchange their duty by landing and moving shifts at a rhythmic pattern.

According to the ballistic walking model proposed by Mochon and McMahon, 1980, muscles act only to establish an initial position and velocity of the feet at the beginning half of the swing phase, then remain inactive throughout the rest half of the swing phase. Here initial position refers to where swing foot and stance foot meets together. Let $v_L$ and $v_R$ be the speed, $a_L$ and $a_R$ be the accelection, $p_L$ and $p_R$ be the position of left and right foot respectively, where both speed, acceleration and position are restricted to a horizon-

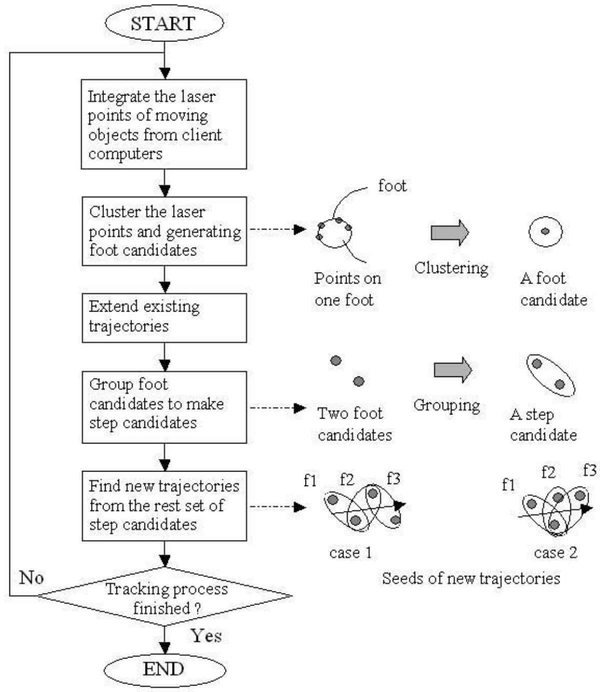


Figure 5: Flow of the tracking process

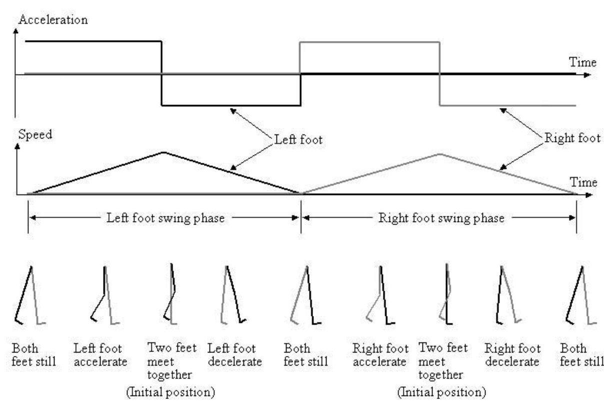


Figure 6: A simplified pedestrian's walking model



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tal plane, and relative to the two-dimensional global coordinate system that has been addressed in previous sections. In the case $|v_L| > |v_R|$, where $\cdot$ is the norm of the vector, left foot swings forward by pivoting on right foot. At the beginning half of the swing phase, left foot shifts from rear to initial position, and swings from standing still at an accelerated speed. Here the acceleration $|a_L|$ is a function of muscles strength. We define $|a_L| = f_L(muscle\_strength) * \dot{v}$, where $\dot{v}$ is the normalized directional vector. During the rest half of the swing phase, left foot shifts from initial to front position, and swings with a decelerated speed from a certain speed to standing still. Here the acceleration $|a_L|$ is a minus value which comes from the forces other than that of left foot muscles. We define $|a_L| = -f_L(other\_forces) * \dot{v}$. During the whole swing phase, right foot keeps almost still, so it has $|v_R| \approx 0$ and $|a_R| \approx 0$. In the same way, we can deduce the speed and acceleration parameters when right foot swings forward by pivoting on left foot, where acceleration $|a_R| = f_R(muscle\_strength) * \dot{v}$ and $|a_R| = -f_R(other\_forces) * \dot{v}$ at the beginning and end half of swing phase respectively, $|v_L| \approx 0$ and $|a_L| \approx 0$ during the whole swing phase. In this research, we simplify pedestrian's walking model by assuming that the acceleration and deceleration on both feet from either muscle strength or other forces ($|a_{L|R}|$) are equal and constant during each swing phase, and they have only smooth changes as the pedestrian steps forward. Fig.6 shows an example of the simplified pedestrian's walking model.

### 3.3 Definition of state model

As has been described in previous section, pedestrian's walking model consists of three kinds of state parameters, position, speed, and acceleration. Position and speed vectors of each pedestrian change continuously, while acceleration parameters change by swing phase in a discontinuous way. A discrete Kalman filter is designed in this research by dividing the state parameters into two vectors as follows.

$$s_{k,n} = \Phi s_{k-1,n} + \Psi u_{k,n} + \omega \qquad (1)$$

Where, $s_{k,n}$ consists of the positions and speed vectors of both feet of pedestrian $n$ at range frame $k$, while $u_{k,n}$ consists of the acceleration parameters. $\omega$ is the state estimation error.

$$s_{k,n} = \begin{pmatrix} p_{L\_x,k,n} \\ p_{L\_y,k,n} \\ v_{L\_x,k,n} \\ v_{L\_y,k,n} \\ p_{R\_x,k,n} \\ p_{R\_y,k,n} \\ v_{R\_x,k,n} \\ v_{R\_y,k,n} \end{pmatrix} u_{k,n} = \begin{pmatrix} a_{L\_x,k,n} \\ a_{L\_y,k,n} \\ a_{R\_x,k,n} \\ a_{R\_y,k,n} \end{pmatrix} \qquad (2)$$

Transition matrix $\Phi$ relates positions and speed vectors at previous time step to those of current one, while $\Psi$ relates acceleration values to the change in positions and speed vectors. They are defined as follows, where $\Delta t$ is the time interval between range frames. In this research, $\Delta t \approx 0.1sec$.

$$\Phi = \begin{pmatrix} 1 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & \Delta t \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad (3)$$

$$\Psi = \begin{pmatrix} 0.5\Delta t^2 & 0 & 0 & 0 \\ 0 & 0.5\Delta t^2 & 0 & 0 \\ \Delta t & 0 & 0 & 0 \\ 0 & \Delta t & 0 & 0 \\ 0 & 0 & 0.5\Delta t^2 & 0 \\ 0 & 0 & 0 & 0.5\Delta t^2 \\ 0 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & \Delta t \end{pmatrix} \qquad (4)$$

In addition, the state vector $u_{k,n}$ is predicted by identifying the swing phase as follows, where $\dot{v}$ is the normalized directional vector.

**Algorithm** Predicting $u^-_{k,n}$
  if left foot swings
    if left foot is the rear foot
      $a^-_{L,k,n} = f_L(muscle\_strength) * \dot{v}_{L,k,n-1}$
      $a^-_{R,k,n} = 0$
    else
      $a^-_{L,k,n} = -f_L(other\_force) * \dot{v}_{L,k,n-1}$
      $a^-_{R,k,n} = 0$
  else if right foot swings
    if right foot is the rear foot
      $a^-_{R,k,n} = f_R(muscle\_strength) * \dot{v}_{R,k,n-1}$
      $a^-_{L,k,n} = 0$
    else
      $a^-_{R,k,n} = -f_R(other\_force) * \dot{v}_{R,k,n-1}$



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$$a^-_{L,k,n} = 0$$

As has been addressed previously, in this research we assume the acceleration on both feet from either muscle strength or other forces are equal and constant during each swing phase, and it changes smoothly as the pedestrian steps forward. The acceleration function is updated whenever a cycle of left foot and right foot swing phase is finished, and it is conducted by taking the mean of the change of a number of latest swing phases. Suppose $N$ latest swing phases have been counted from time step $j$ to $k$, the acceleration function is calculated as follows. Where, $S_{L|R}$ is the average of left or right foot's step size.

$$S_{L|R} = \frac{\sum |p_{L|R,k,n} - p_{L|R,k-1,n}|}{N} \quad (5)$$

$$f_{L|R} = \frac{S_{L|R}}{(k-j+1)^2 * \Delta t^2} \quad (6)$$

The discrete Kalman filter updates the state vector of $s_{k,n}$ based on the measurements as follows.

$$m_{k,n} = \mathbf{H} s_{k,n} + \epsilon \quad (7)$$

Where $m_{k,n}$ denotes the measurements of pedestrian $n$ at time step $k$. $H$ relate the state vector $s_{k,n}$ to measurements $m_{k,n}$. $\epsilon$ represents the measurement error.

$$m_{k,n} = \begin{pmatrix} p_{L\_x,k,n} \\ p_{L\_y,k,n} \\ p_{R\_x,k,n} \\ p_{R\_y,k,n} \end{pmatrix} \quad (8)$$

$$\mathbf{H} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \quad (9)$$

### 3.4 Tracing process using Kalman filter

In tracking each trajectory, the state vector $u_{k,n}$ is first predicted by identifying the swing phase, $s_{k,n}$ and $m_{k,n}$ are then predicted according to Eq.1 and Eq.7 respectively. A searching area is defined on the predicted $m_{k,n}$. If foot candidates of the current frame are found inside the search area, the nearest ones are exploited to compose the updated $m_{k,n}$. Otherwise, missing counter starts. If the missing counter is larger than a given threshold, e.g. 20 frames ($\approx 2sec$), then the tracing of the trajectory stops. Otherwise, the predicted $m_{k,n}$ is exploited as the updated one to update the state vector $s_{k,n}$ and Kalman gain. The process continues until all the trajectories are traced.

| | |
|---|---|
| Max Range Distance | 30 m |
| Max Scanning Angle | 180 degree |
| Max Scanning Rate | 37.5 Hz |
| Angular Resolution | 0.5 degree |
| Distance Resolution | 1 cm |
| Range Error | 4 cm |
| Data Interface | RS422 |
| Voltage | 24V/1.8A |
| Electric Power | 20W |
| Weight | 4.5kg |

Figure 7: Major specification of LMS200

| | |
|---|---|
| Max Pixel Size | 1280*960 |
| Valid Pixel Number | 1,450,000 |
| Frame Rate | 7.5/3.75 fps |
| Data Interface | IEEE 1394 |
| Size | 50*50*110(mm) |
| Data Interface | RS422 |
| Electric Power | 3.3W |
| Weight | 250kg |

Figure 8: Major specification of DFW-SX900

## 4 Experimental Results

An experiment, real-timely monitoring visitors and analyzing the change of their pathes along with time, is conducted at a large exhibition, which lasted for three days and had about 30,000 visitors totally. Four LMS200, by SICK Germany, are located on the floor near a cross point, horizontally scanning at a plane of about 16cm above the ground. The integrated laser scans cover an area of about $30 * 30m^2$ around our booth. On the other hand, a video camera DFW-SX900, by Sony, is set on the top of a booth, about $3.0m$ above the floor, monitoring visitors at a slant angle of about $45^o$, and covering a floor area of about $5*6m^2$. Some major spec of LMS200 and DFW-SX900 are shown in Fig.7 and Fig.8 respectively. A map of sensor layout and measurement coverage is shown in Fig.9. The setting of both laser scanners and video camera are rather flexible. Calibration of all sensor were conducted on-site, which took about totally 10 minutes to calculate the external parameters of laser scanners, and, both internal and external parameters of video camera. Each sensor is controlled by an IBM ThinkPad X30 or X31, which has a CPU of 1GHz or 1.4GHz, and RAM of 512MB. They are connected through 10/100 Base LAN to a server PC, which has a CPU of 1.5GHz and RAM of 1.0GB. Currently, the server computer can simultaneously track trajectories



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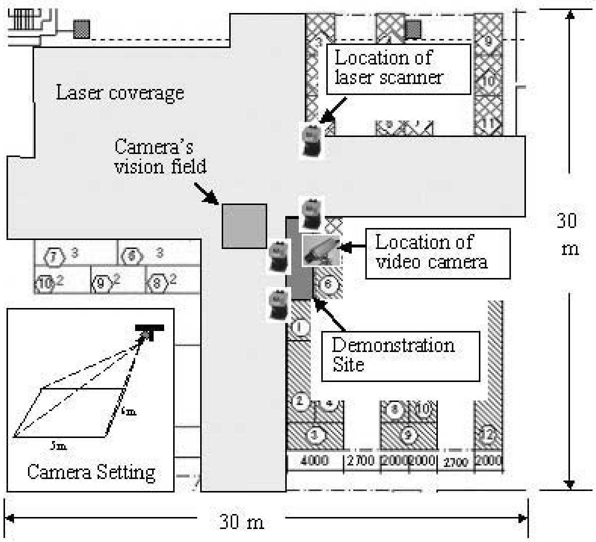


Figure 9: Sensor layout and measurement coverage at the experiment

up to about 30 visitors due to the limitation of computation power. Since on rush hour, there were more than 80 visitors inside laser scanners' measurement coverage, in this experiment, only the visitors inside or nearby video camera's vision field were tracked realtimely, and their trajectories were back projected onto video image on the air. A picture of the experimental site is shown in Fig.10. A result of visitor's tracking from laser points is shown in Fig.11. A result of back projecting trajectory data onto video image is shown in Fig.12. On the other hand, visitor's flow nearby the crossing point, and its change along with time is examined by analyzing the motion behavior of each visitor in an off-line mode. The exhibition was opened on 10:00a.m. and closed on 5:00p.m. every exhibition day. The change of crowd density during a day is shown in Fig.13, where blue means low but non-zero crowd density, while red means high crowd density.

# 5 Conclusion and Future Study

In this research, we propose a novel system of monitoring pedestrians and tracking their trajectories in a wide and open area, using a network of single-row laser range scanners and video cameras on some spots. A pedestrian's walking model on the horizontal cross section of ground level is defined and a tracking algorithm is developed to detect and trace the rhythmic swing feet from laser scans. Trajectory data of two-dimensional coordinates are back projected onto video images, so

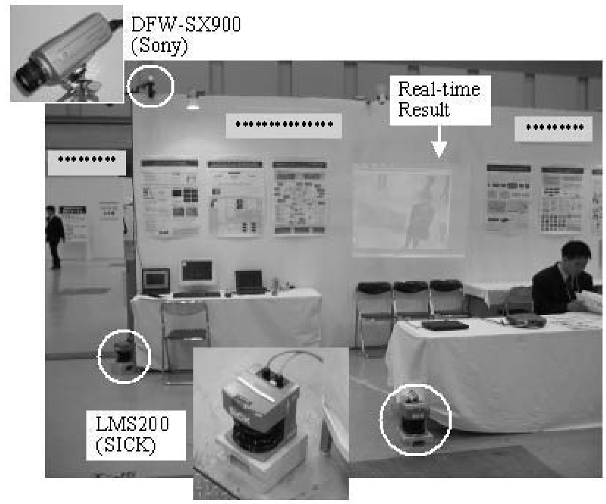


Figure 10: A picture of the experimental site

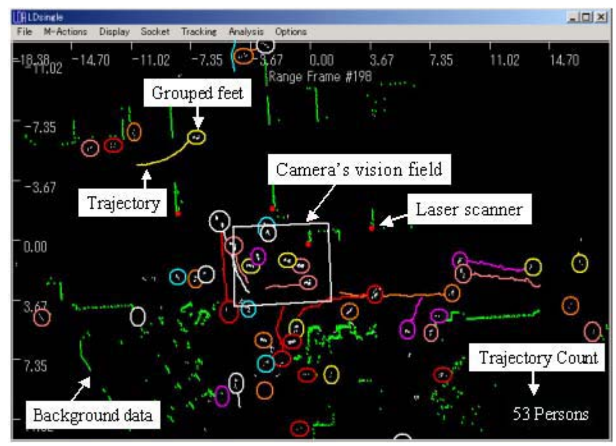


Figure 11: A result of tracking from laser points

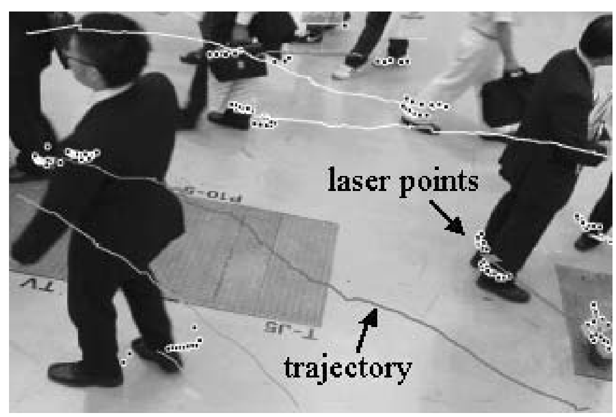


Figure 12: A result of backprojecting trajectory data onto video image

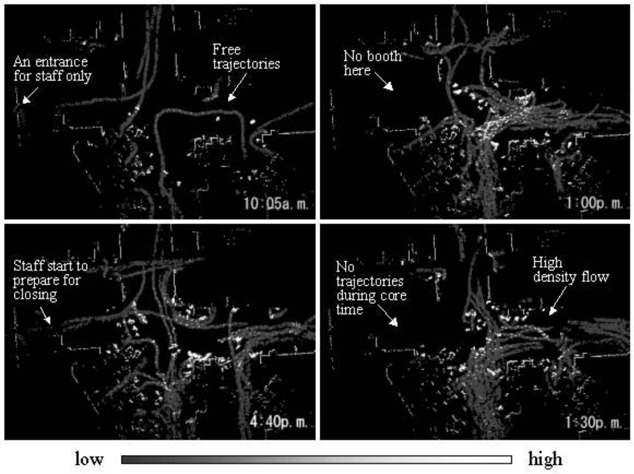


Figure 13: The change of crowd density during an exhibition day

that the attributes, such as the height, cloth color, face of the pedestrian, can be extracted from video image by other existing research efforts, and associated to each trajectory. In future study using trajectory attributes to reduce the mistrackings on laser points, applying the trajectory data for behavioral study and motion analysis will be addressed.

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