Air quality monitoring using CCD/ CMOS devices

K. L. Low, C. E. Joanna Tan, C. K. Sim,
M. Z. Mat Jafri, K. Abdullah and H. S. Lim
Universiti Sains Malaysia
Penang, Malaysia

1. Introduction

The atmosphere, which makes up the largest fraction of the biosphere, is a dynamic system that continuously absorbs a wide range of solids, liquids as well as gases from both natural and man-made sources (M. Rao, Air Pollution, 1989).
The environmental pollution such as the air pollution is a common global issue especially in Malaysia. We encounter haze problem every year. This is due to the open burning after the harvest season in the country and also from the neighboring country. The worst of these events caused Malaysia to declare an emergency in 1997 for Kuching, Sarawak, and in 2005 for Port Klang and the district of Kuala Selangor. Air pollution was defined as "the presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, gas, mist, odor, smoke or vapor in quantities of characteristics, and of duration, such as to be injurious to human, plant, or property, or which unreasonably interferes with the comfortable enjoyment of life and property" (Lawrence K. Wang *et.al.*, 2004), is not a recent phenomenon.

Air pollution affects human health and reduces the quality of our land and water. We cannot escape from it, even in our own homes. In particular, environmental pollution is a persistent problem in Malaysia. Atmosphere contains various sizes of particles. Light is absorbed when sunlight penetrates through the atmospheric layer. This is because aerosol reduces 10% of light intensity when light reaches the earth surface. Air quality data is an important formula for monitoring and managing the environment. Air pollution can cause death, impair health, reduce visibility, bring about vast economic losses and contribute to the general deterioration of both our cities and country-side. It can also cause intangible losses to historical monuments such as the Taj Mahal which is believed to be badly affected by air pollution (M. Rao, 1989).

Air pollution also means different things to different people. To the householder it may be an eye irritation and soiled clothing, to the farmer damaged vegetation, to the pilot dangerously reduced visibility and to industries problems of process control and public relations (M. Rao, 1989).

Generally, human activities also cause some mankind sources to air pollution for instance cooking, invented heating appliances and pets often make important contribution to expose and induce monotonous accumulation of pollutants. Road traffic, however, generally provides the major source of ambient particulate pollution.

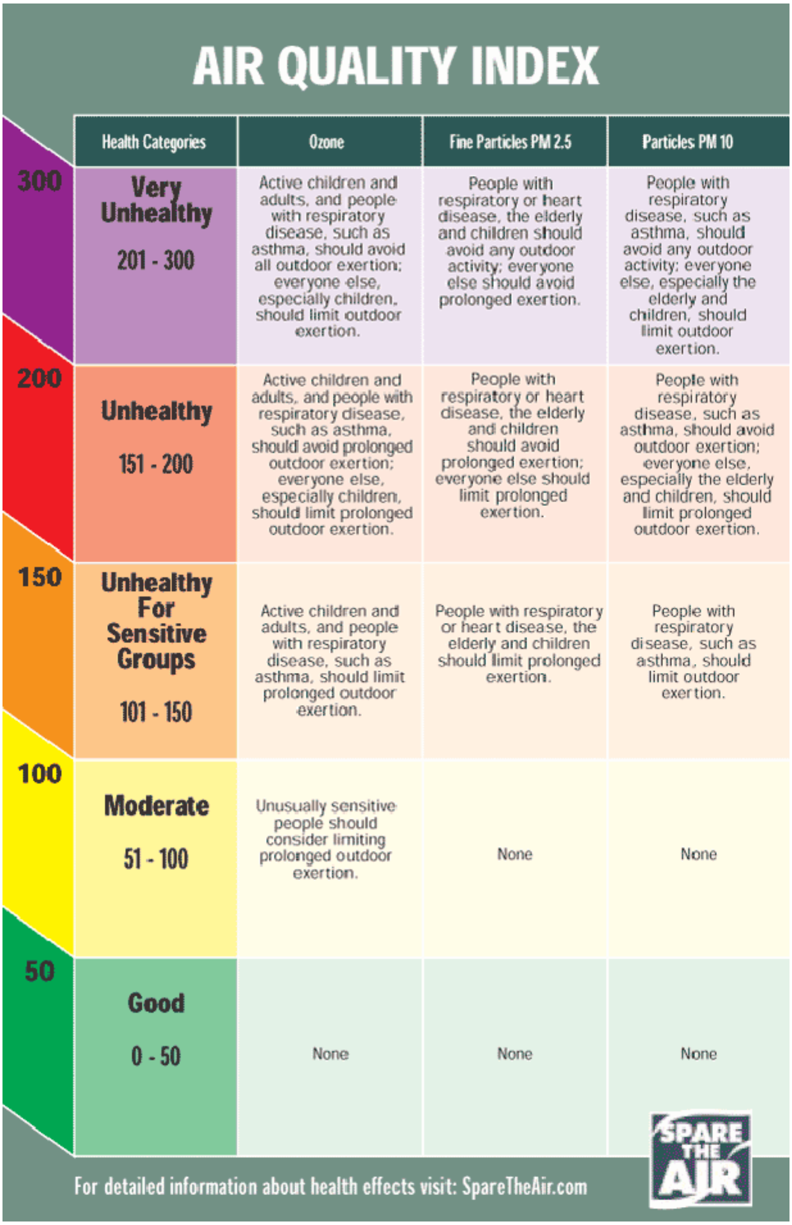
Remote sensing techniques have been widely used for environmental pollution application such as water quality (Dekker *et.al.*, 2002, Doxaran *et. al.*, 2002 and Tassan, S. 1997) and air pollution (Ung, et.al., 2001b). Several studies had shown the relationships between satellite data and air pollution concentration (Ung et al., 2001a; Weber, et.al., 2001). Other researchers used satellite data in such environment atmospheric studies such as NOAA-14 AVHRR (Asmala Ahmad and Mazlan Hashim, 2002) and TM Landsat (Weber, et.al., 2001). But the main drawback of satellite images is the difficulty in obtaining cloud-free scenes especially at the Equatorial region. This problem can be overcome by using airborne images. In fact, air quality can be measured using ground instrument such as air samplers. But these instruments are quite expensive and a limited number of stations are available in each area. So, they cannot provide a good spatial distribution of the air pollutant readings over a city.

The objective of this study is to test the potential of using remote sensing and digital image processing techniques for air quality measurements. The digital images were captured using a normal CCTV and webcam. We used visible digital CCTV and webcam imageries for this purposed. This study tested a normal CCTV and webcam for air quality detection. This CCTV and webcam captured images in visible wavelengths. In situ PM_{10} data were collected simultaneously with the acquired digital imageries. This corresponding data were used for algorithm regression analysis. This study showed the feasibility of using the digital camera for the determination of PM_{10}. An algorithm was developed based on the atmospheric characteristic in the visible bands. The development of the algorithm was developed base on the aerosol characteristics in the atmosphere.

1.1 The measurement of air quality - Air Quality Index (AQI)

The Air Quality Index (AQI) (also known as Air Pollution Index (API) or Pollutant Standard Index (PSI)) is a tool developed by EPA to provide people with timely and easy to understand information on local air quality and whether it poses a health concern. The air quality index is shown in Figure 1. It provides a simple system that can be used throughout the country for reporting levels of major pollutants regulated under the Clean Air Act, including ground-level ozone and particulate matter.

The AQI converts measured pollutant concentration to a number on scale of 0-500. The higher the index value is, the greater the health concern. For most of the criteria pollutants, the AQI valued of 100 corresponds to the National Ambient Air Quality Standard established for the pollutant under the Clean Air Act. This is the level that EPA has determined to be generally protective of human health (Scott Hedges, 2002).



AIR QUALITY INDEX

	Health Categories	Ozone	Fine Particles PM 2.5	Particles PM 10
300	Very Unhealthy 201 - 300	Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion.	People with respiratory or heart disease, the elderly and children should avoid any outdoor activity; everyone else should avoid prolonged exertion.	People with respiratory disease, such as asthma, should avoid any outdoor activity; everyone else, especially the elderly and children, should limit outdoor exertion.
200	Unhealthy 151 - 200	Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion.	People with respiratory or heart disease, the elderly and children should avoid prolonged exertion; everyone else should limit prolonged exertion.	People with respiratory disease, such as asthma, should avoid outdoor exertion; everyone else, especially the elderly and children, should limit prolonged outdoor exertion.
150	Unhealthy For Sensitive Groups 101 - 150	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.	People with respiratory or heart disease, the elderly and children should limit prolonged exertion.	People with respiratory disease, such as asthma, should limit outdoor exertion.
100	Moderate 51 - 100	Unusually sensitive people should consider limiting prolonged outdoor exertion.	None	None
50	Good 0 - 50	None	None	None

For detailed information about health effects visit: SpareTheAir.com

Fig. 1. Air Quality Index (SpareTheAir.com)

1.2 The root cause and new invention of Air Quality Monitoring CCD/CMOS Devices

Air pollution is one of the most important environmental problems. In Malaysia, the country encounters the haze problem almost every year. It is due to the illegal open burning activities after each harvesting season in the country as well as in the neighbouring country.

The worst cases of air pollution lead to the emergency declarations at Kuching, Sarawak in 1997, and at Port Klang as well as the district of Kuala Selangor in 2005. The declarations were made when the Air Quality Index (AQI) which is also known as Air Pollution Index (API) or Pollutant Standard Index (PSI) values reached dangerous levels. Haze contains different sizes of pollutants. They are harmful and dangerous to human being as they can affect our respiratory system as well as cause death. However, with human naked eyes, it is hard to measure the air quality or the particle concentration in air to take prevention steps especially to those having respiratory problem patients. Therefore, a new method which is cheap and simple but effective to detect air pollution is introduced in this chapter to monitor the air quality.

The advance development in CCD/ CMOS devices such as CCTV and webcam enables us to capture images in real time and also in digital format. Digital camera is then calibrated with irradiance.

The calibrated digital camera coefficients are

$$y_1 = 0.0004x_1 + 0.0612 \quad (1)$$
$$y_2 = 0.0006x_2 + 0.0398 \quad (2)$$
$$y_3 = 0.0005x_3 + 0.0511 \quad (3)$$

where

y_1 = irradiance for red band ($Wm^{-2}\ nm^{-1}$)
y_2 = irradiance for green band ($Wm^{-2}\ nm^{-1}$)
y_3 = irradiance for blue band ($Wm^{-2}\ nm^{-1}$)
x_1 = digital number for red band
x_2 = digital number for green band
x_3 = digital number for blue band

After that, the irradiance values were converted into reflectance values for each band by using equation (4). Each reflectance value represents, ρ_T the total reflectance value of digital images. This equation requires the sun radiation value on the surface transmittance detected by spectroradiometer. The parameter depends on factors such as atmosphere and sun position.

$$R_{atm} = \frac{\pi L(\lambda)}{E_s(\lambda)} \quad (4)$$

where

$L(\lambda)$ = sun radiation ($Wm^{-2}sr^{-1}\mu m^{-1}$)
$E_s(\lambda)$ = radiation of sunlight on the surface measured by the spectroradiometer. ($Wm^{-2}\mu m^{-1}$)

Then, an algorithm was developed based on the relationship between the atmospheric reflectance and the corresponding air quality. The captured images were separated into three bands namely red, green and blue and their digital number values were determined. A special transformation was then performed to the data. Ground PM10 measurements were taken by using DustTrak™ meter. The algorithm was calibrated using a regression analysis. The proposed algorithm produced a high correlation coefficient (R) and low root-mean-square error (RMS) between the measured and produced PM10. The analysis was carried out using data collected by a webcam (K. L. Low, 2007) and Penang Bridge CCTV system. (K. L. Low, 2006, 2007, 2007)

2. Methodology

In this study a modification was made to the model developed by Ahmad and Hashim (1997). Skylight is an indirect radiation, which occurs when the radiation from the sun being scattered by elements within the air pollutant column. It is not a direct radiation, which is dominated by pixels on the reference surface. Figure 2 shows electromagnetic radiation path propagating from the sun towards the digital camera penetrating through the air pollutant column (Source: Modified after Ahmad and Hashim, 1997).

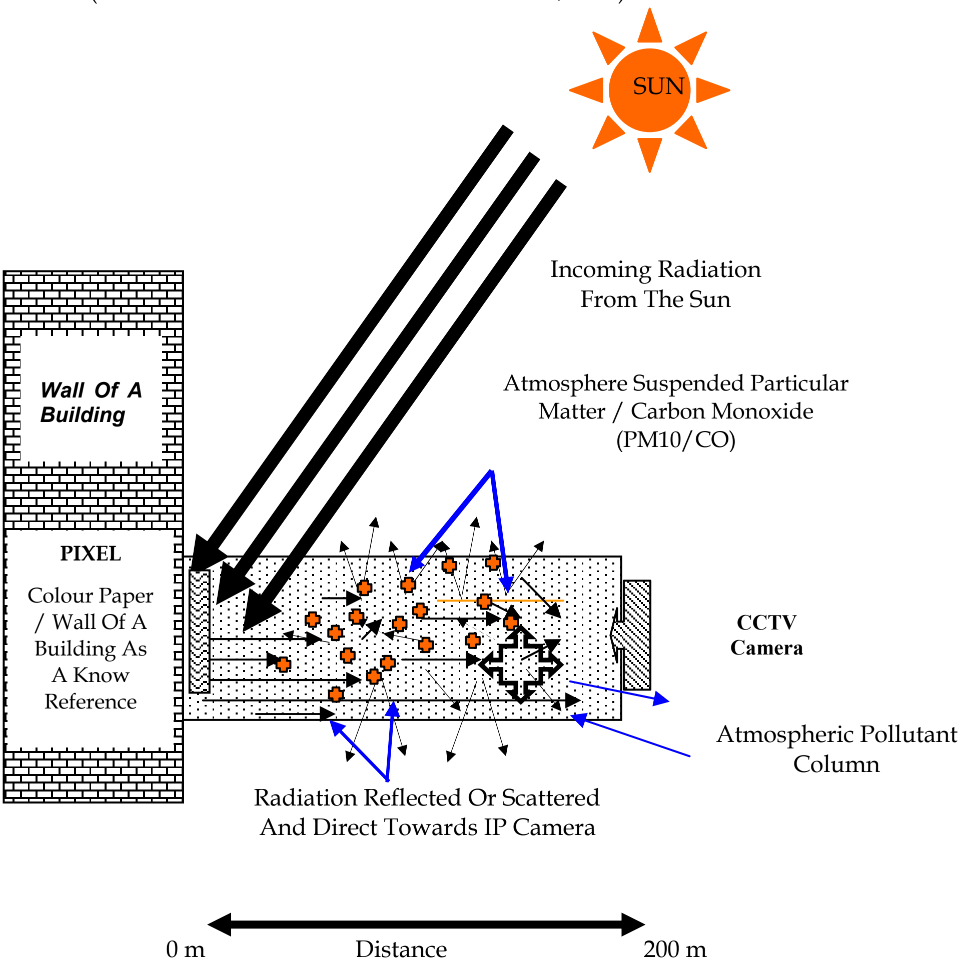


Fig. 2. The skylight parameter model (Source: Modified after Ahmad and Hashim, 1997)

The modified model is described by:

$$R_s - R_r = R_a \quad (5)$$

where R_s = reflectance recorded by IP camera sensor, R_r = reflectance from the known reference and R_a = reflectance from atmospheric scattering.

2.1 Algorithm Model

The atmospheric reflectance due to molecule, R_r, is given by (Liu, et al., 1996)

$$R_r = \frac{\tau_r P_r(\Theta)}{4\mu_s\mu_v} \quad (6)$$

where τ_r = Aerosol optical thickness (Molecule), $P_r(\Theta)$ = Rayleigh scattering phase function, μ_v = Cosine of viewing angle and μ_s = Cosine of solar zenith angle. We assume that the atmospheric reflectance due to particle, R_a, is also linear with the τ_a [King, et al., (1999) and Fukushima, et al., (2000)]. This assumption is valid because Liu, et al., (1996) also found the linear relationship between both aerosol and molecule scattering.

$$R_a = \frac{\tau_a P_a(\Theta)}{4\mu_s\mu_v} \quad (7)$$

where τ_a = Aerosol optical thickness (aerosol) and $P_a(\Theta)$ = Aerosol scattering phase function. Atmospheric reflectance is the sum of the particle reflectance and molecule reflectance, R_{atm}, (Vermote, et al., 1997).

$R_{atm}=R_a+R_r$ (8)

where R_{atm}=atmospheric reflectance, R_a=particle reflectance and R_r=molecule reflectance.

$$R_{atm} = \left[\frac{\tau_a P_a(\Theta)}{4\mu_s\mu_v} + \frac{\tau_r P_r(\Theta)}{4\mu_s\mu_v}\right]$$

$$R_{atm} = \frac{1}{4\mu_s\mu_v}\left[\tau_a P_a(\Theta) + \tau_r P_r(\Theta)\right] \quad (9)$$

The optical depth is given by Camagni and Sandroni, (1983), as in equation (10). From the equation, we rewrite the optical depth for particle and molecule as equation (11) and (12)

$\tau = \sigma\rho s$ (10)

where τ = optical depth, σ = absorption and s = finite path

$\tau = \tau_a + \tau_r$ (Camagni and Sandroni, 1983)

$$\tau_r = \sigma_r\rho_r s \quad (11)$$

$$\tau_p = \sigma_p\rho_p s \quad (12)$$

Equations (11) and (12) are substituted into equation (9). The result was extended to a three bands algorithm as equation (13). Form the equation we found that PM10 was linearly related to the reflectance for band 1 and band 2. This algorithm was generated based on the linear relationship between τ and reflectance. Retalis et al., (2003), also found that the PM10 was linearly related to the τ and the correlation coefficient for linear was better that exponential in their study (overall). This means that reflectance was linear with the PM10. In order to simplify the data processing, the air quality concentration was used in our analysis instead of using density, ρ, values.

$$R_{atm} = \frac{1}{4\mu_s\mu_v}\left[\sigma_a\rho_a s P_a(\Theta) + \sigma_r\rho_r s P_r(\Theta)\right]$$

$$R_{atm} = \frac{s}{4\mu_s\mu_v}\left[\sigma_a\rho_a P_a(\Theta) + \sigma_r\rho_r P_r(\Theta)\right]$$

$$R_{atm}(\lambda_1) = \frac{s}{4\mu_s\mu_v}\left[\sigma_a(\lambda_1)PP_a(\Theta,\lambda_1) + \sigma_r(\lambda_1)GP_r(\Theta,\lambda_1)\right]$$

$$R_{atm}(\lambda_2) = \frac{s}{4\mu_s\mu_v}\left[\sigma_a(\lambda_2)PP_a(\Theta,\lambda_2) + \sigma_r(\lambda_2)GP_r(\Theta,\lambda_2)\right]$$

$$P = a_0 R_{atm}(\lambda_1) + a_1 R_{atm}(\lambda_2) \tag{13}$$

where P = Particle concentration (PM10), G = Molecule concentration, R_{atmi}= Atmospheric reflectance, i = 1, 2 and 3 are the band number and a_j= algorithm coefficients, j = 0, 1, 2,… are then empirically determined.

3. Applications

3.1 WebCAM

3.1.1 Study area

The study area is Universiti Sains Malaysia, Penang Island, Malaysia. It is located at longitude of 100^0 17.864′ and latitude of 5^0 21.528′. The university campus is situated in the northeast district of Penang island (Figure 3).

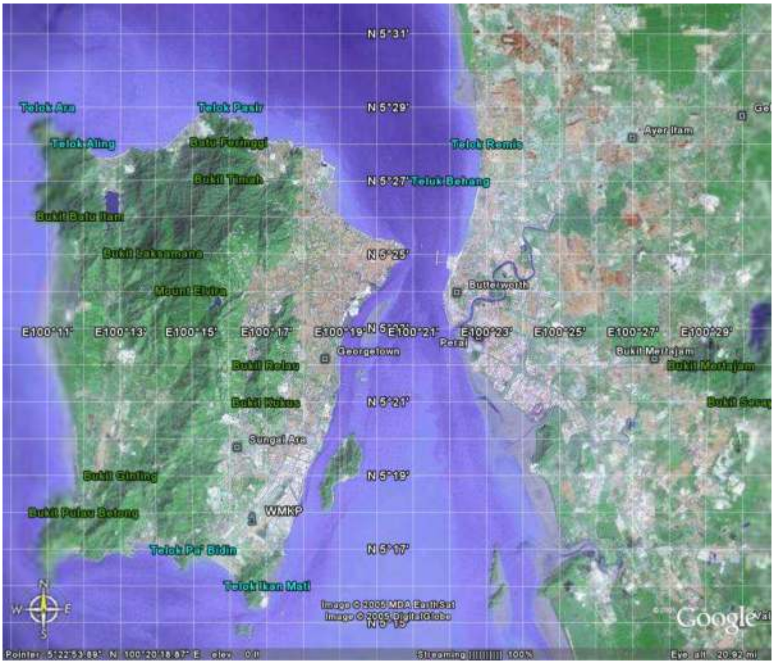


Fig. 3. Study area

3.1.2 Methodology

The digital images were captured during a period from 9.00am to 6pm. The images were captured at half an hour interval and simultaneously with the air quality data measurement. The sample image is shown in Figure 4. The digital number values of the images were extracted and converted into irradiance values using equations (1), (2) and (3) and then converted into reflectance values using equation (4) for each visible band.

Fig. 4. The image captured by using webcam

After that, the reflectance recorded by the web cam was subtracted by the reflectance of a known surface feature (equation(5)) and we obtained the reflectance caused by the atmospheric components. The relationship between the atmospheric reflectance and the corresponding air quality data was determined by using a regression analysis. For the proposed regression model, the correlation coefficient, R, and the root-mean-square deviation, RMS, were noted. The proposed equation is shown in equation(14). The proposed algorithm produced the correlation coefficient of 0.7320 between the predicted and the measured PM10 values and RMS value of 18.7137 mg/m^3. With the present data set, the R and RMS values produced by the proposed algorithm for PM 10 is shown in Figure 5.

$$PM10 = -484.8459 y_1 + 3249.8387 y_2 - 741.5425 y_3 - 1374.4198 \quad (14)$$

where y_1 = irradiance for red band (Wm^{-2} nm^{-1})
y_2 = irradiance for green band (Wm^{-2} nm^{-1})
y_3 = irradiance for blue band (Wm^{-2} nm^{-1})
$PM10$= particulate matter 10µg/m^3

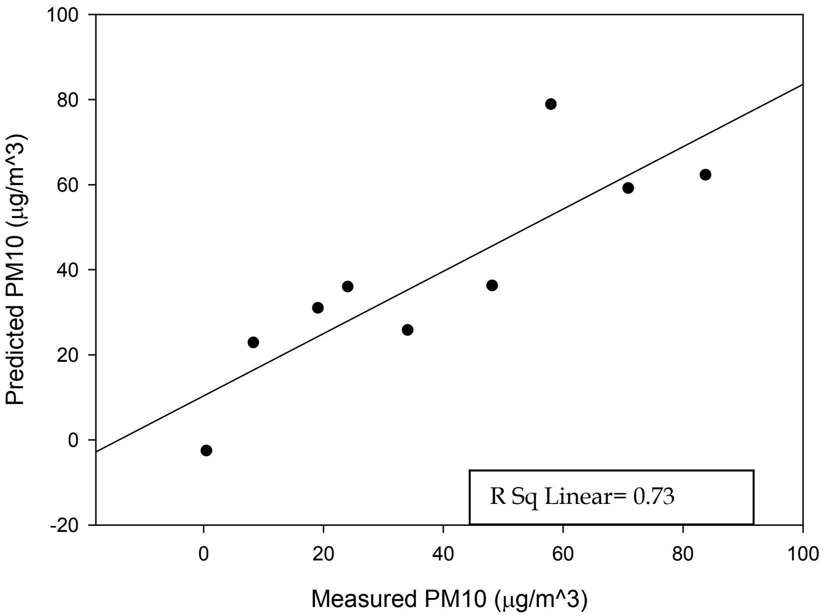


Fig. 5. Correlation coefficient measured and estimated PM10 (mg/m^3) value for calibration analysis

3.2 Penang bridge CCTV

3.2.1 Study Area

There are 8 CCTV cameras installed at 8 different places on Penang Bridge and as shown in Figure 6. The purpose of the camera system is to monitor the flow of traffic on the Penang Bridge. The access of data from the cameras is open for public and is available on http://pbcam.blogspot.com. Not all of the 8 cameras could be used for the air quality study. The camera that we used was Cam 3 because the scenes captured by this camera contained the most number of vegetation pixels. It is suitable to be used as reference target.

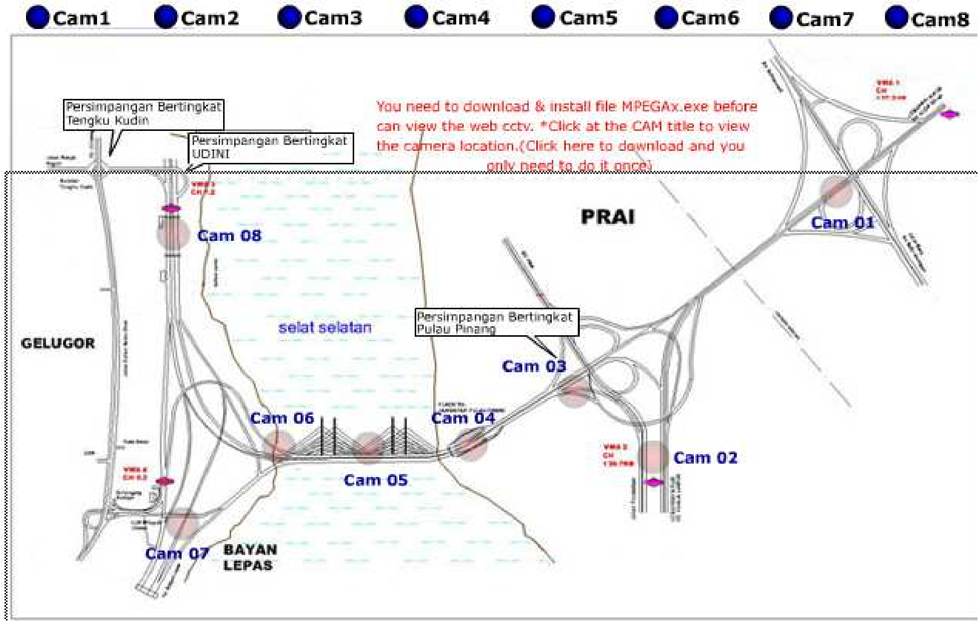


Fig. 6. Locations of the CCTV along the Penang Bridge.

3.2.2 Methodology

The CCTV camera Cam 7 is located at Bayan Lepas interchange to Penang Bridge (Penang Island). It captured digital images of Penang Bridge (Figure 6). We used green vegetation as our reference target. The camera was at about 90° with the plane of the reference target. Our reference targets are images of green vegetation canopies located at near and at a kilometer away from the camera. The data were captured from 9.00am until 5.00pm at every 1 hour interval. The example image is shown in Figure 7. All image-processing tasks were carried out using PCI Geomatica version 9.1.8 digital image processing software at the School Of Physics, University Sains Malaysia (USM). A program was written by using Microsoft Visual Basic 6.0 to download still images from the camera over the internet automatically and implement the newly developed algorithm. The digital images were separated into three bands (red, green and blue). The DN values were extracted and converted into irradiance values using equation (1), (2) and (3), and then converted into reflectance values using equation (4) for each visible bands.

Fig. 7. The digital image used in this study.

After that, the reflectance recorded by the IP camera was subtracted by the reflectance of the known surface (equation (5)) and we obtained the reflectance caused by the atmospheric components. The relationship between the atmospheric reflectance and the corresponding air quality data for the pollutant was carried out using regression analysis. For the proposed regression model, the correlation coefficient, R, and the root-mean-square deviation, RMS, were noted. The proposed algorithm is shown in equation(15). The proposed algorithm produced the highest correlation coefficient of 0.7650 between the predicted and the measured PM10 values and lowest RMS value of 0.0070 mg/m^3. Red and green bands are considered in this algorithm model because it produced the highest correlation coefficient. With the present data set, the R and RMS values produced by the proposed algorithm for PM 10 is shown in Figure 8.

$$PM10 = 0.3664 y_1 - 0.3728 y_2 - 0.0547 \tag{15}$$

where y_1 = irradiance for red band (Wm^{-2} nm^{-1})
y_2 = irradiance for green band (Wm^{-2} nm^{-1})
*PM*10= particulate matter 10mg/m^3

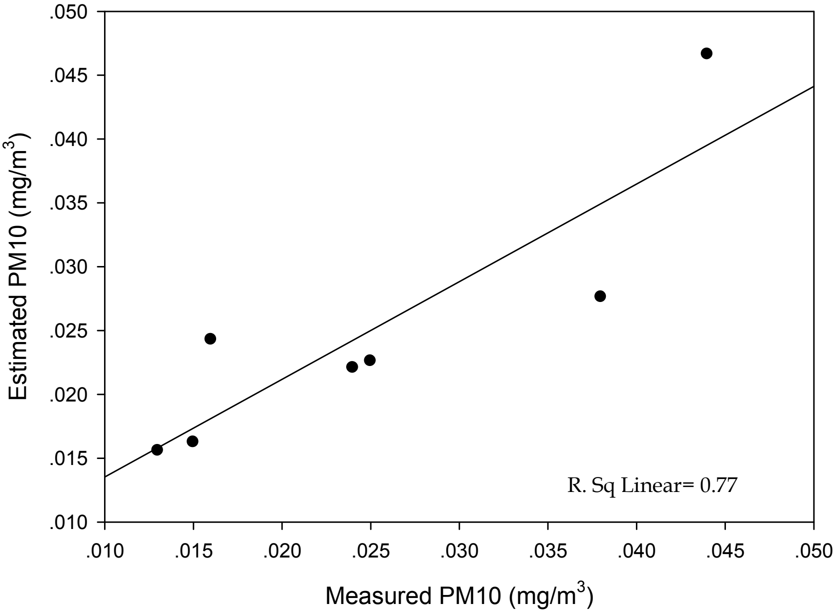


Fig. 8. Correlation coefficient of the measured and estimated PM10 (mg/m3) value for calibration analysis

4. Conclusion

In this chapter, we showed a method for measuring of the air quality index by using the CCD/CMOS sensor. We showed two examples to obtain index values by using webcam and CCTV. Both devices provided a high correlation between the measured and estimated PM10. So, the imaging method is capable to measure PM10 values in the environment. Futher application can be conducted using different devices.

5. Acknowledgements

This project was carried out using a USM short term grants. We would like to thank the technical staff who participated in this project. Thanks are extended to USM for support and encouragement.

6. Reference

Ahmad, A and Hashim, M., 1997, Determination of Haze from Satellite Remotely Sensed Data: Some Preliminary Results, [Online] available: http://www.gisdevelopment.net/aars/acrs/1997/ps3/ps3011.shtml.

Camagni, P. and Sandroni, S., 1983, Optical Remote sensing of air pollution, Joint Research Centre, Ispra, Italy, Elsevier Science Publishing Company Inc.

Dekker, A. G., Vos, R. J. and Peters, S. W. M. (2002). *Analytical algorithms for lakes water TSM estimation for retrospective analyses of TM dan SPOT sensor data*. International Journal of Remote Sensing, 23(1), 15−35.

Doxaran, D., Froidefond, J. M., Lavender, S. and Castaing, P. (2002). *Spectral signature of highly turbid waters application with SPOT data to quantify suspended particulate matter concentrations*. Remote Sensing of Environment, 81, 149−161.

Fukushima, H., Toratani, M., Yamamiya, S. and Mitomi, Y., 2000, Atmospheric correction algorithm for ADEOS/OCTS acean color data: performance comparison based on ship and buoy measurements. Adv. Space Res, Vol. 25, No. 5, 1015-1024.

King, M. D., Kaufman, Y. J., Tanre, D. dan Nakajima, T., 1999, Remote sensing of tropospheric aerosold form space: past, present and future, Bulletin of the American Meteorological society, 2229-2259.

Lawrence K.Wang, Norman C. Pereira, Yung-Tse Hung, Air pollution control engineering, 2004

Liu, C. H., Chen, A. J. and Liu, G. R., 1996, An image-based retrieval algorithm of aerosol characteristics and surface reflectance for satellite images, International Journal Of Remote Sensing, 17 (17), 3477-3500.

M. Rao, H.V.N. Rao, Air Pollution, McGraw Hill, 1989

Retalis, A., Sifakis, N., Grosso, N., Paronis, D. and Sarigiannis, D., Aerosol optical thickness retrieval from AVHRR images over the Athens urban area, [Online] available: http://sat2.space.noa.gr/rsensing/documents/IGARSS2003_AVHRR_Retalisetal_web.pdf. SpareTheAir.com

Scott Hodges, Planning and implementing a real-time air pollution monitoring and outreach Program for Your Community, 2002.

Tassan, S. (1997). A numerical model for the detection of sediment concentration in stratified river plumes using Thematic Mapper data. International Journal of Remote Sensing, 18(12), 2699−2705.

Ung, A., Weber, C., Perron, G., Hirsch, J., Kleinpeter, J., Wald, L. and Ranchin, T., 2001a. Air Pollution Mapping Over A City – Virtual Stations And Morphological Indicators. Proceedings of 10th International Symposium "Transport and Air Pollution" September 17 - 19, 2001 – Boulder, Colorado USA.

Ung, A., Wald, L., Ranchin, T., Weber, C., Hirsch, J., Perron, G. and Kleinpeter, J., 2001b., Satellite data for Air Pollution Mapping Over A City- Virtual Stations, Proceeding of the 21th EARSeL Symposium, Observing Our Environment From Space: New Solutions For A New Millenium, Paris, France, 14 – 16 May 2001, Gerard Begni Editor, A., A., Balkema, Lisse, Abingdon, Exton (PA), Tokyo, pp. 147 – 151,

Vermote, E., Tanre, D., Deuze, J. L., Herman, M. and Morcrette, J. J., 1997, Second Simulation of the satellite signal in the solar spectrum (6S), Weber, C., Hirsch, J., Perron, G., Kleinpeter, J., Ranchin, T., Ung, A. and Wald, L. 2001. Urban Morphology, Remote Sensing and Pollutants Distribution: An Application To The City of Strasbourg, France. International Union of Air Pollution Prevention and Environmental Protection Associations (IUAPPA) Symposium and Korean Society for Atmospheric Environment (KOSAE) Symposium, 12th World Clean Air & Environment Congress, Greening the New Millennium, 26 – 31 August 2001, Seoul, Korea.

K. L. Low, C.J. Wong, H. S. Lim, M. Z. MatJafri, K. Abdullah, Siti Munirah bt Azmi and Nurharin bt Che Mohamed Nor, 2006, Air Quality Monitoring Along Penang Bridge Over Internet Through Surveillance Camera, International Conference on Space Technology and Geo-informatics 2006.

K. L. Low, H. S. Lim, M. Z. MatJafri, K. Abdullah, H. G. Ng and C. J. Wong, Evaluation Of CCTV Camera Images For PM10 Monitoring, National Conference on Environment & Community Development 2007.

K. L. Low, H. S. Lim, M. Z. MatJafri, K. Abdullah, C. J. Wong, *"Real Time Pm10 Concentration Monitoring On Penang Bridge By Using Traffic Monitoring CCTV"*, SPIE 2007.

K. L. Low, H. S. Lim, M. Z. MatJafri, K. Abdullah, C. J. Wong, H. G. Ng, "Air Quality Monitoring Using Webcam", ECOMOD 2007.