

VISUAL SURVEILLANCE TECHNIQUES IN AN ENTRANCE MONITORING APPLICATION

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Abstract

In this thesis, the methods of video analysis for visual surveillance are studied in order to develop an algorithm that detects, tracks and recognizes people at an entrance to a room. To detect people, background subtraction and silhouette analysis are used. To track and recognize people, the colour of a person's clothing is used.

Each background pixel is modeled using a single Gaussian distribution. This model is updated using the corresponding pixel intensity and the variation in intensity of the pixel from one image in the sequence to the next. A pixel in the current image is considered foreground if its intensity is not within a given number of standard deviations of the corresponding background pixel model.

Silhouette analysis is used to determine if a foreground region represents a person. The curvature of the top portion of a silhouette is analyzed to determine if it conforms to the shape of a person's head. Then the percentage of foreground pixels in a region of size proportional to the width of a detected head and immediately below the detected head is determined. If this value is large enough then a person is detected.

To track and recognize people, colour histograms extracted from each person's clothing in a luminance and perceptually uniform chrominance space are compared using the Earth Mover's Distance. Clothing colour is extracted from the same region defined for person detection. The goal is to determine whether a person has entered or exited the room and to associate a sequence showing a person leaving the room with the previously recorded sequence showing that same person entering.

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Chapter 1

Introduction

1.1 Computer Vision

Computer vision involves capturing digital images of a scene and using a computer to analyze these images in order to extract the desired information. To achieve this objective, one may be inclined to design a computer to mimic the human visual system. Wandell [14] reasons that the human brain interprets images using statistical inferences based on prior knowledge of the physical characteristics of our universe and the objects in it. Many vision algorithms have been developed based on this reasoning. For example an algorithm which tracks people in a sequence of images can be simplified if the assumption is made that people walk upright on the floor and not on the ceiling or walls. With the development of faster computers and better digital image capturing devices many of these algorithms are being applied to accomplish a variety of tasks such as inspecting objects, interpreting image sequences and modelling real three dimensional environments.

1.2 Visual Surveillance

Before video cameras were common, surveillance involved having people directly observe the locations which one desired to keep under surveillance. When video cameras

became common and relatively inexpensive, these observers were replaced by several cameras and, most commonly, a person viewing the scenes on video screens from a central location along with a device to record the output from the cameras. A problem with this type of system is that a person can only focus on one scene at a time and is prone to distraction from duty thus some activities may not be reacted to promptly. A solution to this problem is to use computers to process, analyze and react to the images from the cameras.

Common objectives of computer automated visual surveillance systems are to detect and classify all human activities in a scene. Consequently many methods have been developed to accomplish these objectives. Detecting and classifying all human activities in a scene can be broken down into the following steps: image acquisition, background extraction, moving objects segmentation, person detection and person tracking. The information obtained from the execution of these steps can be analyzed by the computer to identify the activities that take place and attempt to recognize the detected people. The computer can also be programmed to record and retrieve this information.

Image acquisition involves projecting the three dimensional reality of the scene onto a two dimensional image that is then used as an input to the computer. Projecting the three dimensional scene onto a two dimensional image can be done using any type of video camera that produces an image of the scene that has as little distortion as possible. For example a camera with a fisheye lense is not desired for this application. The main challenge of image retrieval is choosing the position and orientation of the video camera such that human activity can be detected and classified.

Background extraction involves estimating the intensity value (vector, if colour is being used) of each pixel in the image when the pixel represents a part of a background object given a sequence of images. The main challenge of background extraction is obtaining an accurate estimate of the intensity value (vector) in the presence of image sensor noise, lighting variations and moving objects.

Segmentation of moving objects involves deciding whether a pixel in an image

corresponds to a foreground object or a background object. How well moving objects are segmented depends on how well the background is extracted therefore the main challenge is accurately segmenting moving objects in the presence of image sensor noise using a background model that is not likely to be perfectly accurate.

Person detection involves analyzing the result of moving object segmentation to determine if a foreground region represents one or more persons. The main challenge of detecting a person using shape information is that the shape of each person's body differs from everyone else's to varying degrees, a person can move his appendages (arms, legs, hands, ...) in many ways which can change his shape, and the foreground regions may not accurately represent the shape of the person.

Person tracking involves determining the path of each person as he passes through the scene. The main challenge of person tracking is determining the correspondence of a person detected in one image with the same person detected in previous images if there are more than one person in the scene.

Visual surveillance techniques are being employed in a large variety of scenarios and for many purposes. One scenario in which it is desired to employ visual surveillance techniques is the entrance to a room with restricted access. The purpose of surveying the entrance to such a room can be to record all activity, to determine who is in the room at any given moment, etc.

The environment in which a surveillance system is designed to monitor greatly influences the methods used. For the purposes of visual surveillance the most important environmental factors are the lighting, the expected activity in the scene being observed and the amount of motion in the background.

Some situations such as multiple people interaction, people occluded by other people, or people occluded by large moving background objects (eg. a door opening and closing) may cause the system to not detect or track people passing through the scene.



Figure 1.1: An image of the entrance to the V.I.V.A. lab

1.3 Objectives

The objective of this work is to capture an image sequence of the entrance to a room at a minimum rate of two frames per second, to record any activity in this scene, to keep count of how many people are in the laboratory at any given time and to keep a record of the activity that occurs in the laboratory. The scene under observation shows the entrance portion of the lab and also includes a view of a door giving access to an adjacent room. Fig. 1.1 is an image of the scene taken from the camera being used in this application.

Specifically, the algorithms developed for this system detect, track and recognize people in indoor scenes. The algorithms were tested by implementing them on a personal computer connected to a camera via the USB port and using this setup to observe the entrance to the V.I.V.A. lab.

The following is a list and a brief description of each algorithm in the order in which they are performed for every cycle.

1. The background is estimated by computing the weighted sum between the current image in the sequence and the previous estimate of the background. The value of the weight for each pixel in the current image depends on the motion that occurred between the pixel in this image and the same pixel in the previous image. Segmentation is accomplished by applying a threshold to the absolute

difference between the current image and the background estimation.

2. To detect a person, the foreground regions resulting from segmentation are analyzed to determine if the shape of a head appears on the border of the foreground regions and if a body is below a detected head.
3. Tracking is done by determining temporal correspondences between the people detected in the current image and those detected in previous images using a similar method used for person recognition. In this case the histogram extracted from a person detected in the current image is compared to the histogram extracted from any person detected in previous images.
4. To recognize a person, colour histograms on a luminance and perceptually uniform chrominance space are extracted and accumulated from each image of a person's clothing as they are being tracked in the scene. To compare histograms, a metric called the earth mover's distance [27] is used.

Chapter 2

Literature Review

2.1 Segmentation Using Background Subtraction

This section describes several methods that were previously developed to estimate the background and segment foreground objects in image sequences.

The first step in segmentation using background subtraction is estimating the background. Given a sequence of images of the scene under surveillance, the background is estimated as an image such that each pixel in this image has an intensity value(s) that visually resembles the corresponding portion of the background. Depending on the method of background estimation, each pixel may have more than one intensity value, each of which represents a different estimate of the background at that pixel. The result of background estimation should yield one or more images that look very similar to the scene under observation excluding any foreground objects.

Background subtraction refers to the comparison of each pixel of the current image with a set of pixels in the neighborhood of the corresponding pixel in the background image(s). This comparison usually involves subtracting the intensity value of a pixel in the current image and the intensity value of the corresponding pixel in the background image and applying a threshold to this result to determine if the pixel in the current image represents a part of a foreground object.

When developing a method of background estimation and subtraction, one must

take into consideration the scene which the system will observe. Depending on the scene being observed, one may need to consider changes in lighting conditions, changes to the background, constant motion in the background, the occurrence of shadows and small movements of the image capture device when developing a background estimation technique.

[16] models the background using the pixel-wise temporal median over a set of L previous images in the sequence and computes the absolute difference in pixel intensity between the current image and the background. Then the absolute difference in edge density between the current image and the background image is computed. A threshold is applied to both of these differences and the resulting binary images are combined using a logical or operation to form the segmented image. The values of both thresholds are determined experimentally.

[1] thresholds temporal difference images and uses tensor voting to segment the foreground region so that each segment represents a single object. The value of the threshold is determined experimentally.

[9] thresholds the absolute difference between each incoming image and an adaptive background image which is updated using temporal integration. The value of the threshold is determined experimentally.

[30] models each pixel in the background image as a single Gaussian distribution. A pixel is labelled as foreground if its value is not within a predetermined number of standard deviations of the Gaussian distribution.

[26] models each pixel in the background image as a mixture of Gaussian distributions. For each pixel in the incoming image, if the pixel has a value that is within a constant multiplied by the standard deviation of one of its Gaussian distributions with a high enough weight, then the pixel is labeled as part of the background.

- [31] models the background using an adaptive Hidden Markov Model (HMM). The HMM is trained with a set of images of the scene void of any significant moving objects using the Baum-Welch algorithm with the average intensity of the images as the observations. Each state in this model represents each known possibility of the background. The viterbi algorithm is performed to determine the most likely state of the background given the observation from which any object that is not a part of the background will be segmented via background subtraction and the application of a threshold.
- [33] models each pixel in the background image as a Gaussian random variable by estimating the probability density function of each pixel in the background image using a fixed number of recent intensity values of the pixel and a Normal kernel estimator function. To reduce the effects of shadows on segmentation, only the chrominance values of each pixel are used to estimate the density function. Segmentation is achieved by using the corresponding density function estimate to compute the probability that the current value of a pixel represents a background object. If the probability is below a threshold then the current value of this pixel represents a foreground object. To remove any false positive foreground detections due to any motion in the background (eg trees moving because of wind), the maximum of several probabilities that the current value of a pixel represents a background object is determined and if this probability is greater than a threshold then the current value of this pixel represents a background object. These probabilities are computed using the density function of every pixel in a small neighborhood of the pixel under consideration.

The most widely used methods of background extraction and image segmentation compare the current image with a reference or background image. Any pixels in the current image which differ according to some criteria from the background image are labeled as foreground pixels. The main difference between these methods is how the background is determined. The most common approaches use either a mixture of Gaussians or temporal median to estimate the background image. Another less

commonly used method segments images by comparing the current image with one or more previous images.

The methods described in [9] [26] [16] were designed to segment images taken of outdoor scenes while the methods described in [31] [1] take only indoor scenes into consideration.

2.2 People Detection

This section describes several previously developed methods to detect people in images.

To detect people in images a pattern recognition technique must be used. Pattern recognition usually proceeds as follows:

1. Certain desired features are extracted from the data.
2. The extracted features are compared with a model of a known pattern using a method that yields either a pattern match or not. The method of comparison may be based on statistics, neural networks, etc.

In the case of detecting people in images, the most commonly desired features to be extracted from the image data are shape features. These features may be detected foreground regions, edges, corners, etc.

The main issue is choosing what features to extract, what model to use and what comparison method to use such that a person can be detected in a wide variety of common poses and in the presence of noise in the extracted features.

[1] observes that the curvature of the head and shoulders of most people are very similar to each other in that the top of each shoulder and head have relatively little curvature in the vertical direction when compared to the curvature of the sides of the head. This characteristic is exploited by approximating the first derivative with respect to the horizontal coordinates of the curvature of the

top portion of each foreground region as a feature and determines if the shape of a head and shoulders is present by locating regions with a low value of the derivative (these regions may correspond to the top of a head or shoulder) along with regions with a high value of the derivative (these regions may correspond to the side of a head).

- [9] observes that the silhouettes of most pedestrian poses are very similar to each other with respect to several characteristics of their shapes such as extremes of curvature, area, aspect ratio, etc. Likewise for cyclists. To detect pedestrians and cyclists the features that represent these shape characteristics are extracted from each foreground silhouette. A foreground silhouette is classified as one or more pedestrians or a cyclist by determining if the extracted features satisfy a set of predetermined conditions.
- [4] observes that when a person is walking, their head is usually almost directly above their torso. To detect people walking through the scene the extreme convex points of curvature and the vertical projection histogram of each foreground region are extracted. If a peak in the histogram is close to an extreme convex point of curvature then there is a head of a person in this region. If more than one head is detected in the same foreground silhouette then the local geometry of this silhouette is used to segment it into separate people.
- [28] observes that the silhouette of most people who are standing have very similar aspect ratios and areas, and that a person's head is usually almost directly above their torso. To subdivide each foreground region into separate people a horizontal and vertical projection histogram, area of the foreground region and the foreground region aspect ratio are used.
- [29] observes that people in a lineup at a retail store check out each have been in line for different lengths of time and that each person moves independently of other people. Each individual person in a foreground region is detected by grouping

the foreground pixels according to the amount of time the pixels are labeled foreground and according to the motion the foreground pixels.

[30] makes the same observations as [4] as well as observing that most people walk in a similar manner to each other. The shape and vertical projection of the foreground regions are used to detect people. Then motion templates are used to recognize walking motion which is used to verify person detection.

[6] observes that the shape of a person can still be seen if edge detection is used. The shape of a person is extracted using a pseudo two dimensional hidden Markov model of edge features extracted from sample images of a person before the system is brought on line. When the system is on line, the Viterbi algorithm is used to segment people from the background in an image.

The most common approach to people detection involves analyzing the result of motion based image segmentation using some criteria. The shape of the foreground region is commonly used whereas foreground temporal properties as in [29] are rarely used. A less common, more computationally expensive and more flexible method employs edge detection and a complex statistical model to detect people.

2.3 Colour Feature Extraction and Matching

This section describes several previously developed methods that use colour to either segment an image or to recognize an object in an image.

To use colour information to accomplish a task one must take into consideration image acquisition noise and lighting conditions. Minimizing the effect of image acquisition noise and lighting conditions on how well a method accomplishes a given task requires using an appropriate colour representation, an appropriate method to extract colour information from an image and an appropriate method of analyzing the extracted colour information to achieve the best results possible.

- [5] recognizes people by accumulating the colour of all the foreground pixels which are identified as part of a single person into a measurement vector. They then determine if the features extracted from different images of people match using a χ^2 probability function. The colour representation used is a non-uniformly quantized version of the (y,u,v) colour space.
- [11] recognizes objects by using constrained active appearance models as the features and an optimization technique for matching by minimizing the difference between a synthesized model image and the target image.
- [17] uses colour moments of varying order and degree as features to recognize colour patterns even with changes in illumination and viewing position. The (r,g,b) colour space is used.
- [18] recognizes objects by using histograms constructed using both the colour of each pixel and the relative spatial locations of each pixel in an image with respect to all other pixels in this image. Two such histograms are compared by computing their intersection. If the result is large enough then the histograms are said to represent the same object. The (r,g,b) colour space is used.
- [19] approximates the physical properties of Lambertian surfaces from several training images and uses statistical models to segment images according to differing materials.
- [20] presents several colour ratio gradients that are invariant to object pose and lighting conditions. Colour ratio gradient histograms are used in a quadtree-based split and merge segmentation to segment an image by texture. The goal of this is to retrieve images from a database that show the same object that is shown in a query image.
- [26] presents a method to compare two multidimensional histograms. A measure of dissimilarity between two histograms is computed by determining the minimum amount of "work" required to "move" the contents, or weight, of each bin in one

histogram to a corresponding bin with similar weight in the other histogram. This metric is used to compare colour histograms for the purpose of image retrieval. The CIE-Lab colour space is used because of its perceptual uniformity.

[8] presents a method to compare two multidimensional histograms. A measure of similarity between two histograms is computed by determining the intersection between the histograms. The intersection is the sum of the minimum value of each corresponding bin taken over all bins in the histogram.

These methods show that colour can be used to segment images, to find images in a database, to recognize objects or to recognize colour patterns. The issues considered in these publications were lighting conditions, object pose and sensor noise.

The most commonly used colour features involve computing various types of histograms with the choice of colour space depending on the expected conditions under which the images will be acquired.

2.4 Person Tracking

This section describes a few previously developed methods used to track people in a sequence of images.

The purpose of tracking is to determine the trajectory (actual or image projected) of every person that passes through the scene under surveillance. This involves detecting every person within view of the camera, determining his location, and determining the correspondence between a person detected in one image and the same person that was detected in previous images. To determine this correspondence the trajectory of every person that was detected in previous images and a person's appearance may be used.

Trajectory information usually refers to the position, velocity and acceleration of an object. This information is normally used under the assumption that objects do not undergo many extreme changes in acceleration while moving. For example, if a person is traveling at a certain velocity and acceleration when it is detected at

a certain position in an image then the next position that this person is likely to be detected can be extrapolated using this information. A person's trajectory is estimated using the position of a person in each image of the sequence. This estimate may be subjected to errors due to inaccurate segmentation.

Appearance information refers to any visual characteristics that can be used to distinguish one person from most other people. An example of such a characteristic is a person's face. Such appearance information may be subjected to noise during image acquisition, and to variations in the appearance of the person due to changes in pose and lighting conditions.

- [6] tracks a single person using a Kalman filter whose state vector consists of the location, velocity and bounding box dimensions of the person. The assumption made is that the velocity of the person does not change significantly from one image of the sequence to the next.
- [10] tracks multiple people by assuming that the position of a person changes by a small distance from one image to the next in the sequence. Tracking, therefore, is done by searching an area of the current image surrounding the last known position of a person. If a person is detected in this area then this person is matched with the person detected in the previous frame.
- [4] tracks multiple people by using intensity characteristics of a person's head and estimates of each person's velocity and acceleration. The median position and edges of foreground pixels are used estimate the position of each person.
- [5] tracks multiple people by using colour features extracted from the entire body of each person. These features are compared using the χ^2 probability function.
- [2] tracks multiple people by using the points of extreme curvature on the boundary of each extracted silhouette and a local search to match these features across different images in the sequence. The velocity of each feature is estimated and the features are grouped according velocity. Each of these groups of features represents a different person.

All information used to track a person can be classified as either motion or appearance information. Motion information can include the spatial distance between an object detected in one frame and the same object detected in the next, the velocity of an object over several frames and the acceleration of an object over several frames. Appearance information can include colour and intensity features such as edges and corners.

2.5 Activity Recognition

This section describes a few previously developed methods which recognize certain activities in a sequence of images.

The goal of activity recognition is to determine what each detected object is doing. The most common class of methods used to recognize activity are those that track one or more objects to determine their trajectories and then analyze these to ascertain what these objects are doing. These methods may detect and track whole objects such as a person or a car, or they may detect and track parts of an object such as a person's head or hands. The types of activities that these methods may recognize are those that involve motion such as a person walking, a person pressing a button, a car entering or leaving a parking lot, etc.

Another class of methods uses an object's pose to determine what that object is doing. Such methods may be used to recognize what an object is doing when it is not moving. For example, these methods may be used to determine if a person is standing, sitting, pointing, etc.

[21] recognizes human activity by using the motion of a person's head. A person's head is tracked and the change in position of the head from one image of the sequence to the next for each image in the sequence is the extracted feature vector. Conditional probabilities are used to determine how likely a certain activity is given the extracted feature.

[22] recognizes hand gestures by estimating hand motion and using a time-delay

neural network to classify this motion. Motion is estimated using motion fields which then are used to segment each image into regions of similar motion. The motion fields are computed using region matching across successive images.

- [23] recognizes person to person interaction by analyzing for each image in the sequence the relative distance between two people, the rate of change of the relative distance between the two people, and each person's absolute velocity. Matching is done using minimum absolute difference between the features of a detected interaction and the training set of interactions.
- [24] recognizes activity of a person by extracting the angles of the torso, upper and lower legs as a feature vector and uses the nearest neighbor to classify the feature vector. These angles are extracted using skeletonization of foreground silhouettes.
- [25] recognizes object activity by analyzing the shape, location and orientation of a generalized cylinder created by the 2d projections of a moving object on to the image plane for each image of the sequence. Here, the third dimension is time. To compensate for the view point of the current action possibly being different than the view point of the training set, epipolar lines and the fundamental matrix are used to compare features.

Each of these methods was developed to recognize a specific, predetermined set of activities. Most of these methods rely on the motion of certain body parts. Other methods use the shape of the object.

Chapter 3

Camera Placement

This chapter presents several issues related to placing the camera in visual surveillance applications.

The placement of the camera has a great influence on how well the surveillance application performs. The methods used in the application should be taken into account when deciding where to place the camera.

Placing the camera to observe an entrance to a room involves setting the values of the following parameters.

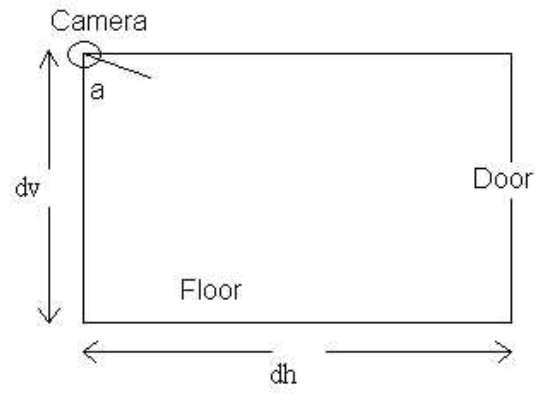
d_h : The perpendicular distance between the camera and the plane in which the door to the lab lies.

d_v : The perpendicular distance between the camera and the floor.

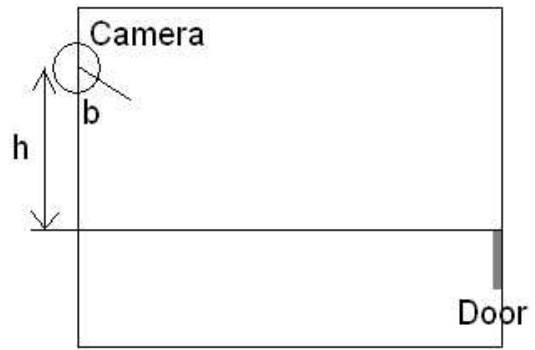
a : The camera view angle with respect to the vertical.

h : The horizontal, perpendicular distance between the camera and the plane perpendicular to the door which passes through the edge of the door nearest to the camera.

b : The camera view angle with respect to the horizontal.



(a)



(b)

Figure 3.1: Diagram showing the position and angle of the camera with respect to the door and floor of the scene from (a) side view, (b) directly above

Fig. 3.1 shows two diagrams which visually indicate the physical meaning of each parameter.

There are a few factors which one must take into consideration when deciding how to set up the camera to observe a scene.

1. Structure surrounding the scene.
2. Amount of irrelevant activity taking place within the view of the camera.
3. Effect on recognition rate.
4. Effect on person detection.

The structure surrounding the scene refers to the walls, ceiling and any large fixed objects which are on the border of the open area where people will be passing through. These must be considered when choosing a location for the camera because the camera must be attached to something so that it has an unobstructed view of the scene and it is stationary.

We would like to minimize the probability of irrelevant activity occurring within the camera's view because any images in which there is some motion will be stored on a hard disk. Therefore, any irrelevant activity within the camera's view will result in wasted memory space. Since the purpose of this application is to detect any person entering or leaving via the entrance under observation, any activity not related to someone entering or leaving is considered irrelevant. A good place to put the camera, in order to satisfy the above criterion, is in the room facing the entrance and not so far from the entrance that most of the room is within the view of the camera. Fig. 3.2 (c) shows how placing the camera too far from the entrance may result in more irrelevant activity occurring within the camera's field of view.

The recognition rate of this system depends, among other things, on how much information can be extracted from a person passing through the scene. A camera that is placed very close to the door, ($d \approx 0$) and is facing the door, see Fig. 3.2 (b), will capture a small number of high resolution images of anyone passing through the

scene. A camera that is placed very far from the door ($d \gg 0$), see Fig. 3.2 (c), will capture a large number of low resolution images of anyone passing through the scene. Some situations may arise which require the off line determination of the identity of a person who has entered the lab so each image of this person should clearly show his face (taking for granted that his face is not covered up). This consideration eliminates using a direct overhead view ($a \approx 0^\circ$), see Fig. 3.2 (d).

A situation which may occur in a scene being observed by a camera is there are people in the scene who are directly between the camera and some other people in the scene thus these people are not detected, see Fig. 3.2 (a). To reduce the frequency of this situation occurring, f must be set as high as the first and third considerations allow. Once f and d are set then a is set so that the top of the door to the lab is approximately aligned with the top of the captured images. Fig. 3.2 (d) shows how a camera that is placed directly above the scene and facing down greatly reduces occlusions but also makes recognition more difficult.

If background subtraction is used for person detection then a rapidly changing background such as a door opening and closing could prevent people from being detected. The frequency of occurrence of this situation can be reduced by selecting the position of the camera so that in the most common situations anyone passing through the scene will not be directly between the door and the camera for most of the time that they are in the scene. More specifically h and d should be set to minimize the frequency of occurrence of this situation. Once h and d are set then b is set so that the entire scene can be viewed from the camera.

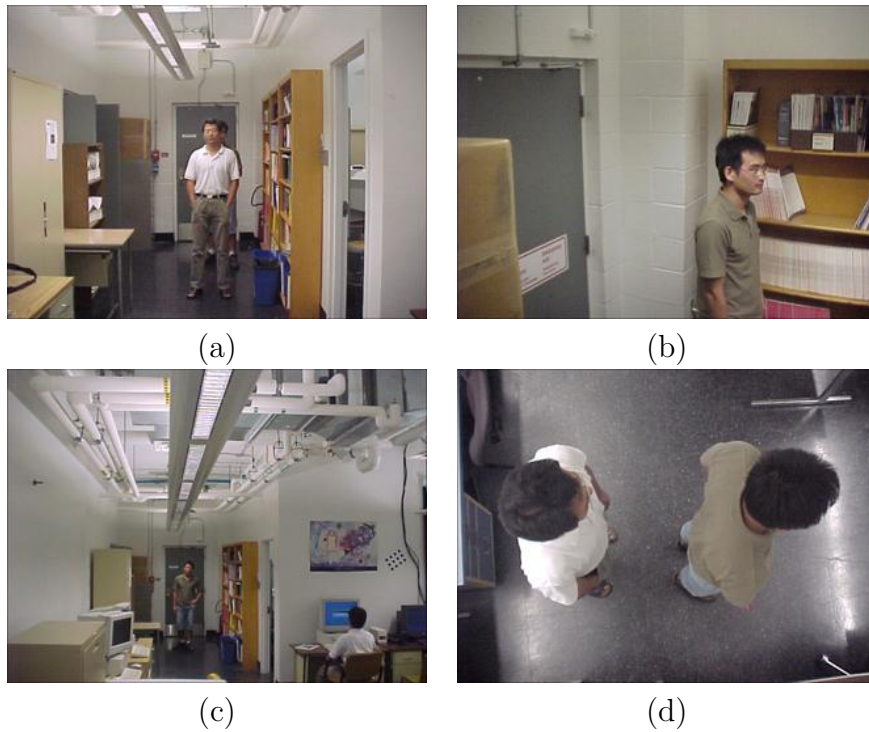


Figure 3.2: (a) an image taken when the camera is close to the floor; (b) an image taken when the camera is very close to the door; (c) an image taken when the camera is too far from the door; (d) an image taken when the camera is above the scene looking straight down

Chapter 4

Background Subtraction

This chapter discusses how to segment foreground objects from the background of the image.

The foreground regions of an image are extracted by a pixel wise comparison between this image and a background image. Any pixels which differ by more than a threshold are labeled as foreground (white) pixels in a binary image. All other pixels are labeled as background (black). The background model used is similar to that used in [26] with the main difference being that each pixel will be modeled using only one Gaussian distribution and the coefficient used to update the mean and variance of the model is computed by comparing two consecutive images. Indeed observing an indoor scene with good lighting conditions, stable background, and with moving objects (people) of relatively important size does not necessitate the use of a more complex background model such as the model presented in [26] with each pixel being modeled using a mixture of Gaussian distributions. This method was chosen because it yields good results for our scenario with minimum complexity.

4.1 Background Subtraction Algorithm

For the purpose of detecting motion and foreground segmentation the luminance of each pixel is used because experiments have shown that the foreground was segmented

reasonably well using the luminance.

The following is a list of symbols and their descriptions representing values and data used to perform foreground segmentation.

\mathbf{Y}_t : The luminance component of image t in the image sequence.

\mathbf{M}_t : An image where each pixel represents the running average of the observed intensity values at that pixel in each image of the sequence up to and including image t .

\mathbf{V}_t : An image where each pixel represents the variance of the observed intensity values at that pixel in each image of the sequence up to and including image t .

\mathbf{A}_t : An image where each pixel is used as a weighting factor when updating both \mathbf{M}_t and \mathbf{V}_t . $0 \leq \mathbf{A}_t \leq 1$

$abs(\mathbf{I})$: Yields an image in which each pixel has a value equal to the absolute value of the corresponding pixel in the image \mathbf{I} .

\mathbf{D}_t : An image where each pixel represents the absolute difference between \mathbf{Y}_t and \mathbf{M}_{t-1} .

N_{coef} : The number of coefficients in the median filter applied to \mathbf{D}_t .

\mathbf{T}_t : An image where each pixel represents the threshold applied to the corresponding pixel in \mathbf{D}_t .

\mathbf{B}_t : A binary image that represents the result of segmentation.

N_{dile} : The number of times morphological dilation and erosion are performed on \mathbf{B}_t .

N_o : The number of foreground pixels in \mathbf{B}_t .

N_c : The minimum number of foreground pixels in \mathbf{B}_t required to perform person detection.

N_m : The maximum number of foreground pixels in \mathbf{B}_t permitted to perform person detection.

Each pixel $\mathbf{M}_t(x, y)$ and $\mathbf{V}_t(x, y)$ is updated using equations 4.1 and 4.2 respectively.

$$\mathbf{M}_t(x, y) = (1 - \mathbf{A}_t(x, y))\mathbf{M}_{t-1}(x, y) + \mathbf{A}_t(x, y)\mathbf{Y}_t(x, y) \quad (4.1)$$

$$\mathbf{V}_t(x, y) = (1 - \mathbf{A}_t(x, y))\mathbf{V}_{t-1}(x, y) + \mathbf{A}_t(x, y)(\mathbf{Y}_t(x, y) - \mathbf{M}_t(x, y))^2 \quad (4.2)$$

The value of $\mathbf{A}_t(x, y)$ determines how much $\mathbf{Y}_t(x, y)$ affects $\mathbf{M}_t(x, y)$ and $\mathbf{V}_t(x, y)$. The larger $\mathbf{A}_t(x, y)$ is the more it affects $\mathbf{M}_t(x, y)$ and $\mathbf{V}_t(x, y)$. It would be desirable that if $\mathbf{Y}_t(x, y)$ represents a foreground object then $\mathbf{A}_t(x, y)$ would be very small so that the background model would not be greatly affected by the foreground object. Conversely, it would be desirable that if $\mathbf{Y}_t(x, y)$ represents a background object then $\mathbf{A}_t(x, y)$ would be very large so that the background model would adapt fairly quickly to the background object. Since our goal is to detect people who are entering or leaving an area, any foreground objects of interest will be in motion. The motion of an object at a given pixel in two consecutive images, $\mathbf{Y}_{t-1}(x, y)$ and $\mathbf{Y}_t(x, y)$, can be estimated by the absolute difference between the pixel intensities. $\mathbf{A}_t(x, y)$ is computed using this estimation so that if the intensity variation is large then $\mathbf{A}_t(x, y)$ is small and if the intensity variation is small then $\mathbf{A}_t(x, y)$ is large. The method of computing $\mathbf{A}_t(x, y)$ such that the previously discussed characteristics are satisfied is shown in equation 4.3.

$$\mathbf{A}_t(x, y) = \text{max}A - \frac{\text{abs}(\mathbf{Y}_t(x, y) - \mathbf{Y}_{t-1}(x, y)) * \text{max}A}{\text{max}Y} \quad (4.3)$$

$\text{max}A$: The desired maximum value of $\mathbf{A}_t(x, y)$.

$\text{max}Y$: The maximum possible value of $\mathbf{Y}_t(x, y)$.

From equation 4.3 it can be shown that if $abs(\mathbf{Y}_t(x, y) - \mathbf{Y}_{t-1}(x, y)) \approx maxY$ then $\mathbf{A}_t(x, y) \approx 0$; also if $abs(\mathbf{Y}_t(x, y) - \mathbf{Y}_{t-1}(x, y)) \approx 0$ then $\mathbf{A}_t(x, y) \approx maxA$.

Each pixel intensity, $\mathbf{Y}_t(x, y)$, is compared to the background model via equation 4.4 and the corresponding pixel, $\mathbf{B}_t(x, y)$ is labeled either foreground or background, 1 or 0 respectively, by applying a threshold to \mathbf{D}_t using equation 4.6.

$$\mathbf{D}_t(\mathbf{x}, \mathbf{y}) = abs(\mathbf{Y}_t(x, y) - \mathbf{M}_{t-1}(x, y)) \quad (4.4)$$

Before a threshold is applied to the difference image, \mathbf{D}_t , it is filtered using a square median filter. This is done to remove any impulsive noise in the difference image. The greater the number of coefficients in the median filter the more impulsive noise will be removed, the more distortion will occur in the shape of the silhouettes and the more computation will be required to filter the image.

The threshold, $\mathbf{T}_t(\mathbf{x}, \mathbf{y})$, is then computed.

$$\mathbf{T}_t(\mathbf{x}, \mathbf{y}) = max(m * \sqrt{\mathbf{V}_t(x, y)}, minT) \quad (4.5)$$

m : A parameter chosen off line that allows for gradual lighting changes in the scene.

$minT$: A chosen minimum value for the threshold.

$$\mathbf{B}_t(x, y) = \begin{cases} 1 & \text{if } \mathbf{D}_t(x, y) > \mathbf{T}_t(x, y) \\ 0 & \text{otherwise} \end{cases} \quad (4.6)$$

A minimum threshold, $minT$, is used to prevent any perturbations in the scene from causing a large number of false positive foreground pixels if the variances of the pixels become very small.

If there is a person passing through the scene, this person's shape as seen in the binary image \mathbf{B}_t is sometimes slightly fragmented. This fragmentation may cause most person detection methods to fail. To remove as much of this fragmentation as possible a morphological closing operation is performed on \mathbf{B}_t . Morphological closing involves dilating the binary image N_{dile} times and then eroding the resulting binary



Figure 4.1: (a) an image of a person’s silhouette extracted without the use of either median filtering or morphological operations; (b) an image of a person’s silhouette extracted with the use of both median filtering and morphological operations

image the same number of times. The greater N_{dile} is the larger the gaps and holes that will be filled in by the operation, the more distortion in the silhouette shape will occur, and the more computations that will be required to perform the operation.

Fig. 4.1 and Fig. 4.2 show segmented images with and without the use of median filtering and morphological operations. These images show that median filtering removes most of the false positive foreground regions and that morphological operations improve the shape of a person’s extracted silhouette. They also show that these operations cause some small deviations from the proper shape of the silhouettes.

The number of pixels in \mathbf{B}_t which have a value of one is counted to give N_o . If N_o is greater than a predetermined constant, N_c , and less than a predetermined constant, N_m , then there is enough activity in the scene that may be caused by a person and there is not so much activity that further analysis will yield erroneous results. If this condition is satisfied then person detection is performed. How N_c is determined depends on a number of factors. N_c should be directly related to the smallest expected image size of a person. This size depends on the smallest expected actual size of a person, the furthest expected distance of the camera from a person and the dimensions, in pixels, of the image. The main issue here is if N_c is too large then significant activities will be missed; if N_c is too small then many insignificant



Figure 4.2: (a) an image of a person's silhouette extracted without the use of either median filtering or morphological operations; (b) an image of a person's silhouette extracted with the use of both median filtering and morphological operations

activities will be unnecessarily analyzed. Conversely, N_m should be chosen to be small enough to prevent unnecessary analysis of the foreground regions and large enough to allow the analysis of meaningful foreground regions.

Many video cameras automatically adjust the image exposure time to the current lighting conditions so when such a video camera is activated, the first few images captured will initially be too bright and will darken gradually until the proper exposure time is reached. This change in brightness will cause the background subtraction method to yield erroneous results so when the system is first activated, the first few captured images are discarded.

4.2 Segmentation Results

This section presents several images that were segmented using the method described in this chapter.

For all segmentation results shown, the following are the values of each parameter used.

$$\text{maxA} = 0.05$$

$$maxY = 255$$

$$m = 3$$

$$minT = 5$$

$$N_{coef} = 25$$

$$N_{dile} = 5$$

$$N_c = 40$$

$$N_m = 50000$$

Sequences 1 and 2 in Appendix A show the segmented images of two people passing through the scene under surveillance. As you can see, the silhouettes of each person, formed using the segmentation method, fairly closely resembles the actual shape of the person for most images in the sequence.

Any deviations in the shape of the silhouette from the actual shape of the person may have many possible causes. A few such causes could be the similarity between the colour of a part of a person and the colour of the background at the same position, or the partial occlusion of a person by an object, or a door being opened behind a person.

The similarity between the colour of part of a person and the colour of the background estimate at the same image position could have two causes. It could be caused by coincidence that this part of the person is very similar in colour to the part of the scene behind this person or it could be caused by the background adaptation incorporating this person into the estimate of the background.

Some of these deviations appear as square holes in the silhouette. These holes are due to the colour of the background object at these positions being very similar to the colour of the foreground objects at the same positions. These holes are square because the morphological operations applied to the silhouette after segmentation use the eight point connectivity rule when erosion is applied. This type of erosion changes



Figure 4.3: (a) an image of two people; (b) an image showing the result of segmentation

a foreground pixel into a background pixel if it is adjacent to a background pixel. So if there is a hole that is one pixel in size in a foreground region then a single erosion operation will enlarge this hole making it a square that is three pixels wide. Further application of erosion operations will enlarge this square.

Some foreground regions that do not correspond to a moving object are very small when compared to the foreground regions that correspond to people. These false positive foreground regions are caused by CCD sensor noise, or by shadows or reflections of a moving object in the scene. Fig. 4.3 shows an example of the extracted silhouette of a person whose shape is affected by false positive foreground regions. These regions are so small that the shape of the silhouette still fairly closely resembles the shape of the person.

Large false positive foreground regions are caused by either a door being opened or by a sudden extreme change in the illumination of the scene. Fig. 4.4 shows the result of segmentation when a door has been opened. From this figure, we can see that the foreground silhouette does not represent the shape of the person.

Two sequences of images that show people passing through the scene and the corresponding extracted foreground regions can be found in appendix A.



Figure 4.4: (a) an image of a person who is in between the camera and a recently opened door; (b) an image showing the result of segmentation

Chapter 5

Person Detection

Once the silhouettes have been formed they must be analyzed to determine if they represent one or more people. The goal of person detection is to estimate the location of each person in an image and what regions of the image correspond to each person. This must be done because sometimes one silhouette represents multiple people or sometimes a silhouette does not represent any people.

The part of a person's body that undergoes the least amount of change in shape and whose shape is most consistently and accurately represented by the silhouette obtained by background subtraction is a person's head. These characteristics make detecting the shape of a person's head in a silhouette relatively fast and easy when compared to detecting the shape of other parts of a person's body. It is for this reason that we search for the shape of a person's head in a silhouette to detect a person.

5.1 Detection Algorithm

We search for the head of each person in the scene by first locating all local vertical peaks on the boundary of each silhouette using Quasi-Topological Codes in a similar fashion to what was done in [9]. This method scans a binary image from left to right using a rectangular, two element window with two rows and one column.

$$\begin{pmatrix} u \\ l \end{pmatrix}$$

The scan can be in one of six possible states after a location in the image has been scanned. The state of the scan after a location has been scanned depends on the previous state of the scan and the values of u and l at that location. The following table shows what the next state of the scan will be for given values of u and l and a given previous state. Each state and transition was chosen so that every possible combination of the values u and l as well as every possible order in which these combinations occur are accounted for, and there are no terminal states.

Inputs		States/Output					
u	l	0	1	2	3	4	5
0	0	0	0/o	0	0	0	0
0	1	1	1	1	4	4	1
1	0	2	2/o	2	5	2	5
1	1	3	3	3	3	3	3

If the scan produces an output 'o', then the location in the image in which this output has been produced is a local vertical peak.

From each local peak found, the silhouette boundary is scanned in the left and right directions recording the curvature using a square four element window.

$$\begin{pmatrix} p1 & | & p2 \\ \hline p4 & | & p3 \end{pmatrix}$$

$$c = p1 + 2p2 + 4p3 + 8p4 \quad (5.1)$$

$$p1, p2, p3, p4 = 0 \text{ or } 1$$

c : A value representing the curvature of the silhouette boundary at a given pixel.

M_{conv} : The minimum number of pixels on the silhouette boundary that have a convex curvature for the silhouette to be considered as representing a person's head.

M_{drop} : the minimum number of pixels on the silhouette boundary that have a vertical orientation for the silhouette to be considered as representing a person's head.

M_{scan} : the maximum number of scan iterations.

The value of c determines what the curvature of the boundary at a certain point is. If tracing the silhouette boundary starting from the maximum point in the left and right directions yields a convex curve and then a vertical drop, then this boundary is likely to be the boundary of a head. A convex curve is achieved when $c = 12$ for a minimum number of scan iterations, M_{conv} . A vertical drop is achieved when $c = 9$, or $c = 11$ for a minimum number of scan iterations, M_{drop} . If either one of these conditions is not satisfied before M_{scan} iterations in either direction have been executed then the scan is stopped and the local peak probably does not represent a person's head.

Next, the width of each putative head is determined by recording the horizontal coordinate of the pixel on the boundary of the head which is furthest left of the local maximum point and the pixel on the boundary of the head which is furthest right of the local maximum point.

The final criteria for determining if each putative head is in fact a person's head is that it must have a body under it. To determine this, a region is defined for each putative head which is bounded horizontally by the extreme horizontal coordinates of the boundary of the head found above, on top by the vertical coordinate of the maximum point and on the bottom by the vertical coordinate of the top plus the width of the head multiplied by some constant.

b : The Estimated vertical coordinate of the bottom of the torso.

m_y : The vertical coordinate of the peak of the putative head.

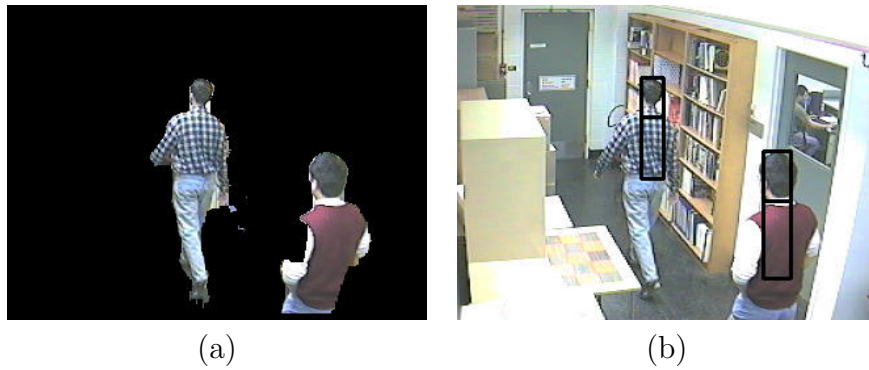


Figure 5.1: (a) Segmented image of two people. (b) Image showing two people with the region in which the percentage of pixels is computed to determine if a person is detected

w : The estimated width of the putative head.

k : An approximate value of the ratio of the height of a person's head above the bottom of their torso to the width of their head.

M_{body} : The minimum percentage of pixels in the torso region of the binary image that are foreground required for this region to be considered a person.

$$b = m_y + k * w \quad (5.2)$$

Where m_y is the vertical coordinate of the maximum point, k is the expected ratio of a person's height to the width of his head, and w is the width of the head. In this application we limit the height to the length from the top of the head to the beginning of the legs. The possible head is considered above a body if this defined region of the binary image has a percentage of pixels labeled as foreground that is greater than a given value, M_{body} . Fig. 5.1 shows a segmented image of two people in the scene and an image in which the region defined above is indicated for each person by black rectangles.

A person that is detected according to the above criteria may not be entering or exiting the room. This person will likely not be considered to be entering or exiting the room by the people tracking algorithm which takes into consideration how many times the same person is detected and the location of this person each time they are detected.

5.2 Person Detection Results

This section presents the results of performing the person detection method described at the beginning of this chapter on the segmented images presented in chapter 4.

The results of person detection shown were generated using the following parameter values.

$$M_{conv} = 3$$

$$M_{drop} = 3$$

$$M_{scan} = 20$$

$$k = 5$$

$$M_{body} = 0.7$$

The sequences in Appendix B show the segmented images and the original images with black rectangle indicating the people that have been detected.

The most important characteristic of these sequences is that every person who passes through the scene under observation has been detected at least twice. Any instance in which a person was not detected was due either to poor segmentation, partial occlusion, or a door being open behind the person. When there were people in the scene and they were not occluded by an opening or closing door or by another person, then these people were detected 94.3 percent of the time. This value was computed by looking at 240 images of at least one person in the scene and counting how many times every person who satisfied the above criteria was not detected.



Figure 5.2: (a) an image showing the silhouettes of two people; (b) an image showing neither person being detected

Fig. 5.2 shows how two people were not detected even though they were in the scene. One person was not detected because the door was being opened resulting in an extracted silhouette that does not represent the person's head. The other person was not detected because a large part of this person's body was not labeled as foreground and thus not enough pixels in the rectangle shown in Fig. 5.1.

Fig. 5.3 shows how two people were not detected even though they were in the scene. One person was not detected because the shape of the extracted silhouette in the region of this person's head does not fit the criterion for head detection defined in this chapter. The other person was not detected because shape of one side of this person's head was not accurately represented by the extracted silhouette. This inaccuracy was caused by the other person in the image being in such a position behind this person that part of this person's head is between the camera and the other person.

Some false detections did occur but they will not be mistaken as objects of interest by the tracking algorithm due to their low frequency of occurrence and inconsistency of the colour of the part of the scene contained within the corresponding black rectangles. Two hundred forty images in which activity was occurring yielded thirteen false positive detections. This means that false positive detections occur approximately

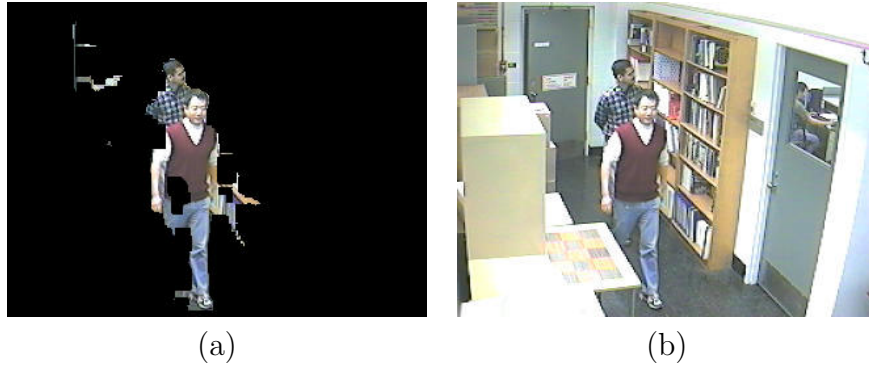


Figure 5.3: (a) an image showing the silhouettes of two people; (b) an image showing neither person being detected

5.4 percent of the time.

Fig. 5.4 shows two false detections that occurred in an image. These were the result of the shape of certain regions of the extracted silhouettes which, by chance, fit the criteria defined in this chapter for the shape of a person's head and body.

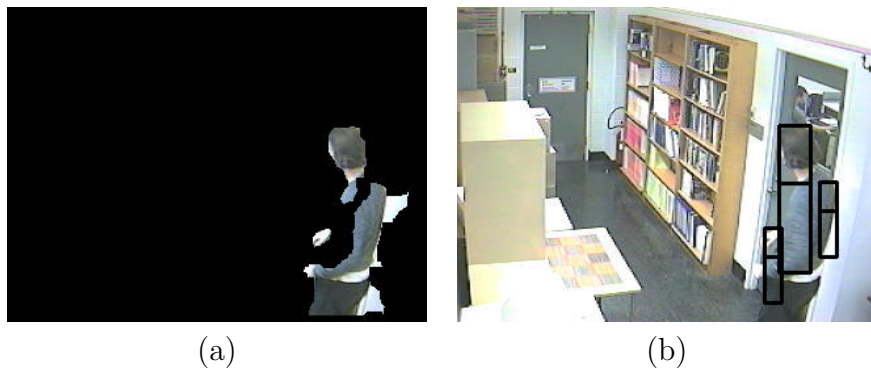


Figure 5.4: (a) an image showing the silhouette of a person; (b) an image showing two false detections

Chapter 6

Person Recognition

In order to monitor the activities which occur in the room under observation, we have to be able to recognize a person that passes in front of the camera. More specifically our goal is to associate a sequence showing a person leaving the room with the previously recorded sequence showing that same person entering the room. To distinguish between different people we decided to use colour information extracted from each person's clothing. This will work well if the observed people wear a good variety of clothing and if we expect that they will not change their clothing once inside the room. Since this system monitors an area where people are passing through and therefore are seen from different angles, we choose not to use skin or hair colours. These attributes are more likely to be similar between different people and are more difficult to reliably extract from different angles. Moreover clothing colour information is generally radially invariant. In other words, the colour of one's clothing tends to stay the same whether it is viewed from the front or the back of a person. Facial features are not used because a single camera which captures images at 320x240 resolution is used to monitor an area that is too large to get an image of a person's face with high enough resolution to successfully perform facial recognition.

6.1 Feature Extraction Algorithm

To extract colour information, a three dimensional histogram is used. We choose to use a histogram because, as will be shown later, the histograms of the colours extracted from people wearing different coloured clothing are clearly different whereas histograms of the same person taken at different times are more similar to each other.

A three dimensional histogram is used because all psycho-visual experiments that have been performed have concluded that each colour that the human visual system can see can be composed by a linear combination of three primary colours. These primary colours can be considered as the basis vectors of a vector space. This vector space is commonly referred to as a colour space. For example, the most commonly used colour space uses certain shades of red, green and blue as its primary colours. Any colour in a colour space is represented by a three dimensional vector so as a vector in one vector space can be transformed to a vector in another vector space, a colour in one colour space can be converted to a colour in another colour space. The choice of colour space depends on the purpose of representing colour in an application. In this application where different colours must be distinguished from each other based on human perception a perceptually uniform colour space is used.

Two of the primary colours used describe the chrominance, $q_{u'}$ and $q_{v'}$, defined by the CIE Uniform Chromaticity Scale and the third primary colour describes the luminance defined by the y component of the CIE XYZ colour space.

Note that only pixels that are labeled as foreground and do not represent a part of the person's head will be added to the histogram.

$$y = 0.2127R + 0.7152G + 0.0722B \quad (6.1)$$

$$x = 0.4125R + 0.3576G + 0.1804B \quad (6.2)$$

$$z = 0.0193R + 0.1192G + 0.9502B \quad (6.3)$$

$$q_{u'} = \frac{4x}{x + 15y + 3z} \quad (6.4)$$

$$q_{v'} = \frac{9y}{x + 15y + 3z} \quad (6.5)$$

R : The red component of a pixel's colour from the Rec 709 Primaries.

G : The green component of a pixel's colour from the Rec 709 Primaries.

B : The blue component of a pixel's colour from the Rec 709 Primaries.

y : The y component of a pixel's colour from the CIE XYZ colour space.

x : The x component of a pixel's colour from the CIE XYZ colour space.

z : The z component of a pixel's colour from the CIE XYZ colour space.

$q_{v'}$: A chrominance of a pixel's colour from a perceptually uniform colour space.

$q_{u'}$: A chrominance of a pixel's colour from a perceptually uniform colour space.

The chrominance defined above are perceptually uniform which means that two colours which are at a fixed Euclidean distance from each other on the $(q_{u'}, q_{v'})$ plane will have the same relative perceptual difference to a human no matter where these colours are located on the $(q_{u'}, q_{v'})$ plane. This characteristic allows one to decide numerically which pair of colours look more alike given several colours.

The luminance of a colour signal represents most of the energy in the colour signal so it is more susceptible to lighting variations and shadow effects than the chrominance. For this reason it is desirable to be able to quantize the luminance more coarsely than the chrominance. This is why we convert the colour signal from RGB to luminance and chrominance.

The domain of each dimension of the histogram is chosen to be the range of the corresponding colour component. The number of bins and the bin boundaries are chosen off line and are fixed. These parameters are fixed to make accumulating colour information from several images of the same person in the image sequence into a single histogram more efficient. The number of bins, in other words the coarseness of quantization, for each dimension is chosen depending on how much computational power is available. The higher the number of bins, the better the recognition results and the more computational power required.

The alternative to this would be to make the histogram dimension range, bin sizes and bin boundaries depend on the colour data being processed. For example the range of the dimension representing the luminance will have an upper bound equal to the maximum luminance value found in the image and the lower bound equal to the minimum luminance value found in the image. The drawback to using such a flexible histogram is that if a histogram is created from the data in one image then it cannot be used to accumulate the data from any other images. Therefore it would be inefficient to use a flexible colour histogram to accumulate the colour information taken from several images of a person into a single histogram.

Another important factor in extracting the colour of a person's clothing is from what region in the image to extract the colour. This region should most likely be void of any background, parts of other people, skin or hair. A simple region that satisfies this criterion is a rectangular region below the person's neck. Choosing to extract the colour from this region greatly reduces the possibility of colours from other people in the image being mixed with the colours extracted from the person of interest due to overlap of body parts. The area of the head and neck of a person is approximated by a rectangular region of width equal to that of the head and height proportional to the width. Fig. 6.1 and Fig. 6.2 show the areas of the heads and necks, region enclosed by the black squares, of several people. Fig. 6.3 shows the head regions and the colour extraction regions of several people. The width and height of the head and colour extraction regions are defined as follows:

head region width: width of the head.

head region height: twice the width of the head.

colour extraction region width: width of the head.

colour extraction region height: three times the width of the head.

To demonstrate how the colour histogram of a person is more similar to the colour histogram of the same person taken at a different time than the colour histograms taken from different people, Fig. 6.4 shows two images of the same person, one taken from the front and the other taken from behind, and two images, each of a different person taken from the front. Contour diagrams of the chromaticity dimensions of the colour histograms extracted as described above are shown beside their corresponding images. The two histograms taken from the same person are much more similar to each other than those taken from the other people.

When a person passes through the scene this person is tracked and the luminance and chrominance information discussed above is accumulated from every image of the person as he passes through the scene into the colour histogram. The histogram is then normalized so that each bin now contains the percentage of the total number of pixels accumulated in the histogram. This procedure is performed for each person passing through the scene resulting in a different histogram being created for each person regardless of how many people are passing through the scene at any given time. The method used to track each person is presented in chapter 7. In the cases when a histogram extracted from a person does not represent the true colour of this person's clothing this histogram will likely not be added to the cumulative histogram because of the tracking algorithm. The tracking algorithm has a criterion that the measure of dissimilarity between a current histogram and a histogram extracted from a person currently being tracked must be less than a given value for the current histogram to be added to the cumulative histogram.



Figure 6.1: sample images showing 4 detected persons and their head regions



Figure 6.2: sample images showing 4 detected persons and their head regions



Figure 6.3: sample images showing 4 detected persons, their head regions and the colour extraction regions

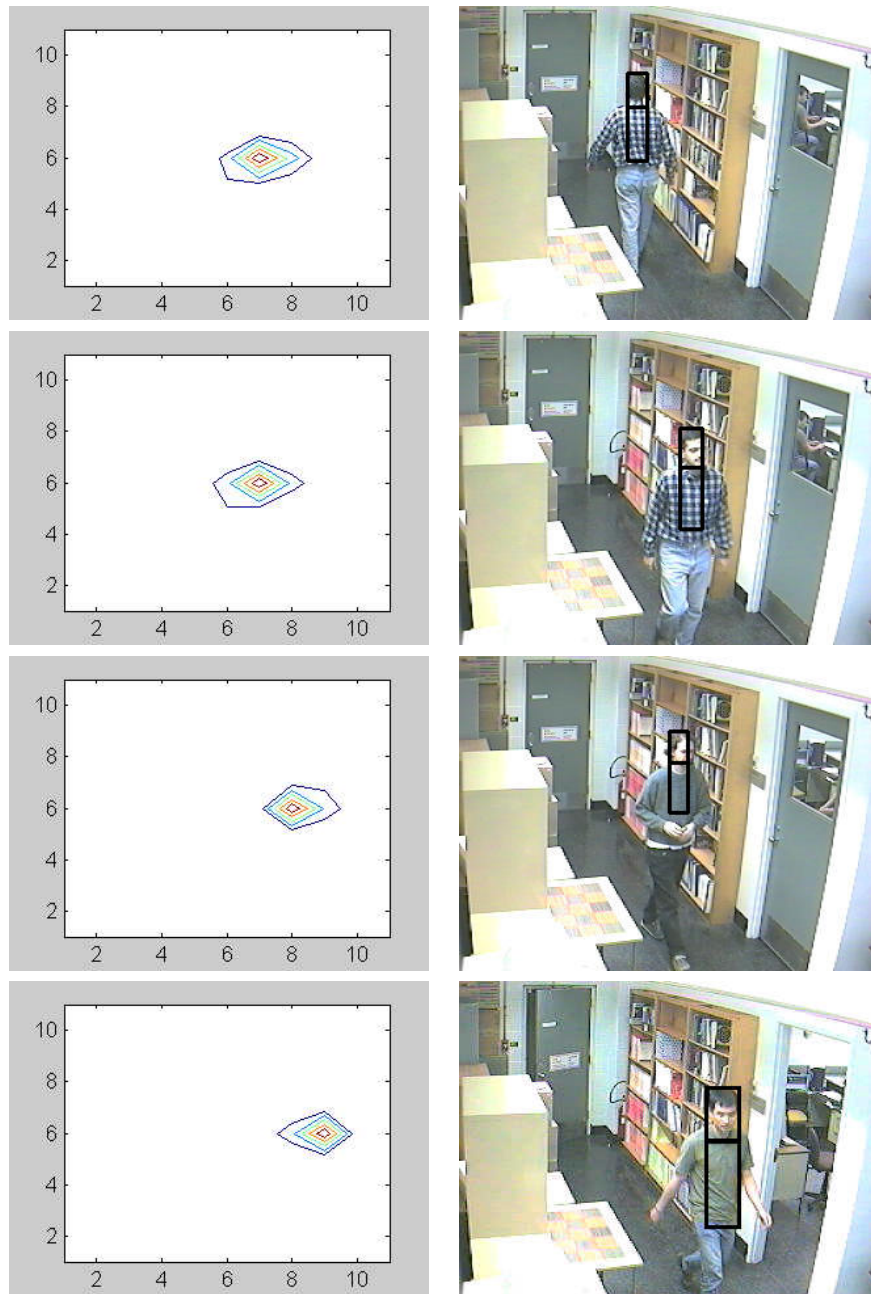


Figure 6.4: Images of three different people and the corresponding contour diagrams of the two chrominance dimensions

6.2 People Matching Algorithm

To compare two histograms a measure of dissimilarity is computed using the Earth Mover's Distance, EMD, presented in [27]. For this measure, one of the histograms, called the source histogram, is like several piles of earth on a field where each pile represents a bin in the histogram, the mass of earth in each pile represents the value of the histogram at the corresponding bin and the field represents the domain of each dimension of the histogram. The other histogram, called the destination histogram is like several holes in a field where a hole represents a bin in the histogram, the volume of each hole represents the value of the histogram at the corresponding bin and the field is the same as the field described for the source histogram. The EMD is the minimum energy required to fill the holes in the field with the earth from the piles in the field.

If a perceptually uniform colour space is used then the EMD is a true numerical measure of the perceptual difference between two sets of colours. Since the EMD also considers the distance between the bins in one histogram and those in the other as well as the value of each bin, it is less prone to error due to noise than methods that compare each bin in one histogram to only the corresponding bin in the other histogram.

Computation of the EMD given two, three dimensional colour histograms, H_s and H_d , proceeds as follows.

signature: represents a histogram as an array in which each element corresponds to a bin in the histogram. Each element consists of the coordinates of the corresponding bin and the value of the histogram at this bin.

S_x : signature that represents H_x .

i_{xj}^y : index of the y dimension in the j 'th element of S_x .

i_{xj}^{qu} : index of the qu dimension in the j 'th element of S_x .

i_{xj}^{qv} : index of the qv dimension in the j 'th element of S_x .

c_{xj} : $(i_{xj}^y, i_{xj}^{qu}, i_{xj}^{qv})$, coordinate in the j 'th element in S_x .

w_{xj} : the value of the j 'th element in S_x .

$\{c_{xj}, w_{xj}\}$: the j 'th element in S_x .

d_{jk}^{sd} : the distance between c_{sj} and c_{dk} .

f_{jk}^{sd} : the amount of 'earth' moved from the j 'th element in S_s to the k 'th element in S_d .

n_x : the number of elements in S_x .

1. Construct the source signature, S_s , from H_s and the destination signature, S_d , from H_d , such that only bins with a value greater than a minimum value, M_{bin} are represented in the signatures.
2. Find the value of f_{jk}^{sd} , $1 \leq j \leq n_s$ and $1 \leq k \leq n_d$ such that W is minimized.

$$W = \sum_{j=1}^{n_s} \sum_{k=1}^{n_d} d_{jk}^{sd} f_{jk}^{sd} \quad (6.6)$$

such that:

- (a) $f_{jk}^{sd} \geq 0$
- (b) $\sum_{k=1}^{n_d} f_{jk}^{sd} \leq w_{sj}$
- (c) $\sum_{j=1}^{n_s} f_{jk}^{sd} \leq w_{dk}$
- (d) $\sum_{j=1}^{n_s} \sum_{k=1}^{n_d} f_{jk}^{sd} = \min(\sum_{j=1}^{n_s} w_{sj}, \sum_{k=1}^{n_d} w_{dk})$
- (e) $1 \leq j \leq n_s$
- (f) $1 \leq k \leq n_d$

Finding the value of f_{jk}^{sd} that minimizes W is the same as the transportation problem in linear programming and is done using the simplex method.

3. The measure of dissimilarity, D , is found.

$$D = \frac{\sum_{j=1}^{n_s} \sum_{k=1}^{n_d} d_{jk}^{sd} f_{jk}^{sd}}{\sum_{j=1}^{n_s} \sum_{k=1}^{n_d} f_{jk}^{sd}} \quad (6.7)$$

When several sequences of people passing through the seen are compared to a new image sequence in this way, the two sequences which yield the lowest value for D are considered the most likely to be the same person.

Person recognition is performed to find the correspondence between a person who has just left the room and a person who was in the room immediately before the person left the room.

6.3 Recognition Results

To measure the effectiveness of the recognition method we proceeded as follows:

1. Image sequences of twenty different people are captured. Two sequences are captured for each person: one of the person entering the lab and one of the person leaving the lab.
2. n out of the twenty people are randomly selected and these people are assumed to be in the lab.
3. The matching technique is used to compare a person's leaving sequence to each entering sequence of the people in the lab before this person left. If the minimum value of D is less than a threshold and is generated from comparing two sequences of the same person then recognition is successful. Else the recognition is unsuccessful and the leaving person cannot be found in the room.
4. Step 3 is repeated using a different person's leaving sequence until each of the n people has been the leaving person.

5. Steps 2 to 4 are repeated ensuring that a different set of n people are chosen each time until each of the twenty people have been included in at least one of these sets.
6. Steps 2 to 5 are repeated for each value of n ranging from two to twenty.

Recognition rate for each value of n , R_n , is then calculated.

$$R_n = N_n^s / N_n^t \quad (6.8)$$

N_n^s : The number times step 3 is performed for the same value of n and results in a successful recognition.

N_n^t : The total number of times step 3 is performed for the same value of n and results in either a successful recognition or not.

These results were generated using histograms with 16 bins for the two chrominance dimensions, 8 bins for the luminance dimension and the value of M_{bin} equal to 0.1.

Fig. 6.5 shows a graph of recognition rate, R_n versus the number of people in the lab, n . This graph shows that the average recognition rate is at least eighty percent.

Fig. 6.6 shows the values of D when each person's leaving sequence and entering sequence are compared to each other. Fig. 6.7 shows the average values of D when each person's leaving sequence is compared to every other person's entering sequence. These two figures demonstrate how comparing a person's leaving sequence to every other person's entering sequence yields, on average, significantly higher values of D than when a person's leaving and entering sequence are compared to each other.

Fig. 6.8, Fig. 6.9 and Fig. 6.10 show sample images taken from sequences in which a person is leaving the room (image 0 in each figure) and sample images taken from sequences in which a person is entering the room (images 1 - 4 in each figure) along with the corresponding measure of dissimilarity. For example, in Fig. 6.8 the measure of dissimilarity between sequence 0 and sequence 1 is 0.87, the measure of dissimilarity between sequence 0 and sequence 2 is 0.85, and so on. Each histogram

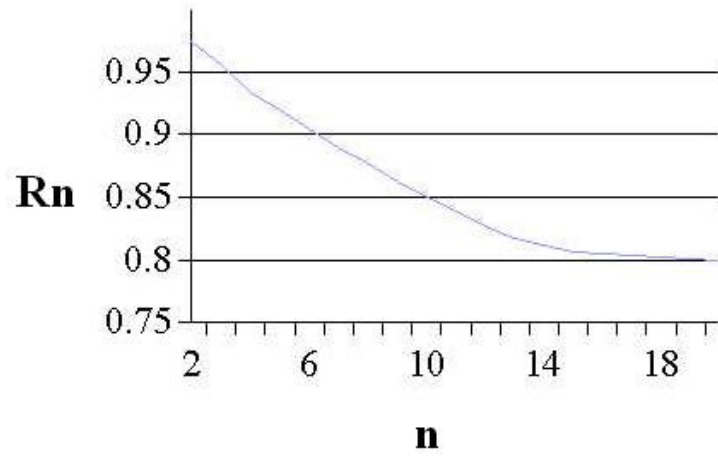


Figure 6.5: A graph showing recognition rate vs. the number of people currently in the room

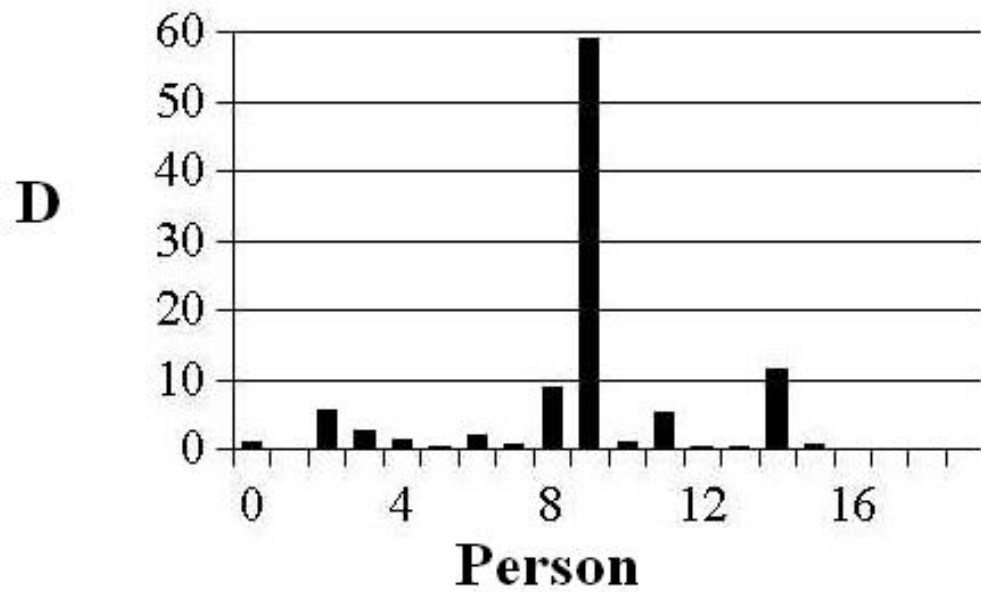


Figure 6.6: A graph showing the values of D when each person's leaving sequence and entering sequence are compared to each other

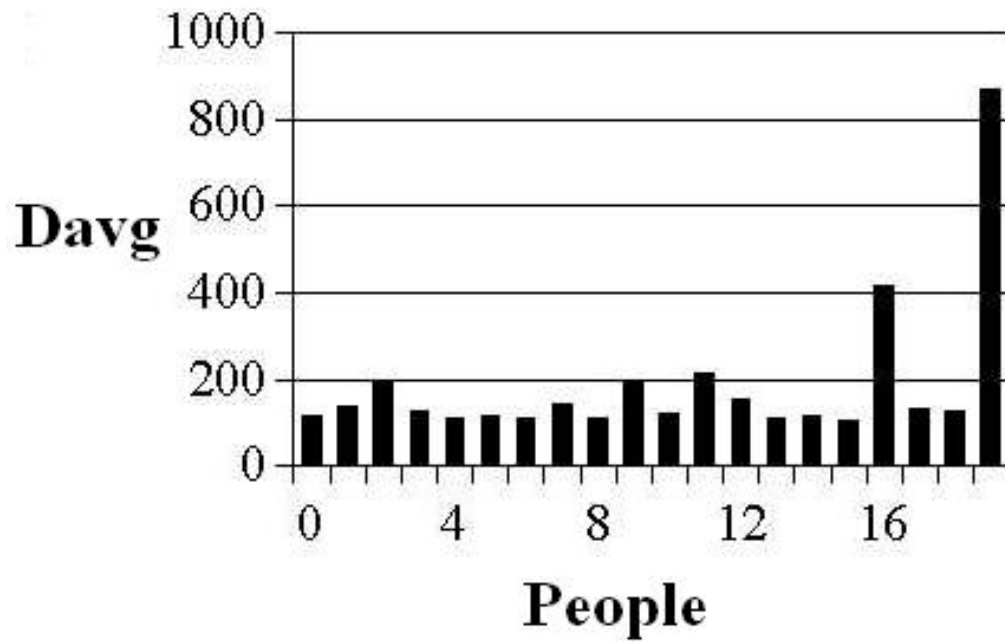


Figure 6.7: A graph showing D_{avg} , the average values of D , when each person's leaving sequence is compared to every other person's entering sequence

that was used to compute the measure of dissimilarity was accumulated from each image of the person in a sequence. For example if a person was detected in five images while entering the room then the histogram used to recognize this person is accumulated from each of the five images of this person.

From these figures you can see that the lowest values of D occur when comparing a person's leaving sequence with that same person's entering sequence most of the time. The exception being in Fig. 6.8, for sequences 0 and 2 which yield a lower value than that yielded by sequences 0 and 1 which contain the same person. This failed recognition is due to the similarity of clothing between the two people.



Figure 6.8: An image representing a person leaving (0) and four images representing a person entering along with the corresponding measure of dissimilarity



Figure 6.9: An image representing a person leaving (0) and four images representing a person entering along with the corresponding measure of dissimilarity



Figure 6.10: An image representing a person leaving (0) and four images representing a person entering along with the corresponding measure of dissimilarity

Chapter 7

Person Tracking

When monitoring the entrance of a room we need to determine whether any detected person has entered or left the room. To do this each person who is detected in the scene under observation must be tracked to find from which direction this person entered the scene and which direction this person left the scene. For example, if a person entered the scene from the direction of the door and left the scene in the direction of the room then this person most likely entered the room. We track a person by using the colour of their clothing, in a similar way as was described in chapter 6, to determine if this person is the same person that was detected in recent frames of the sequence. After this person has left the scene, the frame indices of when this person was detected and the person's position in each of these frames are used to determine if this person has entered or left the room. The position of a person detected in previous images is not used because the system operates at such a low frame rate, two frames per second. When the frame rate is very low the number of times a person is detected is usually too small to be able to accurately estimate a person's velocity or acceleration due to errors in the measurement of the position of a person. Also the acceleration of a person can change significantly resulting in significant errors in an estimate of a person's velocity or acceleration.

7.1 Tracking Algorithm

For each frame of the sequence, the tracking information of each person currently being tracked is updated according to the results of person detection on the current frame and the results of people matching between people detected in the current frame and those currently being tracked.

D_t : The measure of dissimilarity computed using the EMD between the colour histogram extracted from an image of a person detected in the current image and the colour histogram extracted from the last image of a person currently being tracked. The colour space and number of histogram bins used are the same as was used for person recognition.

M_t : The maximum value of D_t for which the two people being compared can be considered the same person.

When people are detected and no one is currently being tracked then these detected people have probably just entered the scene and a track is initiated for each person detected.

When people are detected in the current frame and at least one person is currently being tracked then D_t is computed between each person detected and each person currently being tracked. All detected/tracked pairs for which D_t is greater than M_t are removed from contention as possible matches. Then each person currently being tracked is updated with the info from a person detected in the current frame if the value of D_t for this pair is smaller than that of any other pair involving either of these two people. If any person that is detected in the current frame does not get matched with any person currently being tracked then this person has probably just entered the scene and a track is initiated for this person. If a person who is currently being tracked and has not been matched to a person that has been detected in at least one of N consecutive frames since they were last detected then this person has probably left the scene and a decision is made on whether this person has entered or left the room based on their tracking information.

Tracking information for each person includes their position, the index of the frame in which they were detected and their extracted colour histogram. The centre of the colour extraction region of a person is used as that person's position. Tracking information is updated by adding the position of the person detected in the current frame and the current frame index to the tracking information. Also the previous colour histogram extracted from the person currently being tracked is replaced by the colour histogram extracted from the current image of the person.

7.2 Entered or Exited the Room

Once a person has left the scene a decision must be made as to whether this person has entered or exited the room. This is done using this person's tracking information described in the previous section.

In order for successfully determine whether someone has entered or exited the room the camera should be placed such that the image position of a person standing in the doorway is different than that of a person standing further in the room.

If the relative positions between the image pixel coordinates representing an area of the scene near the door and those furthest in the room are known then a person's displacement, the difference between the coordinate of the person when they were last detected and that of when they were first detected, can be used to determine whether this person entered or exited the room. This is done by converting the displacement vector into polar coordinates and assigning one set of angles to people entering and the supplementary set of angles to people exiting.

Choosing which set of angles corresponds to which activity depends on how the camera is placed and is determined experimentally.

7.3 Tracking Results

This section presents the results of tracking two people in an image sequence using the method described in this chapter.

All parameters pertaining to person matching used to generate these results are the same as those used for generating person recognition results.

Two sequences in appendix C show two people passing through the scene. Each person detected in the current image is compared to each person detected in the previous image using the method presented in chapter 6. For example, the top two images in sequence 1 show two people. The person indicated by the red rectangle and the letter 'B' in the lower image is compared to

1. the person indicated by the red rectangle and the letter 'B' in the upper image yielding $D_{BB} = 1.23$.
2. the person indicated by the blue rectangle and the letter 'A' in the upper image yielding $D_{BA} = 59.21$.

Similarly the person indicated by the blue rectangle and the letter 'A' in the lower image is compared to

1. the person indicated by the red rectangle and the letter 'B' in the upper image yielding $D_{AB} = 47.83$.
2. the person indicated by the blue rectangle and the letter 'A' in the left hand image yielding $D_{AA} = 2.9$.

Tracking is successful when either D_{BB} or D_{AA} is less than D_{BA} and D_{AB} and both D_{BB} and D_{AA} are less than M_t . The red rectangle and the letter 'B' always correspond to the same person in a sequence; likewise for the blue rectangle and the letter 'A'.

Fig. 7.1 shows two consecutive images, the top image being the previous frame and the bottom image being the current frame, in which tracking is lost for one person.



$$D_{BB} = 84.85 \quad D_{BA} = 40.31 \quad D_{AB} = 27.56 \quad D_{AA} = 3.82$$



Figure 7.1: Two images in which one of the people in the scene was not tracked



Figure 7.2: The next image in the sequence after that of the lower image shown Fig. 7.1

If M_t is set equal to 10 then tracking for one person is lost for one frame. This value of M_t was determined experimentally and was found to minimize the number of false matches while minimizing the number of true matches that are removed due to this threshold. At the beginning of the sequence there were two active tracks. The tracking loss occurred in the lower frame shown Fig. 7.1. Person 'A' is properly tracked in both frames. Person 'B', however, was not tracked properly because the value of D_{BB} between the two images in Fig. 7.1 was greater than M_t . When this occurred a new track was initiated using the information extracted from the image of person 'B' in the lower frame. There were three active tracks after this occurred. Then the two people detected in the next frame, shown in Fig. 7.2, were compared to each of the three active tracks with the results being as follows:

$D_{AA} = 4.16$: Result of the comparison between the image of person 'A' in the lower image shown in Fig. 7.1 and that of person 'A' in the image shown in Fig. 7.2.

$D_{AB1} = 40.58$: Result of the comparison between the image of person 'A' in the image shown in Fig. 7.2 and that of person 'B' in the upper image shown in Fig. 7.1.

$D_{AB2} = 53.48$: Result of the comparison between the image of person 'A' in the image shown in Fig. 7.2 and that of person 'B' in the lower image shown in Fig. 7.1.

$D_{BA} = 30.95$: Result of the comparison between the image of person 'B' in the image shown in Fig. 7.2 and that of person 'A' in the lower image shown in Fig. 7.1.

$D_{BB1} = 1.35$: Result of the comparison between the image of person 'B' in the image shown in Fig. 7.2 and that of person 'B' in the upper image shown in Fig. 7.1.

$D_{BB2} = 94.25$: Result of the comparison between the image of person 'B' in the image shown in Fig. 7.2 and that of person 'B' in the lower image shown in Fig. 7.1.

The track of person 'B' created from the lower frame of Fig. 7.1 was not continued because D_{BB2} was greater than M_t . It turned out that this track was terminated N frames after the frame shown as the lower image in Fig. 7.1 because no detected person was matched to this track in any of these frames. The original track of person 'B' created from the first frame in sequence 1 of appendix C was continued because D_{BB1} was less than M_t and less than D_{AB1} . It turned out that this track was continued throughout the the rest of sequence 1 of appendix C.

The loss of tracking was caused by a person quickly changing the direction he was facing and thus the part of his clothing that was different in colour from that of the previous image was in the colour extraction region.

Sequence 3 in appendix C shows three people walking through the scene and Fig. 7.3 shows three images, each of which shows the path of each of the three people extracted from this sequence. This figure shows that each person in the scene was tracked in the presence of occlusions and the path that each person took was fairly accurately determined.



Figure 7.3: Three images each of which show the paths of each of the three people shown in sequence 3 of appendix C

Chapter 8

Discussion

8.1 Results

The effectiveness of the motion segmentation and person detection method is shown in sequences 1, 2, 3 and 4. The foreground segmentation method is effective at segmenting a person's head and body from the cluttered background. As can be seen in sequences 1 and 2, the lower region of the silhouette does not represent the shape of the person as closely as the upper region does. But this does not significantly hinder the effectiveness of the person detection method because only features taken from the upper part of the silhouette are used.

The method used to determine whether a silhouette represents a person or not uses a few assumptions: the top edge of the silhouette of a person's head is horizontal at its highest point and then curves downwards to become nearly vertical on both sides, people do not wear anything on their head which would cause the silhouette of their head to deviate significantly from the normal shape, and everyone is upright when they pass through the scene. The assumption about the shape of a person's head is not very stringent which minimizes the probability of false negatives. This was done to avoid using any computationally expensive pattern recognition techniques. A problem with this is that false positives can occur because of objects moving in the scene whose shape satisfies the first assumption or because of badly formed silhouettes. The first

problem can only be solved using a more stringent assumption but then false negatives will occur more frequently. The effect of the second problem is negligible because it is usually caused by any combination of noise, shadows or reflections which rarely repeat in consecutive images so they are not likely to cause a false positive tracking.

From Fig. 6.5, the person recognition method described in section 6.2 is very effective when there are only a few people in the lab and the recognition rate decreases as the number of people in the lab increases. This is expected because even if no recognition is used, the probability of finding a correct match by guessing decreases as the number of people in the lab increases and the more people there are the more likely it is for two or more people to be wearing clothing with very similar colours. Since the colour of a person's clothing, as seen from the camera, depends on the light reflecting off it, the colour of light in the scene must not change significantly between the time someone enters the room and when they leave for the person to be recognized. As can be seen in sequences 1 - 6, the lighting near the entrance to the lab remains approximately the same in all images of the scene.

Sequences 5 and 6 are two examples of the system tracking two people who are passing through the scene. As was mentioned in section 7.1, tracking is done by using colour. Spatial information such as position and velocity could also be used but this information becomes obsolete when there is too much time between two consecutive instances in which the same person is detected. The reason for this is that a person can change the direction in which he is moving within this time thus any predictions of the next position of a person made using position, velocity and acceleration are not going to be accurate. The minimum time between two consecutive instances in which the same person is detected is equal to the frame period and there is no maximum time because it is possible that a person may go several frames without being detected.

8.2 Thesis Contributions

This thesis has made contributions in two areas, image segmentation and people matching, and has resulted in two publications [34] [35].

To segment images into foreground and background, the background model is updated using an adaptive coefficient for each pixel in the image. This coefficient adapts to the amount of variation in pixel intensity across a set of images in the sequence. This results in the background model adapting more quickly to any changes in the actual background.

To match people in a sequence of images clothing colour is used as the distinguishing characteristic, clothing colour is extracted using histograms defined on a luminance and perceptually uniform chrominance space and the Earth Mover's Distance [27] is used as a measure of dissimilarity between histograms. People matching is used to track people as they pass through the scene and to recognize people who have previously been in the scene. A person is tracked by matching each person detected in an image with the proper person that was detected in previous images. A person is recognized by accumulating the clothing colour extracted from each image of a person as they pass through the scene into a histogram and using it to match the sequence in which this person entered the room with the proper sequence in which this person exited the room.

These algorithms, along with one that detects people in binary images, were designed and implemented to run in real time at two frames per second on an Intel Pentium 2 processor running at 266 MHz with an image resolution of 320×240 . This implementation was tested using image sequences of the entrance to the V.I.V.A. laboratory.

8.3 Future Work

As with any system, this system can be improved upon if more resources are used. By adding more processing power, either by using a faster processor, or by using more

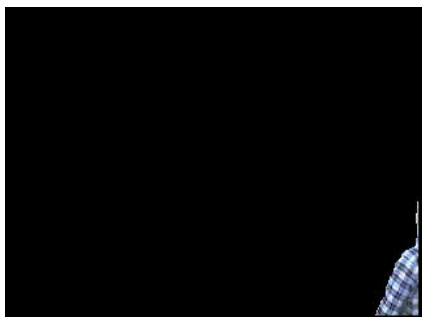
processors, or both, this system can be made more flexible so that it can be used in a wider variety of environments. As was previously mentioned, this can be done by using a more complex foreground segmentation method which detects shadows. Foreground segmentation can also be improved by detecting reflections. More complex models of the background which take into consideration any rapidly changing regions of the background can be used. Thus the door opening will not prevent anyone from being detected. With additional processing power the image capture period can be reduced which would improve the effectiveness of the recognition and tracking methods. Another resource one can add to the system is an additional camera. If placed in the right position, an additional camera could reduce or even eliminate the possibility of occlusions and increase the recognition rate.

The focus of future work will be on improving the recognition method. One way to improve recognition may be to isolate the lower and upper garments which a person wears. To do this, the location of the bottom of the upper garment (the shirt for example) and the top of the lower garment (pants for example) must be determined. Determining this location may be done using colours and textures as well as the locations of these colours and textures. This would improve person recognition because spatial information related to the location of colours on a person's clothing is being used so a person wearing a blue shirt and black pants will be distinguished from a person wearing a black shirt and blue pants.

Appendix A

Sequences Showing Segmentation Results

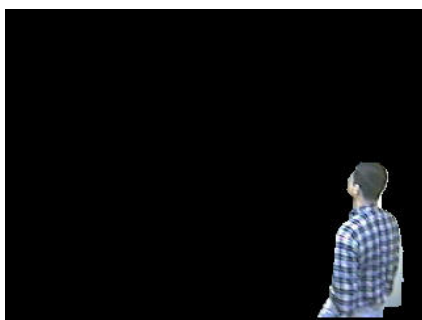
Sequence 1



0



0



1



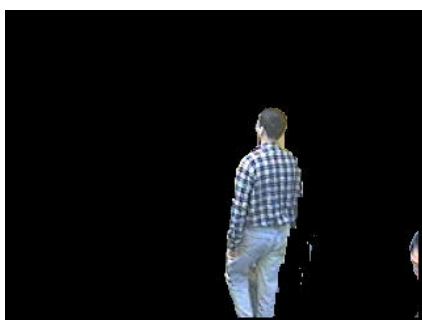
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2



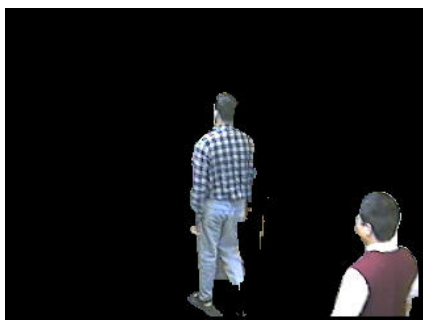
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3



3



4



4



5



5



6



6



7



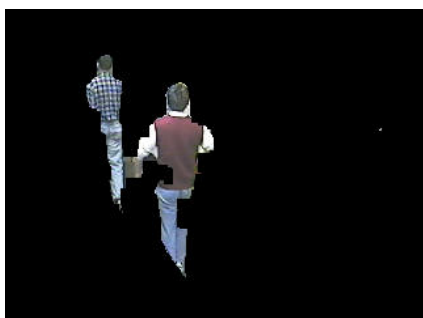
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9



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10



10



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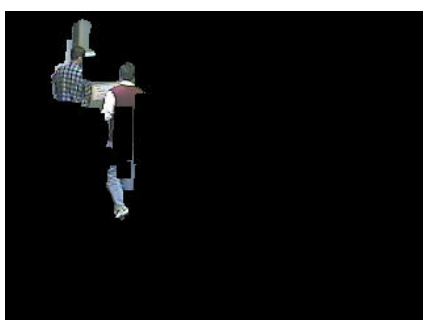
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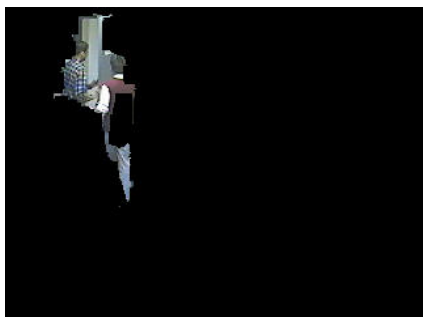
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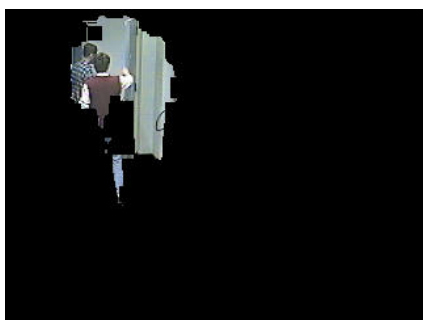
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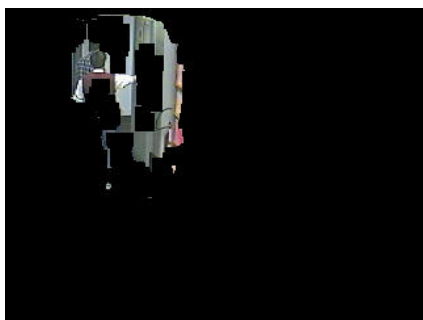
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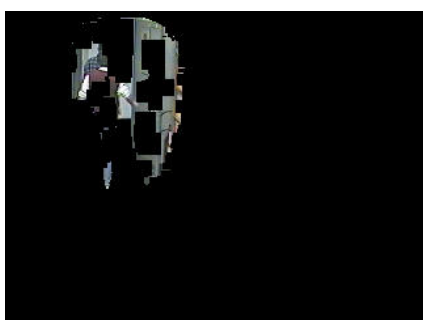
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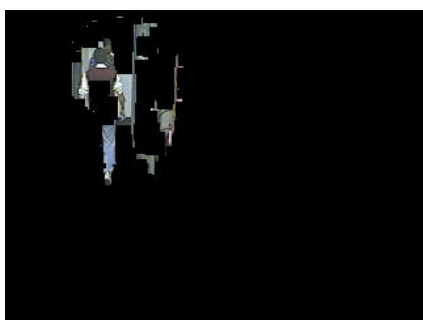
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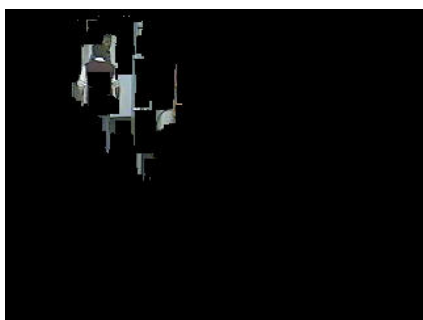
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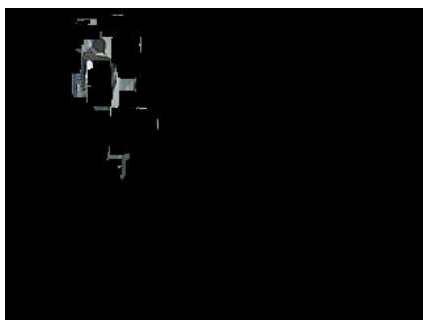
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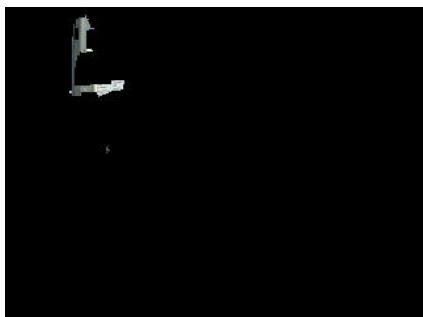
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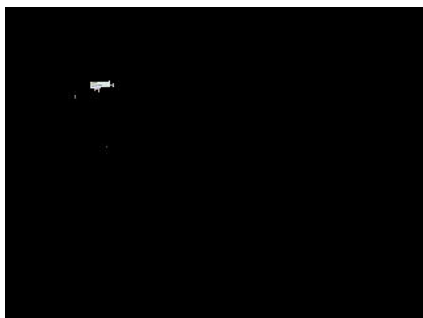
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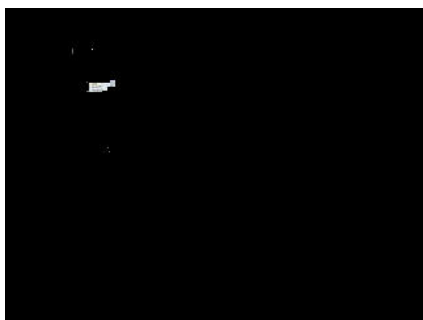
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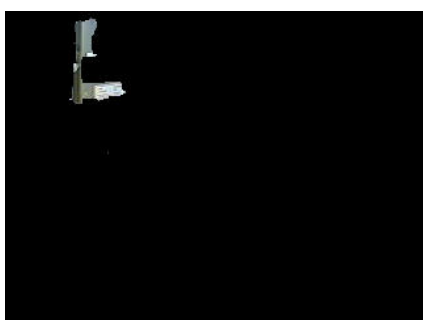
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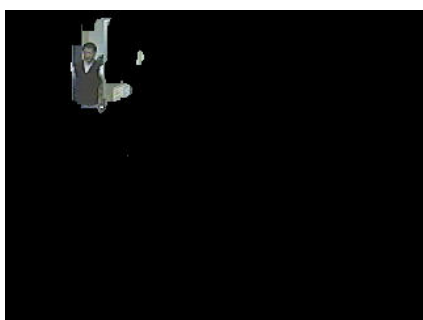
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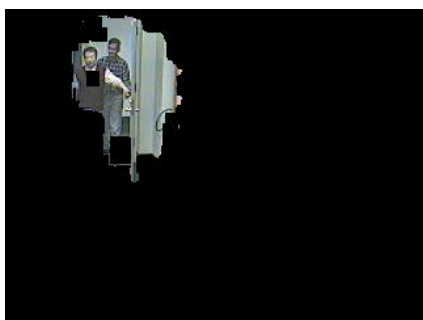
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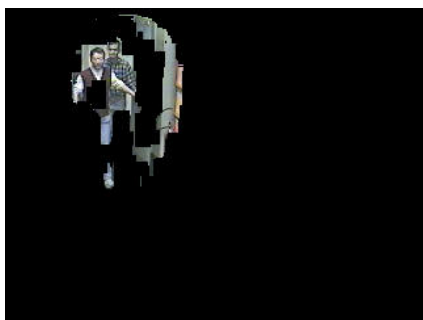
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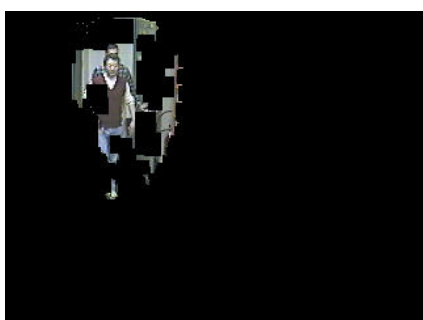
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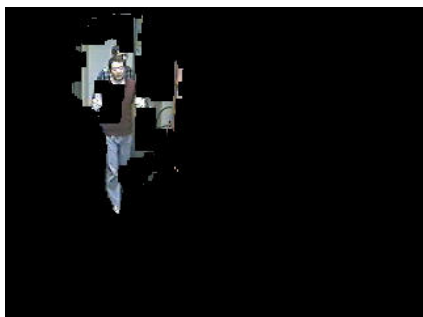
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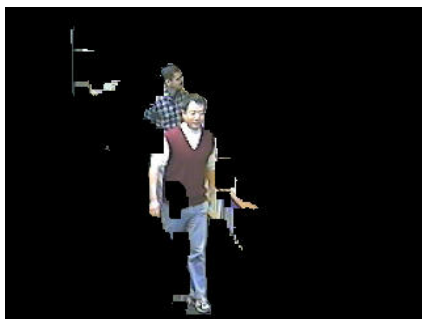
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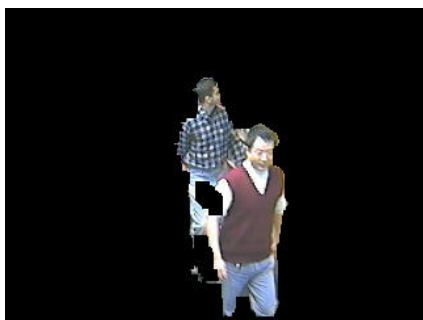
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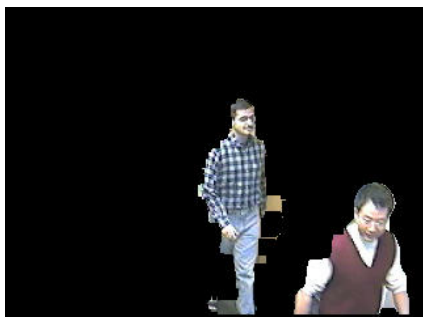
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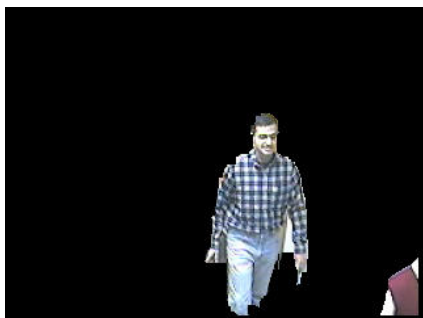
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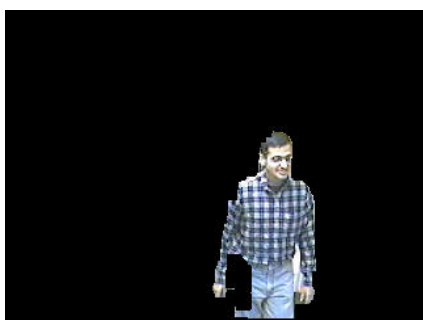
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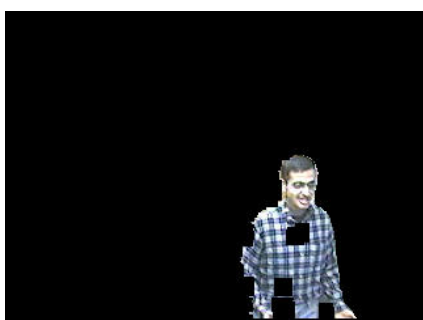
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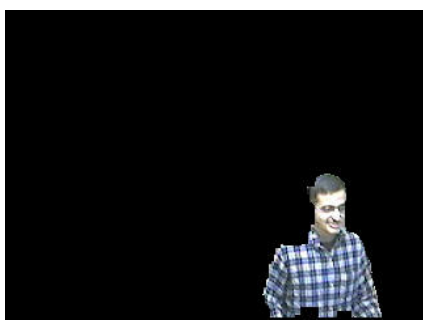
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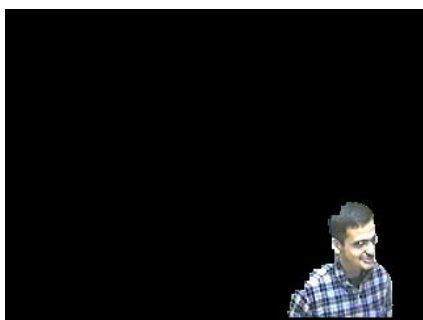
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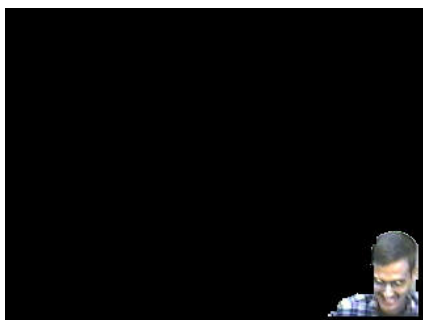
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Sequence 2



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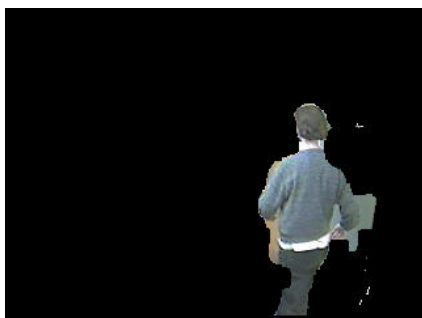
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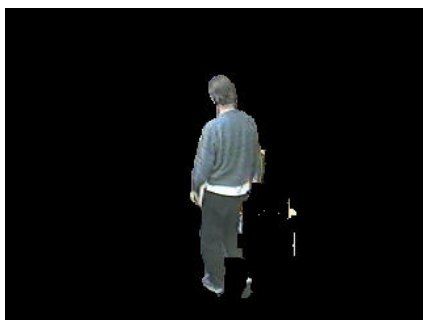
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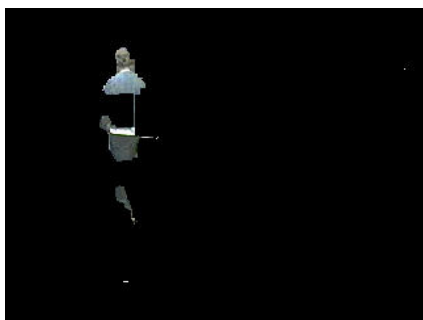
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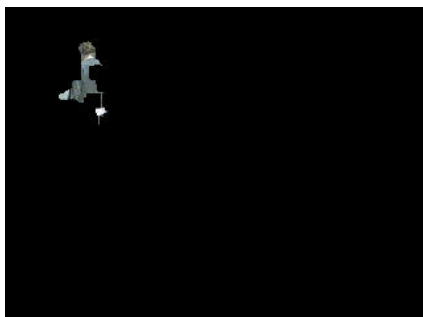
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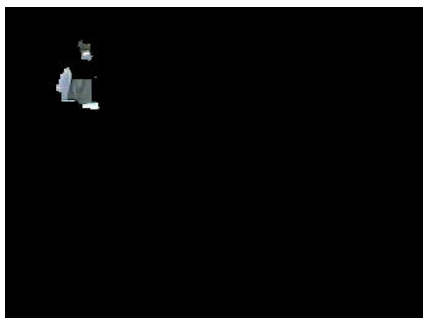
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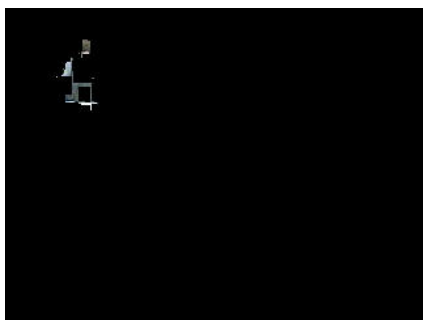
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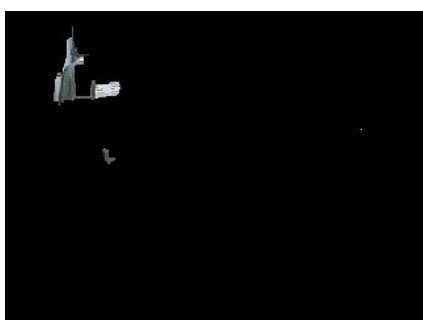
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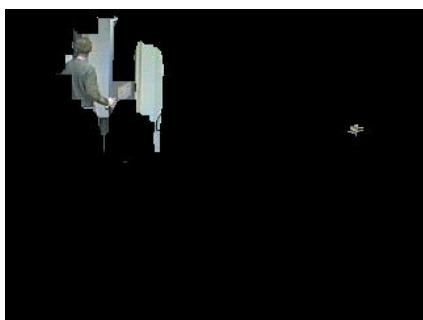
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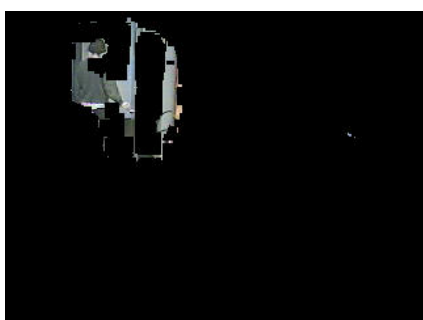
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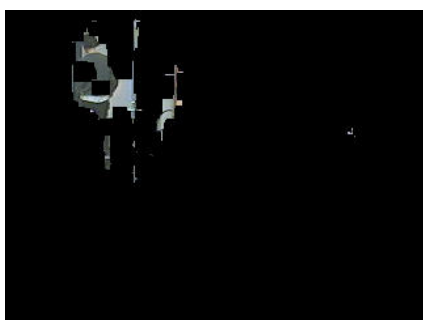
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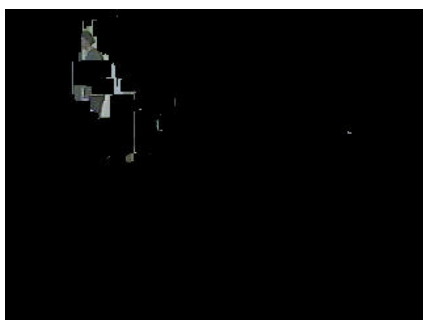
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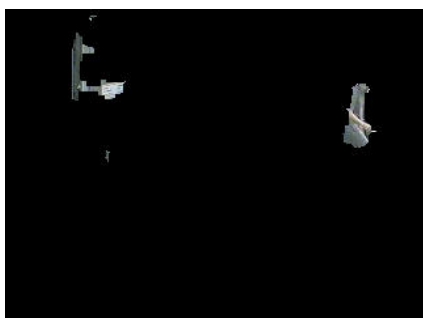
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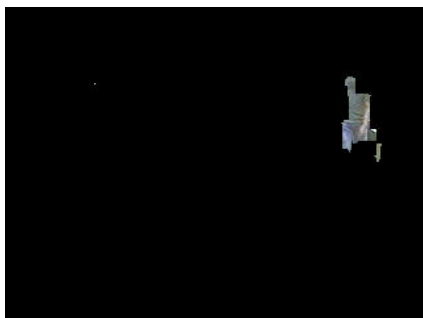
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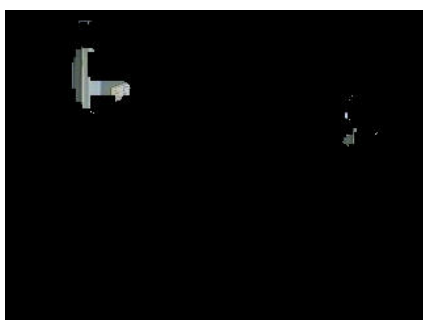
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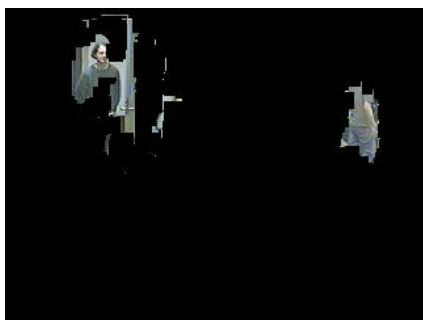
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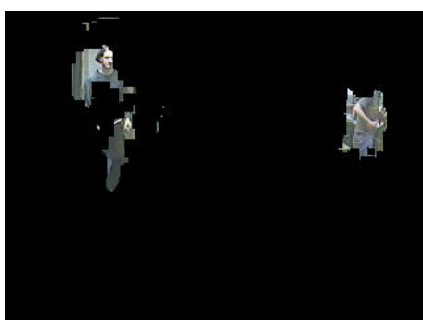
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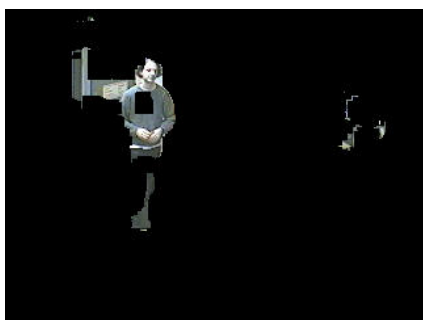
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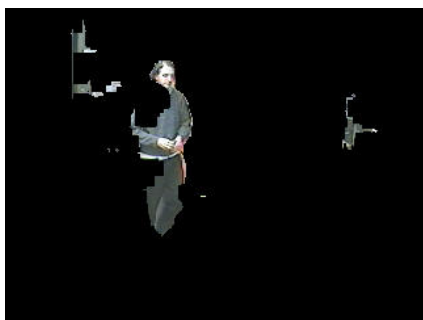
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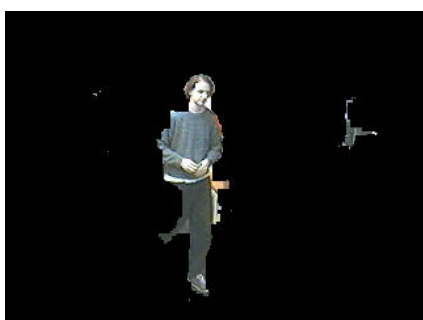
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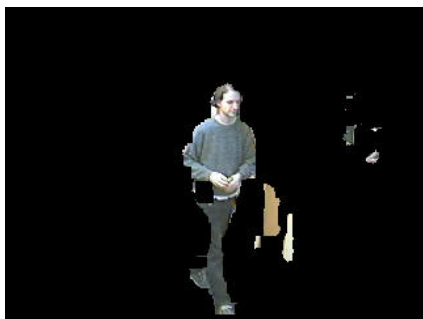
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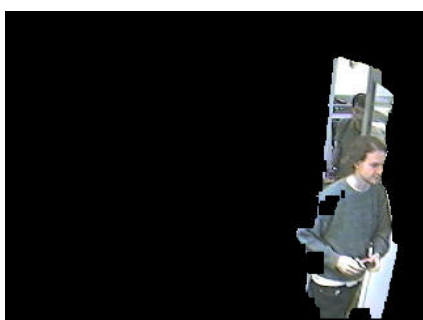
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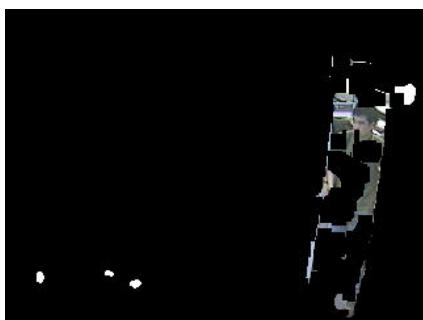
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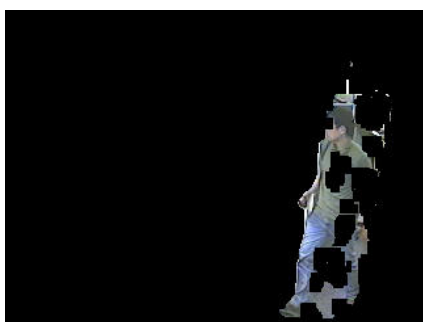
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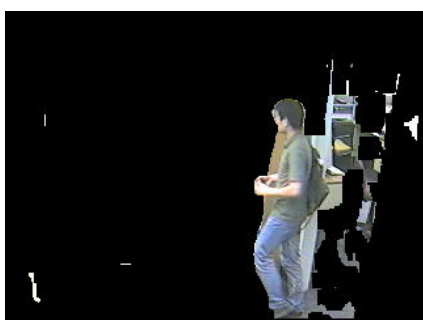
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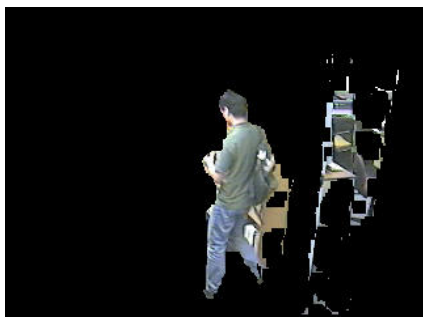
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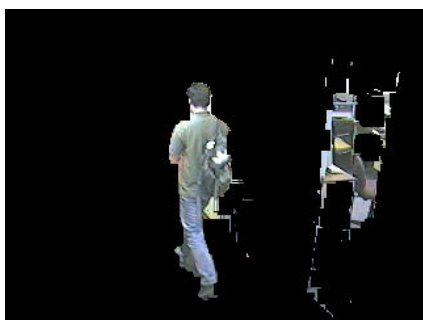
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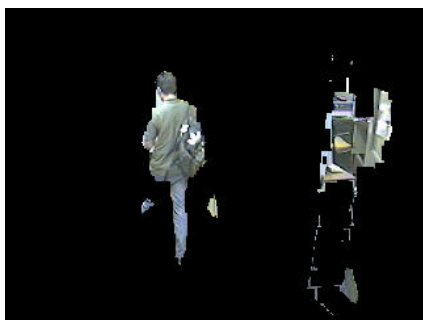
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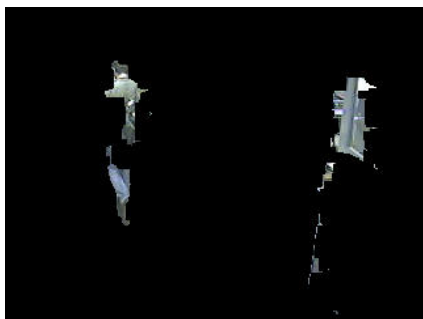
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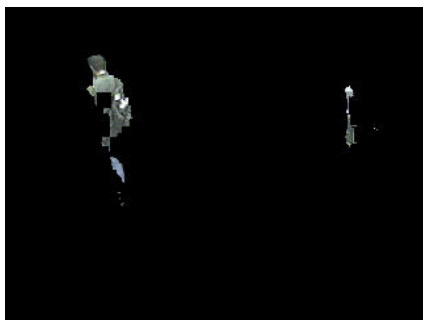
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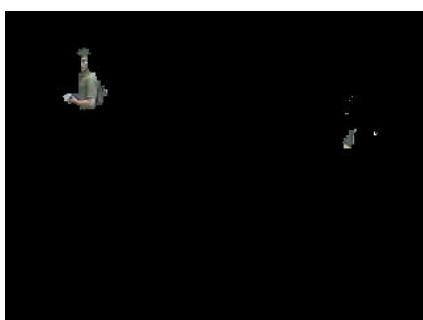
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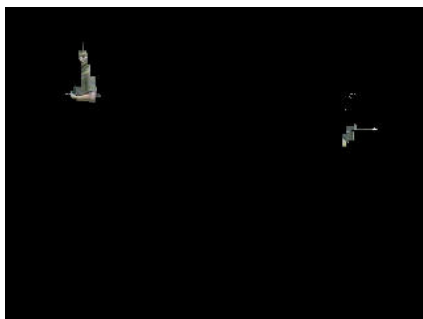
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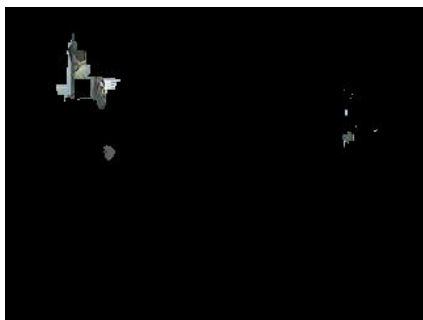
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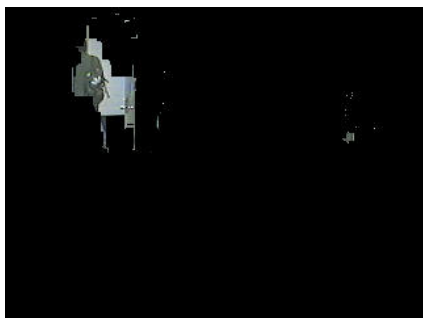
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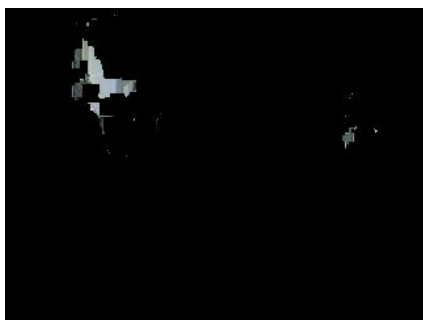
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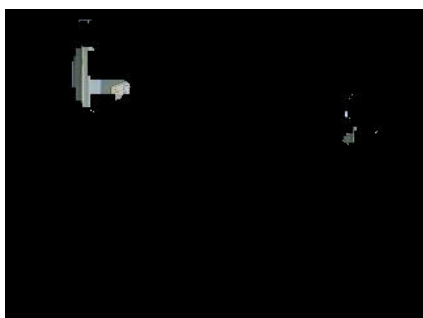
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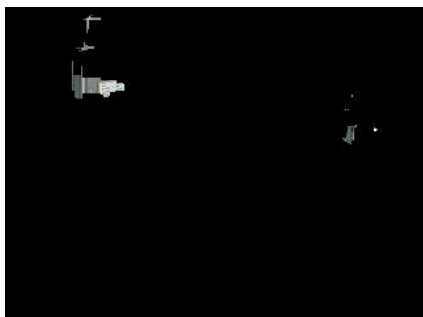
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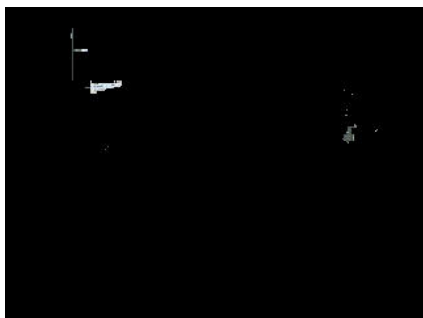
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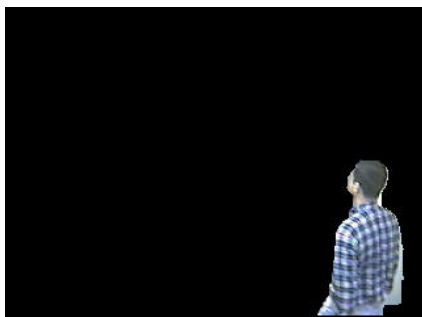


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Appendix B

Sequences Showing Person Detection Results

Sequence 1



0



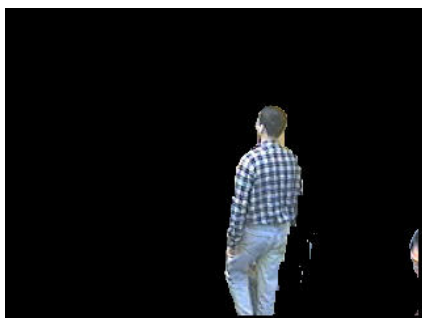
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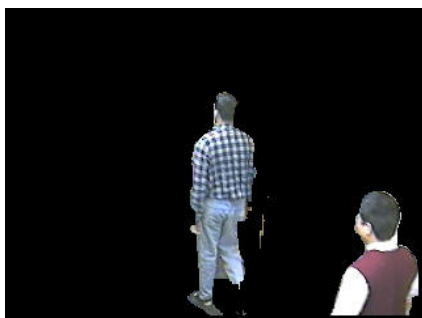
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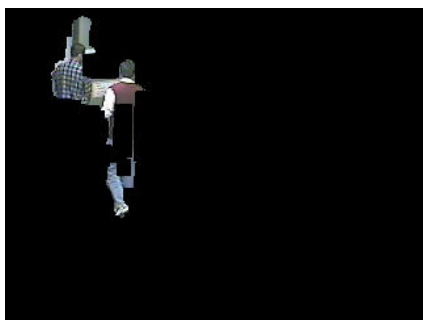
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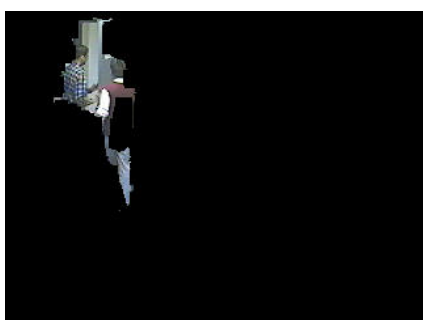
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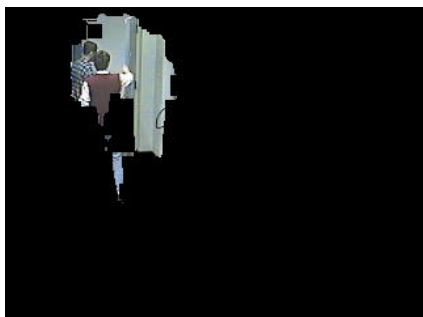
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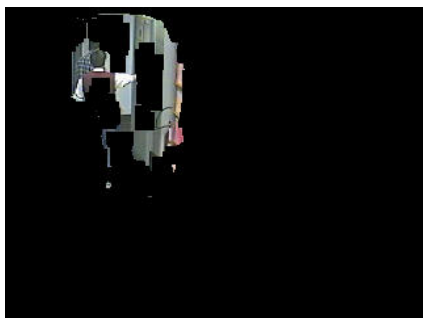
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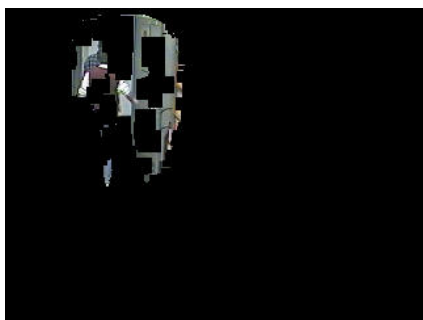
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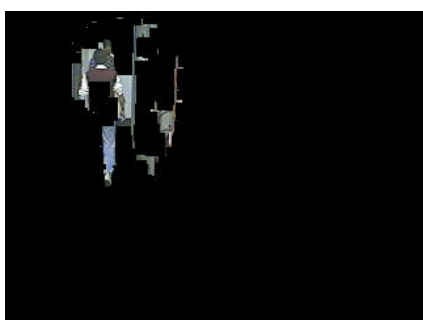
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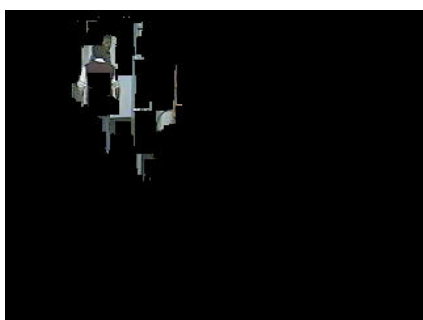
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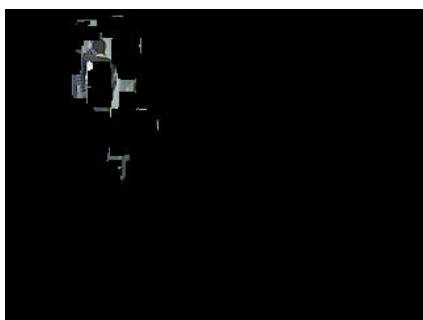
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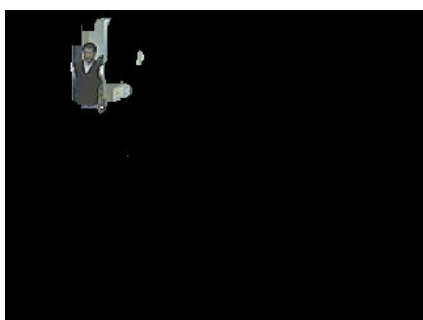
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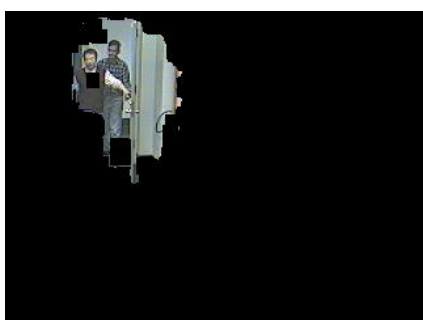
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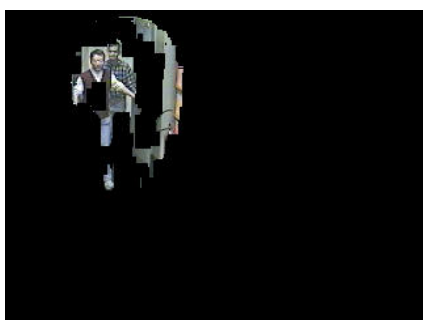
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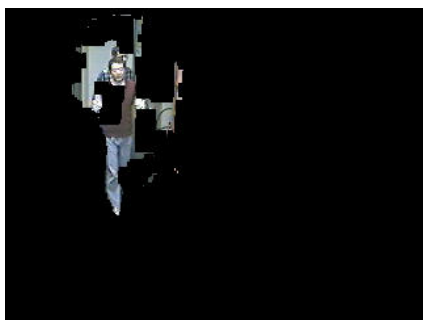
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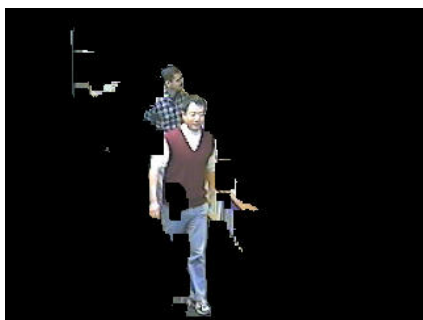
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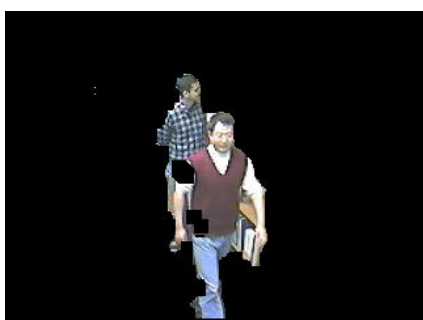
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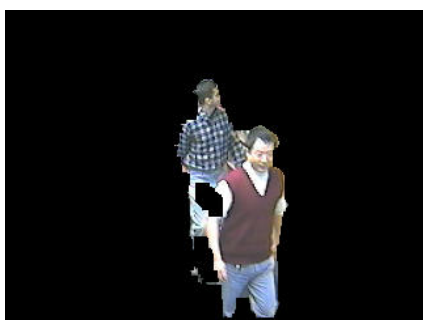
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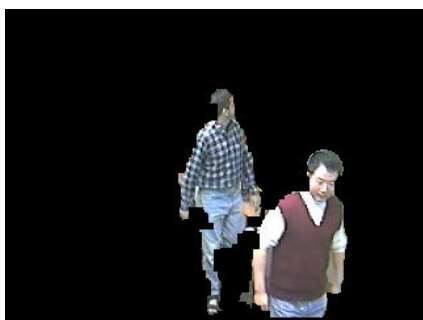
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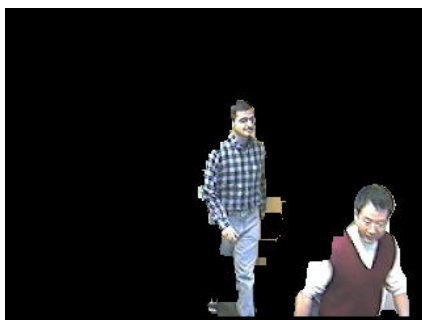
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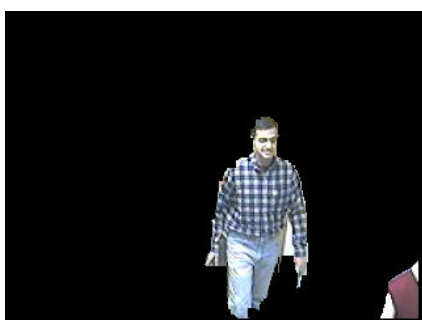
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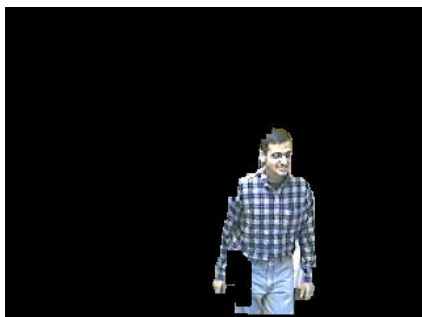
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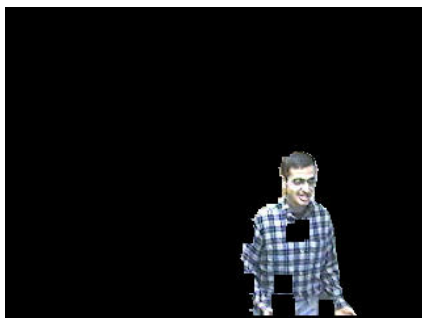
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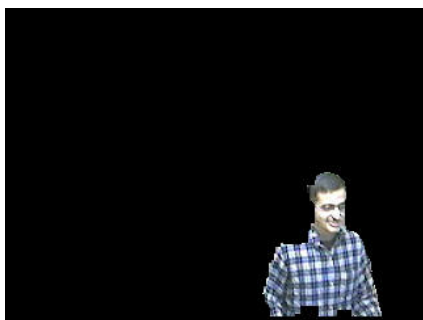
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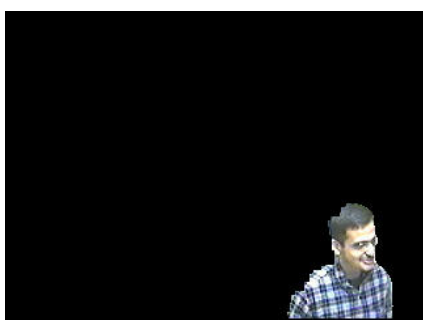
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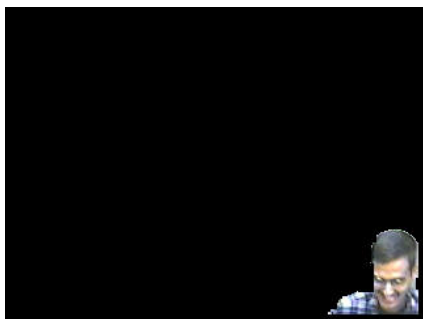
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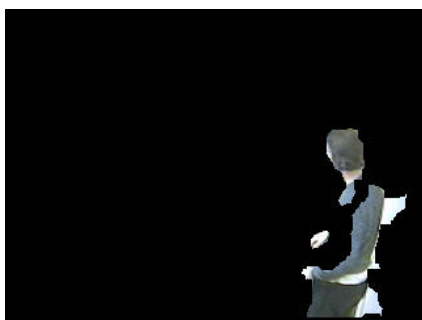
Sequence 2



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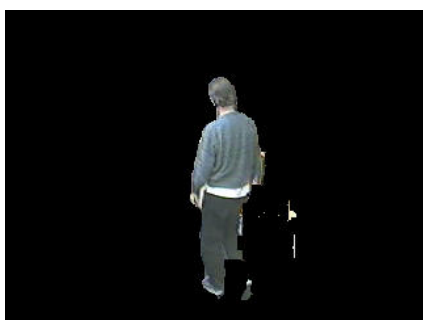
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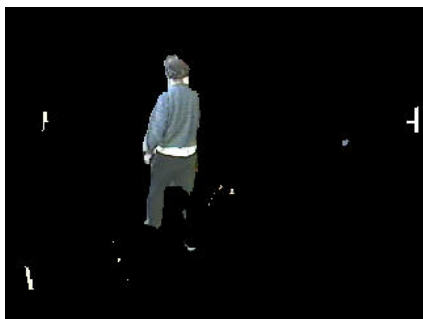
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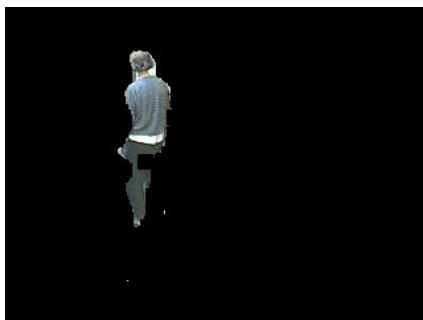
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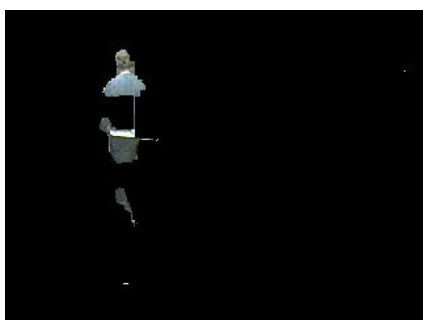
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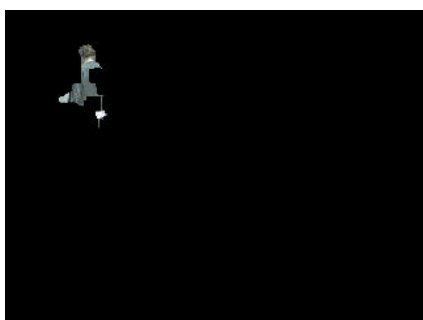
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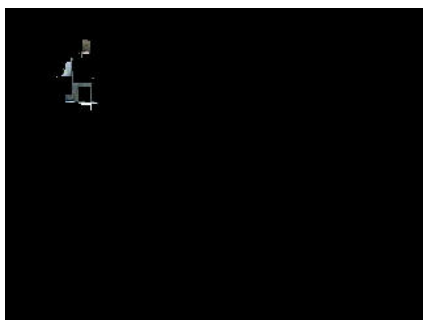
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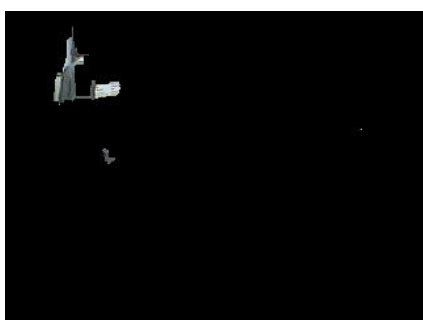
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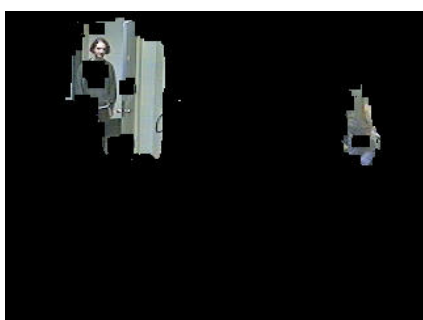
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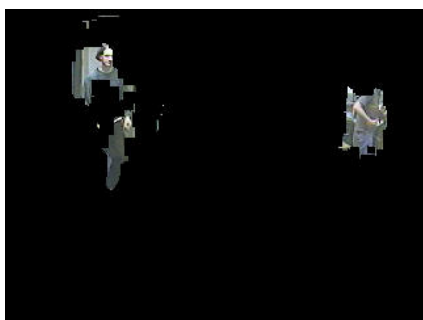
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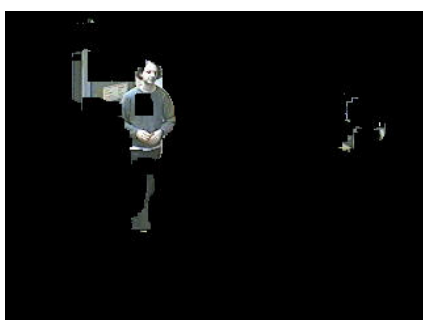
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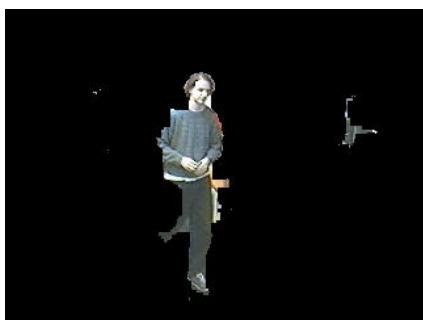
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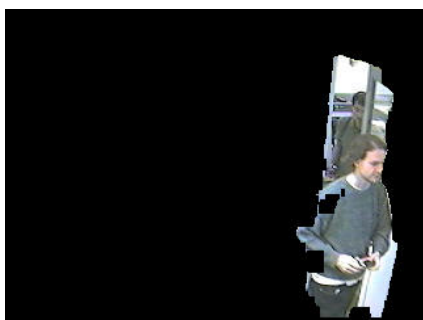
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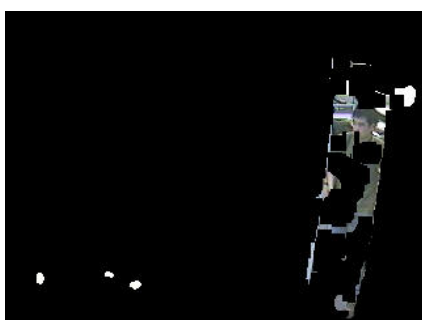
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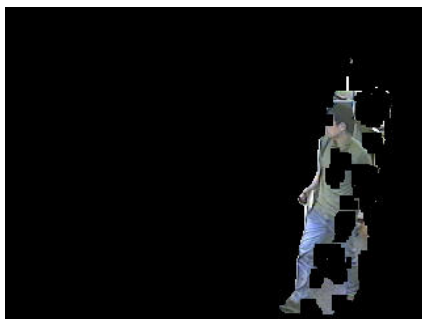
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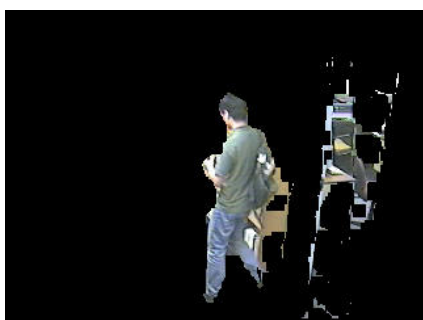
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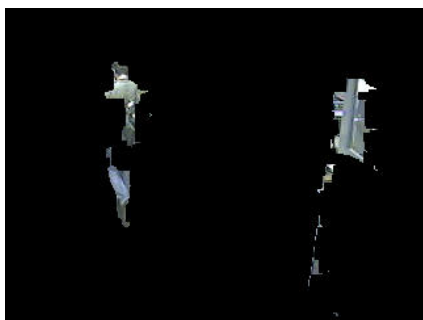
34



35



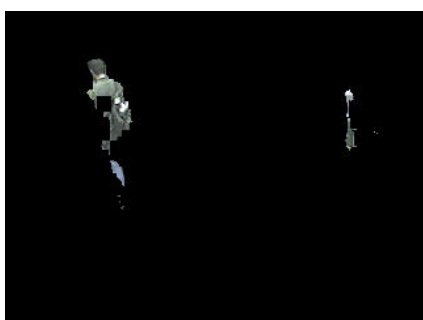
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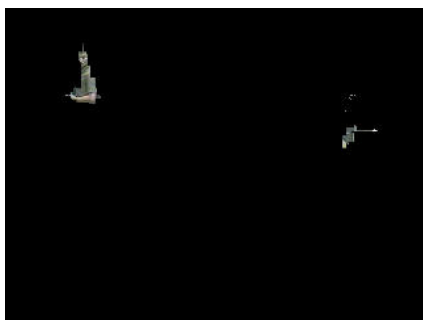
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Appendix C

Sequences Showing Person Tracking Results

Sequence 1



$$D_{BB} = 1.23 \quad D_{BA} = 59.21 \quad D_{AB} = 47.83 \quad D_{AA} = 2.9$$



$$D_{BB} = 2.77 \quad D_{BA} = 41.26 \quad D_{AB} = 42.69 \quad D_{AA} = 2.29$$



$$D_{BB} = 84.85 \quad D_{BA} = 40.31 \quad D_{AB} = 27.56 \quad D_{AA} = 3.82$$



$$D_{BB} = 94.25 \quad D_{BA} = 25.55 \quad D_{AB} = 53.48 \quad D_{AA} = 4.16$$



$$D_{BB} = 0.74 \quad D_{BA} = 12.86 \quad D_{AB} = 4.77 \quad D_{AA} = 0.65$$



$$D_{BB} = 1.65 \quad D_{BA} = 7.8 \quad D_{AB} = 6.9 \quad D_{AA} = 0.48$$



$$D_{BB} = 5.59 \quad D_{BA} = 5.35 \quad D_{AB} = 17.75 \quad D_{AA} = 0.53$$



$$D_{BB} = 6.20 \quad D_{BA} = 16.88 \quad D_{AB} = 7.94 \quad D_{AA} = 1.46$$



$$D_{BB} = 1.46 \quad D_{BA} = 8.87 \quad D_{AB} = 12.01 \quad D_{AA} = 0.91$$



$$D_{BB} = 0.35 \quad D_{BA} = 10.46 \quad D_{AB} = 16.7 \quad D_{AA} = 2.30$$



$$D_{BB} = 3.18 \quad D_{BA} = 22.70 \quad D_{AB} = 20.0 \quad D_{AA} = 0.55$$



Sequence 2



$$D_{BB} = 0.43 \quad D_{BA} = 59.62 \quad D_{AB} = 56.41 \quad D_{AA} = 2.24$$



$$D_{BB} = 0.34 \quad D_{BA} = 60.04 \quad D_{AB} = 55.21 \quad D_{AA} = 0.6$$



$$D_{BB} = 0.44 \quad D_{BA} = 51.49 \quad D_{AB} = 28.42 \quad D_{AA} = 4.97$$



$$D_{BB} = 1.03 \quad D_{BA} = 30.95 \quad D_{AB} = 83.82 \quad D_{AA} = 21.87$$



$$D_{BB} = 0.51 \quad D_{BA} = 102.36 \quad D_{AB} = 28.45 \quad D_{AA} = 3.76$$



$$D_{BB} = 0.7 \quad D_{BA} = 25.1 \quad D_{AB} = 40.36 \quad D_{AA} = 0.68$$



Sequence 3



0



1



2



3



4



5



6



7



8



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