Computer Vision Based Object Tracking as a Teaching Aid for High School Physics Experiments

G.D. Illeperuma
Department of Physics
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
gdilleperuma@gmail.com

D.U.J. Sonnadara
Department of Physics
University of Colombo
Colombo 03, Sri Lanka
upul@phys.cmb.ac.lk

***Abstract*— Experiments play a vital role in science education. In high school physics, especially in mechanics, many experiments are conducted where tracking a single or multiple objects are required. In most situations students visually observe the motion of objects and take the measurements. This manual method is time consuming, generates higher error and incapable of producing multiple readings rapidly. The research described in this work introduces a simple mechanism to integrate computer vision based tracking to enhance the quality of measurements and to new ways of looking at experiments. The case study consists of three standard experiments. In the first experiment a motion of the simple pendulum was tracked. Using computer vision students were able to obtain a correlation of 0.99 between the calculated period and the theoretical period. In addition, it was possible to calculate the position and the velocity of the bob more than 30 times during a single oscillation. Students were able to plot the extra data points for a better understanding of the simple harmonic motion, which was not possible in the manual method. Second experiment was focused on measuring the terminal velocity of a ball moving through a viscous medium. Final case study was on tracking multiple particles in a moving fluid. In all three experiments computer vision based system provided more accurate and higher number of data points than the manual method. This helps students to understanding the underline theory better. The tracking system was consisted of a digital camera, image preprocessing sub system, feature extraction subsystem, object identification subsystem and data export subsystem. The system was successfully tested on a normal PC which is cost effective to be used in high schools. Based on the case studies it was concluded that such systems can be used in high schools to improve the quality of experiments conducted.**

Keywords—Object tracking; Computer Vision; Physics Experiment; Optical Flow

I. Introduction

Experiments play a vital role in science. They are the base, in which hypothesis are tested, certain values in equations are estimated and sometimes remind us of the need of a new theory [1]. However, at the high school level, science laboratory experiments play a different role. Here students are not expected to make new discoveries or to learn to work in cutting edge of science. The main objective of such a class room is to teach the fundamentals of scientific method, improve the skill on data gathering, data analysis and making conclusions [2]. It also serves as a method of verifying the theories students had learned and to observe the differences between theories and practical applications. In addition, students learn how to use variety of instruments, gain good laboratory practices through hands on experience and change their attitude towards science.

While the science research had moved forward with new instruments techniques and tools, most high school experiments, especially in the developing countries, remained same for decades [3]. But with the advances of technology it is possible to improve these experiments to better realize above goals.

In this work, computer vision was used to aid several physics experiments at high school level. The experiments described here are based on physics, but they are to be taken as an example or a guideline since these techniques can be applied to many different areas of science.

II. Methodology

A. Computer Vision Based Object Tracking

Detecting the location of object through time is called tracking the object. There are multiple methods for tracking an object. In active tracking, an object is designed to be tracked. For example, an RF transmitter may periodically transmit a signal allowing time difference of arrival to be used to calculate its position. In passive tracking, such as tracking the ball in a cricket match using the hawk-eye system, the tracking system needs to track the object without making any alternations to the object.

Tracking an object manually, using human vision, is the method used in many high school laboratories, where one or more students observe the object of interest and estimate its time and location. This method is cost effective and easy to implement, but has several disadvantages. Firstly, the limitation of human vision. If the scene changed faster than 0.1s , humans are unable to detect this change. Secondly it is hard to determine the exact location of the object. Thirdly if students are to make continuous multiple observations, rapidly memorizing the locations is impractical. It is impossible to 'play back' to check for accuracy. Lastly, quantifying the properties such as speed and acceleration is impossible using the manual method.

978-1-5386-0549-3/17/$31.00 ©2017 IEEE

Computer vision based tracking can address all the above issues plus several extra features such as tracking many objects simultaneously and tracking for a prolong period of time, which is impossible to achieve using human observers.

B. Design of the system

The tracking system consists of several modules (Fig 1). Image acquisition system, Image preprocessing system, Feature extraction system, Object identification system and Data export system.

C. Image acquisition system

Image acquisition can be carried out with any device capable of recording a video. In our experience, increasing the resolution beyond 1 Mpx does not increase the accuracy considerably. On the other hand, higher resolution creates larger files which take more time to process. However higher frame rates increase the data points and the accuracy of the system. Frame rate above 15 fps is sufficient for most experiments. Otherwise moving objects may appear blurred.

A low end digital camera is enough for most of the experiments. They are easy to find, portable and cost effective. A web camera has the added advantage of real time video streaming. Unfortunately, most web cameras do not have enough frame rate and is only suitable to track slow moving objects. CCTV security cameras were also tested as acquisition devices. These have higher frame rates and higher resolution than web cameras and can stream data in real time. They can be installed in laboratory conditions or in outdoors. Drawback is the requirement of extra hardware to connect the camera to a computer. Another low cost alternative is to use a mobile phone camera to record the video. Again the resolution and frame rate needs to be considered based on the experiment.

D. Image preprocessing system

The raw image captured by camera needs to be preprocessed. This is done in the preprocessing stage. It is desirable to crop the image to include only the region of interest (ROI) If the image has a higher resolution it needs to be resized. Depending on the tracking algorithm, it may require to convert image to grayscale color space. Histogram equalization, contrast adjustments and brightness adjustments are used to enhance the image.

E. Feature extraction system

Set of features allow different regions to be identified separately. Colors can be used to identify an object, if it is distinctively different from the scene. Most computer vision algorithms employ L*a*b or HSV color space, rather than RGB color space [4]. These color spaces are less sensitive to illumination changes, but more sensitive to noise [5]. Edges represent the boundaries created on the two-dimensional image. They have high intensity gradients. Another advantage is the simplicity of implementing an edge detector such as canny edge detector or the differential edge detector [6].

Texture is more robust to illumination changes compared to color-based identification. However, when multiple properties are used, the algorithm may be computationally heavy [7].

Optical flow identifies the object by comparing it with surrounding flow vectors. Therefore, this method utilizes the motion of an object for identification which is different from other mechanisms.

F. Object identification system

After features are identified, an algorithm needs to identify the object itself [8]. In the point detect algorithm, points with interesting features are identified. Some common point detectors are Harris [9], KLT [10], and Moravec [11].

A background estimation model is based on deriving a background scene and then identifying the deviations as objects [12]. Adjacent frames can be used to build the background as long as the camera and background are fairly static [13].

Segmentation methods utilize segmenting of the image into areas with similar properties. An object of interest can be composed of one or more regions. Mean shift clustering and graph cuts [14] are two common methods for segmentation.

Soft computing techniques [15], such as artificial neural networks for support vector machines, can also be used to identify objects [16]. However, they usually require a large data sample.

In this work, optical flow was used as a feature to detect the objects via background estimation.

After the object is identified, it needs to be represented using a model. Sometimes we may need to represent only the centroid of each object [17]. An example might be the tracking of a simple pendulum to calculate the period of oscillation. In this situation, representing the pendulum using a single point is the best method. Sometimes multiple points are used to represent an object [18].

Instead of a single point, it is possible to use primitive shapes to estimate the effected region. As an example, if collisions between billiard balls are to be observed, it is possible to assume spherical ball would be observed as a circle. This is mostly used when tracking rigid objects. The next step would be to represent an object using a collection of primitive geometric shapes. For example, the shape of a human can be represented as a set of ellipses, each representing hands, legs, etc. Such a method may enable the identification of the pose of a human [19]. The method allows tracking the changes of shape, while tracking the overall position of the object.

Fig. 1. Data flow of the system

Representing an object by using outline is called contour representation. The area inside the boundary is called the silhouette. It can be utilize to represent non rigid objects [20]. When object identification is important, skeletal representation can be utilized [21].

G. Data export system.

Once the object representation step is completed, its properties, such as location, speed, shape is recorded against time. These data can be used for further analysis.

Following section describes three experiments commonly used in high school laboratories, their draw backs and how computer vision was used to improved those.

III. Experiment 1: Tracking simple pendulum

A. Standard method

This is the starting experiment for many high school physics courses. A simple pendulum is created by hanging a weight with a thread. Students need to calculate the period of oscillation. This is done by averaging the time taken for 50 or 100 swings. Students use a stop watch for timing and a pointer as a referencing device. Experiment may be repeated with different lengths of string. In this classical setup, objective is to use the period to calculate the gravitational acceleration (g).

There are several drawbacks of this method. The accuracy is not high. Students have to spend considerable time on the experiment. Due to air resistance, in practice, this is a damped oscillation. Students may not be convinced how different amplitudes affect the period. Also, by the time students conduct the experiment, they have derived the equation and know that it should represent simple harmonic motion. But this experiment does not illustrate the characteristic of that motion. This is mainly due to inability to measure velocity at multiple points in a single cycle. Following section describes how it can be improved by using the aids of computer vision based tracking.

B. Proposed method

In the experiment, a metal sphere with a diameter of 16.2 ± 0.1 mm was attached to a string. The motion of the pendulum was captured using a digital camera with 20 FPS with 600 × 400 px resolution.

After the recording of the video, it was preprocessed. This included resizing and cropping the image to increase the efficiency. Video was converted to grayscale to support optical flow detection (Fig. 2-a). The Horn Schunk method was used to calculate the optical flow (Fig. 2-b). Magnitude of the optical flow vectors at each region was calculated.

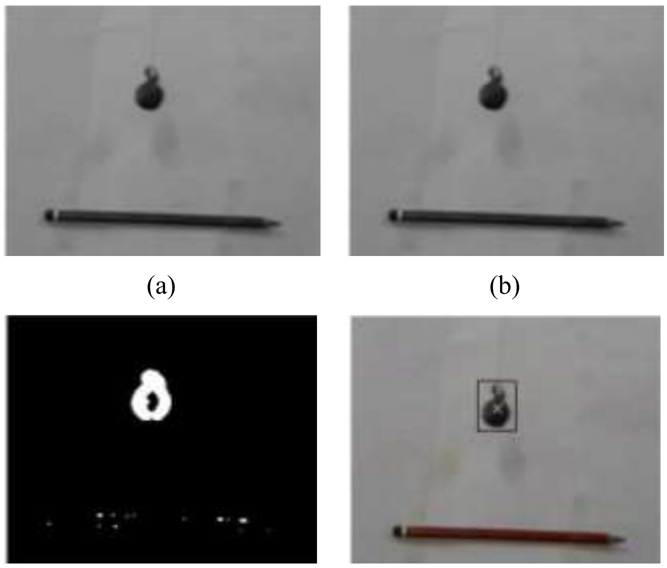
By comparing against preset threshold, pixels with movements were identified (Fig. 2-c). This logical matrix was used to calculate blobs. Eight connects were used to increase the accuracy. It was noted that salt and pepper noise and variations in illumination sometimes caused several pixels to appear as moving. By setting a minimum size for each blob, these were eliminated. Once blobs were identified, their properties could be extracted. Fig. 2-d illustrates the initial results.

C. Results

The calculated *x* location varied with time as expected. However, when the pendulum was at an endpoint, a sudden change was observed. This was due to the fact that, at the extremes, the pendulum stops momentarily before swinging in the opposite direction. Since the optical flow was designed to track moving objects, at that moment pendulum became 'invisible' to the algorithm. In Fig. 3these periods are marked as drops in the curve. This can be overcome by understanding, if an object is not moving it should be at its previous location. An auxiliary coding was added to track the objects and if it's not moving to set the last known location as the new location. Corrected locations are marked as blue dots in Fig. 4.

A correlation of 0.99 was found between the calculated period and the theoretical period of the pendulum.

The proposed method estimated the location of the pendulum many times during a single cycle. By plotting these points, student is able to clearly identify the behavior of SHM. In addition, it can be extended to include the relationships between velocity, accelerations and displacement. This method is more efficient, accurate and provides deeper knowledge to the student. In addition, it opens the possibility of creating new experiments such as finding relationship between displacement and acceleration which is more closely matched with the theory of SHM.



(a) (b) (c) (d)

Fig. 2. Different steps in tracking a pendulum a) Grayscale image b) Optical flow vectors c) Thresholded image d) Tracked pendulum

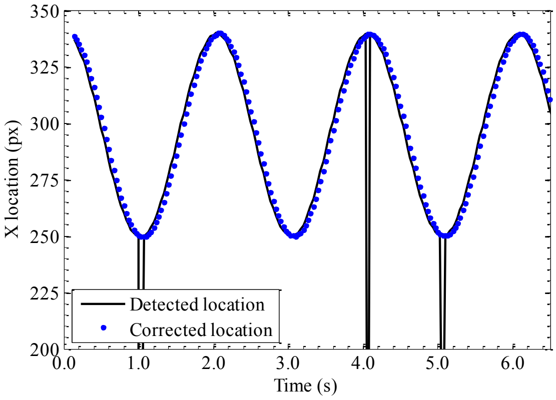


Fig. 3. Detected and corrected locations of the pendulum

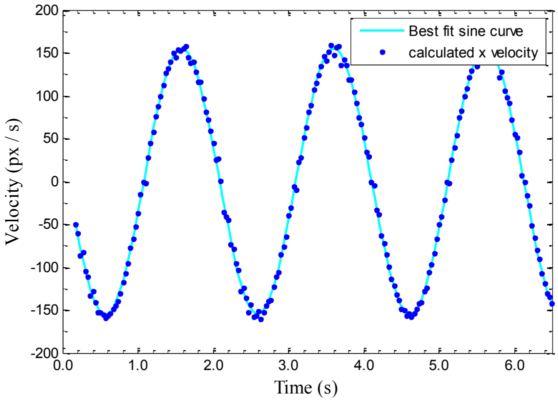


Fig. 4. Calculated velocity of the pendulum

IV. Experiment 2: Terminal Velocity of a Ball Moving Through a Viscous Medium

This experiment is designed to illustrate the Stokes' law and to estimate the terminal velocity of a metal sphere falling through a viscous medium.

A. Standard method

To conduct this using classical method two students are required. First student will drop a ball in to a long vertical tube filled with dense liquid (Fig 5). Second student will use a stop watch to measure the time taken for the ball to pass between two given points. By using balls with different radii and by changing the distance and location of the markers, it is possible to observe how each parameter affects the velocity.

All the draw backs found in simple pendulum experiment is present in this classical setup too. Especially, the experiment needs to be conduct multiple times to measure velocity at different locations. Even then, the number of data points is highly limited and uncertainties are high.

B. Proposed method

In the proposed setup, a camera was used to capture the video from the side, as the ball drops through the viscous fluid. Fig. 6 shows intermediate results of the program.

C. Results

Fig. 7 illustrates the detected location of the three balls with different sizes. In order to maintain the clarity of the image, every 3rd data point is plotted. Radii of the three spheres are 3.2±0.1 mm, 4.0±0.1 mm and 4.7±0.1 mm, respectively.

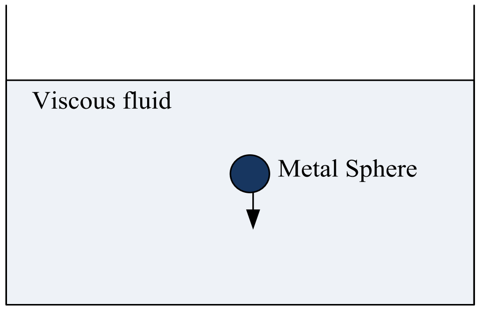


Fig. 5. Experimental setup used to observe strokes law

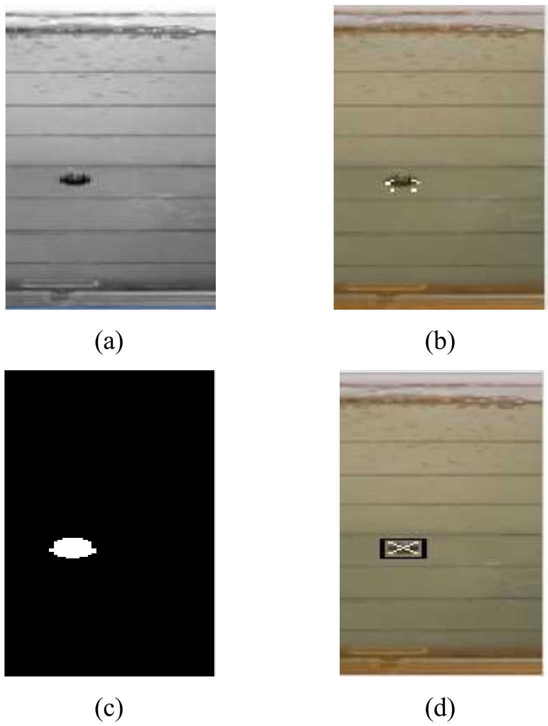


Fig. 6. Steps in tracking the ball a) Grayscale image b) OF calculated c) OF threshold image d) Tracked sphere

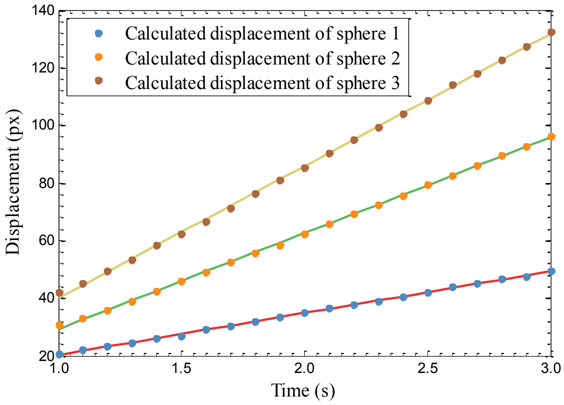


Fig. 7. Tracked location of the ball against time

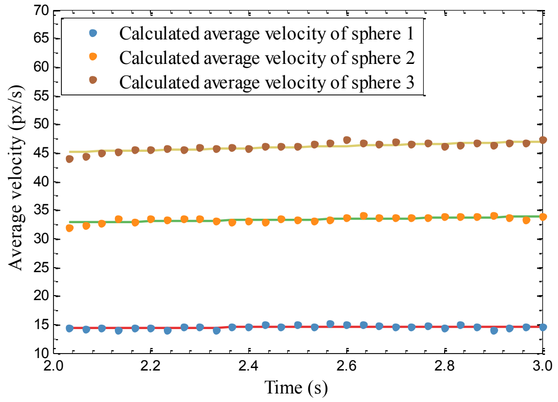


Fig. 8. Average terminal velocity of different size spheres

Velocity of spheres were calculated using two consecutive frames where the difference in time is 1/30 s. By increasing the time difference, smoother values can be obtained.

Average velocity on Fig. 8 was obtained by using a moving average filter with one second window.

With the new setup, calculating terminal velocity is easier and more accurate.

V. Experiment 3: Experiments in Fluid Dynamics

This is not an experiment currently conducted in high schools due to limitations in the presently available laboratory tools. This is a setup that can quantify the speed of a fluid motion is a 2-D plane. The setup can be used in a variety of experiments such as effect of different shapes and skin frictions on the drag force. Using a laser beam to shine at different heights setup can be extended to measure speed in the 3-D space too. The setup is described in Fig. 9.

Water was pumped through the container at a steady rate of flow. Two laminar flow filters created a laminar flow. Small particles (e.g. powdered tea leaves) were suspended between the filters, moved along with the flow. A camera fixed directly above the container captured a video of the motion of the particles. Extra filters were added to prevent particles clogging the outlet laminar filter.

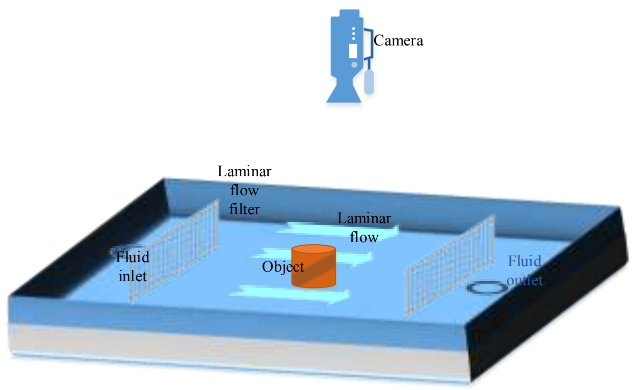


Fig. 9. Experimental setup for tracking fluid flow

The video was enhanced and optical flow vectors were calculated for consecutive frames. Since the flow was laminar, particles at a given point always followed a similar path. By setting a minimum threshold for the speed, it was possible to identify the pixels that included a particle in any given frame. This was important, since large portions of the frame only contained the fluid, and the camera could detect no motion. After a few seconds, if a particle entered that region, it could be followed to determine the flow pattern in the region. By concatenating several such frames, a complete flow pattern could be deduced.

A. Results

In the experiment, a video with 600 frames was used with 640 x 480 resolution. It was possible to calculate over 10,000 points of velocity vectors. Part of the detected flow pattern can be seen in Fig. 10, the vortex of flow in the top right side is clearly visible.

Fig. 11 is another example of how optical flow was able to calculate a detailed view of the flow speeds of the fluid at different locations. A vortex can be seen at the middle of the image.

VI. Discussion

In all three experiments discussed earlier, results were highly encouraging. Major drawbacks include the cost, lack of technical skill and psychological barrier of conducting physics experiments by using computer vision.

A camera and computer is the required hardware. Different types of cameras are discussed earlier with cost and suitability. The image processing can be carried using an average personnel computer. MATLAB was used as the software for image processing in this research. However, it is a proprietary software. Alternatively, free and open source software like ‘Octave’ can be used with appropriate packages. Using Open CV is another possibility.

Second challenge is the lack of technical skills. If the software or the code to track the objects is readily available, minimum technical skill is required. If not considerable programming skills are required.

Thirdly some teachers were concerned about students asking questions about the tracking method, which they are not very comfortable. Some teachers may be reluctant to test new methods. However, with proper training teacher issues can be solved.

VII. CONCLUSION

Several standard high school physics experiments were conducted where computer vision based tracking was used to aid the data gathering. All the experiments resulted in producing better results than the standard methods used in laboratories. The proposed technique can be used to increase the accuracy and to create new ways of conducting science experiments. Although there are several limitations, they can overcome by careful planning.

VIII. ACKNOWLEDGMENT

Financial assistance by the University of Colombo Research Grant number 2012/CG/14 and Titan X GPU provided by the NVIDIA Corporation is acknowledged.

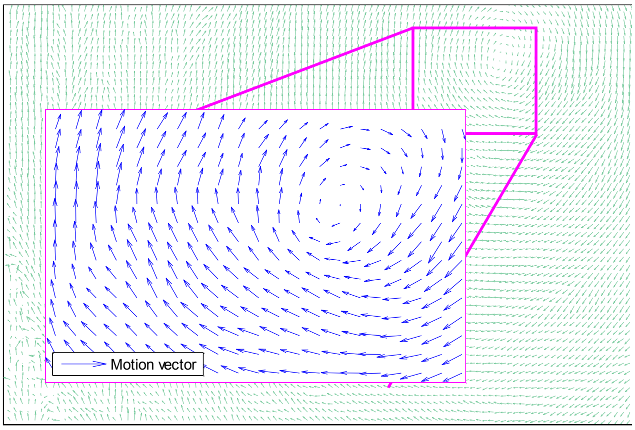


Fig. 10. Detected O.F. pattern

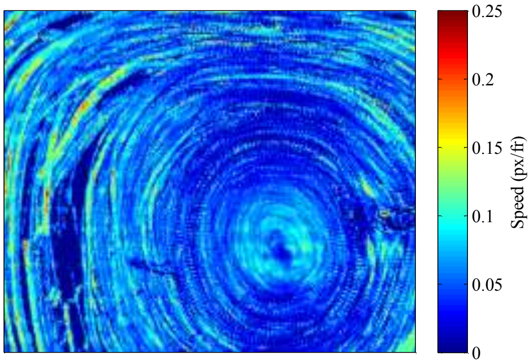


Fig. 11 Heat map of the speeds estimated at different regions

IX. REFERENCES

[1] I. Lakatos, "The role of crucial experiments in science," Stud. Hist. Philos. Sci. Part A, vol. 4, no. 4, pp. 309–325, Feb. 1974.

[2] C. Hammond, D. Karlin, and J. Thimonier, "Creative Research Science Experiences for High School Students," PLoS Biol., vol. 8, no. 9, , Sep. 2010.

[3] V. K. Otero and D. E. Meltzer, "100 Years of Attempts to Transform Physics Education," Phys. Teach., vol. 54, no. 9, pp. 523–527, Dec. 2016.

[4] G. Paschos, "Perceptually uniform color spaces for color texture analysis: an empirical evaluation," IEEE Trans. Image Process., vol. 10, no. 6, pp. 932–937, Jun. 2001.

[5] K. Y. Song, J. Kittler, and M. Petrou, "Defect detection in random colour textures," Image Vis. Comput., vol. 14, no. 9, pp. 667–683, Oct. 1996.

[6] L. Ding and A. Goshtasby, "On the Canny edge detector," Pattern Recognit., vol. 34, no. 3, pp. 721–725, Mar. 2001.

[7] P. S. Hiremath and J. Pujari, "Content Based Image Retrieval based on Color , Texture and Shape features using Image and its complement," Int. J. Comput. Sci. Secur., vol. 1, pp. 25–35, 2007.

[8] G. D. Illeperuma and U. J. Sonnadara, "Object Tracking Using Optical Flow," in Science Faculty Sessions, University of Colombo, 2011, 2011, vol. 31, no. 2011, pp. 319–323.

[9] K. Derpanis, The harris corner detector. 2004.

[10] Jianbo Shi and Tomasi, "Good features to track," in Proceedings of IEEE Conference on Computer Vision and Pattern Recognition CVPR-94, 1994, pp. 593–600.

[11] H. P. Moravec, "Rover visual obstacle avoidance," Proc. 7th Int. Jt. Conf. Artif. Intell. IJCAI, vol. 2, pp. 785–790, 1981.

[12] S. Javed, S. H. Oh, A. Sobral, T. Bouwmans, and S. K. Jung, "Background Subtraction via Superpixel-Based Online Matrix Decomposition with Structured Foreground Constraints," in Proceedings of the IEEE International Conference on Computer Vision, 2016, vol. 2016-Febru, pp. 930–938.

[13] A Elgammal, R. Duraiswami, D. Harwood, and L. S. Davis, "Background and foreground modeling using nonparametric kernel density estimation for visual surveillance," in Proceedings of the IEEE, 2002, vol. 90, no. 7, pp. 1151–1163.

[14] Z. Wu and R. Leahy, "An optimal graph theoretic approach to data clustering: theory and its application to image segmentation," IEEE Trans. Pattern Anal. Mach. Intell., vol. 15, no. 11, pp. 1101–1113, 1993.

[15] A. Blum and T. Mitchell, "Combining labeled and unlabeled data with co-training," in Proceedings of the eleventh annual conference on Computational learning theory - COLT' 98, 1998, pp. 92–100.

[16] C. P. Papageorgiou, M. Oren, and T. Poggio, "A general framework for object detection," in Sixth International Conference on Computer Vision, ICCV, 1998, pp. 555–562.

[17] C. J. Veenman, M. J. T. Reinders, and E. Backer, "Resolving motion correspondence for densely moving points," IEEE Trans. Pattern Anal. Mach. Intell., vol. 23, no. 1, pp. 54–72, 2001.

[18] D. Serby, E. K. Meier, and L. Van Gool, "Probabilistic object tracking using multiple features," in Proceedings of the 17th International Conference on Pattern Recognition, 2004. ICPR 2004., 2004, vol. 2, pp. 184–187.

[19] D. Comaniciu, V. Ramesh, and P. Meer, "Kernel-based object tracking," IEEE Trans. Pattern Anal. Mach. Intell., vol. 25, no. 5, pp. 564–577, May 2003.

[20] A. Yilmaz, Xin Li, and M. Shah, "Contour-based object tracking with occlusion handling in video acquired using mobile cameras," IEEE Trans. Pattern Anal. Mach. Intell., vol. 26, no. 11, pp. 1531–1536, Nov. 2004.

[21] A. Ali and J. K. Aggarwal, "Segmentation and recognition of continuous human activity," in Proceedings IEEE Workshop on Detection and Recognition of Events in Video, 2001, pp. 28–35.